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BOOK OF ABSTRACTS

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CONTENTS

International Conference and School on Plasma Physics and Controlled Fusion ICPPCF-2016 follows the previous International Conferences, which were held in Alushta in 1998, 2000, 2002, 2004, 2006, 2008, 2010, 2012 and in Kharkov in 2014. ICPPCF conferences were organized by the National Science Center "Kharkov Institute of Physics and Technology" of the National Academy of Science, N.N. Bogolyubov Institute for Theoretical Physics and V.N. Karazin Kharkiv National University. More than 100 participants (from 11 countries) presented about 200 reports during ICPPCF-2014 Conference.

ICPPCF-2016 is sponsored by the National Academy of Science of Ukraine, National Science Center "Kharkov Institute of Physics and Technology", Bogolyubov Institute for Theoretical Physics, European Physical Society (EPS) and Science and Technology Center in Ukraine (STCU). About 200 abstracts were submitted by Ukrainian and foreign authors and selected by the Program Committee for presentation at the ICPPCF-2016 Conference. All the abstracts have been divided into 8 groups according to the topics of the Conference Program.

Since the abstracts presented in this volume were prepared in camera-ready form, and the time for the technical editing was very limited, the Editors and the Publishing Office do not take responsibility for eventual errors. Hence, all the questions referring to the context or numerical data should be addressed to the authors directly.

We hope that the contributed papers and invited talks, to be given at the Conference, will supply new valuable information about the present status of plasma physics and controlled fusion research. We also hope that the Conference will promote further development of plasma physics and fusion oriented research as well as the scientific collaboration among different plasma research groups in Ukraine and abroad.

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I-01

STUDIES OF STEADY STATE MIRROR BASED FUSION NEUTRON SOURCES CONCEPTS

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Intense neutron sources offer a possibility for application of fusion in a not too distant future. Application areas include fusion material testing, power production and incineration of spent nuclear fuel. The fusion neutron source has to be capable of steady-state operation, which rules out axisymmetric toroidal devices constrained by the need to drive an inductive plasma current. Our studies are for this reason restricted to mirror machines and stellarators. The stellarator-mirror concept is introduced by Khipt at Kharkiv. Our studies address several critical issues on particle confinement, plasma heating, plasma stability and magnetic coil design, where critical material problems may be handled by careful geometrical arrangements. Reactor safety and engineering requirements of the design are also addressed in Monte Carlo computations for the neutrons.

The SFLM (Straight Field Line Mirror) concept is based on a quadrupolar magnetic mirror field to achieve gross MHD stability. Expanders outside the confinement region have large plasma receiving surfaces to withstand heat load and particle bombardment. The mirror effect, which is a consequence of the conservation of the particle's energy and magnetic moment, is a mechanism for particle confinement in the longitudinal direction, but also radial confinement is required, where radial drifts introduced by a quadrupolar field is a threat. However, our derivations predict that radial confinement for all particles, in the collision free approximation, can be arranged by a weak radial electric field, which can be controlled by biased endplates. The mechanism involved is the enforced slow plasma rotation around the magnetic axis. This conclusion is supported by the observed confinement improvement in several experiments where biased electric fields have been introduced. The derived perfect radial confinement is associated with the existence of a radial constant of motion.

The mirror and stellarator-mirror concepts have several features in common, such as steady state operation, a local neutron production and similar solutions for access to the plasma, feeding of plasma heating and designs of fission core. A main advantage of the toroidal concept is the elimination of longitudinal losses, where a moderate price is paid for added complexity, but new threats arise in stellarators for radial loss: Nested magnetic surfaces exist only in a certain region, but even in these regions a collision free radial drift loss can be present due to magnetic drifts. A spontaneously generated radial electric field is predicted to introduce a dramatic improvement in radial confinement in these regions. The generation of a slow plasma rotation around the magnetic axis is the responsible mechanism also in this case.

Special schemes are worked out for plasma heating (by ICRH or neutral beams injection), where care is also taken to shield components. 3D superconducting coils can produce the magnetic field, with sufficient space available for shielding. An important prediction is low value of the fusion Q factor required for power production. This correspond to scenarios with high power amplification by fission. Within the reactor safety studies made, power production may be possible with $Q = 0.15$. Several reactor safety issues are studied, such as passive circulation of coolants and loss of coolant scenarios. Although the predictions on reactor safety and other designs criteria are encouraging, it should be emphasized that the studies need to be deepened further.

I-02

ICRF heating in ASDEX Upgrade with W wall

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The ASDEX Upgrade system for ICRF (Ion Cyclotron Range of Frequencies) heating is used in various studies of tokamak scenario development and fast particle physics. However since the installation of high-Z tungsten (W) coated limiters on the ICRF antennas, the ICRF heating was accompanied by a significant increase of the W content in the plasma. The beneficial effect of the ICRF heating was often counteracted by significant plasma cooling due to the W radiation. Two methods to tackle this issue are applied at AUG: a) tailoring the SOL (Scrape-Off Layer) properties by local gas puffing to increase the density locally at the antennas and reduce the plasma edge temperature; b) reducing sheath driving RF electric fields close to the antenna limiters by an optimised RF antenna design.

The increase of density close to the antenna limiters at the outer wall by using local gas valves reduces the W sputtering as well as improves the antenna RF loading. This local density modification is now better understood with the help of the 3D EMC3-Eirene simulations that show the strongest density inhomogeneity for the gas valves at the outer wall.

The reduction of the sheath driving RF electric fields is achieved by development of antenna concepts based on the principle of minimization of local RF image currents at protruding antennas structures. The newly installed 3-strap antennas show a consistent reduction of the W sputtering and of the W content in the plasma. The measurements of the core W concentration show that the W release associated with the 3-strap antennas is the same as that associated with the 2-strap antennas with low-Z boron coated limiters. The local response of the RF image currents at the antenna limiters to scans of the antenna feeding parameters is consistent with that from the electro-magnetic calculations, although the density fluctuations in the SOL strongly affect their local superposition.

I-03

TRANSPORT AND PLASMA CONTROL IN THE TJ-II STELLARATOR

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Recent improvements in TJ-II plasma diagnostics, including the operation of a dual Heavy Ion Beam Probe and a pellet injection system, have allowed us to perform studies to get a better understanding of plasma confinement properties. TJ-II plasmas studied here were heated by ECRH (2 x 300 kW gyrotrons, at 53.2 GHz, 2nd harmonic, X-mode polarisation) and NBI (co and counter 700 kW port-through power at 33 kV). The following topics have been investigated in TJ-II:

Impurity transport: We present the calculation results that show that electrostatic potential variations within the same magnetic flux surface affect impurity accumulation, so direct measurements of such asymmetries in ECRH TJ-II plasmas are presented: the asymmetry value and its observed dependency on the electric field are reproduced by neoclassical MC calculations. The dependence of the impurity confinement time on charge and mass has also been studied experimentally, showing different scaling laws for light and heavy impurities. The impurity hole physics, formerly observed in LHD, is studied as well.

Momentum transport and electromagnetic effects: Experiments have shown evidence of the influence of ECRH on turbulent mechanisms, increasing both the fluctuation level and the amplitude of Long-Range-Correlations, which could be a proxy of Zonal Flows (ZF), as well as affecting NC radial electric fields. Radial electric fields, ZF-like structures that resemble ZFs, time memory and radial correlations are modulated by modulated by MHD activity stemming from low order rationals[1]. It is shown that magnetic oscillations associated with rational surfaces play a key role in confinement transitions. Furthermore, evidence of the mutual interaction of NC and turbulent mechanisms in qualitative agreement with GK simulations is presented.

Innovative power-exhaust scenarios using liquid metals: Novel solutions for plasma facing components based on liquid metals like Li and Sn/Li alloys have been developed. Biasing of Li limiters with respect to carbon ones has evidenced the role of the secondary electron emission of plasma exposed surfaces[2]. As an advantage of Li coating, NBI plasma start up has been achieved in TJ-II under Li coated walls without the help of any external power supply.

Plasma stability studies: It has been shown that a reduction of magnetic well has a direct impact on fluctuations without reducing plasma confinement drastically, suggesting that Mercier stability calculations are missing some stabilization mechanisms[3].

Plasma fuelling experiments and neutral dynamics: First core plasma fuelling experiments using a cryogenic pellet injector are presented, being the radial redistribution of particles qualitatively understood from NC predictions. These results show that pellets that do not reach the magnetic axis may still be able to mitigate core density depletion. First results on the impact of neutral fluctuations on the observed turbulent structures will be also reported.

Role of ECRH and configuration on fast ion confinement: TJ-II results show that ECRH[4], iota-profile[5] and magnetic well[6] are potential tools for Alfvén modes control. The two first tools can trigger frequency chirping in some conditions, while magnetic well scan modifies the frequency and amplitude. Low frequency AEs in NBI-heated plasmas are explained as global (GAE), helical (HAE) and discrete shear-AEs induced by magnetic islands in TJ-II[7]. The latter offer perspectives for AE control via magnetic configuration.

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I-04

FORMATION OF AMMONIA DURING N_2-SEEDED DISCHARGES IN TOKAMAKS WITH METALLIC PLASMA-FACING SURFACES

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**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint-Petersburg, Russia*

Based on the concerns over fuel retention and dust production from carbon-fibre composite plasma facing components (PFCs), and encouraged by the successful transition to full metal inner walls at ASDEX-Upgrade (AUG) and later JET, the decision was made that ITER will be built with a full-W divertor. In order to keep the divertor heat load within the limits set by the power-handling capabilities of PFCs, impurity seeding will be used routinely. Impurity seeding promotes energy dissipation through radiation in the plasma edge. Among the tested impurities, nitrogen (N_2) has been shown to provide the most favourable results on the heat-load mitigation and overall plasma performance. However, N can be retained in the plasma-facing surfaces by ion implantation and nitride formation. More importantly, N can react with hydrogen fuel species to form ammonia (NH_3). Due to high sticking of NH_3 to surfaces, the accumulation of tritiated NH_3 in plasma-shaded surfaces, pumping lines and cryopumps NH_3 in the active phase of ITER operation will contribute to the tritium inventory which is a serious safety and operational issue. Predictions of NH_3 formation in ITER critically rely on data of NH_3 formation in N_2 seeded discharges in present-day tokamaks.
The primary diagnostic for ammonia detection in tokamaks like JET and AUG is residual gas analysis (RGA). RGA is based on the use of small-sized, differentially pumped quadrupole mass spectrometers, adapted to the specifics of the tokamak environment (magnetic shielding, high sampling frequency in the discharge phase). A statistical model is used to distinguish NH_3 from methane and water which overlap in the same mass range in a mixed D-H-system. Evidence of NH_3 formation is also detected in the plasma phase from the visual range emission band of the ND radical.

New results from AUG and JET show that the volume of injected N has the biggest impact on overall NH_3 production. In a dedicated experiment at AUG, performed as a series of discharges with identical discharge parameters, the amount of formed NH_3 exhibited a steady build-up over 4 discharges. In the overall NH_3 production, the legacy effect tended to dominate over the influence of other plasma parameters. Preliminary analysis links the observed behaviour of NH_3 production to the gradual build-up and evolution of the machine N_2 inventory, however further experiments are required to verify this.

I-05

RECENT DEVELOPMENT OF NEW GENERATION PLASMADYNAMICAL FILTER FOR MICRODROPLETS ELIMINATIONS

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This work is to give the concise review of recent development and ongoing research of plasmadynamical systems based on the fundamental plasma optical idea magnetic electron insulation, equipotentialization magnetic field line and the axial-symmetric cylindrical electrostatic plasma lens (PL) configuration. The crossed electric and magnetic fields inherent the PL configuration provides a suitable method for establishing a stable discharge at the low pressure. Using PL configuration in this way several low maintenance and high reliability plasma generation devices were developed. These kind of devices are part of a large class plasma devices (hall-type plasma accelerators, jet propulsions, magnetically insulated diodes) that use a discharge in crossed electric and magnetic fields with closed electron drift for the generation, formation and manipulation of intense ion beams and ion plasma flows.

In the present work we describe the original approach for effective additional evaporation and elimination of micro droplets in a dense ion plasma flow of cathodic arc plasma. This approach is based on application the cylindrical PL configuration for introducing at volume of propagating along axis's dense low temperature ion plasma flow convergent radially energetic electron beam generated self-consistently by ion – electron secondary emission from electrodes of plasma optical tool. The theoretical estimations and experimental demonstrations that have been carried out at the IP NASU provide confidence and optimism that proposed idea for removal and clearing the micro droplet component from dense metal plasma has the high practical potential for elaboration novel state-of-the-art plasma processing for the filtering of micro droplets (or their reduction to the nanoscale) from the dense low temperature plasma formed by erosion plasma sources like vacuum arc and laser produced plasma. In these first experiments was used DC vacuum arc discharge regime. In order to proceed ahead with further development for comprehensive study all merits and drawbacks this method it convenient to use repetitively pulsed operating regime. In the present paper is described the first experimental results investigation propagating along the axis PL wide-aperture, high-current, low energy metal ion plasma flow produced by cathodic – arc repetitively pulsed discharge at low pressure.

The work is partly supported by the STCU-NASU Grant N 6059 and grants of NAS of Ukraine N P13/16-32 and Pl-16-32.

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I-06

Damage effects of secondary radiation on ITER divertor and nearby hidden components during transient events

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During abnormal and disruptive operations in tokamaks, the evolution of secondary plasma radiation in the divertor area may contribute a high heat load to nearby components. The secondary plasma developed as a result of disruptions and ELMs is composed mainly from divertor materials that will greatly increase the radiation flux to nearby components in comparison to radiation from the clean DT plasma. Our preliminary simulations showed significant increase of the radiation fluxes and accordingly the components heat load in the case of high-Z (i.e., tungsten) secondary plasma. These intense radiation source could seriously damage hidden nearby components such as stainless steel umbrella tubes and dome structure. We have developed and implemented comprehensive enhanced physical and numerical models in our comprehensive integrated HEIGHTS package for 3D simulation of detailed photon and particle transport in the evolved secondary plasma during various instabilities [1, 2]. HEIGHTS is now being used to simulate full 3D realistic ITER geometry, including the reflector plates designed to protect interior components, to assess the damage of these components resulting from various plasma instabilities. HEIGHTS predicted, for the first time, the fine details of heat loads and temperatures evolution of both divertor and nearby components due to transient events of ELMs and disruptions. This secondary radiation generated from the divertor produced plasma evolution and expansion showed to cause serious damage to hidden internal components (e.g., umbrella and dome structures) that were not directly exposed to the DT plasma. The current ITER divertor design may require changes to mitigate such effects and further protect interior components that will be hard and costly to repair in case of transient events and disruptions.

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I-07

MAIN RESULTS OF THE FIRST EXPERIMENTAL CAMPAIGN IN THE STELLARATOR W7-X

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In this report, a summary of the first experimental campaign (OP1.1) in the stellarator Wendelstein 7-X is given. Restrictions such as operation with a plasma limiter, short discharge duration (much shorter than the *L*/*R* time), etc., are described. The available diagnostics, the heating parameters and the most important experimental results are shown. For discussion, typical examples of successful ECRH discharges with quasi-stationary plasma of duration up to 6 sec and heating power up to 4 MW are selected. It must be mentioned, however, that only the electron and ion temperatures, T_e and T_i, were established well during the discharges, while the – profile was quite far from the steady state.

The main conclusion after the campaign OP1.1 is that the confinement in the core of plasma is in a good agreement with predictions of neoclassical transport theory. In particular, for density about (1-3)$\times 10^{19}$m^{-3} the achieved temperatures were $T_e \approx 8\ldots10$, $T_i \approx 1\ldots2$ keV, and the energy confinement time was about 0.15 sec, which confirms the results of numerical transport simulations for 'electron-root' confinement regime.

Additionally, future upgrade of W7-X as well the expectations for the campaign OP1.2 will be described.

I-08

RECENT PROGRESS OF THE HIGH TEMPERATURE PLASMA STUDY IN THE LARGE HELICAL DEVICE

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The Large Helical Device (LHD) is a large scale superconducting heliotron-type device with a major radius of 3.9 m, and a minor radius of 0.65 m, which has been operated since 1998. A set of $l = 2 / m = 10$ continuous helical coils and three pairs of poloidal coils generate the plasma confinement magnetic configuration in steady state with the toroidal magnetic field strength, B_t, of up to about 3 T. The aims of the LHD project are achieving the reactor relevant plasma condition in the heliotron-type magnetic configurations, and exploring the related plasma physics and fusion technologies. The targets of the plasma performance in LHD are to achieve: (1) high ion temperature plasmas exceeding 10keV at electron density of 2×10^{19} m^{-3}, (2) high density plasmas exceeding 4×10^{20} m^{-3} with electron temperature of 1.3 keV, (3) high plasma pressure exceeding $\beta = 5$ % at $B_t = 1$ T, and (4) long pulse plasma operation exceeding 1 hour with the heating power of 3 MW. These targets have not been achieved, but the high temperature plasma study has made steady progress with the working gas of hydrogen or helium. In recent experiments, the ion temperature of 8.1keV at electron density of 1×10^{19}m^{-3}, $\beta = 4.1$ % at $B_t =$ 1 T, and the plasma discharge with 48 minutes long with the heating power of 1.2 MW are achieved, respectively. For further improvement in plasma performance, deuterium is going to be used as a working gas. By comparison between hydrogen and deuterium plasma properties, it is expected that the mechanism of the isotope effect in high temperature plasma confinement is understood.

In this presentation, the progress of high temperature plasma study and current status in LHD will be shown, and the physical background of the progress will be discussed.

I-09

RADIO-FREQUENCY PLASMA START-UP AND HEATING AT URAGAN STELLARATORS

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A frame antenna with a broad spectrum of parallel wavenumbers (with respect to the magnetic field) is used for radio-frequency (RF) plasma production in Uragan-3M stellarator type device. The plasma of density up to 10^{13} cm^{-3} is created when the frequency is in the range f = 0.7…0.9 f_{ci}, where f_{ci} is the cyclotron resonance frequency. Outside this frequency range the plasma is also produced, but with substantially lower density. The delay between the start of RF pulse and the discharge development (breakdown time) is analyzed as functions of the neutral gas pressure and anode voltage of the RF generator. The reproducibility of the RF discharges is improved by the pre-ionization by the pulse of the three-half-turn antenna preceding the main RF pulse. This antenna creates the plasma of the density $n_e \leq 10^{10}$ cm^{-3}. The pre-ionization also results in shortening of the breakdown time for the frame antenna. The Langmuir probe measurements are made with two probes located at the plasma edge near and far from the double frame antenna. The measurements give rather high electron temperature, about 100 eV, at the initial stage of the frame antenna discharge both near and far from the antenna. The discharge development is faster in the vicinity of the antenna. The information on the plasma build-up is also available from chord Hα measurements and integral Hα signals at different positions around the torus.

In the Uragan-2M stellarator, the RF discharge is initiated by a pulse of the frame antenna. The RF power from the crankshaft antenna is applied afterwards to increase the plasma density (up to $5\cdot10^{12}$ cm^{-3}) and temperature. At the last Uragan-2M campaign the average plasma density measurements become available for each shot. The chord measurements of the spectral lines emissions were improved by widening of the observation scope. The discharge is initiated by a RF pulse of the frame antenna. The crankshaft antenna increases the plasma density up to $5\cdot10^{12}$ cm^{-3}. The plasma heating is indicated by the soft x-ray signals and CV line emission. Such emissions last 3–4 ms and then the discharge fades. The most probable reason of this is contamination by the impurities. The influx of the impurities not only increases power losses, but also changes the plasma dielectric properties that often results in worsening the conditions for the RF heating. The improved chord measurements demonstrate that the OV line emission profile is hollow. This fact indicates transition of O^{4+} ion to O^{5+} state. For the CV line emission the hollow profile is not observed.

I-10

PLASMA CHEMISTRY FOR CONCEPT OF SUSTAINABLE DEVELOPMENT

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Green chemistry is concerned with the efficient use of (preferably renewable) resources in conjunction with the elimination of waste and avoidance of the use of toxic and/or hazardous reagents and solvents in the manufacture and application of chemical products [1]. Sustainable development, on the other hand, is defined as development that meets the needs of the present generation without compromising the needs of future generations to meet their own needs [2]. Sustainability consists of three components: societal, ecological and economic. In contrast to sustainability, green chemistry does not contain an economic component. In order for a technology to be sustainable the following conditions must be fulfilled: natural resources should be used at rates that do not unacceptably deplete supplies over the long term and residues should be generated at rates no higher than can be assimilated readily by the natural environment [2]. Plasma chemistry must meet the requirements set by green chemistry and sustainable development.

It is abundantly clear, for example, that a society based on non-renewable fossil resources (oil, coal and natural gas) is not sustainable in the long term. Therefore, there is currently a growing emphasis on the substitution of non-renewable fossil resources by renewable biomass as a sustainable feedstock for the manufacture of commodity chemicals and liquid fuels [2, 3]. A switch to renewable biomass as a feedstock will result in the environmentally beneficial reduction in the carbon footprint of chemicals and liquid fuels. However, it is widely accepted that the use of first generation biomass feedstock, such as maize and edible oil seeds, is not a sustainable option in the longer term because it competes, directly or indirectly, with food production. Nonetheless, in the European Union emphasis is firmly on the use of second generation biomass comprising of lignocellulose, waste oils and fats as feedstock [2]. Renewable biomass can be converted into drop-in hydrocarbons (lower olefins, alkanes and aromatics), which form the backbone of petrochemical refineries or into the synthesis gas, which can be subsequently converted to liquid fuels or platform chemicals using established technologies (Fischer-Tropsch process, methanol synthesis).

The traditional thermo-chemical (temperature > 1000 K) and traditional plasma chemistry conversion of renewable biomass leads to the appearance of undesirable by-products and waste. In case of the catalytic conversion, the large amount of impurities in the biomass feedstock negatively affects the product yield and longevity of the catalysts. Plasma-catalytic approach is an emerging alternative to the traditional conversion technologies. Plasma-catalytic approach uses active species (OH, O, H) generated in plasma from non-toxic and/or non-hazardous reagents to initiate the chain reactions of renewable biomass conversion at low temperature (~ 500…600 K). However, plasma-catalytic approach requires the development of new plasma sources, which would generate the wide-aperture flow of non-thermal plasma, have long life time and control chemical processes in the reaction chamber using plasma only as a catalyst.

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I-11

RECENT DEVELOPMENTS IN THE ISTTOK HEAVY ION BEAM DIAGNOSTIC

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The heavy ion beam diagnostic (HIBD) presents a powerful tool for investigations of hot plasmas in thermonuclear devices with magnetic confinement and is known since 1970 by the pioneer work of F.C. Jobes and R.L. Hickok on the ST tokamak [1]. When injected into the plasma, the primary probing beam of singly charged positive ions is ionized to a doubly charged state by impact with the plasma electrons and separated from the primaries due to the confining magnetic field of the plasma device. The resulting secondary ions are collected outside the plasma. The plasma parameters, which are locally measured by the HIBD, are: the plasma electron density and temperature and the electric and magnetic potentials (the HIBD is the only method measuring the plasma potential directly). The HIBD was successfully applied on a number of tokamaks, stellarators, bumpy torus, reversed pinch and tandem mirror with the energy of probing beam ranging from dozens of kilovolts to megavolts. On the small tokamak ISTTOK (R = 0.46 m, a = 0.085 m, B = 0.5 T, I_p = 4…6 kA, $\langle n_e \rangle = 5 \times 10^{18}$ m^{-3}, T_e = 100 eV), the HIBD (fully operated since 1993 [2]) is based on a 20 keV Xe^+ (or Cs^+) beam injector and a multiple cell array detector (MCAD) collecting a fan of secondary Xe^{2+} (or Cs^{2+}) ions emerging from the plasma along the primary beam trajectory. The ISTTOK HIBD was the first diagnostic which used a plasma ion source type to produce the probing beam and a MCAD for detection of the secondary ions emerging from almost whole plasma cross-section. This presentation describes the recent developments and improvements in the ISTTOK HIBD secondary beam detection (MCAD modification, signal conditioning), allowing to start a detailed study of the plasma MHD activity and the electrode biasing regimes. A novel approach of the HIBD use in real-time vertical plasma position control is also considered. Finally, the last developments of the multichannel multi-slit 90^o cylindrical energy analyzer for the plasma potential and its fluctuations measurements are presented.

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I-12

COMMENTS ON RECENT STUDIES OF HIGH-TEMPERATURE PLASMAS AT THE NCBJ IN POLAND

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This invited lecture presents comments on the most important results of theoretical and experimental studies of high-temperature plasma, which have been carried out at the NCBJ in Otwock-Swierk, Poland, since the previous ICPPCF-2014 held in September 2014. The main scientific tasks, which concerned studies of fast electrons, ions, neutrons, and X-rays emitted from different research facilities of the PF-, RPI-, ICF- and Tokamak-type as well as experimental investigations of high-temperature plasma streams and their interactions with various solid targets, are summarized. The first part presents the authors' opinion about experimental studies of the generation of fast runaway electrons and their mitigation techniques. These studies were performed in a framework of the EURO-fusion Consortium. Probes of the Cherenkov type were used during two experimental campaigns at the COMPASS tokamak in Prague, and they recorded long electron signals and some very short peaks. Other electron measurements, which were performed with the Cherenkov probes within the FTU tokamak in Frascati, showed modulated electron signals, which were correlated with evolution of magnetic islands and/or injection of deuterium pellets.

The second part presents the authors' comments on applications of solid-state nuclear track detectors (SSNTDs) for studies of fast ions and fusion reaction products. The NCBJ scientists participated in the PALS experiments in Prague, where $p^{11}B$ nuclear reactions were studied. Changes in sensitivity of the nuclear track detectors after their long-term storage were also investigated. The next part presents the authors' comments on experimental studies of the X-rays, ions and electrons emission from PF-type discharges. Attention was focused on X-ray pinhole images which demonstrated the appearance of plasma filaments or "hot-spots" in discharges within the PF-1000 U facility. The NCBJ team performed also a detailed analysis of time-resolved measurements performed with PIN diodes located behind filtered pinholes. Some efforts were devoted to measurements of fast electron beams emitted from a PF-360U facility. For this purpose magnetic analysers with miniature Cherenkov- or scintillation-detectors were applied, and correlations of electron beams with "hot-spots" were analysed.

The last part presents the authors' comments on studies of plasma-streams interactions with tungsten targets in the PF-1000U facility by means of the OES technique. Emission spectra enabled identification of tungsten spectral lines. In addition mass-losses caused by the irradiation of W-samples were also found. Interactions of plasma streams with CFC targets within an RPI-IBIS device were also investigated. Changes in the plasma electron density were determined from analysis of the D_β line. Observations of spectral lines from exited atoms and ions, as produced from the irradiated targets, enabled a target erosion dynamics to be studied. Morphological changes of the irradiated targets were also analysed. The authors' critical comments are followed by proposals of future theoretical and experimental studies.

PACS: 52.70.-m; 52.40.Hf; 52.50.Dg; 52.55.Fa; 52.58.Lq; 52.59.Hq

I-13

INVESTIGATION OF X-RAY EMISSION FROM HIGH-CURRENT DISCHARGES OF THE PF TYPE

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This invited paper reports on x-ray emission studies performed during several experimental campaigns at the PF-1000U facility which was operated under different static and dynamic initial gas conditions. The investigated high-current discharges were carried out at the deuterium filling with or without a small (1%) neon admixture. The initial pressure equal to p_0 = 0.9 or 1.5 Torr and at the initial charging voltage U_0 = 16 or 18 kV. The formation of a dense plasma column (plasma-focus) was confirmed by recording characteristic peculiarities (so-called "current dips") on oscilloscope traces of the discharge current and its derivative, as well as by hard x-ray and neutron signals recorded by means of scintillation probes. Additional confirmation was delivered by silver activation counters of fast fusion-produced neutrons.

Time-integrated images of the x-ray emission from the dense plasma column were recorded by means of a filtered pinhole camera with a sensitive x-ray film. That camera was placed side-on the experimental chamber and made it possible to observe internal micro-structures of the plasma column at various experimental conditions [1]. Time-resolved x-ray signals were obtained from 4 diodes of the PIN type, which were equipped with separate collimators and pinholes with exchangeable absorption filters. Particular attention was focused on observations of 2 plasma regions situated near the electrode outlets. Two PIN diodes were equipped with 7-mm and 10-mm thick beryllium filters, respectively. These detectors were used to observe soft x-rays from a 30-mm-diam. region which had a centre at a distance of 30 mm from the anode end. Two other PIN diodes, equipped with similar filters, looked at the second 30-mm-diam. region which had a centre at a distance 60 mm from the anode.

A comparison of time-resolved signals, as recorded with different detectors, enabled averaged electron temperature values to be estimated in the observed plasma regions. In discharges with the pure deuterium filling the estimated electron temperatures ranged from 75 eV to about 250 eV, depending on the initial gas pressure and charging voltage. In discharges with the neon admixture the electron temperatures were higher and reached values above 1 keV. This effect may be explained by the fact that during discharges in deuterium with the neon admixture the amount of free electrons was larger and stronger non-linear effects (i.e. "plasma filaments" and "hot-spots") were observed [2]. The appearance of such plasma micro-structures was accompanied by the generation of local electric fields accelerating charged particles more effectively.

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I-14

MASS SPECTROSCOPY OF PLASMA FOR FUNCTIONALIZATION OF CARBON NANOSTRUCTURES

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Because of their unique properties carbon nanotubes (CNTs) are widely used in range of applications, which include e.g.creating bio-nanocomposits for fabricating components for biosensors. CNTs are chemically inert; therefore it is necessary to activate their surface in order to attach bio-active molecules. Beside the techniques of wet chemistry, the plasma functionalization is an important alternative way to functionalize CNTs. In order to get the optimal parameters for low-temperature plasma polymerization the diagnosis and control of plasma is necessary. Radiofrequency (RF) discharge of nitrogen and oxygen are rich in different kind of active species that include positive and negative ions and radicals. In our experiment we use the mass spectroscopy to monitor the positive ion fluxes in different discharge conditions. Beside the main ions expected (O_2^+ or N_2^+) the large flux of ions emerging from water impurities are present. The origins of different impurity ions and the driving ion - molecule reactions are analyzed according to known kinetic schemes. In addition, plasma functionalized CNTs are analyzed by means of XPS and Raman spectroscopy, which indicate the correlation between the ion fluxes and the surface activation of CNTs.

I-15

NONLINEAR CONVECTIVE TRANSPORT AND AVALANCHES IN MAGNETIZED TEMPERATURE FILAMENTS: THEORY, SIMULATION AND EXPERIMENTS

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Results are presented from basic heat transport experiments and gyrokinetic simulations of multiple magnetized electron temperature filaments in close proximity. This arrangement samples cross-field transport from nonlinear drift-Alfven waves and large scale convective cells and is used to study elements of chaotic heat flow and transport avalanches[1]. Experiments are performed in the Large Plasma Device (LAPD) at the University of California. A biased LaB_6 cathode injects low energy electrons (below ionization energy) along a strong magnetic field into a pre-existing large and cold plasma forming an electron temperature filament embedded in a colder plasma, and far from the machine walls. A carbon masking plate with several holes (each 1cm diameter, 1.5cm apart) is used to create 3 electron temperature filaments. By covering two holes in the mask drift-Alfven and thermal waves from a single filament have been characterized and compared to previous studies with a different electron beam source[2]. The observed eigenmode structures also compares favorably with recent 3D gyrokinetic simulations[3]. The 3-filament case exhibits a complex wave pattern and enhanced cross-field transport. Detailed mode analysis and comparison with nonlinear simulations is reported.

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I-16

CHARGE PARTICLE BEAM GUIDING FOR FAST IGNITION SCHEME IN INERTIAL CONFINEMENT FUSION

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One of the requirements of the fast ignition scheme is the acceleration of a relativistic electron beam with a high energy (kJ level), high intensity (> 10^{20} W/cm^2) and short duration (~ 1 ps) laser pulse. A large amount of theoretical and experimental work has been performed within previous years to optimize the fast electron source parameters and its transport. Due to the natural divergence of fast electron beams, the problem of efficiently delivering the required mean electron energy to the D-T core for ignition became apparent. Therefore the development of techniques for controlling fast electron beam divergence is a task of primary importance.

Several schemes potentially allowing control of the beam divergence were based on the physical processes of self-collimation of the electron beam, resistivity guiding and the use of imposed magnetic fields. This work is mostly oriented towards guiding by i) self-induced and ii) imposed laser-driven magnetic fields.

i) Fast electron beam collimation using two consecutive intense laser pulses has been recently proposed to optimize electron transport and collimation into a solid targets [Robinson2008]. The idea is to use the two consecutive laser pulses, to generate two successive co-axial electron populations such that the seed azimuthal magnetic field created by the first laser pulse will be amplified by the second incoming beam which will be also guided. Experimental results have confirmed the efficiency of the scheme with optimal delay and intensity ratio for the best guiding effect [Volpe2014]. Preliminary numerical simulations with joint parametric studies were made for an upcoming campaign at the LULI ELFIE facility.

ii) We explored the interaction between a powerful laser and the variety of coils shaped for production of particular magnetic field configurations, characterized by proton-deflectometry, B-dot probing and Faraday-rotation. The kilo-Tesla range B field was reached via a short-pulse laser-matter interaction [Santos2016]. The experimental results of imposing such magnetic fields on relativistic electron transport in solid targets are interesting for further integrated fast ignition experiments, the idea of which is to confine electrons into a small radius with use of high strength magnetic field generation [Fujioka2012].

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I-17

POLARIZATION EFFECTS IN MACROPARTICLE INTERACTIONS IN PLASMAS AND PLASMA-LIKE MEDIA

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The concept of effective potential is one of the key approaches to the description of systems with highly charged particles of the finite size in the neutralizing background. In particular, various models of effective potentials are used in order to describe collective behavior of macroparticle systems in plasmas and plasma-like media (grains in dusty plasmas, charged colloidal particles in colloidal suspensions). However, the models which are usually used disregard many important details of interaction of plasma particles (counter-ions) with macropartice and thus it would be highly desirable to have more consistent effective potentials. One more problem related to the concept of effective potential concerns the influence of collective (in particular, polarization) effects on particle interactions.

The purpose of the present contribution is to study the polarization influence on effective interaction between two macroparticles. The results of the numerical studies of the interaction forces between two finite size charged particles embedded into weakly ionized plasma are presented. The studies are performed for the case of particles with fixed electric charge under the assumption that particles do not absorb electrons and ions from the surrounding plasma as well as for particles (grains) charged by plasma currents. The dynamics of grain charging is described in the drift-diffusin approximation. It is shown that at the large distances in the first case the interaction force has the Debye screened asymptotic while in the second case the Coulomb-like behavior is observed. The dependence of the grain charge collected due to the plasma particle absorption on the distance between two grains is studied. The possibility to introduce effective Coulomb description of finite size grain interaction in weakly ionized plasma is discussed.

I-18

RUNAWAY ELECTRON INVESTIGATIONS IN EAST TOKAMAK

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Three main results from the runaway electron investigations in the recent EAST experiments will be shown in this presentation:

A detailed analysis of the spectra and spot shape of synchrotron radiation emitted by runaway electrons are presented. Our investigation indicated that the effect of drift runaway electron orbit shift, the pitch angle value, and safety factor profile $q(r)$ can significantly affect the synchrotron radiation spot shape. Our results can explain the asymmetrical ring-like synchrotron radiation spot shape from runaway electron beams in EAST experiments.

Peculiar phenomena were observed during experiments with runaway electrons: rapid changes in the synchrotron spot and its intensity that coincided with stepwise increases in the electron cyclotron emission (ECE) signal (cyclotron radiation of suprathermal electrons). Our results show that these non-thermal ECE step-like jumps were related to the abrupt growth of suprathermal electrons induced by bursting electric fields at reconnection events during this MHD plasma activity. Local changes in the current-density gradient appeared because of local enhancement of the runaway electron generation process, and this runaway electron generation can be a possible trigger for enhancement of the magnetohydrodynamic plasma activity and fast changes in runaway beam behavior. Those suprathermal electrons may potentially be seed runaways that can cause avalanching growth of the number of runaways.

Recently, the production of runaway electrons during spontaneous disruptions in the EAST tokamak has been observed in the experiments when lower hybrid wave (LHW) heating was used during disruptions. The runaway plateau lengths were very different in different discharge conditions. A self-consistent modelling of the generation and loss mechanisms of runaway electrons during disruptions is developed to understand the runaway electrons generated during spontaneous disruptions in EAST tokamak. The results indicate the important role of the seed fast electrons and magnetic fluctuations on the generation and loss of runaway electrons.

Keywords: runaway electrons, synchrotron radiation, tearing mode, disruption, EAST.

I-19

PLASMA GASIFICATION: BASIC THERMODYNAMIC AND KINETIC RELATIONS

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This study is devoted to the development of plasma technologies for processing carbon-containing waste, including – hazardous one. Nowadays, they are presented by numerous publications in the world scientific literature, united by a common idea extract the energy potential of the carbonaceous waste in the course of their processing («plasma-assisted Waste to Energy») [1–4]. In the cases the carbon from waste is converted into synthetic gaseous fuel $nCO + mH_2$. The syngas can be used: 1) to drive the reciprocal gas power stations; 2) for conversion into methane; 3) for the conversion into the liquied fuel based on Fischer-Tropsch process.

The most general assessments of ecological benefits and energy efficiency of plasma-steam gasification technologies are given.

A general thermodynamic analysis of the gasification processes of carbonaceous raw materials by using plasma technologies is fulfilled; basic ratio and reference data for typical reagents of gasification processes and obtained products are presented. A concrete example of thermodynamic calculations of the sewage sludge processing allows determining the energy efficiency of plasma technology.

Waste recycling is associated also with the risk of presence of dangerous gas substances. The lecture addresses the numerical analysis of the processes of nitrogen oxides formation in the model device of plasma gasification. Calculations are conducted for the cases of dry and moist air with the usage of thermally nonequilibrium plasma chemical model. It has been shown that NO and NO_2 concentrations at the outlet of arc discharge differ principally from their equilibrium values at a given temperature of the arc. It has been revealed that the presence of water vapor in air strongly affects the formation of nitrogen oxides.

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I-20

ON THE SYNTHESIS AND PROCESSING OF NANOPARTICLES BY PLASMAS

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Synthesis and processing of nanoparticles (NPs) for different applications have received numerous attentions during the last years due to the extraordinary characters and fantastic properties of NPs. In spite of employing various plasma configurations in advanced technologies for the synthesis of NPs and materials processing, many aspects of the role of plasmas in these processes are still unexplored. Here, the role of plasma parameters and plasma chemistry in the synthesis of metal-oxide NPs and their influence on stabilizing the NP generation rate, are overviewed. Furthermore, the mutual interaction between a metal NP beam and a radio frequency (RF) hollow electrode discharge is investigated.

A gas aggregation source (GAS) combined with a conventional DC magnetron sputtering is used to generate NPs from silver and/or titanium targets. The quantitative assessment of the preliminary experiments reveals that the NP generation of reactive metals, such as titanium, is possible only in the presence of a reactive gas admixture in the nucleation zone [1]. The NP formation rate strongly depends on competition between sputtering process and target poisoning process [2]. The obtained results also indicate that switching to the pulsed DC magnetron discharge increases the rate of TiOx NP generation, significantly [3, 4]. At this regime, the pulsing parameters as well as the content of the oxygen admixture have crucial contributions in adjusting the dominant mechanisms in the clustering process [3, 4].

The NP processing in complex environments (such as plasmas), is of interest not only for the fabrication of functional materials but also from a physical point of view. To study the plasma-NPs interactions, a home-made hollow electrode, with special geometry, was installed beyond the GAS to modify a silver NP beam immediately after generation. It is demonstrated that the ignited RF discharge can significantly influence on the characteristics of the passing NP beam by charging the metal NPs. The hollow plasma can also change the geometry of the deposited spot by redistributing the metal NPs in the beam [5].

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1-01

STELLARATOR THEORY STUDIES AND OPTIMIZATION UNDER EUROFUSION

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The EUROfusion roadmap establishes several Missions to be accomplished by the EUROfusion consortium in order to achieve commercial fusion. Mission number 8 is devoted to bring stellarators to maturity and the work is divided into two workpackages, WPS1 and WPS2. The first one is devoted to the scientific exploitation of W7-X, extracting the necessary physics knowledge. The WPS2 is entitled "Stellarator Optimization: Theory, Development, Modelling and Engineering" and is targeted to the development of tools for designing new optimised configurations and to support W7-X exploitation. We present here a summary of the results that have been achieved under WPS2 up to date.

Ray tracing calculations have been used to identify the best ECRH regimes in W7-X as well as to estimate the driven current, including collisions. In particular X2 and O2 heating scenarios have been identified, developed and tested successfully during the first experimental phase in W7-X. Finally, a model for OXB heating in overdense plasmas (including the description of non-planar regions of O-X conversion) has been built.

Fast ion dynamics and confinement has been also studied in optimized Helias-like configurations with reduced bootstrap current. The influence of the number of field periods is also studied. The study of ICRH-generated fast ions and their confinement is performed using SCENIC, a suit of codes that includes equilibrium calculation, full wave propagation and absorption, and fast ion orbits. Hit points on the vacuum vessel are also calculated.

Basic transport theory based on Hamiltonian techniques is used to characterise the properties of configurations regarding the confinement quality. Quasi-Symmetric configurations were studied to develop the tools starting by the simplest case. The effects of the deviation from Omnigeneity are also considered. These findings have been implemented in numerical tools for fast NC calculations, which allows one to compute neoclassical transport in low collisionality regimes for optimized stellarators, which might be useful as a component of an optimization code. Analytical computation of the effect of high-helicity deviations in the sqrt(nu) regime and in the superbanana-plateau one is also considered.

Turbulent optimization will be relevant in NC-optimised stellarators, where turbulent transport will not be negligible. ITG optimization of Helias configurations have been carried, then we have investigated the possibility of optimizing configurations taking into account both the ITG and TEM transport channels combined. On top of that, fast semianalytical calculations for optimization are developed in order to estimate the zonal flow properties to explore the influence of the ZF on the saturation of the turbulence. The ZF oscillation frequency will be calculated and compared to GK simulations. Linear and non-linear GK simulations have been performed in stellarator configurations, where asymmetries in the potential will be identified. Semianalytical study of electrostatic potential perturbations, non-constant on the flux surfaces, with an assessment on their impact on impurity transport. Several configurations will be studied, including Helias-like one.

The influence of magnetic topology and equilibrium on confinement is also studied. It has been found a decoupling of the NC transport of the rotational transform value, despite the positive confinement scalings with iota, and the weak influence, if any, of magnetic well on confinement. On top of that, the symmetry-breaking caused by magnetic islands is considered as a possible generator of ZF by neoclassical effects.

1-02

OBSERVATION OF 1…20 kHz FLUCTUATIONS IN THE URAGAN-2M TORSATRON

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An H_α camera designed and recently installed in Uragan-2M (U-2M). It allows localize plasma fluctuations radially, allow determine poloidal mode number and direction of the rotating plasma modes. Modulations of the H_α emissivity brightness represent fluctuations of the plasma density. The H_α emissivity fluctuations are coherent with the line-averaged density fluctuations measured by the 140 GHz interferometer. First observations of quasi-coherent fluctuations in the frequency range of 1…20 kHz in different plasma conditions of the U-2M torsatron are presented. Bursts of 1…2 kHz, $m = 1$ oscillations caused by the rotating modes are always observed at the heating degradation stage of the crankshaft antenna operation. They appear at the SXR decrease stage and disappear when the SXR signals is dropping close to the zero level in standard U-2M discharges ($B_0 = 0.35$T). They are localized in the central region of the plasma column. In U-2M discharges with low RF power, and $B_0 = 0.35$T the density fluctuations are observed in some symmetric lines of sight of the H_α camera but substantially decrease in the inner regions and absent in outer regions. In these discharges 10…15 kHz plasma density fluctuations are strongly localized at the region of substantial H_α emissivity gradients. Transient burst of 6 kHz, $m = 1$ central fluctuations are observed in the medium magnetic field ($B_0 = 0.067$ T) discharges. Strong $m = 1$ fluctuations in the frequency range of 10…20 kHz are observed in the plasma conditioning discharges with low magnetic field ($B_0 = 0.01$ T). These fluctuations are localized in the central part of the plasma. Direction of its poloidal rotation is reversed during the discharge simultaneously with its substantial amplitude increase and frequency decrease from 20 kHz to 10 kHz. The fluctuations observed in standard U-2M discharges have frequency below the geodesic acoustic mode (GAM) frequency and can be caused by drift plasma modes. The frequency of fluctuations in the plasma conditioning discharges evidently exceeds the GAM frequency. It can be formally classified as an Alfvén egenmodes. Due to lack of the fast particles in the low temperature plasma the mechanism of these modes excitation is unclear for now.

1-03

PARTICLE AND ENERGY CONFINEMENTIN URAGAN-2M TORSATRON PLASMAS

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The Uragan-2M is a middle-size $l = 2$ and $m = 4$ torsatron with an additional toroidal field, reduced helical ripples, the moderate shear and the magnetic well. It has a major radius $R = 1.7m$, the average minor plasma radius $a \leq 0.24m$ and the toroidal magnetic field $B_0 \leq 1T$. The separate control of the currents in the toroidal and helical coils provides the possibility of wide-range optimization of the magnetic configuration parameters.

In plasma fusion experiments the regime of improved plasma confinement (which is characterized by formation of external and internal transport barriers) has been intensively studied for tokamaks and stellarators. Along the plasma discharge those regimes are primarily identified by increase in particle and energy confinement time. Therefore, the elaboration of plasma diagnostics capable of reliably measuring the particle τ_N and energy τ_E confinement time in thermonuclear plasma is of great importance. At the present time the largest operating stellarator devices, the W7X and LHD are advancing their physics programs to the near-reactor operational regimes. Nevertheless, existing small-to-medium stellarators could provide considerable information and guidance for the further development of the stellarator concept. Their currentless operation allows experiments to explore phenomena that could be scale to large devices (stellarators and tokamaks) operating at much higher density, temperature and power.

Before last experimental campaign (March 2016) 140 GHz super-heterodyne interferometer has been installed for the 'routine' line density measurements on "every shot" basis. According to the spectroscopic measurements it was found that the process of ionization of molecular hydrogen is the primary mechanism for RF plasma production in all phases of the discharge in Uragan-2M torsatron. For the time when plasma RF heating went off the data from the intensity of the H_β line along the central chord and the line electron density $\langle n_e l \rangle$ were used for the particle and energy confinement time estimation. For different operational plasma discharge parameters: magnetic field, pressure, RF heating power the dependencies on τ_N were found. At first during plasma decay phase the functional dependence of the temporal behavior of the line density experimental data was numerically approximated. Then the corresponding particle confinement time was calculated. In the same manner the experimental data of the line intensity was used to estimate the energy confinement time τ_E. The analysis shows that in the case $\tau_E = const$ there is no approximation match for experimental data. Only if we assume that $\tau_E \sim 1/T_e \sim 1/\nabla T_e$ and $\nabla T_e \sim T_e/a_p$ the obtained conversion from spectroscopy data to corresponding T_e lies within reasonable error: $T_e(appx) = 3.5 \pm 0.5eV$. Finally we can conclude that energy confinement time could be mainly defined by temperature drift instability which is caused by anomalous transport originated from PF plasma production method. The proposed technique for the τ_E, τ_N estimation will give us an important guide-line on the efficiency of plasma production and confinement.

1-04

NON-LOCAL QUASILINEAR MODELLING OF THE NEOCLASSICAL TOROIDAL VISCOSITY IN TOKAMAKS

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Violation of the toroidal symmetry of the magnetic field leads in tokamaks to a toroidal torque onto the plasma which affects the toroidal plasma rotation. In the most plasma volume, except for close vicinities of resonant rational flux surfaces, the perturbed magnetic field is well de-scribed by the ideal MHD theory. Toroidal torque from such ideal magnetic perturbations is usually termed as neoclassical toroidal viscosity (NTV). Due to the smallness of the perturbation field amplitude, dominant NTV regimes in tokamaks are the quasilinear regimes, i.e. such regimes where particle motion tangential to flux surfaces is only slightly perturbed and where, respectively, the NTV torque is a sum of independent, quadratic in amplitude contributions of different toroidal perturbation modes. A set of quasilinear equations for these regimes has been proposed and realized within a specific version of the NEO-2 code in Ref. [1]. In this reference as well as in Ref. [2] where NEO-2 has been applied for the modelling of NTV in ASDEX-Upgrade, this code has been benchmarked against few analytical models and numerical codes based on the standard, local neoclassical ansatz used also in the original version of NEO-2. Within this standard ansatz, radial drift is ignored in the orbits employed for the perturbed distribution function so that these orbits stay strictly within a given flux surface. However, this approach fails in description of resonant transport regimes [3] where the toroidal particle precession due to the magnetic drift is important. In this report, the nonlocal quasilinear model which properly takes into account the toroidal magnetic drift and which has been recently im-lemented in NEO-2 code [2] as well as its benchmarking against the Hamiltonian model [3] which naturally takes into account effects of the finite orbit width on the toroidal paticle preces-
sion are presented.

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1-05

CONCERNING LOCALIZATION OF THE RF ABSORPTION AREA VERSUS MAJOR RADIUS IN THE COLD PLASMA OF THE U-2M AND U-3M TORSATRONS IN TERMS OF H_α PROFILE DATA

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In the cold, low density plasma discharges under consideration the H_α spectral line irradiated from the regions with sufficient electron temperature and density. In the partially ionized plasma, energy losses due to interaction with neutrals can be comparable with the cross-field plasma losses and even influence on the smoothing of the plasma temperature and density along the magnetic surface. Fast H_α camera, installed in URAGAN torsatrons (U-3M and U-2M) recently, open possibility of the H_α distribution monitoring in these discharges [1]. According to our measurements, in the low temperature discharges (at the initial stage of the normal RF discharges and especially in the low magnetic field ($\omega >> \omega_{ci}$) plasma conditioning discharges) distribution of the H_α emissivity is not symmetric around the magnetic flux surfaces. The distribution of the H_α emissivity along the major radius qualitatively marks location of the RF power deposition. According to the measurement of radial distribution of the H_α emissivity along poloidal plan from top windows, shift of the plasma from high field side to the low field side is always observed at the beginning of all U-2M and U-3M discharges. The shift duration is less than 100…200 μs. This shift is evidently associated with the RF wave heating peculiarities [2]. One more interesting feature of the RF breakdown is related with the role of the ion cyclotron zone. Measurements in the low temperature U-3M discharges show systematic shift of the of the plasma area from low field side toward high field side with magnetic field decrease. Calculation show that the location of the considerable H_α emissivity in the low magnetic field ($B_0 = 0.5$ T) and low temperature U-3M discharge is linked with the ion cyclotron zone location. This fact demonstrates substantial role of the ion cyclotron zone at the low temperature stage of the U-3M RF discharges. The wall conditioning plasma discharges ($B_0 = 0.01…0.03$ T, $\omega >> \omega_{ci}$) used in the U-3M and U-2M are one more example of the low temperature discharges. According to the recent work [3], fast magnetosonic wave (FMSW) is possible candidate for the plasma heating the low magnetic field ($\omega >> \omega_{ci}$) plasma conditioning discharges. Non-resonant character of the FMSW damping [3] should create plasma in whole confinement region, although possible geometrical resonances of the FMSW itself [3] can cause inhomogeneity of its absorption. According to the H_α emissivity distribution, U-2M RF heating area in the conditioning discharges strongly depends on the RF antenna type. In the frame antenna discharges, after fast (previously mentioned) initial shift, H_α emissivity is localized in the low field side. In the crankshaft antenna discharges [4] location of the H_α emissivity is substantially shifted in the high field side. One of the possible reasons of the observation can be related to different distance from the H_α measurement cross-section to the crankshaft and to the frame antennas.

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1-06

PHENOMENOLOGICAL MODELLING OF THE SUPRATHERMAL ELECTRON GENERATION DURING MAGNETIC FIELD LINE RECONNECTIONS IN EXPERIMENTAL ADVANCED SUPERCONDUCTING TOKAMAK (EAST)

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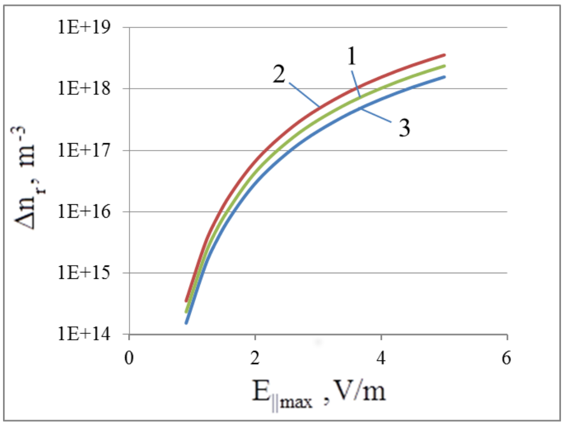
Runaway electrons pose a potential threat to the safe operation of large tokamaks, especially to ITER [1, 2]. The energy of runaway electrons can reach as high as tens of MeV.

The peculiar phenomena were observed during EAST experiments with runaway electrons: rapid changes in the synchrotron spot shape and its intensity that coincided with stepwise increases in the electron cyclotron emission (ECE) signal (cyclotron radiation of suprathermal electrons) and the MHD (m/n = 2/1) Mirnov signal spikes (m and n are the poloidal and toroidal mode numbers, respectively) [3]. In this experiment runaways were located around the q = 2 rational magnetic surface.

In [4] it has been shown that local runaway electron generation was a possible trigger for enhancement of MHD tearing mode activity and fast changes in runaway beam behavior during this experiment. The non-thermal ECE step-like jumps were related to the abrupt growth of suprathermal electrons induced by bursting electric fields at reconnection events during this MHD plasma activity [5]. The investigated runaway discharge was an ohmic shot in the limiter configuration ($V_{loop} \approx 1.1$ V), with toroidal magnetic field B_0 = 2 T, plasma current I_p = 250 kA, central line – averaged density $\langle n_e \rangle = 2.2 \times 10^{19}$ m^{-3}, plasma major radius R = 1.86 m and minor radius a = 0.45 m.



In presented report the dependence of instant changes in suprathermal electron density, Δn_r, from maximum amplitude of bursting electric field, $E_{\|\max}$, was investigated for three values of burst duration of induced electric field (in Fig. curve 1 corresponds to 2.5 ms of burst duration, curve 2 corresponds to 3.75 ms, curve 3 corresponds to 1.7 ms, respectively). These burst durations are close to experimental values [4]. Obtained results may be used for comparisons with experimental EAST results.

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1-07

ICRF - VOLUME CHARGE-ANTENNA EDGE INTERACTIONS IN THE TORSATRONS U-3M AND U-2M
Part 1. FORMATION OF A VOLUME SPACE CHARGE (VSC) OF POSITIVE IONS

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The ion cyclotron range of frequencies (ICRF) is used for plasma formation and heating in the torsatrons U-3M and U-2M [1]. In the near-antenna surface region the electrons are moving under the influence of rf field $E = E_m \cos \omega t$ and are oscillating with an amplitude A= $\mu_0 E_m / \rho\omega$. The electrons with a maximum oscillation amplitude at $\omega t = 0,\ \pi$ quickly get the antenna surface and thus form volume-space charges (VSC) of positive ions creating quasi-constant potentials φ. The resulting potentials on the frequency half-period ω, where the electric fields are maximum, form a potential well for electrons with amplitudes $A < A_{max}$. The electrons oscillate and re-reflect alternately from the one edge to other. This promotes the increase of the oscillating parallel electron current. The central oscillating voltage increases and drops as a doubled applied frequency. So, in the rf sheath the rf voltage rectification occurs and the second large-number harmonic is generated [2]. To analyze the mechanism of higher harmonic generation in the torsatron U-3M we have used the direct interaction of the external rf wave with VSC having nonlinear properties [3].

Despite the small thickness of VSC layers ($d \approx r_D$) the processes flowing in the edge plasma are determining at the start and during the rf discharge. The volume space charge is, in essence, a link connecting the processes in the ICRF-VSC-antenna chain. The ICRF-plasma interaction occurs in the very thin VSC layers near the antenna surface. This reduces to a minimum the direct diagnostic measurements of edge processes. For the most part they are reproduced by the analyses of many theoretical, modelling and experimental works even on the small plasma facilities.

This paper summarizes the previous experiments carried out on torsatrons U-3M and U-2M with taking into account the experimental, theoretical and modelling results on this subject obtained by other authors. It consists of three parts. The next second part includes the rf antenna-VSC interactions. The final third part presents the discussion on the mechanisms of ICRF-volume charge interaction. A phenomenon of VSC formation exerts a determining influence on the rf discharges and this fact promotes its further investigations.

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1-08

ICRF – VOLUME CHARGE-ANTENNA EDGE INTERACTIONS IN THE TORSATRONS U-3M AND U-2M
Part 2. VSC-RF ANTENNA INTERACTION

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In case of a rf pulse feed to the antenna near its surface, a narrow layer of a low-density plasma is formed due to the maximum electric field value. Electrons, having a mobility μ_0 higher than that of ions, arrive to the antenna surface in the immediate period. Then from the antenna surface side an electron-depleted region is formed and from the plasma side a region with a higher density of positive ion charges takes place. (This region is named also as a space-volume charge (SVC) region or rf sheath). Due to SVC the capacity formed makes the plasma (despite its quasi-neutrality), on the whole, a positively-charged one relatively to the antenna. A capacitive antenna-plasma coupling component transforms the charge in the hybrid one [1]. The conduction current, flowing in the quasi-linear plasma in this case, is circuited in the electrode region with a displacement current [2]: $div[e(\mu_e n_e + \mu_i n_i)\vec{E} + \frac{1}{4\pi}\frac{d\vec{E}}{dt}] = 0.$

It means that the rf power supply to the plasma can be performed by both the inductive channel and the capacitive channel. In the SVC self-consistent field the ions gain high energies and bombard the antenna surface. Thus the emission of electrons and neutral impurities from the antenna surface is promoted. During this emission in the rf discharges many mechanisms take part, namely: thermoelectronic-, autoelectronic-, autothermoelectronic-, explosive-, secondary-, photoelectron emissions and emission from dielectric films [3]. Each individual electron emission mechanism may be unimportant, however, each of them stimulates the action of other emission mechanisms. A common stimulator of the significant emission from the "cold" antenna is the SVC formation near its surface. A Coulomb field of positive ions accelerates the electrons emitted from the antenna surface. The electron beams can participate in the starting phase of gas ionization along with the longitudinal electric field component. This process can explain a rather quick ionization process in U-3M ans U-2M, and, at the same time, the breakdown onset instability. A part of emission electrons can pass into runaway electrons that is confirmed by the process of ionization after switching off the rf pulse [4]. A very negative consequence of the antenna bombarding with accelerated ions is the heavy impurity emission into the plasma confinement volume [4].

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1-09

ICRF – VOLUME CHARGE-ANTENNA EDGE INTERACTIONS IN THE TORSATRONS U-3M AND U-2M
Part 3. ICRF-SVC INTERACTION

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In the stationary plasma its state is determined in main by the processes running in the confinement volume. In rf discharges the ICRF-space volume charge (SVC) edge interactions play a dominant role. At high rf power levels the ICRF systems can leads to the antenna surface deterioration, increase of heavy impurity emission from the antenna, change of the value and profiles of n_e и T_e in the peripheral plasma, high rf power dissipation. These effects can cause the plasma degradation in the central region [1]. At present the experiments on a series of plasma facilities, including the torsatrons U-3M and U-2M, evidence that many effects, impairing the ICRF-edge plasma interaction are provoked by the SVC (rf sheath) formation in the rf discharges. To decrease these unwanted effects one uses commonly the Faraday screens and buffer end screens for rf antennas, which a purposed to be displaced radially for determining the optimum connection of ICRF systems with the plasma. The decrease of Z impurity content is provided by the carbonization of all elements in the vacuum chambers. In U-3M and U-2M all such means are unavailable. Therefore, the plasma heating efficiency increase by the ICFR waves is problematic. However, at the same time, this problem can stimulate a study of direct edge interaction phenomenon.

In the U-3M torsatron the excitation of Bernstein ion waves was observed experimentally near the higher harmonic peaks at the rf field frequency [2]. In the U-2M torsatron, where two rf oscillators were operating with a little difference of frequencies f_1 and f_2, besides the higher harmonics $f_n = nf_1$ and $f_m = mf$, their combination frequencies $nf_1 \pm mf_2$, have been recorded. Unlike U-3M in U-2M also the combination frequencies $nf_1 \pm mf_2$ were recorded (between the higher harmonics) and the oscillations frequencies of $[(f_n - \Omega),\ f_n(f_n + \Omega)]$ type determined as side frequencies [3]. The results obtained evidence on the strong nonlinear pump wave-SVC interaction followed by the parametric decay processes.

In many papers on this subject is shown that the level of these edge interactions depends directly on the rf antenna-plasma distance and on the phasing of currents between the antenna half-turns and the rf power of external oscillators.

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1-10

THE REFLECTION AND RE-EMISSION COEFFICIENTS OF HYDROGEN PARTICLES IMPINGING FROM PLASMA ON THE WALL IN THE TORSATRON URAGAN-3M

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The radial profiles of emissivity of H_α and H_β lines radiated from hydrogen plasma of the torsatron Uragan-3M are computed routinely by the methods of optical spectroscopy. The modeling of these profiles with programming code "KN1D" [1] requires data on reflection and re-emission coefficients of hydrogen particles H^+, H, H_2, and H_2^+ impinging from plasma on stainless steel surfaces (the chamber walls and the casings of a helical winding of a magnetic system) in RF discharge. To study the balance of particles at the wall during the discharge, the range of kinetic energy E_0 of each particle type was taken based on parameters of typical RF discharge.

Some of impinging atoms and protons are reflected from wall surfaces. The rest impinging flux penetrates into the surface. The assumed gas release mechanisms are rediffusion to the wall surface, molecular recombination ($H + H \rightarrow H_2$), and thermal desorption. The reflection coefficient R_N of the reflected (backscattered) flux was calculated with a program "SRIM-2010". The re-emission coefficient j_0 of the desorbed molecular flux was found using formulas [2].

The reflected atoms are present in the right-hand sides of the processes: (i) H (low-energy atoms, $E_0 = 3…10$ eV) + wall → H; (ii) H_{CX} (high-energy CX atoms, $\bar{E}_0 \sim 120$ eV) + wall → H. For the desorbed flux, the molecules are present in the right-hand sides: (iii) H + wall → H_2; (iv) H_{CX} + wall → H_2. The impinging ions H^+ and H_2^+ were not taken into account because they move in divertor flows mainly to the rear, not seen from plasma, sides of helical windings. Then the ions are backscattered or re-emitted in a chamber and income as molecules to the common molecular flux to the plasma.

The flux balance was taken, on the one hand, for the impinged flux, and, on the other hand – for the reflected and desorbed fluxes, and the flux diffused into the bulk [1, 2]. The sum of terms of the reflected flux density in the right-hand sides of the processes (i) – (ii) was balanced by the sum of terms in the left-hand sides where each term is a product of the impinging flux density and the coefficient R_N. The balance for the processes (iii) – (iv) was found with the penetrated flux and coefficients j_0.

In the process (v) H_2 + wall → H_2, low-energy molecules impinge on the wall. A temperature of molecules corresponds to the room temperature of the vessel wall. For the balance, the coefficient j_{0m} of molecular re-emission on the stainless steel wall was approximated with that on the Ni surface, known from the literature. The coefficients R_N, j_0, and j_{0m} were estimated at normal incidence of particles here.

In this article the reflection and re-emission coefficients were calculated for the atoms and molecules impinging on the walls in RF discharge of the torsatron Uragan-3M. In prospect, these coefficients can be used in the program modeling of particle profiles with the code "KN1D" in the plasma or the near-plasma region of the torsatron.

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1-11

SUPPRESSION OF FLOWS OF RUNAWAY ELECTRONS AND PECULIARITIES OF THE WORKING GAS BREAKDOWN IN THE URAGAN-2M TORSATRON

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This material is the result of a continuation of researches directed to study and to control of runaway electrons (RE) flow in Kharkov stellarator-type devices Uragan-2M and Uragan-3M. In paper [1] a theoretical basis on RE flow control by means of an electrostatic field was described and the results of the first experiments at the torsatron Uragan-3M were presented and discussed. In [2, 3] the methods on stimulation of the RE flow were suggested and realized.

The material contains the results of an experimental research on runaway electrons flow suppression at the torsatron Uragan-2M [4]. The experiments on suppression of the RE were carried out by the use of direct or pulsed potential applied to the midpoint of a frame antenna through a high-pass filter, when antenna was not connected to the vacuum chamber. The RF discharge was initiated by the second, so called crankshaft antenna. Suppression of RE was achieved by applying to the antenna of direct voltage pulses of 60 V in amplitude and duration from 1 s to 10 ms. The presence of RE was traced by measuring a hard X-ray radiation. The influence of RE flow presence or absence was also studied by analyzing the data on the start of the discharge.

It was shown that in the availability of the electron runaway flux the gas breakdown occurs, on average, 1.5 ms earlier in comparison with the breakdown time without RE. Practically full suppression of hard X-ray radiation from plasma was achieved by suppression of the RE flow. It was noted also the impact of runaway electrons flow on plasma parameters, what will be discussed in the presentation.

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1-12

EDGE MAGNETIC ISLAND EXCITATION IN THE U-2M TORSATRON

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Magnetic islands, excited and controlled from the outside on the edge of plasma column confinement in tokamaks and stellarators, are presently recognized as one of the effective tools exerting an impact on the plasma MHD-activity [1, 2]. Also they can promote the helium ash evacuation from the fusion reactor hot zone [3] and have an appreciable effect on the conditions of runaway electron flow formation [4] and on the value of fast ion losses [5, 6]. The magnetic island excitation is put into effect by application of a relatively low value of perturbing magnetic field on the main magnetic field. Usually the planned magnetic field perturbation is produced by means of the coils having a special shape which can be placed outside or inside the vacuum chamber of the device.

In the article via numerical calculations a possibility of the magnetic island structure excitation at the edge of closed magnetic surface configuration is demonstrated in the U-2M torsatron with the additional toroidal magnetic field coils [7]. The simplest applied scheme to realize the structure is founded on a particular shunting of electrical current in one the coils. It is not impossible that the scheme can be beneficial to the other toroidal magnetic systems comprising a discrete set of the toroidal magnetic field coils.

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1-13

EFFECT OF A NON-CIRCULAR SHAPE OF THE TORUS ON THE *l* = 2 TORSATRON MAGNETIC SURFACES

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In a noncircular torus the poloidal cross-section minor radius is $a_n \neq$ const. In the field of fusion research an example of noncircular torus implementation is, in particular, the vacuum chamber of present-day tokamaks, which have a D-shaped poloidal cross-section. For the first time, the stellarator-type magnetic system with a noncircular torus poloidal cross-section highly elongated along the straight *z*-axis of the torus has been discussed in [1, 2]. The authors reported that the influence of toroidal effects on the plasma diffusion and thermal conductivity can be significantly decreased in the system.

In paper [3] were presented the numerical calculation results for the magnetic field of an ideal (with filament-like helical coils) model of the l = 2 torsatron magnetic system with non-circular torus, whose poloidal cross-section shape differs to a lesser extent from the initial circle. The main goal of the investigation was to discover the additional possibility to enlarge the distance between the closed magnetic surface existence region and helical coils, i.e., the first wall-plasma spacing in the stellarator-type fusion reactor [4].

The present study takes into account the model of the l = 2 torsatron magnetic system with the non-circular torus the helical coils of which have real size cross-section. The numerical calculations show that the value $\delta_i \sim 0.2$ of maximal relative deviation of a non-circular poloidal cross-section from basic circular one results in a several-fold contraction of closed magnetic surface existence region. There is some increase in the values of rotational transform angle and the mirror ratio in the central closed magnetic surfaces. A zero-order magnetic well value takes place. An enlarged clearance between the outer boundary of field line stochastic layer, i.e., the boundary of the plasma layer having transient plasma parameters (SOL plasma) and the estimated surface of vacuum chamber can be obtained by the transition from the circular torus to the non-circular torus under consideration.

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1-14

THE DIVERTOR REGION FORMATION IN THE STELLARATOR SYSTEM "YAMATOR"

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By imposing a certain optimum vertical magnetic field and using the equi-inclination law of helical conductors winding, regularizations have been carried out for the region of the edge closed magnetic surfaces and the divertor in the configurations of the $l = 1$, m = 3 and m = 5. Yamators having a low aspect ratio $A_{h1} = R_0/a_{h1} = 3.333$ and the helical magnetic axis [1, 2], where R_0 is the major radius of the torus, a_{h1} is the minor radius of the internal helical conductor. Magnetic configuration modes have been found, at which the narrowest regions with stochastic behavior of magnetic field lines are formed close to the conditional separatrices.

The studies have shown that for creation of the magnetic configuration the best regularization of the peripheral (edge) and divertor regions in the Yamators is attained with application of the equi-inclination law of two-wire helical conductors winding. In this case, the narrow region with stochastic behavior of magnetic field lines in the vicinity of the conditional separatrices of the Yamator appears to be embraced all from the outside by closed magnetic surfaces. Furthermore, these magnetic surfaces also form a closed spatial divertor region of quite great sizes in both longitudinal (azimuthal) and transverse directions. This is particularly significant for uniform distribution and utilization of the heat of plasma that escapes by the divertor from the magnetic trap. It is possible that the divertor structure of this sort and its updated construction would meet the concept [3] that the advanced divertor solutions will set the innovative magnetic geometries.

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1-15

STRUCTURE OF INTENSIVE MHD FLUCTUATIONS IN U-3M TORSATRON IN THE MODE OF RARE COLLISIONS

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MHD-fluctuation structure in the frequency range of $f \approx 0.5...52$ kHz was studied using a set of magnetic sensors in one of the poloidal cross-sections of plasma column. Fluctuation structure was studied under conditions of plasma energy slowdown before proceeding to the improved confinement regime. The amplitude of the detected fluctuations of the magnetic field on the boundary of plasma confinement reached a value of $\tilde{B} \approx 0.1$ Gs.

The detected magnetic field fluctuations represented a set of consecutive groups of fluctuations in each of which several variable fluctuations of amplitude and frequency occurred. Fluctuations in the magnetic field are grouped in the following frequency ranges: $f_1 \approx 1…1.7$ kHz; $f_2 \approx 6.5…7.8$ kHz; $f_3 \approx 13…17$ kHz; $f_4 \approx 20…22$ kHz; $f_5 \approx 35…42$ kHz.

All these fluctuations have a complex three-dimensional structure which is useful to present in the form of Fourier series with poloidal wave numbers m = 0; 1; 2; 3. The available number of magnetic sensors does not allow a confident identification of fluctuations with $m > 3$.

There are 3 types of fluctuations with specific spatial (3D) structure. The first type: special structure amplitude changes slowly and the structure rotates with specific frequency. The second type: spatial structure stands still and its amplitude changes in specific frequency range. The third type: structure rotates with amplitude fluctuations at the same time.

There is a rotation of the spatial (3D) structure both in the direction of ions rotation in the magnetic field, and in the opposite direction.

The most common structures are rotated with m = 2.

1-16

STUDY OF WAVE PROCCESSES AT THE INITIAL STAGE OF RF-HEATING IN U-3M TORSATRON

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Study of wave processes occurring during initial stage of RF-heating was performed using movable magnetic and electric probes in U-3M torsatron. Plasma heating was performed by frame antenna. Electric probe allowed to register the change of plasma density profile and magnetic probes measured the amplitude and the shift between all field components in different points along the plasma column cross-section.

Frequency spectrum of registered fluctuations of magnetic field contains the main frequency that coincides with the frequency of RF-generator and higher harmonics. The amplitude of the second harmonics in this mode can be compared with the amplitude of the basic harmonics.

Increase of plasma density on magnetic axes configuration is observed basically during the heating process at initial stage of RF-discharge. Whereas the largest in magnitude B_R is a component of the registered field at the fundamental harmonic frequency which increases with the increase of density and also has a maximum near the magnetic axis. The fluctuation amplitude of this component reaches values of $B_R \geq 0.6$ Gs. This indicates that at this stage of RF-discharge the basic fraction of RF-power is absorbed in the area of magnetic axes.

Other components B_z and B_φ at early discharge are comparable by magnitude with B_R, however, by the end of the discharge they become almost an order of magnitude smaller and react poorly to changes in the density and magnitude of the magnetic field.

Absence of correlation in the behavior of the amplitude of different components of magnetic field and phase shifts between them allow to assume that there is a set of weakly-coupled linearly polarized waves.

1-17

BEHAVIOR DYNAMICS OF LOW-FREQUENCY MHD-FLUCTUATIONS AND MAIN PLASMA PARAMETERS IN U-3M TORSATRON IN RF-HEATING MODE

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A significant decrease in the intensity of low-frequency MHD-activity is accompanied by sharp increase of plasma energy content in U-3M torsatron. Plasma is generated and heated by RF-fields with frequency of $\omega \approx 0.8\omega_{ci}$ and is in a mode of rare frequency of collisions. A set of 15 magnetic sensors was installed in one of the poloidal cross-sections of torus. The poloidal component of magnetic field was registered. At some point of time there is a sharp decrease of MHD-activity of plasma (see Fig. 1) with a simultaneous increase of plasma energy content (see Fig. 2).

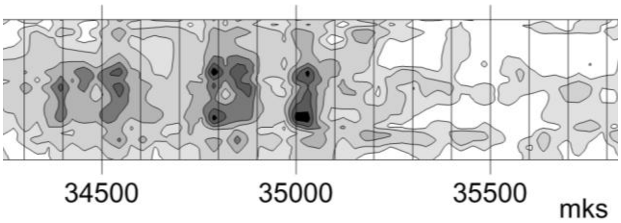

Fig. 1. Distribution of fluctuation power of poloidal magnetic field obtained from magnetic sensors on the measured surface near confinement improvement. The X-axis represents time. At Y-axis shows the poloidal angle from -180 to +180 degrees

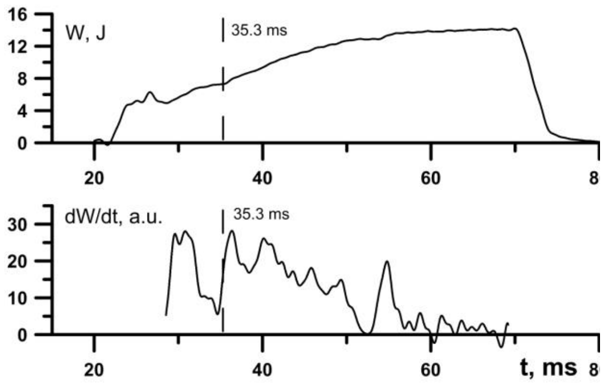

Fig. 2. Plasma energy content (a), time derivative of plasma energy content (b). The dotted line shows the time of sharp rise in plasma energy content

1-18

EXPERIMENTAL STUDY OF HYDROGEN BALANCE IN VACUUM CHAMBER OF U-3M TORSATRON DURING MAIN OPERATION MODES

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Temporal behavior of hydrogen pressure in basic operation modes [1, 2] (1 – mode of RF wall conditioning with weak magnetic field ($B_0 \sim 0{,}025$ T); 2 – mode RF wall conditioning with strong magnetic field (($B_0 \sim 0{,}72$T); 3 – mode of RF plasma heating with strong magnetic field ($B_0 \sim 0{,}72$ T)) was experimentally investigated to study the hydrogen balance in confined plasma and vacuum chamber of U-3M torsatron. Measurements were performed using standard vacuum sensors of ionization (PMI2) and magnetron (PMM32) type in two local areas – in the main volume of vacuum chamber of U-3M and in the volume limited by helical conductors near plasma. The methods to measure the non-stationary pressure by the used vacuum sensors were tested as well as temporal characteristics of vacuum sensors were determined and their calibration was performed before the start of experimental investigations.

Defining characteristics of every operation mode were determined during the performed investigations. It was found that in all modes during RF pulse at quay-stationary stage of RF-discharge there is pumping out of hydrogen from the volume of vacuum chamber. Pumping speed remains constant for every mode. When RF-power is off there is a reverse desorption of hydrogen accumulated during RF-discharge on the wall surfaces of the vacuum chamber and the helical coils. Pumping-out of hydrogen from the main volume of vacuum chamber and from the area close to plasma limited by helical conductors occurs with different speed. This speed depends on the basic plasma parameters such as density and lifetime of the particles in hydrogen plasma, their energy and also RF-heating peculiarities for every operation mode. During and after RF-pulse there is a local hydrogen pressure difference between these areas. Hydrogen balance in the vacuum chamber is mainly determined by the surface mechanisms of absorption and desorption of hydrogen on the wall surfaces of the vacuum chamber and helical conductors. In some modes during RF-pulse there is an activation of the wall surfaces. And thus, when RF-power is off there is pumping-out of hydrogen from the vacuum chamber which is not related to absorption of hydrogen particles leaving the plasma during RF-discharge.

Evaluations of the average lifetime of hydrogen particles in confined plasma for each of the main operating modes were performed based on the measured hydrogen balance and the average density of the confined plasma.

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1-19

RUNAWAY ELECTRONS AND PARAMETRIC INSTABILITY IN THE URAGAN-3M TORSATRON

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In this paper the comparative analysis of the spectra of electromagnetic fluctuations in the peripheral area of the Uragan-3M magnetic trap is carried out. We also compare the spectra of oscillations observed in the volume of plasma confinement with the spectra of modulation of the runaway electrons flow. Namely, we were investigating the dependency of the fluctuations spectrum form on the intensity of the runaway electrons flow [1–3].

The execution threshold for the parametric instability depends on the level of microwave power introduced into plasma. The intensity of interaction between the runaway electrons and plasma is also proportional to the introduced microwave power. The possible influence of the observed phenomena on the conditions of plasma heating and confinement in the Uragan-3M torsatron is discussed.

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1-20

OSCILLATORY AND WAVE ACTIVITY IN THE RUNAWAY ELECTRONS FLOW

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The presence of the accelerated particles flow (the flow of runaway electrons) in the plasma confinement volume may case a number of different instabilities [1–3]. In this work we investigate the spectrum of fluctuations in a flow of charged particles to identify the oscillatory and wave processes observed. Besides, we pay special attention to the interaction between the flow particles and plasma fluctuations. The main evidence of such interaction is the presence of modulation in the particles flow with the corresponding characteristic modulation frequency. Namely, the modulation frequency in such cases corresponds to the frequency of characteristic oscillations of the discharge plasma. Basing on this, we carried out the experimental investigations of spectrum of oscillations observed in the circuits of edge electrostatic probes during the microwave pumping pulse and also on the back edge of the magnetic field pulse.

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1-21

CONCERNING PHOTODIODES SPECTRAL SENSITIVITY INFLUENCE ON THE TWO FOILS SOFT X-RAY TECHNIQUE IN THE URAGAN TORSATRONS

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Soft X-ray (SXR) diagnostics is routinely used in Uragan-3M and Uragan-2M torsatrons. One of the SXR diagnostic applications is based on the plasma temperature estimation. A broadband light emission from plasma is filtered by fin beryllium or aluminum foil in order to separate SXR emission. The SXR energy spectrum, passed through the foil, depends on the foil thickness and material. The ratio of SXR signals passed through two different foils depends only on the plasma temperature under usually applied assumptions [1]. Optimization of the foil thickness and material for the Uragan conditions was done in previous work [1]. It was shown numerically that in assumption of the pure bremsstrahlung emission from the Maxwellian plasma the ration of signals passed through the 1.5 micrometer and 2.25 micrometer aluminum filters is weakly depends on the plasma temperature. Thicker second foil is required for the significant dependence of the ratio in the 0.1…1 keV temperature range, practically interesting for URAGANs plasma. Nonetheless, according to the experimental measurements in URAGAN-3M, the 1.5/2.25 μm signals ratio is substantially exceed predictions. One of the possible reasons of the discrepancy is based on the possible influence of the spectral sensitivity of the photodiodes, used in the SXR measurement systems. The uniform spectral sensitivity of the photodiode is used in the previous work. Real dependence of the sensitivity on the SXR wavelength can substantially modify the signals ratio, especially in the case than the difference of the foils thickness is rather low. The complete data of the spectral sensitivity of the even the AXUV photodiodes [1] and other photodiodes used in Uragans is unknown (especially the sensitivity decay in the 10…30 keV range). The ratios of the SXR signals passed through different foils for different modeling dependences of the spectral sensitivity of the photodiodes has been calculated numerically in our work.

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1-22

FINDIF CODE TEMPERATURE DISTRIBUTION SOLUTIONS FOR LIMITER WENDELSTEIN 7-X CONFIGURATION

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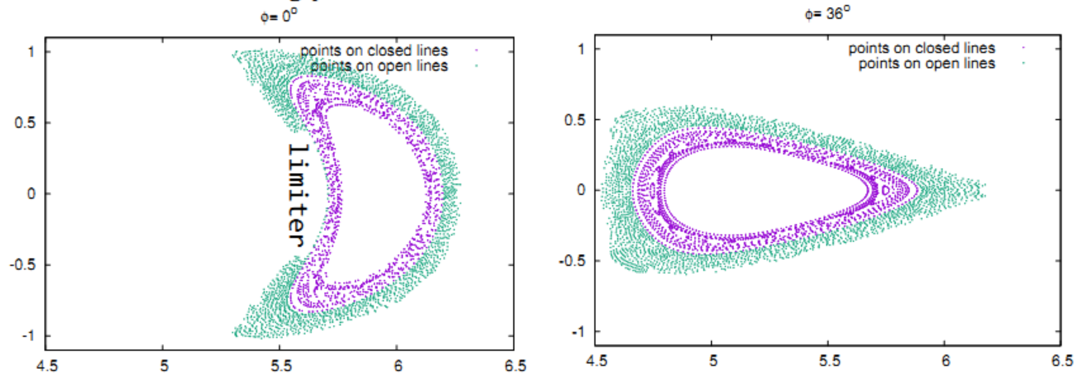
3-D multifluid code Findif directly takes into account huge transport anisotropy in magnetised plasmas directly. Magnetic field lines ('flow motorways') are traced and mesh points are set on the lines' intersections with either fixed-toroidal-angle planes or material surfaces. Since the volume the lines are in is limited (e.g. by the device walls) a simple approach based on avoiding short distances between lines may be enough to ensure quite even distribution of points within the interesting part of the device.



Potentially very large parallel flows are carefully separated from the other components to ensure minimal artificial spread of fluxes due to the discretisation of the equations. The complex stellarator geometry is treated without unnecessary simplifications; local magnetic coordinates are used to transform Braginskii equations into a numeric-friendly form. The code is not fully functional yet (not all transport equations can be solved simultaneously) and we want to present our preliminary results.

1-23

THE INVESTIGATION OF A WAKE POTENTIAL OF NON-RELATIVISTIC PROTONS IN THE CASE OF THEIR ORIENTATION MOTION IN SOLID-STATE PLASMA OF IONIC CRYSTALS

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It is known that at charged particles motion in various media (in plasma, in solids and, may be, in a physical vacuum) so-called "wake potentials" occur due to self-consistent processes of polarization, screening and lag. For example in [1] in the frames of classical electrodynamics it was received for the first time the following expression for a wake potential in the case of ion transference with a positive charge of Ze and a mass of m with the velocity of $\vec{V}$ along the coordinate of z in a plasma with electron concentration of n:

$$\phi(z,\rho,t)=\frac{2Ze\omega_0}{V}\sin\left[\omega_0\left(\frac{z}{V}-t\right)\right]K_0\left(\frac{\rho\omega_0}{V}\right).$$

Here $\rho=\left(x^2+y^2\right)^{1/2}$, $\omega_0=\left(4\pi ne^2/m\right)^{1/2}$ – "plasma frequency", $K_0(x)$ – MacDonald function. The similar expression for a wake potential was found by a quantum-mechanic way in the frames of a plasmon formalism in the case of ion motion in a metal [2].

In the given paper the wake potentials for orientation moving non-relativistic protons are calculated (both a planar and a axial channeling is considered) in crystal lattices of ionic crystals (such crystals may be treated as a peculiar regular solid-state plasma due to the existence of non-screening long-time Coulomb fields) in accordance with a sequence proposed in [3].

For a number of ionic crystals some wake potentials calculated on the basis of the expression of $\Phi(\vec{r},t)=\sum_{n,\bar{n}}\left[\vec{p}_n(\vec{r}_{\bar{n}},t)\cdot(\vec{r}-\vec{r}_{\bar{n}})/|\vec{r}-\vec{r}_{\bar{n}}|^3\right]w_n$ (see [3]) the wake potentials, where $\vec{r}=(\vec{\rho},z)$, $\vec{r}_{\bar{n}}$ – the radius-vector of a separate ion of a crystal lattice, w_n – the probability of a proton settling in n-state of a channeling motion [4], are compared with the expressions obtained at the substitution of Ze in the formula for the wake potential in a metal (see [2]) for the expression of $Ze\left[(\varepsilon_\infty-1)/(\varepsilon_\infty+1)\right]^{1/2}$, where ε_∞ – the optical dielectric permeability of the ionic crystal [5].

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1-24

THE USAGE OF MAXWELL FRACTIONAL EQUATIONS FOR THE INVESTIGATION OF THE WAVEGUIDE PROCESSES

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To describe physical systems having a long-time memory, fraction, scaling, some differential equations in partial derivatives of fractional order are used (derivatives and integrals of fractional order are considered, for example, in [1]). In particular, to investigate the distribution of electromagnetic radiation in fractional media accompanied by dissipation, it is worth using a Maxwell equation with the derivatives of a fractional order by the coordinates [2]. These equations are a generalization of usual Maxwell equations where some fractional generalizations of differential vector operators of divergence and rotors are used determining in their turn through the nabla operator of the type

$$ {}_{(a,b,c)}^{\quad C}\nabla_{(x,y,z)}^{\alpha} = \bar{e}_x\, {}_a^C D_x^{\alpha} + \bar{e}_y\, {}_b^C D_y^{\alpha} + \bar{e}_z\, {}_c^C D_z^{\alpha}, \ (n-1<\alpha<n), $$

where ${}_a^C D_x^{\alpha}$, ${}_b^C D_y^{\alpha}$, ${}_c^C D_z^{\alpha}$ – Caputo operators correspondingly regarding variables of $a \le x < +\infty$, $b \le y < +\infty$, $c \le z < +\infty$ [3]. Further step made in this direction in [4], deals with the choice of nabla operator ${}_{(a,b,c)}^{\quad C}\nabla_{(x,y,z)}^{(\alpha,\beta,\gamma)}$ in a state of so-called mixed orders (here α, β, γ values may be both whole ones and have some arbitrary fractional meanings). Besides, it is easy to show that all the theorems of a fractional vector mathematical analysis (see [2]) are fulfilled.

In the paper for a special case of $\alpha=\beta=1$, $0<\gamma\le 1$ values and also in charges and currents absence, first, some fractional Maxwell equations in Cartesian and cylindrical coordinate systems are written out. Second, some fractional and wave equations are derived. Third, some fractional Helmholtz equations by means of the methods stated, for example, in [5] are found and solved. Note that some fractional and differential equations usage allows to design and study naturally the processes of electromagnetic radiation power fading in various waveguide structures (a fractional derivative possesses a non-conversional property i.e., for example, a fractional Helmholtz equation is not an invariant regarding the substitution of a longitudinal coordinate of $z \to -z$).

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1-25

CALCULATION OF THE MAGNETIC SURFACES OF THE URAGAN-2M TORSATRON WITH ZERO CURRENTIN A SINGLE TOROIDAL MAGNETIC FIELD COIL

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Possibility of existence of closed magnetic surfaces in the Uragan-2M device with switched off one of the coils of an additional toroidal magnetic field has been shown before by numerical simulation in paper [1]. The experiments (see paper [2]) confirmed the existence of closed magnetic surfaces in such a system.

In the present work the existence of closed magnetic surfaces in the Uragan-2M torsatron in case of zero current in one coil of the set of the toroidal field coils is analysed with taking into account the influence of the current-feeds and detachable joints of the torsatron helical winding. A number of characteristic operating regimes of the torsatron is considered. For all regimes the magnetic field is calculated using the Biot-Savart law code [3]. The obtained results can be of interest for studies of plasma neutron sources based on stellarator type magnetic configurations with a mirror part of the magnetic configuration at the place where the coil current is zero (e.g., [4]).

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1-26

MODELING OF THE NEOCLASSICAL TOROIDAL VISCOUS TORQUE IN TOKAMAK PLASMAS

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The toroidal plasma rotation in tokamaks is sensitive even to slight violations of axial symmetry of the confining magnetic fields. The non-resonant part of these non-axisymmetric magnetic perturbations (e.g., toroidal field ripple, error fields, coils for ELM mitigation purposes) produces a toroidal torque acting on the plasma, which is also termed as the neoclassical toroidal viscous (NTV) torque, The effect of the NTV torque on the plasma rotation has been observed in various experiments [1]. Typically, analytical and semi-analytical approaches [2] are used for the evaluation of the NTV torque, which make simplifying assumptions concerning geometry and collision model. A numerical solution to this problem is provided by the quasilinear version of the code NEO-2 [3, 4, 5], which solves the linearized drift kinetic equation without such simplifications. The only assumption is that the perturbations are small enough such that the part of the particle motion within the perturbed flux surface is only weakly affected by the perturbation field (quasilinear approach). With help of the quasilinear approach the dimension of the original 4D integro-differential equation can be reduced by one. In the present report, the numerical discretization of the resulting set of 3D equations (field line parameter ϑ, velocity module v and normalized magnetic moment η) and its implementation in the code NEO-2 is discussed. In NEO-2 the velocity module dependence is treated by a series expansion over test functions (Galerkin method), which can be associated Laguerre polynomials of the order 3/2 (standard version of NEO-2) or localized basis functions (e.g., first order splines) after a recent upgrade of the code. Such localized basis functions are well-suited for the description of resonant transport regimes as shown in [4, 5] The obtained set of coupled 2D equations is solved by a conservative finite difference (finite volume) method on an adaptive grid over (ϑ, η) using a sparse solver. Furthermore the collision model (full linearized collision operator), which has been implemented so far in NEO-2 for a simple plasma (electrons and one sort of ions), has been generalized here for the general case of a multi-species plasma. This would allow computations of the torque for plasmas with significant impurity contents including the computations of the additional impurity transport caused in tokamaks by the violation of the toroidal magnetic field symmetry.

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1-27

TWO DIMENSIONAL CODE FOR MODELLING OF HIGH IONE CYCLOTRON HARMONIC FAST WAVE HEATING AND CURRENT DRIVE

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None-inductive current drive is essential for long-pulse or steady-state operation of spherical tori. Along with Electron Bernstein Waves, the High Harmonic Fast Waves (HHFW) are among the candidates for current drive in these devices. The basic mechanism of HHFW power absorption is electron transit time magnetic pumping (TTMP). Due to high beta value in spherical torus's discharges, the absorption of HHFW is rather high and essential heating [1] and current drive [2] were demonstrated.

In this report, HHFW heating and current drive is modelled numerically in 2D. A numerical code for computation of electromagnetic field of the fast magnetosonic wave in a tokamak at high harmonics of ion cyclotron frequency has been developed. The code gives the finite difference solution of Maxwell's equations for harmonic electromagnetic field in the cylindrical system of coordinates R, φ, Z. Here R is the big radius of the torus and φ is the toroidal angle. The $\exp(il\varphi)$ dependence of wave fields on φ is supposed due to toroidal symmetry. The code uses equidistant rectangular mesh (with the choice of the step-sizes ΔR; ΔZ) for the wave magnetic field and another staggered (by $\Delta Z/2$ for E_R and $\Delta R/2$ for E_φ) grids for the wave electric field in the computational domain. The proper boundary conditions are prescribed at the realistic tokamak vessel. The RF antenna is modelled by the external currents in the equations for the curl of wave magnetic field. The poloidal tokamak magnetic field impact is taken into account by the sequential approximation technique. The input of "kinetic" part of dielectric permeability tensor was included in the same way. The code was verified against the known analytical solutions. The effect of the mesh size on the obtained solutions was also investigated. Distribution of electromagnetic field in the plasma was computed taking into account the real equilibrium magnetic field and magnetic surfaces, incorporated from the equilibrium code EFIT, including the poloidal divertor and using realistic plasma parameter profiles.

The fast wave TTMP current drive efficiency was calculated using the SYNCH code [3] in the local approximation.

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2-01

SECONDARY EMISSION CATHODE AS ALTERNATIVE OF THERMIONIC CATHODE FOR FUSION WITH MAGNETIC CONFINEMENT

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Plasma auxiliary heating and current drive are connecting with application high current thermionic cathode in energy sources. RF and microwave methods [1] are based on application power vacuum tubes with thermionic cathode. Neutral injection heating is used heated cathode application too [2]. Thermionic cathode has several disadvantages that will especially be more important in next step of fusion application as energy sources. That is expensiveness, short lifetime, plasma contamination, long term for performance preparation, low reliability.

There is alternative approach for high current electron flow creation. That is self supported electron electron-exited secondary emission in cross fields. It allows overcome all main disadvantages of thermionic cathode. Now secondary-emission cold cathode are successfully used in microwave magnetron that is developed here in Kharkov [3].

In 1991 on the base of this approach a Secondary Emission Magnetron Injection Gun (SEMIG) was created and tested in NSC KIPT. It is universal long life electron source for power microwave application [4]. Subsequently a similar devise was tested in United Kingdom. Recently a paper with information about achievement high power mode (700 kV 5 kA in short pulse) SEMIG was published [5]. This power level is enough for all fusion applications. Long pulse mode was tested experimentally with SEMIG at low power and pulse duration up several seconds approximately in the same time. Such pulse duration is enough for fusion applications too. SEMIG allowed applying cold secondary-emission cathode in all type power microwave device such as triode, tetrode, traveling wave tube, gyrotron. The SEMIG may be used in efficiency ion source [6] for neutral beam injection. Power electron gun is applied for direct plasma heating in open magnetic trap. The SEMIG may be solution for pulse energy enhancement problem [7]. Recently possibility of start direct heating and current drive are shown for closed magnetic traps [8].

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2-02

FEATURES OF ACTIVE POWER DEFINITION IN HIGH-CURRENT PULSED DISCHARGE

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The feature of high-current pulsed discharges is relatively simple receiving the pulse power from megawatts up to hundreds gigawatts which is absolutely not achievable in stationary systems. Therefore, an actual issue is the correct calculation of input active power into the high-current pulsed discharge.

The method of calculating the active power dynamics in the high-current pulsed plasma diode with a limited working surface of high-voltage electrode has been proposed in this paper. The feature of this system is formation of electrical double layer of space charge in the inductive discharge stage. This system allows obtaining the high power levels more than 100 *MW* at stored energy in capacitor bank up to 200 *J*.

The dynamics of input active power into the discharge $P_d(t)$ was based on the discharge current dynamics using discharge circuit equation of high-current pulse discharge, and is given by:

$$P_d(t) = i^2(t)\frac{dL_d(t)}{dt} + i^2(t)R_d(t) = i(t)\left[V_0 - \frac{1}{C_0}\int_0^t i(\tau)d\tau\right] - (L_c + L_d(t))\,i(t)\frac{di(t)}{dt} - i^2(t)R_c,$$

where $i(t)$ – the discharge current. It is necessary to take into account a number of features.

Since the waveforms of digital oscilloscopes have a negligible level of noise, when using integral-differential equations of active power calculation an important moment is the approximation method choice of the current signal experimental dependence from the noise.

Since any current sensor distorts the real signal, it is necessary to restore the experimentally obtained dependence of the discharge current. It is shown that the slight difference between the real and the observed signal leads to significant errors at further calculations. In case of using the inductive current sensor, when restoring the current signal, it is necessary to consider not only the relation between the total active resistance of measuring circuit R and the inductive resistance of the measuring coil R_w, but also the parasitic capacity of the measuring circuit C. The relation of the discharge current and the observed signal is given by:

$$i(t) = \frac{1}{\mu}\cdot\left[V_R(t)\left(1 + \frac{R_w RC}{L}\right) + RC\cdot\left(\frac{dV_R(t)}{dt} - \left.\frac{dV_R(t)}{dt}\right|_{t=0}\right) + \frac{R_w + R}{L}\cdot\int_0^t V_R(\tau)d\tau\right],$$

where μ – the current sensor sensitivity.

One should choose the most accurate model describing inductance change because of significant share of the discharge inductance L_d in the inductance of the whole discharge circuit L_c. In our case $L_c > L_d$, that allows using simpler model of synchronous changing of the plasma column radius with the discharge current value.

$$L_d(t) = L_{dm} - 2l_d\cdot\ln\left(1 - \frac{\Delta r_d}{r_{dm}}\cdot\frac{I(t)}{I_{m1}}\right).$$

Thus, the proposed method allows adequately calculating the input active power into the high-current pulsed discharge.

2-03

BUILDUP OF PLASMA OSCILLATIONS DURING MODELING THE ELECTROMAGNETIC WAVE PROPAGATION

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Actual problems of the radiolocation require extensive numerical modeling. One of the problems is a calculation of the radar cross sections of various objects when the scattered field is compared with the incident one. In such a way a good numerical model has to describe accurately an incident signal, a propagation of the signal through different (probably dispersive and anisotropic) media, a reflection of the signal from a scatterer (applying the boundary conditions) and an easy separation (during the analysis) of the scattered signal from the incident one. It can be realized by Finite Difference Time Domain (FDTD) method [1].

FDTD method is well developed to model a source of plane wave, wave propagation with the dispersion compensation due to a difference between analytical and numerical dispersions, near-to-far-field transformation using Huygens surface and different types of the boundary conditions including the Perfectly Matched Layer [2, 3]. It works well for nondispersive media with soft anisotropy (the permittivity tensor is a diagonal one). We should like to develop the method for plasmas which are dispersive and anisotropic media.

For plasmas, the Maxwell's equations have to be solved together with the plasma current equations. Both analytical and numerical dispersion equations give a relation between wave frequency and wave vector in plasmas at steady state [4]. But they don't answer the questions how long does it take to buildup the plasma currents when the electromagnetic wave is incident from vacuum on the plasmas and how long does it take to form a wave front of the plane wave in the plasmas. The numerical model of the plane wave source in plasma is interesting in particular for the problems of the wave transmission and reflection through/from an evanescent layer.

Time evolution of the plane wave formation in plasmas is studied numerically by FDTD solver. The electromagnetic wave is incident normally to the plane boundary between vacuum and isotropic plasma. Different harmonics of the plane wave need different time to buildup the oscillations in plasma. It is clear that time of the plane wave formation in plasmas is defined by the slowest harmonic. We study numerically the formation of plane wave in plasmas as a function of the phase and group velocities to use this model in problems of the plasma wave scattering by plasma inhomogeneities.

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2-04

CAPACITIVE COMPONENT OF DOUBLE LAYER CURRENT IN PLASMA

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Electric double layers in plasma are of interest because of being relatively simple used for pulse energy input with a specific power up to several tens *GW* per square centimeter locally into dense plasma. It makes possible to obtain intense neutron fluxes, heavy duty directional radiation, as well as impact of high-gradient effect on solid surface. The last is necessary for modification of structural-phase state in metals, alloys, ceramics, nanocomposites on nano-, meso-, micro- and macro-scale levels.

However, it should be noted that a double layer is a powerful dynamic system which parameters are change at high speed. From electrical point of view it looks like a set of a capacitor and a resistor, which resistance and capacitance are change according to a certain law. When changing the voltage and current of the layer the capacitor charge-discharges and the layer charge-discharge current appears in addition to general conduction current. Therefore, when calculating the active power supplied into a discharge it is important to know the proportion of this current in general discharge current.

In the paper in quasi-MHD approach it has been found the expression for a strong double layer capacitance, it was obtained an equation for the capacitive component of the current layer and it has been shown the method of calculating the charging current by the waveform of general discharge current for the case of recording a signal with a digital oscilloscope. The dynamic of capacitive component of double layer current in pulsed plasma diode with limited working surface of high-voltage electrode was shown as an example. Discharge characteristics were gathered at charging voltage from 4 to 14 kV of the capacitor battery with capacity of about 2 mF. The period of discharge current oscillation was about 2.5 ms, the maximum current in the first half period was up to 40 kA, the maximum current density in the high-voltage electrode was up to 2 MA/cm^2.

Studies have shown that obtained in quasi-MHD approximation expression for the capacitance of strong double layer rather accurately describes its capacity at voltage of about 100 V and it reaches 0.5 μF! But as the voltage raises the capacity of the layer decreases and even at 1 kV does not exceed 10 nF. Obtained expressions for the capacitive component of the current double layer allows calculate them without much difficulty in Excel. Because of data from digital oscilloscope also are gathered as Excel spreadsheets, it makes it easy to automate the experimental results carrying out. This is enough to load the experimental data into pre-prepared Excel form and to output the dynamics of the capacitive component of double-layer current.

Determination of the capacitive component in the discharge current waveform includes a number of preliminary steps, such as purification of the current signal from the noise, the restoration of the true shape of the discharge current and the calculation of the dynamics of the active discharge voltage. For each stage of the calculations are brought the ways of results verification, that allows us to speak about the reliability of the results.

2-05

LOWER HYBRID RESONANCE: FIELD STRUCTURE AND NUMERICAL MODELING

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The upper and lower hybrid resonances (UHR and LHR) appear in cold magnetized plasma when the perpendicular diagonal component $\varepsilon_\perp = \mathbf{e}_\perp \cdot \boldsymbol{\varepsilon} \cdot \mathbf{e}_\perp$ of the dielectric tensor $\boldsymbol{\varepsilon}$ nullifies (here $\mathbf{e}_\perp$ is a unitary vector perpendicular to the steady magnetic field). In case of LHR the WKB solutions predict a regular behavior of the fast magnetosonic wave. The wave number of the slow wave diverges on approach to the LHR layer.

The LHR phenomenon is a base for the lower hybrid heating and current drive. The mode conversion scenario of the minority heating also includes the LHR mechanism for the wave absorption. In a standard minority heating scenario the LHR appears at the plasma periphery, and its role in wave propagation and power balance is not yet studied sufficiently.

In present report, the behavior the electromagnetic fields in the vicinity of the LHR point is studied in case of 1D plasma non-uniformity. The second order equation for the slow wave is extracted from the Maxwell's equations. Its approximate analytical solutions are found in the LHR vicinity. The first of two solutions is singular and describes the wave travelling to the LHR layer. This wave if fully absorbed without reflections. Another solution which is regular describes the wave traveling in opposite direction. To extend the range of validity of the solutions found, they are matched to the WKB solutions.

Presence of the singularity hampers a numerical modeling of wave propagation in plasma when a LHR exists in the calculation domain. A simplest way to proceed is usage of the penalty method in which the singularity in the LHR point is avoided by adding locally an artificial imaginary part to $\varepsilon_\perp$. A more rigorous option is usage of the analytical solutions in the LHR area. For the slow wave, the above obtained solutions may be used. The necessary solutions for the fast wave may be represented via polynomials. The analytical continuation of the Maxwell's equations to the complex plane is the most rigorous approach. These three possibilities for numerical solving the wave propagation problem in presence of the LHR zone are discussed in the report.

2-06

RADIO-FREQUENCY WALL CONDITIONING FOR STEADY-STATE STELLARATORS

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A discharge sustained by excitation of slow waves at frequencies below the ion cyclotron is used for wall conditioning [1]. In the discharge plasma is generated with a density substantially less than the density of neutral hydrogen gas. The mechanism of the wall conditioning consists in the interaction of the plasma ions and neutral hydrogen atoms with the wall surfaces in which volatile substances are formed. The latter can be pumped out from the vacuum chamber. In such a discharge it is important that the plasma density is not high in order to decrease the probability of ionization of desorbed impurities. A similar discharge, but at frequencies higher than ion cyclotron, has been analysed and experimentally tested (see Ref. 2). The advantage of the here considered scenario is the lower frequency that facilitates generator and antenna design and lowers the cost. On the other hand, a high steady magnetic field is necessary that is provided in cryogenic machines. The self-consistent 1D code [3] simulating radio-frequency plasma production in stellarator type machines in the ion cyclotron range of frequencies is used to study such a discharge. For successful start-up of the discharge, it is necessary to provide overlapping of the slow wave global resonances. Following paper [2], this is difficult to provide for low $k_{||}$ resonances. To excite the slow wave with high $k_{||}$, a double frame antenna was used instead of the single frame antenna. This suppresses excitation of long-wave modes. For the reason of good charged particle confinement in stellarator, the continuous discharge with RF power about 10 kW produces dense plasma with low temperature. This is not beneficial for generation of neutral hydrogen atoms which are necessary for wall conditioning. Calculations show that pulsed discharge is more efficient. At the plasma build-up stage, the atoms are generated mainly owing to dissociation of hydrogen molecules by electron impact. When the RF power is off the dissociative recombination of molecular ions with electrons comes to play.

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2-07

CYCLOTRON WAVE ABSORPTION IN D-SHAPED TOKAMAKS

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In order to achieve the fusion conditions in tokamaks an additional plasma heating must be employed. Effective schemes of heating in such plasma systems can be realised by the wave dissipation in the range of ion-cyclotron resonance (ICR) and/or electron cyclotron resonance (ECR) frequencies. As is well known, the kinetic wave theory of high-temperature toroidal plasmas should be based on the solution of Vlasov-Maxwell's equations. However, this problem is not simple even in the scope of linear theory since to solve the wave equations it is necessary to use the suitable kinetic dielectric (or conductivity, or susceptibility) tensor valid in the given frequency range for realistic two- or three-dimensional plasma models. In this paper the transverse dielectric susceptibility elements are derived for radio frequency waves in a two-dimensional (2D) axisymmetric large aspect ratio tokamak with D-shaped magnetic surfaces. A collisionless plasma model is considered. The linearized Vlasov equation is solved separately for untrapped and usual *t*-trapped particles as a boundary-value problem using an approach developed in Refs. [1–3]. Periodicity of the perturbed distribution function over the poloidal angle is used for untrapped (passing or circulating) particles. Whereas, the continuity of the perturbed distribution function at the reflection points (where the parallel velocity is equal to zero) is used for the *t*-trapped particles. The fundamental (first order) cyclotron and bounce resonances are taken into account. To evaluate the wave susceptibility tensor, the perturbed values are Fourier decomposed in a poloidal angle. Due to 2D magnetic field nonuniformity, the whole spectrum of the perturbed electric field is present in the given harmonic of the perturbed current density. The separate contributions of untrapped and *t*-trapped particles to the transverse susceptibility elements are written by summation of bounce-resonant terms, which include the double integration in velocity space, the phase coefficients, the standard elementary and plasma dispersion functions, elliptic and the quasi-elliptic integrals. It must be pointed out that the dielectric characteristics are derived neglecting the drift effects and finite particle-orbit widths. These effects (as well as the finite pressure and Larmor radius corrections) can be accounted in the next order of perturbations over the magnetization parameter. The susceptibility elements, evaluated in this paper, are suitable for estimating the wave dissipation by the fundamental cyclotron resonance damping (e.g. during the plasma heating and current drive generation) in the frequency range of ICR and/or ECR. The dissipated wave power is expressed by the summation of terms including the imaginary parts of both the diagonal and non-diagonal elements of the transverse susceptibility.

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3-01

DAMAGE OF CASTELLATED TUNGSTEN TARGETS IN THE COURSE OF ITER ELM-LIKE HEAT LOADS

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Macro-brush configuration of the divertor targets allow to mitigate the induced currents and minimize cracking of tungsten surface under high heat loads during intense transient events such as the disruptions and Edge Localized Modes in ITER. Nevertheless, castellated edges of macro-brush armour elements can be a source of molten/solid dust particles which are injected into the plasma. Therefore, features of the edges erosion of brush-like divertor surface need to be comprehensively studied both in corresponding simulation experiments and with predictive numerical modelling.

The experimental simulations of ITER transient events at relevant surface heat-load parameters (i.e., energy density and the pulse duration as well as particle loads) were performed with the QSPA Kh-50 quasi-stationary plasma accelerator, which is the largest and most powerful device of this kind. The main parameters of QSPA plasma streams were as follows: ion impact energy was about 0.4…0.6 keV, the maximum plasma pressure amounted to 0.32 MPa, and the stream diameter was equal to about 18 cm. The surface energy loads measured with a calorimeter achieved 0.9 MJ/m^2 (i.e., above the tungsten melting, but below the evaporation thresholds). In all experiments the plasma pulse shape was approximately triangular, and the pulse duration was equal to 0.25 ms.

The tungsten target of 5×5 cm^2 with thickness of 1 cm was irradiated under different number of plasma pulses. The castellated rectangular units about 25×12 cm^2 was formed on the target surface by means of several kerfs. The width of the gaps between the units was 1mm, and the depth of the gaps – 5 mm. Surface analyses of the targets exposed to QSPA plasma streams, with measurements of the erosion patterns in the course of increasing number of plasma pulses has been performed. The mountain of molten material appears on the edge of castellated targets. The dynamics of mountains' formation was studied in the course of different numbers of plasma pulses.

The onset of dust particles ejection from the exposed castellated targets has been studied. Formation of re-solidified bridges through the gaps of castellated target due to the melt motion is studied in dynamics. With following plasma impacts such re-solidified bridges became additional source of W dust. The dust particles were injected both up and down plasma stream.

3-02

THE STUDY OF THE INFLUENCE OF STATIONARY PLASMA THERMAL IMPACT ON THE STRUCTURE OF BERYLLIUM

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One of the key tasks in creating a fusion reactor based on the tokamak is the choice of plasma facing materials, which must withstand to stationary plasma-thermal effects and intense pulsed. Materials such as tungsten and carbon fibre composite are selected for diverter protection and beryllium for the protection of the ITER first wall [1]. So the actual problem is the study of changes in the structure of these materials in plasma-thermal action.

In this regard, in the present work was investigated the changing in the structure of beryllium stamps TGP-56 in the stationary plasma-thermal impact.

Experimental study of stationary plasma-thermal impact on the beryllium samples were conducted on a plasma installation, which is a plasma generator. In the generator to obtain plasma was used plasma-beam discharge. Installation of plasma-beam discharge was developed to support the establishment and operation of the Kazakhstan Material Tokamak for testing of small specimens of KTM materials and equipment [2, 3]. The study of characteristics of plasma-beam discharge in the environment of hydrogen, helium and deuterium was performed using single Langmuir probe. Control of working environment is carried out using a quadrupole mass spectrometer CIS-100.

Irradiation of the samples of tungsten was carried out using a primary beam power of 1-2 kW during 30 min. The samples were submitted to a negative bias potential, which in this series of experiments ranged from 0 to 1600 V. During irradiation, the pressure in the chamber was 2×10^{-3} Torr. The hydrogen, deuterium and helium of high purity were used as working gas. Samples of beryllium 10×10×5 mm before irradiation was brushed and polished. The structure and element composition of the beryllium samples before and after impact was investigated on an optical microscope OLIMPUS BX41M and raster electronic microscope JSM-6390 with energy dispersive microanalysis console.

Microstructural studies of beryllium samples showed the presence in the initial state micropores insignificant size and small number, mostly located on the grain boundaries. After irradiation by hydrogen plasma on the beryllium surface observed defects in the form of small pores. It was determined that the increase in ion energy leads to an increase in pore size. The surface of the beryllium samples exposed to deuterium plasma, characterized by a less pronounced porosity compared to samples surface exposed to hydrogen plasma. The least porosity of the surface is observed in the sample irradiated to the helium plasma. Under irradiation in beryllium, the filling of the pores by hydrogen atoms, deuterium and helium, which leads to a pressure increase inside the pores and thus to an increase in various kinds of stresses at the grain boundaries. The increase in the size and concentration observed in the initial state and there has been, apparently, due to the anisotropy of swelling of the individual crystallites, because there is a tendency of the grains to move relative to each other as a result of the stresses at the grain boundaries.

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3-03

DEUTERIUM AND HELIUM TRAPPING INTO TUNGSTEN-COATED COMPOSITE, STRUCTURES UNDER SEQUENTIAL IRRADIATIONS

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Tungsten coatings of multilayered functional structures are promising materials for devices that come into contact with the plasma in CTF installations. The possibility of their use in such devices depends largely on their radiation resistances to the accumulation of hydrogen isotopes and helium, which are formed as a result of plasma beams. This is a problem so the authors intensively studied it in recent years [1–3]. In the work the processes of trapping and thermal desorption of ion-implanted helium and deuterium in tungsten coatings of composite structures sequentially irradiated by named ions were studied by thermodesorption spectrometry and electron microscopy. The influence of pre-irradiation by ions of one gas on the trapping and retention of particles of another gas was analyzed.

Tungsten coatings of about 1 micron thickness were deposited by the magnetron sputtering of W target in Ar atmosphere on stainless steel substrates with pre-deposited Cu layer and without it. The samples were irradiated with 10 keV D^+ (20 keV D_2^+) and 20 keV He^+ ions to doses in the range $(1.0\ldots5.0)\times10^{17}cm^{-2}$ at the target temperature 290 K by scheme: (He^+ – D^+) or (D^+ – He^+).

Thermal desorption spectra of deuterium and helium from samples in a vacuum were studied, capture coefficients of these gases in the tungsten coatings were estimated. The influence of pre-implantation of one gas particles on trapping and release from W coatings in vacuum of another gas particles was examined. It was found that deuterium accumulation in the tungsten coatings is independent on the previous He^+ ions implantation as well as helium accumulation is independent of the previous D^+ ions implantation.

In single and sequential implantations of D^+ and He^+ ions such regularity was observed: deuterium accumulates in the tungsten coatings at lower concentrations as compared to helium and its capture coefficient was about an order lower. The temperature ranges of deuterium and helium release remain the same. The maxima of peaks in the spectra of thermal desorption are at the same temperatures both in single and sequential implantations of D^+ and He^+ ions.

The mechanisms of implanted gases accumulation into tungsten coatings at single and sequential implantations of named ions are suggested. The gases can be trapped, for example, in formed radiation defects of vacancy type, in interstitial dislocation loops, gas – vacancy complexes and bubbles. The influence of these defects on the structural properties and radiation resistance of tungsten coatings of perspective multi-functional structures for CTF installations is shown.

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3-04

PRODUCING FINE-DISPERSED MATERIALS FOR THE MAGNETOPLASMA SEPARATION

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Experiments were carried out to compare three methods used for the grinding of materials, in particular the method of electrohydropulse crushing, the method of static compression, and the method of destruction by stationary carbon dioxide laser and sputtering by the pulse laser [1]. Using the electrohydropulse method approximately 10 to 20% of the energy input into the pulse is spent on the shock action that results in the destruction; the rest of energy is converted into other types of energy. This method can be used for the destruction of radioactive waste straight in the fuel element cooling liquid. The method of static compression can provide the production of up to 100% of the material in the fine-dispersed phase that has the size less than 1 mm, however this method is realized remotely and requires the robotic automation to transfer the crushed material to the magnetoplasma separator. The stationary laser destructs the materials described in this scientific paper, however their sizes fail to meet requirements set to further separation processing. This method is usually used at multiple exposures of specimens subjected to the destruction to the radiation. The sputtering by the pulse laser is considered to be the most efficient from the standpoint of the optimization of labor conditions and the security of personnel engaged in the generation of particles with the size of 1 μm and less. Technologically, this device can be placed inside the separator. It has an opportunity to vary the parameters that allows us to work with the different types of materials and control their consumption. Microphotography patterns show that the methods proposed allow us to produce the particles of materials simulating the radioactive waste of 100 μm by the short-time heating for about 1 to 10 s up to 2000 C. From our standpoint this would provide an efficient evaporation of fission products. The produced sputtered material can be converted into the plasma in the plants of magnitoplasma type.

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3-05

PHYSICAL PARAMETERS OF A REACTOR-STELLARATOR WITH SMALL RIPPLES OF HELICAL MAGNETIC FIELD

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The results of calculations of physical parameters of a stellarator-reactor in which the helical field ripples are less than the toroidal magnetic field ripples $\varepsilon_h < \varepsilon_t$. In contrast to the earlier work performed [1–4] , where the transport coefficients for the ion component were dependent on the collision rate proportional $\nu^{1/2}$, which corresponds to the case $\varepsilon_h > \varepsilon_t$, adopted in the calculation of the proportionality of the first degree on the collisions frequency $D_i \propto \nu^1$.

The initial parameters for the calculations taken from the reactor R = 8 m, r_p = 2 m, B_0 = 5 T. A numerical code to solve systems of equations, which consists of a spatially one-dimensional heat equation for ions and electrons, and the equality equation of diffusion fluxes, similar to the system to be solved in the papers [1–4]. To be fire mode provides a source of heating capacity of several tens of MW. Gain a sustainable modes of self-sustaining fusion reaction while maintaining the plasma density by DT fuel pellet injection into the central region of the plasma.

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3-06

IMPACT OF LONG-TERM SPUTTERING ON MIRROR SAMPLES FABRICATED FROM DIFFERENT KIND TUNGSTEN

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Tungsten is becoming to be one of the main fusion reactor materials. The tokamak ASDEX is the first all-W-first-wall device; in tokamak JET all divertor area is protected by W protection; the second all-W-first-wall device WEST is under assembling in France. In ITER the total W-coated protection will be 150 m^2: 50 m^2 – divertor receiving plates and 100 m^2 – total area of dome and baffle parts of divertor. The environment conditions for both these W components will be principally different: receiving plates will be subject to high energy plasma fluxes with low energy ions, whereas dome and baffle parts – to sputtering by charge exchange atoms (mainly D and T atoms) of a wide energy distribution with mean atom energy several hundred eV.

In this study we present comparative results obtained with mirror samples made of several kind tungsten produced in China and subjected to long-term sputtering in the course of experimental program modelling the behaviour of dome and baffle W protection in ITER. The samples were made of pure tungsten and W with additions: 0.1%K+0.1%Al **(W-K)**, 2wt%La_2O_3 **(W-La)**, and 1wt%Y_2O_3 **(W1Y)** and 2wt%Y_2O_3 **(W2Y)**. Before the experiments all samples with size of 10x10x2 mm^3 were polished to a quite high optical quality with an aim to use the optical methods to characterize the microrelief that develops under sputtering. To shorten the time of experiment, argon ions with energy 600 eV were used as projectiles instead of hydrogen isotope ions. Sputtering procedures were provided in many steps, and after each step the measurements of mass loss, the reflectance at normal incidence, and the correlation between specular and diffusive component of the light reflected from the mirror under the test were carried out; besides, the surface of samples was photographed in optical microscope. Sputtering procedures lasted during the time needed for sputtering of every sample to the depth ~ 4 μm.

After sputtering the relief on W specimens looked like a typical step structure with the height of steps reaching 1.6 μm, in an excellent agreement with the step difference (up to 1.8 μm) measured by laser prophilometry for recrystallized W specimen after sputtering to similar depth [1]. There is no in-grain relief seen on surface of these specimens within the limit of used imagination, and because of this reflectance at normal incidence did not degrade strongly.

As distinct from pure specimens, the mirror specimens made from doped tungsten behave very differently. Their reflectance at normal incidence is strongly decreasing with increase of the sputtering time because of gradual surface roughness rise.

Maximal sputtering rate difference was within the limit of ~ 11%.

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3-07

IMPACT OF DEUTERIUM PLASMA IONS ON THE BEHAVIOR OF MIRRORS MADE OF AMORPHOUS ALLOYS

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Recent results obtained in experiments on interaction of deuterium plasma ions of different energy with surface of bulk metallic glasses (BMG) are described and discussed. The comparison with the previous data [1–3] is provided to compare behavior of BMG samples from different producers.

The samples of two kinds, were polished to mirror-like quality and, after measuring the initial reflectance at normal incidence, were subjected to impact of ions of deuterium or argon plasma with fixed energy. The main attention was paid to phenomenon on deuterium absorption that reveals as the weight gain after every exposure in deuterium plasma. For a fixed ion energy (in the range 50…100 eV), the amount of absorbed deuterium increased linearly when increasing ion fluence, with different increment for every kind of BMG. When ion energy increases, the mass gain became saturated because of ion sputtering starts to play important role. Routinely, the reflectance at normal incidence (in the wavelength range λ = 320…650 nm) and the quality to transmit an image were measured; also, the surface was photographed in optical and interferometer microscopes.

After accumulation of a certain amount of deuterium, the plane samples became bent with radius of curvature depending on ion fluence. Straitening of samples was observed after the backside of them was exposed to D plasma ions. The fact of bending is a clear indication that deuterium is absorbed not in a whole volume of sample but in its near-surface layer. The thickness of this layer was estimated by measuring the thickness of a chip broken away from the sample: the chip was approximately rectangular shape with thickness ~ 0.25 mm.

Both kinds of BMG had aluminum in their composition (8 and 10%), thus a weak manifestation of chemical processes observed earlier for Al mirror samples [4] was observed, i.e., decrease of reflectance at keV-range ion energy and restoration of reflectance after exposure to low energy ions (~ 50 eV) of the same plasma.

Very different results of long-term sputtering for both kinds of BAG were distinguished for the surface: some features were found on samples of one kind, and no any peculiarities were found on samples of the other kind. The surface of matrix not occupied by those features continued to be smooth. This effect was stronger when exposing BAG samples in deuterium plasma than in argon plasma.

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3-08

A FUEL CYCLE FOR MINOR ACTINIDES BURNING IN A STELLARATOR-MIRROR FUSION-FISSION HYBRID

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The major goal of the stellarator-mirror fusion-fission (SMFF) hybrid [1, 2] is the transmutation of spent nuclear fuel. The transuranic elements of the spent fuel are destroyed by fission in the intrinsic fast nuclear reactor. The SMFF hybrid provides a subcritical regime of functioning for this reactor. The sub-criticality is necessary for safety and robustness of reactor operation. It softens the impact of lack of delayed neutrons in the transuranic content of the spent nuclear fuel.

The fuel for SMFF and other hybrids is prepared in the following way. First the fission products and uranium are extracted. From the remainder either metallic or oxide, nitride or carbide ceramic fuel is manufactured. Thereafter the fuel is used in a reactor until 5…12% of its transuranic content is fissioned. The amount of burned fuel is defined by radiation damage (the DPA limit for fuel material). The transmutation cannot be stopped at this point; otherwise its efficiency would be too low. The newly obtained spent fuel must be reprocessed and used again.

Neutron calculations for a fission blanket of the stellarator-mirror fission-fusion hybrid are performed, and the rates of burning of fuel components are computed. Calculations are performed for pure fuel and the fuel with some admixture of uranium. In both cases the fuel components burning rates appear too different. This means that after burning a new transuranics composition is created. After reprocessing and making new fuel, it will have different properties that make transmutation process not cyclic and may cause reactor safety problems. A solution may be decrease of the reactor reactivity, but this causes necessity to increase the neutron generation rate in the external neutron source.

A new fuel is proposed which remains unchanged during nuclear burning if the transuranics from spent nuclear fuel are continuously supplied. The content of this fuel is found using stationary solution of the model for nuclear elements burning. Then the MCNPX calculations are enabled to analyze the fuel behavior in a particular design of a subcritical fission reactor. The calculated burning rates of the fuel isotopes are proportional to the isotopic content of the spent nuclear fuel, and this feature provides a stationary regime of the reactor operation. Under such conditions, the sub-criticality of the reactor could be decreased which makes the whole device less expensive.

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3-09

USAGE OF THORIUM FUELS IN FUSION-FISSION HYBRIDS AND CRITICAL FAST REACTORS

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Usage of thorium as a nuclear fuel continues to be a challenge since there are no solutions until now with clear commercial potentials. However, the interest in the problem is stimulated by big thorium resources which exceed uranium resources by several times. In such a situation solely thorium fuel cycles without uranium are of particular interest. In all thorium fuel cycles the fertile element, thorium-232, gives birth to the fissile element, uranium-233. The last one has few delayed neutrons, 2.3 times less than uranium-235. Thus, for safe burning in fast reactors, a subcritical system, like the stellarator-mirror fusion-fission hybrid [1–3] is preferred.

In Ref. 3 the transuranic elements composition in mixture with U^{238} isotope is found in which, during neutron irradiation, for each transuranic element the balance between the element production and leakage is met. The production is due to neutron capture by the neighboring isotope or beta-decay of a lighter isotope. The leakage includes fission, neutron capture and decays. Such a fuel, after usage in a sub-critical fast reactor, would have to be reprocessed. The fission products should be separated and stored as a nuclear waste and the remainder should be reprocessed into a new fuel. For such a fuel cycle, the net consumption is only for U^{238}, and the waste is just fission products.

The same approach is applied to Th^{232} and the isotopes of its nuclear transformation chain. The possibilities of the practical application of such an approach are discussed.

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3-10

SURFACE MODIFICATION AND DROPLET FORMATION DURING EXPOSITION OF TUNGSTEN COATINGS TO ELM-LIKE TRANSIENT LOADS

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Durability of plasma facing materials (PFM) and components under steady-state and transient energy and particle loads is the key problem relevant to performance of fusion reactor ITER [1]. Transient heat loads (in course of disruptions, Vertical Displacement of Edge (VDE), Edge Localized Mod (ELM) and other) cause erosion and damages of plasma-facing materials (crack formation, melting, melt motion, droplet injection, etc.). The reference PFMs for fusion reactors are tungsten and tungsten coatings.

Powerful plasma accelerators are used at present for experimental study of plasma-target interaction under transient high heat loads [2]. Such devices also applied for validation of numerical models developed for ITER. Quasi-stationary plasma accelerators (QSPA) are characterized by duration of plasma stream which is compared with the duration of one ITER ELM. Therefore QSPAs became especially attractive facilities for investigations of macroscopic erosion of divertor armor materials under plasma loads typical for ITER off-normal events.

Features of surface modification of tungsten coatings after repetitive irradiation by means of the QSPA Kh-50 are presented. Cracking, development of tungsten surface morphology and emission of droplets are studied. Targets were made from samples of stainless steel covered of tungsten coatings of different thickness–(4, 12, 40 μm). Prepared targets were irradiated with powerful plasma streams of heat fluxes relevant to ELMs in ITER. The main parameters of QSPA plasma streams were follows: ion impact energy about 0.4…0.6 keV, the maximum plasma pressure of 0.32 MPa, and the stream diameter of about 18 cm. The surface energy loads measured with a calorimeter achieved 0.45…0.75 MJ/m^2 (i.e. above cracking but essentially below the evaporation thresholds of tungsten). In all experiments the plasma pulse shape was approximately triangular, and the pulse duration was equal to 0.25 ms.

Surface diagnostics was included optical and scanning electron microscopy, profilometry as well as microhardness, roughness and weight loss measurements. Droplets splashing and ejection of solid dust particles were studied with high speed CCD camera CMOS PCO AG.

Mechanisms of modification and damaging of tungsten coatings under irradiation with powerful plasma streams are discussed.

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3-11

STRUCTURE EVOLUTION OF TUNGSTEN COATINGS EXPOSED TO PLASMA FLOW UNDER ITER ELM RELEVANT CONDITIONS

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Tungsten and tungsten alloys are primary Plasma Facing Materials (PFC) for next-step fusion devices such as ITER and DEMO due to high thermal conductivity, high temperature strength and stability, high recrystallization temperature and high sputtering threshold for hydrogen. Tungsten coatings on different substrates can be a less expensive alternative to bulk tungsten for armoring the first wall in DEMO. Therefore, the most crucial is the problem of stability of the tungsten coatings under cyclic plasma loadings at current failures and boundary localized modes.

At first, structure, substructure and stress state peculiarities of tungsten coatings on bulk copper and steel substrates were studied in initial state. On the copper substrate, the coating was deposited by plasma sputtering method, while on the steel – by vacuum-arc sputtering. Then the structure properties were analyzed after hydrogen plasma exposure.

The tungsten coatings were irradiated by hydrogen plasma using a quasi-stationary plasma accelerator QSPA Kh-50. The basic parameters of plasma flows were as following: particle energy to 400 eV, plasma maximum pressure 3.2 Bar. The surface plasma loads measured with a calorimeter were from 0.45 to 0.75 MJ/m^2, i.e. between the tungsten cracking (0.3 MJ/m^2) and evaporation (1.1 MJ/m^2) thresholds. The plasma pulse shape was triangular with pulse duration of 0.25 ms.

X-ray diffraction (XRD) has been used to study structure, sub- structure and stress state of the samples. $\theta/2\theta$ scans were performed using a monochromatic Cu-K_α radiation. Computer processing of the experimental diffraction patterns was carried out using the "New profile 3.5" software package. The analysis of diffraction peaks intensity, profiles, width (B), angular positions was applied to evaluate stress state, texture and coherent lengths. Residual macro-stresses (σ) and the lattice parameter in the unstrained state (a_0) were determined using $a - \sin^2\psi$-plots. Analysis of the average coherence length (associated with the density of dislocation in the boundaries of grains) and the value of the average micro strain (density of chaotically distributed dislocations inside the coherence length) has been carried out by the approximation method.

The initial state of the W/steel coating was characterized by non-uniform distributions of residual stresses and the lattice parameter a_0 in the sub-surface layer. The maximum stress level $\sigma \approx 1.6$ GPa was registered in the layer of 0.07 μm, whereas $\sigma \approx 65$ MPa was observed at the depth of 1 μm with maximum lattice parameter $a_0 = 0.31646$ nm; while it was lowered to 0.31525 nm beneath the surface. In the initial state, the no texture of coating was observed. But the texture with axis [100] normal to the surface appeared as result of plasma irradiation due to recrystallization of affected material. Plasma irradiation promoted an increase of coherence length from 60 nm to 80 nm. The average micro-strains initially about $1.7\cdot10^{-3}$ have been completely annealed as well as the initial dislocation density ($9.2\cdot10^{10}$ cm^{-2}) has lowered twice in the exposed surface layer.

3-12

EROSION FEATURES OF TUNGSTEN SURFACES UNDER COMBINED STEADY-STATE AND TRANSIENT PLASMA LOADS

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Fusion devices slowly progress from experimental prototypes like ITER and DEMO toward power plants. Efficiency of fusion reactors is defined by a number of economical factors. One of them is lifetime of plasma-facing components (PFC). Erosion of PFC restricts the operation time of next-step fusion reactors, leads to contamination of the hot plasma by heavy impurities and can produce a substantial amount of the dust. There are few factors, which contribute to the main degradation of PFCs. Among them are: steady-state heat and particles fluxes from plasma, transient events (disruptions, Vertical Displacement Edge (VDE), Edge Localized Mods (ELMs), etc). The experimental studies of erosion plasma facing materials (PFM) in present-day fusion devices are quite problematic. Nevertheless, a number of problems related to fusion reactor PFMs should be solved during a short period of time. First of all, contribution of the steady-state and transient plasma loads to erosion of PFMs should be estimated.

Present work continues the studies of features damage of the tungsten surfaces under combined exposure. Steady-state hydrogen ion fluxes (2×10^{22} $m^{-2}s^{-1}$, $5\text{-}8\times10^{25}$ m^{-2}, average ion energy of 2 keV) were alternated with the pulsed plasma loads which were chosen below the tungsten melting threshold (hydrogen plasma streams with energy density of 0.45 MJm^{-2} and the pulse duration of 0.25 ms). Steady-state bombardment was provided by FALCON ion source, pulsed loads were performed by means of QSPA Kh-50 device. Following the exposures, the sample surfaces have been examined with an optical microscope MMR-4 equipped with a CCD and scanning electron microscopy. X-ray diffraction (XRD) has been used to study structure, sub- structure and stress state of targets. Precise measurements of the surface roughness were also performed.

Studies have revealed that symmetrical thermal residual stresses in exposed surfaces are created mainly due to pulsed irradiations. Steady-state exposure leads to annealing of both linear and complex of point defects. As result of this, residual stresses decrease. Detailed XRD studies have shown that lattice parameter increased negligibly, i.e. impurities have not been introduced into the lattice during the irradiation. The combined plasma loads result in development of tungsten surfaces roughness. Rise of surface roughness is caused by cracks appearing and growth of edges of grains on exposed surfaces.

3-13

RELATIVISTIC NEOCLASSICAL TRANSPORT COEFFICIENTS WITH MOMENTUM CORRECTION

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It was shown recently [1] that relativistic effects in collisional neoclassical transport in hot plasmas appear even for electron temperatures about few tens keV, typical for D-T fusion reactors, and surely are non-negligible for future aneutronic fusion reactors with temperatures about 70 keV. However, all transport codes developed to date and applied for simulations of the reactor scenarios are still based on the non-relativistic approach and the validity of the model for hot electrons is not justified. Fully relativistic description of neoclassical transport processes based on a general relativistic kinetic theory requires a development of new transport codes from scratch. In contrast, the main advantage of the approach proposed in [1] is the possibility to take the relativistic effects into account without making any significant changes in transport solvers.

As it was suggested in [1], it is possible to reformulate the non-relativistic transport model to take into account the relativistic effects by modification of the energy-dependent part of the transport coefficients, while the pitch-dependent part can be calculated from the monoenergetic solver of the non-relativistic drift-kinetic equation (DKE). With a proper choice of parameters and the right-hand-side of DKE, the output parameters of such solver can be re-interpreted as relativistic ones and the transport fluxes can be calculated according to relativistic definitions.

Alternatively, there is the way (see [2] and the references therein) to calculate transport fluxes without solving the DKE. The particle fluxes and the heat fluxes are obtained as the solution of a system of two coupled equations. The key point in this method is the representation of both distribution function and fluxes as an expansion in Sonine polynomials $L_n^{(3/2)}(x)$ (here, x is the normalized energy) followed by the calculation of the first moments of the DKE. As was shown in our previous publication [3], this method can also be effectively modified to take the relativistic effects into account.

Following [3], the electron fluxes of particles and heat are rigorously derived from the relativistic DKE and represented as an expansion in $L_n^{(a)}(x)$ polynomials with $a = 3/2+R$, where R, the non-linear function of T_e/mc^2, is the measure of relativistic effects. Finally, applying the same algorithm as in [2], the corresponding Braginskii matrix elements are calculated and the first relativistic correction terms are obtained.

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<u>4-01</u>

SUBESEMBLE CONCEPT IN 2D MAGNETIZED PARTICLE TRANSPORT MODEL

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Transport of magnetized particle undergoing random frozen electrostatic field is considered. Because of infinitely long field correlation time and particle trapping this problem is of particular interest as a test for closure of statistical equations. Earlier we proposed the closure [1], which was compared with the decorrelation trajectory method [2]; advantages of both methods were analyzed in [3]. One of concepts that is inherent to the DCT method and concerns subensembles we incorporate here in our approach. Note that this approach developed for particle transport in frozen field would help to describe transport processes in a time varying field with a finite correlation time.

Existence of subensembles in a problem of 2d frozen electrostatic turbulence relies on the fact that particle motion in an approximation of zero Larmor radius occurs along electric potential contour lines. Thus dynamics of each group of particles moving in vicinity of a definite potential level is particular. This brings the idea to split the whole particle ensemble in subensembles, marked by values of potential levels, and describe dynamics of subensembles separately. Statistical characteristics, such as a diffusion coefficient, particle displacement are then calculated as a superposition of partial contribution from subensembles. This gives more accurate statistical characteristics of the whole ensemble.

To verify validity of this approach its results were compared with a direct numerical simulation of particle spread in a frozen isotropic random electric field and strong magnetic field, when finite Larmor radius effects was neglected. Lagrangian field correlation function along with evolution of particle displacement was calculated. Comparison shows improvement of quantitative agreement attained by the use of subensemble concept.

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ANALYTICAL DESCRIPTION OF THE ELECTROSTATIC POTENTIAL OF DUST GRAIN IN WEAKLY IONIZED PLASMA

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The electrostatic potentials of the absorbing macroparticles (grains) in plasma are of great interest in dusty plasma physics [1]. The electrostatic potential distribution around solitary charged grain embedded into weakly ionized strongly collisional plasma within the drift-diffusion approximation is studies numerically. Nonisothermal and isothermal plasma as well as various grain sizes a are considered. The comparison of calculated potential and plasma particles distributions with analytical expressions are performed. It was shown that potential is described with precision to several percent by the sum of Coulomb potential and Debye potential with scaled screening length [2]

$$\varphi(r) = (q - \tilde{q})\frac{e^{-pr/\lambda_D}}{r} + \frac{\tilde{q}}{r}\,, \qquad (1)$$

where q is the grain charge.

The effective charge in Coulomb part of the potential $\tilde{q}$ is proportional to the charging current and grows with a/λ_D decrease. Our calculations show that in nonisothermal plasma the unscreened charge can exceeds the screened charge and in the limit of small grains for $\tau = T_e/T_i = 10$ it reaches 90% of the macroparticle total charge. The values of unscreened charge has to be taken from the computations or for the small grains from the analytical formula

$$\tilde{z}_g = \frac{z_g}{e^{z_g} - 1}\left(\frac{D_e}{D_i} - 1\right)\frac{1}{1+\tau}\,, \qquad (2)$$

where $z_g = \frac{qe_e}{aT_e}$, $D_{e,i}$ – diffusion coefficients of electrons and ions.

The parameter p was found from the approximation of calculated potential by the formula (1) using the method of minimization of maximum relative error. Fig. 1 shows that value of p approaches the unity for $a \ll \lambda_D$ in isothermal plasma and it sharply decreases with grain radius growth up to ≈ 0.22 for $a/\lambda_D = 3$. In nonisothermal plasma ($\tau = 10$) value of p is approximately twice less than in isothermal. As follows, absorption of electrons and ions leads not only to the appearance of Coulomb part in the grain potential, but also to substantial increase of the screening length.

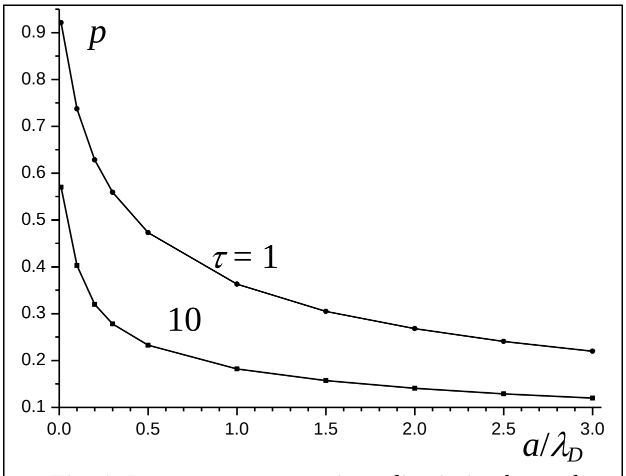

Fig. 1. Parameter p vs grain radius in isothermal and nonisothermal plasma ($\tau = 10$)

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4-03

DIRECT PARALLEL POISSON SOLVER WITH THE MULTIPLY GRID SPACING SUPPORT FOR PLASMA SIMULATION VIA PIC METHOD

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Computer simulation via PIC method demonstrates the high accuracy of the plasma behavior description [1]. For the wide class of problems the characteristic length of the system is of the order of 10^3 Debye radii and the simulation time is of the order of 10^3 Langmuir periods (see, e.g., [2]). But PIC method needs the large RAM capacity and high computing performance. Consequently such problems need the clusters which are often based on single program, multiple data (SPMD) with the distributed memory architecture [3]. Algorithms used for such clusters must satisfy such important conditions as minimal volume of data transferred between the mesh nodes and uniform nodes' loading. Very attractive is the use of general-purpose computing on graphics processing units (GPGPU).

Important part of PIC method is the solving of the equation set for electromagnetic field (or Poisson equation for the electrostatic approximation). But for today the efficient parallel algorithm for the Poisson equation solving was not yet designed. The proposed iteration methods don't provide the required performance, and the direct solving methods need the large number of the data transfer between the mesh nodes [4].

This report proposes the parallel direct method of the Poisson equation solving with the first boundary conditions. This method includes decomposition of the simulation area to the smaller subdomains with the boundary conditions of the first kind and further linking of the obtained results via introduction of the screening charges' layers (similarly to [5, 6]).

The method proposed makes possible to use the meshes with different steps for every subdomain. Consequently it moves to the adaptive dynamic balance of the loading. The problems with the complex geometry can be treated (including non-rectangular boundary conditions and conductive insertions). The data volume of the transferred data and number of arithmetic operations during the linking has been substantially decreased. The application of GPGPU to improve the performance of the algorithm was demonstrated.

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4-04

THE IMPLEMENTATIONS OF MODERN PLASMA SIMULATION CODES BY LARGE PARTICLES-IN-CELL METHOD FOR PARALLEL COMPUTING SYSTEMS

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Computer simulation has become one of the important methods of research in plasma physics. The particle-in-cell (PIC) method is one of the most common methods for such modeling. However, existing packages are imperfect. In particular, this applies to used parallelization schemes. The purpose of this work is investigation of the possible ways for improving these packages.

The implementation of modern simulation programs by PIC was considered. The review includes the programs XOOPIC (1996 p.), PSC (2012 p.), PICCANTE(2014-2016 pp), PIConGPU (2013 p) and CPIC(2014) [1-3]. All of the programs supporting work on distributed parallel computing systems with MPI.

The advantage of most modern applications is the use of general-purpose computing for graphics processing units (GPGPU), which provides a significant performance boost by using video accelerator. Another important improvement is the use of dynamic load balancing, that is relevant for parallel systems with distributed resources.

The significant feature of the most advanced programs are using of finite-difference time-domain method(FDTD). This approach is efficacious and simple for parallelization. However, many problem can`t be considered by this method. Iterative methods are often used to solve divergence equation(Poisson eq.). There is a lot of parallel implementation for iterative methods, but their performance is low for many modeling tasks.

Modern microprocessor architectures are very demanding to calculations algorithms implementation. It is important to provide efficient use of processor cache, branch predictor and vector extensions (SSE, AVX) for maximum performance [4]. However, the specifics of integrating the equations of motion requires additional techniques to achieve efficient caching. Monte Carlo method of elementary interactions modeling makes difficult to use branch prediction. These questions remain unexplored in most programs.

The results of the review is a set of requirements for high-performance parallel implementation of PIC. In particular, the ways to improve Poisson and motion equations solving was proposed.

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4-05

TUNABILITY OF THE HIGH POWER OUTPUT RADIATION USING FREE ELECTRON LASERS

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An analytical formalism for the generation of high power terahertz radiation in the presence of plasma has been developed. A prebunched relativistic electron beam (REB) is an effective source for the emission of radiation at wavelengths longer than the bunch length. The REB acquires a transverse velocity on interaction with the wiggler in the plasma environment. This velocity component couples with the perturbed and modulated beam densities to give rise to non-linear current density which leads to the emission of the radiation. The output THz radiation can be tuned by varying the parameters of the wiggler, plasma medium and the energy of the electron beam. . The efficiency of the radiation increases with the modulation. Plasma can withstand with high field and gives high output. The results of the present study may be particularized for the practical applications of THz radiations.

4-06

THE INFLUENCE OF THE EXTERNAL MAGNETIC FIELD ON ENERGY LOSSES OF A CHARGED PARTICLE IN AN ELECTRON GAS

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Energy losses of a massive charged particle in the magnetized electron gas are obtained. General expression of a polarization operator of the magnetized electrons is calculated. In linear approximation of the magnetic field strength, the results of numerical calculations are in a good agreement with the analytical approximations obtained in the frame of a quantum field theory [1, 2].

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4-07

THEORETICAL STUDIES OF SLOW WAVE PLASMA HEATING IN URAGAN-3M TORSATRON

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The paper concerns the propagation and absorption of the slow electromagnetic wave with the frequency of the order of ion cyclotron frequency ($\omega \sim \omega_{ci}$) in the plasma of Uragan-3M torsatron. In this device, as well as in Uragan-2M torsatron, the currentless plasma is produced and heated by unshielded frame-type (or three- and for-half turn) antennas which are located in the scrape-off layer [1]. Previously it focused on fast wave Alfven resonance plasma heating [2]. But, the current-carrying conductors of these antennas are directed at the certain, not right angle to the torsatron magnetic field. So, essential part of RF power is launched as the slow wave, which has the electric field component parallel to the torsatron magnetic field. Therefore it is very important to find out location of the slow wave penetration and absorption regions. It is impossible to carry out this problem analytically due to complicate 3D structure of the torsatron magnetic surfaces and confining field. Moreover, the numerical modeling of full wave problem faces insuperable difficulties caused by 3D unhomogeneity and problem stiffness. On the other hand, for typical plasma periphery parameters (electron density $n_e \sim 10^{10} cm^{-3}$ and electron temperature $T_e \sim 50\, eV$ [3]) the slow wave wavelength is much less than the average plasma radius. Therefore geometrical optics approximation is valid for this analysis. Ray tracing code "U3Ray" was developed. It uses torsatron magnetic field and flux surfaces data calculated by magnetic potential series expansion in toroidal harmonics [4] and special spline interpolation library. Antenna currents were expanded into Fourier series of poloidal and toroidal angles [5] and each combination of poloidal *m* and toroidal *l* harmonics was traced independently. Let us define parallel wave number as $k_{\|} = (l + m\iota/2\pi)/R$, where $\iota/2\pi$ is the rotational transform (~ 0.3 at the plasma boundary) and *R = 100 cm* is the big radius of the torus. For typical values of *l* we have an estimation $k_{\|} \sim 0.05...0.25$. So, as $Z_i = (\omega - \omega_{ci})/(\sqrt{2} k_{\|} v_{Ti}) >> 1$ and $Z_e = \omega/(\sqrt{2} k_{\|} v_{Te})$ may be >1 or <1, we use hydrodynamic form of dielectric permeability tensor components ε_1 and ε_2 but kinetic expression for ε_3 component. The features of slow wave propagation and absorption in the Uragan-3M plasma were investigated. It was revealed that this wave penetrates poorly into the plasma core and heat the plasma periphery above all.

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4-08

ELECTROMAGNETIC WAVE PROPAGATION THROUGH MAGNETOACTIVE PLASMA LAYERS

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Interaction of the electromagnetic radiation with overdense plasma has been extensively studied in various contexts for many years. For the waves with frequencies beyond ω_{pe} plasma acts as a mirror, but in layered structures it could behave differently. For instance, a symmetric three-layer structure containing layer of overdense plasma sandwiched between two layers of less dense plasma has anomalously high transparency for certain frequencies and angles of incidence. Similar effect is also observed in asymmetric two layer structure. It opens ways for building various kinds of tunable filters and spatial and spectral multiplexers or overcoming the blackout in radio communication with spacecrafts reentering the atmosphere.

We study transmission of a *p*-polarized electromagnetic wave through layered plasma structure immersed in an external magnetic field. Earlier we found that the structure absolutely transparent only for specific values of wave frequency and incidence angle. For thick layers the resonance condition for transparency is close to dispersion relation for surface waves at plasma-plasma interface.

In this study we calculate energy flux, energy density and the velocity of energy propagation of the wave through the structure composed of the layers of arbitrary thickness for different magnitudes of magnetic field.

4-09

STOCHASTIC DIFFERENTIAL EQUATIONS OF CHARGED PARTICLE MOTION IN TOROIDAL PLASMAS

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With the theory of stochastic processes we obtain the correct stochastic equations of charged particle motion which correspond to the drift kinetic approach. In terms of Ito theory of stochastic processes [1] we get the expressions for stochastic differentials of the full set of drift variables associated with the kinetic theory of charged particles in plasma with Coulomb collisions. Our treatment is done for the Maxwellian plasmas of axisymmetric toroidal configurations. Equations obtained may be used for the modelling of fast charged particle motion in toroidal plasmas, namely for Monte-Carlo simulation the dynamics of charged fusion products and beam ions in tokamaks. Obtained stochastic equations are consistent with the theory of Coulomb collisions and are not more complex as compared to those used in the conventional model approaches [2].

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4-10

DUST GRAINS CHARGING OF LOW TEMPERATURE DUSTY PLASMAS UNDER ION ACOUSTIC PARAMETRIC INSTABILITY ONSET

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The process of dust grains charging in low temperature dusty plasmas of low pressure is considered under parametric ion acoustic instability development. The secondary electron emission from the dust grain surface and a dust grain polarization under the action of the self-consistent electric field are taken in account. The results of the numerical 2D3V simulation of dusty plasmas charging in RF discharge are presented in cylindrical geometry. For self-consistent simulation of dust grain charging process we use the numerical model that comprises three models: "Particle-in-Cell" (PIC), "Monte Carlo Collisions" (MCC) and "Particle-Particle Particle-Mesh" (P3M) models. Such a simulation gives a realistic picture of dusts grains interaction with plasma and allows take into account the short length force between dust grains and plasma particles.

The growth rate and saturation level of the unstable ion acoustic oscillations, the rate of temperature growth and the distribution functions of electrons and ions at the quasi-stationary stage are obtained as a result of the computer simulation. The results of the computer simulation of the dust grains charging are compared with the conclusions of the analytical theories: "orbit motion limited"(OML) theory, which originates from the work of H. Mott-Smith and I. Langmuir and then it is advanced by other researchers [1], and "radial motion" (ABR) theory, developed by J.E. Allen, R.L.F. Boyd, and P. Reynolds and then extended by F. Chen [2].

The computations show the dust charging time agrees with the charging time predicted by OML theory, although the time to achieve the quasi-stationary state of charging turns out greater at the plasma periphery than in the bulk plasma. At the same time the results for the cold ions better agrees with ABR theory than with OML one. Nonstationarity of the RF discharge under the condition of the ion acoustic parametric instability increases the amplitude of the dust grains charge fluctuations in comparison with the estimate derived on the base of the relation between thermal energy and electrostatic potential at the distance of one dust grain radius.

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4-11

EXACT RELATIVISTIC MAXWELLIAN MAGNETIZED PLASMA DIELECTRIC TENSOR EVALUATION FOR ARBITRARY WAVE NUMBERS

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Theoretical study of propagation and absorption of electromagnetic waves in magnetized plasma in ECR frequency range requires accurate accounting relativistic effects, associated with masse increasing of fast enough electrons.

The basis for studying linear plasma waves is exact evaluation of the relativistic plasma dielectric tensor. Two original exact integral forms of this tensor were given by Trubnikov [1], however, in general case their applicability has been rather limited. Later this limitation was been quite weakened by the one more tensor form [2].

Neglecting ion dynamics, the last form is given as double series: in the cyclotron harmonic numbers n and in the exact relativistic plasma dispersion functions with coefficients of expansion of the functions $A_n(\lambda) = e^{-\lambda} I_n(\lambda)$ in the parameter λ, where $\lambda = (k_\perp \rho_e)^2$, $k_\perp$ is wave number and ρ_e is the electron Larmor radius.

In applications of this form to study the fast ECR waves in thermonuclear plasmas the condition $\lambda << 1$ is usually true and, consequently, series in λ converges so rapidly that its accurate estimation requires summarizing only a few terms.

However, for the study of the ECR slow or plasma waves in laboratory or astrophysics magnetic traps λ can increase and reach of values $\lambda \sim 1$ and even $\lambda >> 1$. In this case series in λ due its increasing converge slower and slower and can cause difficulties in their summation, even in the case of the weakly relativistic plasmas [3]. Obviously, in fully relativistic plasmas these difficulties can be more significant. Those unfavorable cases require looking for some alternative form, suitable for accurate applications.

The main purpose of the present work is the further progress to resolve a problem of the exact relativistic Maxwellian plasma dielectric tensor evaluation for arbitrary values of λ.

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4-12

CYCLOTRON WAVE ABSORPTION IN LARGE ASPECT RATIO ELONGATED FAST COMPUTATION OF THE COMPLEX ERROR FUNCTION OF THE REAL ARGUMENT

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The plasma dispersion function Z(z) relating to the complex error function *W(z)* as is one of the key concepts of the theory of plasma waves. It describes the absorption and dispersion properties of plasma along the magnetic field lines and is often used in plasma wave applications. For example, computation of this function is a necessary part of ion cyclotron wave analysis in thermonuclear laboratory plasmas. Routinely, in applications it is evaluated massively, therefore the efficiency of the involved numerical algorithm is of primary importance.

At the present time, the most efficient of such methods is the algorithm 680 developed by Gautschi and Poppe-Wijers [1, 2]. It allows the one value of this function to be calculated with accuracy of up to 14 significant digits during the time which is necessary for the calculation of 10 values of the exponential function with the same accuracy.

The main goal of present work is to give a new algorithm based on the use of the Euler-Maclaurin formula and the nonsingular formula for the Cauchy principal value $P\int_{-\infty}^{\infty}\frac{f(t)}{t-b}dt = \int_{-\infty}^{b}\frac{f(t)-f(2b-t)}{t-b}dt$ from [3]. Numerical calculations performed with the proposed method allow evaluating one value of this function during the time to compute 5 values of the exponential function.

The efficiency of this method was used to increase performance of calculations for investigation of ICR plasma heating in a JET-type tokamak by means of the Fast Wave conversion into the Slow Wave as an example of the fusion application.

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4-13

EQUILIBRIUM AND STABILITY OF ENSEMBLE OF IONS PRODUCED IN PLASMA IN CROSSED FIELDS AT POSITIVE RADIAL ELECTRIC FIELD

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Collisionless plasma in crossed fields is created and used in numerous technological devices. The produced ions often appear unmagnetized and the ensemble of such ions should be described kinetically.

In present report the kinetic equilibrium of ensemble of the ions produced in plasma, placed in crossed longitudinal magnetic field and positive radial electric field, is considered. Radial electric field is supposed to be below the critical value ($0 < E_r < E_r^{cr} \equiv m_i \omega_{ci}^2 r / 4e_i$). In such field ions are confined on radius.

The equilibrium distribution function (**DF**) of ions is derived. It is anisotropic and has the form: $F = \frac{m_i N_i}{2\pi} \frac{\Omega_i}{\omega_{ci}} Y(\varepsilon_\perp - e_i \Phi(b_i))\, \delta\left(\varepsilon_\perp - e_i \Phi\left((2M/m_i \omega_{ci})^{1/2}\right)\right) \delta(v_z)$, $r > b_i$. (1)

In (1) $N_i = N_i(r_0)$ is the total density of ions, produced on radius r_0 , Ω_i is the frequency of ion oscillations on radius, ω_{ci} - cyclotron frequency, e_i, m_i – a charge and mass of ion, $\varepsilon_\perp$, M, v_z – transversal energy, the generalized angular momentum and longitudinal velocity of a particle, $\Phi(r)$ – the electrical potential, $b_i \equiv (\Omega_i/\omega_{ci}) a = a(1 - E_r/E_r^{cr})^{1/2}$ makes a sense of a confinement radius of ion of i-kind in plasma, a - radius of plasma and a metal casing. DF adequately reflects the fact of production of ions in a state of rest. This peculiarity is described by δ - function of Dirac. Heaviside's function Y describes the contribution of the ions produced on radii $r_0 < b_i$. The ions produced on radii $r_0 > b_i$, if those also were, do not give the contribution to equilibrium, because during a single radial oscillation such ions cross the boundary of plasma and are lost on a metal casing. DF in region $r < b_i$ has the form (0), in which it is necessary to put $Y = 1$.

Radial distribution of ion density, of rotation frequency and the contribution of ions into the dispersion equation are performed in the report for positive radial electric field. They can be derived by direct integration of DF. However in the report they are obtained in another more graceful way using the results obtained earlier [1, 2] for ensemble of ions in the negative radial electric field. It is shown that the trajectory of the ion produced on radius r_0 in the positive radial electric field E_r , observed in a frame of reference rotating with frequency $\omega_{rot} = -2cE_r/(Br) < 0$, coincides with trajectory of the ion born on radius $r_0' = r_0(\omega_{ci}/\Omega_i)$ in the negative field E_r'. Its value is equal: $eE'/(m_i r) \equiv \omega_{rot}^2 + \omega_{ci}\omega_{rot} + eE/(m_i r)$. This correspondence, and also the correspondence for densities of total ion production in the positive ($N_i(r_0)$) and negative ($N_i'(r_0')$) fields ($N_i'(r_0') = N_i(r_0)(\Omega_i/\omega_{ci})^2$) allow to transfer on a case of positive field all results obtained earlier [1, 2] for ensemble of ions in the negative radial electric field.

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4-14

IMPACT OF WAVE PHASE JUMPS ON STOCHASTIC HEATING

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As is known, particles are heated up in collisions with random waves. Jumps of wave phases can influence the intensity of heating significantly. Waves with jumping phases can also penetrate in overdense plasma, and initiate a new type of discharge [1, 2] which can be interesting for applications. Some effects of particle heating by the waves with jumping phases were considered earlier [2, 3].

Here we study the impact of wave phase jumps on heating intensity. The evolution of particle ensemble caused by waves with randomly jumping phases is calculated numerically. We compare processes of particle heating by waves with regular phases, waves with jumping phases and singular random impulses of electric field. Decomposition of the waves with stochastically jumping phase in waves with regular phases and stochastic impulses is done and contribution of both components to heating is estimated.

Various types of field impulses are examined. Evolution of particle ensemble statistical characteristics is found. It is shown that there exist regimes when the main contribution to particle heating comes from jumps of phases that act similarly to separate impulses.

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4-15

FINITE LARMOR RADIUS EFFECTS ON TURBULENT TRANSPORT OF TEST-PARTICLES

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We study magnetized test-particle transport in a random electrostatic field in a frame of the model which is based on the microscopic description of particle motion. The model accounts for particle trapping effects and helps to analyze transport mechanisms in magnetized plasmas. Our previous analytical approach recovers the results of direct numerical simulation of magnetized particle undergoing a field of frozen electrostatic turbulence in the limit of zero Larmor radius [1].

Here we generalize this approach to account the finite Larmor radius effects and obtain the equations of particle motion in a field averaged over their gyration. There are two ways to make such averaging – either in terms of field itself, or in terms of field correlation function. Both methods were considered in literature [2, 3], and look equally reasonable, but their results are somewhat different.

To find what way of gyroaveraging is better a direct numerical simulation of exact particle motion is performed and evolution of mean square displacement of particle gyrocenters is calculated. Results of simulation and prediction of two analytical approaches are compared and discussed.

The work is supported by project STCU №6060.

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4-16

OPTIMAL STARTING CONTROL FOR THE MULTI-TERM TIME-FRACTIONAL DIFFUSION EQUATION

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Sub-diffusion processes with a logarithmic growth of the mean square displacement have been extensively studied recently (e.g. [1, 2]). Such processes can be modelled by the time-fractional diffusion equations of distributed order. In particular, an optimal starting control problem with a multi-term time-fractional diffusion state equation and a quadratic cost functional is considered in this paper. The state equation has a unique solution (as shown in [3, 4]), so the existence and uniqueness of the solution can be proved for the original control problem. For parabolic problems with derivatives of integer order necessary and sufficient conditions for optimality have been presented in [5]. Similar approach is used to obtain a characterization of the optimal solution in the case of time-fractional diffusion.

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4-17

PARTICLE DISTRIBUTION FUNCTION OF PLASMA IN AXIAL MAGNETIC AND RADIAL ELECTRIC FIELDSFOR THE TRANSVERSE INJECTION OF NEUTRAL GAS

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Particle distribution function of plasma created in crossed axial magnetic and radial electric fields due to ionization of gas is obtained. It is assumed that the neutral gas is injected transverse to the magnetic field and it rotates up to the ionization at constant angular velocity. The distribution of speeds of gas particles in the rotating frame of reference is considered to Maxwellian. Produced plasma particles move in crossed fields without collisions. The obtained distribution function is written in the coordinates of the guiding center where the independent variables are the radial coordinate of the guiding center and Larmor radius of particles, which are the integrals of motion. Previously, the similar distribution function of plasma particles was obtained under the assumption that the gas does not rotate [1]. From the general expression the special cases of distribution functions are also obtained. In particular, we consider the cases when the angular velocity of rotation of the gas is equal to the angular velocity of drift rotation of plasma in crossed fields, as well as the cyclotron frequency of the produced ions.

Obtained distribution function can be used for analyzing the stability of plasma created in crossed fields of substance vapors. The application of that plasma, created by the reflective discharge in order to separate elements and isotopes was discussed for example in [2]. The usual analysis of the stability of plasma with a known distribution function can also be supplemented by finding the optimum particle distribution function of vapor of working substance that could enhance the effectiveness of the separation of elements. Choosing an appropriate gas angular rotation velocity depending on the ion cyclotron frequency of a particular element, or the velocity of the drift motion of plasma particles in crossed fields makes it possible to control the particle distribution function of plasma, thereby regulate the plasma wave processes, as well as to affect on the process of separation elements.

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5-01

NOVEL STEP OF HIGH POWER QUASI-STATIONARY PLASMA STREAMS GENERATION: QSPA-M DEVICE

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High energy quasi-stationary plasma streams are used in basic plasmadynamics studies, for experimental simulation of fusion reactors transient events and different technological applications. Quasi-stationary plasma accelerator QSPA Kh-50 is largest and most powerful device of its kind. In this facility the plasma streams are injected into the magnetic system with the longitudinal field of the order of several kGs. As result, the hydrogen plasma streams of 250 μs duration, ion energy up to 0.6 keV, and the heat load up to 30 MJ/m^2 were obtained [1, 2]. Nevertheless, during such injections a significant part of the plasma stream energy was lost in dissipation processes at the entrance of the magnetic system. In the QSPA Kh-50 facility any further increase in the B-field value up ITER relevant magnitudes was impossible due to a fast rise of the energy and plasma particles losses. The one possibility to increased electron temperature in generated plasma stream and optimization of working gas mass flow rate, first of all in near anode region, is application of longitudinal magnetic field on accelerating channel [3].

Therefore, the novel powerful facility of new type of QSPA-M with external longitudinal magnetic field was developed. Accelerator construction, power supply system, magnetic system and other device parts are described. Parameters of generated plasma streams will be varied by both changing the dynamics and quantity of gas filled the accelerator channel and changing the working voltage of accelerator QSPA-M. The first experimental results of discharge in QSPA-M facility and plasma streams parameters are presented. The characteristic of plasma streams injected and propagated in longitudinal magnetic field are also discussed.

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5-02

INVESTIGATION OF SOME FACTORS INFLUENCE ON THE WORK OF EXTRA PURE HYDROGEN GENERATOR

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Earlier the method was suggested for hydrogen production when super pure hydrogen is generated in only one technological process [1, 2]. On the realization of this technology the process of extra pure hydrogen production could be carried out at the same time with hydrocarbon materials utilization (combustion), e.g., during heating of water. The process of hydrogen generation is realized with help of diffusion-catalytic membrane which is placed in the flame of combustion and separates the volume of hydrocarbon combustion from the volume for pure hydrogen accumulation.

It had been designed, produced and tested two models of pure hydrogen generators HG-1 (hydrogen productivity is about 3.5 l/hour with the use of Pd-membrane and about 1 l/hour in the case of Ni membrane) and HG-2 (hydrogen productivity is about 7 l/hour with two Pd membrane) which use above mentioned technology. In parallel with hydrogen generation water heating could be performed. The influence of kind of fuel (gas, benzene, alcohol), membrane temperature and form, installation of additional screens etc. were investigated

So called hydrogen compremator (accumulator-compressor) was designed, produced and tested. This is the special device with the function to accumulate low pressure pure hydrogen flow (pressure is less than 1 Torr) from generator and to convert it to high hydrogen pressure of about 15 atm in the compremator volume. This allows to use such system for hydrogen feeding through the autonomic system inlet. Two compremator on the base of Zr-Ni getter was produced and tested. Generator HG-2 had been completed with these compremators. The combined work of hydrogen generator and compremators was investigated in various regimes. The HG-1 generator was tested in the regime of pure hydrogen puffing in plasma device DSM-1, providing the required parameters during experiment on the examine of metal erosion. The examines had shown capacity for work of both hydrogen generator and compremator in the conditions of real plasma physical experiments.

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5-03

RELATIVISTIC ELECTRON BEAM GUIDING BY USING TWO-CONSECUTIVE LASER PULSES

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For understanding the underlying physics of fast ignition scheme for inertial confinement fusion, it is necessary to investigate the generation and transport of fast electron beams into a large panel of the plasma of various densities and temperatures. It´s known that for ignition the fast electron beam should deposit $E_{ign} \cong 18$ KJ into a dense core (ρ= 300 g/cc) over a $\tau_{ign} \cong 20\ ps$ duration and in a hot spot radius r_{hs} = 20 um. Therefore the control of the transport of divergent relativistic electron beam is of primary importance. There are several physical processes that could allow to control the divergence such as: self-collimation of electron beam, resistivity guiding and imposed magnetic field. In this work we will consider the processes of self-collimation by the intense electromagnetic fields generated by the fast electron beam.

A scheme using two consecutive intense laser pulses has been proposed recently to optimize electron transport and collimation in the solid targets [1]. The two laser pulses, of different intensities, are focalized into a solid target at a variable delay, to generate two successive co-axial electron populations. It has been shown that the azimuthal magnetic field generated by the first electron beam can guide the second one. Experimental results have confirmed the general validity of the scheme [2]: optima delay and intensity ratio yield the best guiding effect, as validated by simulations coupling the 2D radiation hydrodynamic code CHIC with a fast electron transport module [3]. More recent simulations have also shown the important role played by the pre-formed magnetic field extension and the diameter of the second electron beam in determining the final guiding efficiency [4]. A parametric effect is to be experimentally evidenced in an upcoming campaign at the LULI ELFIE facility. This scheme promises an efficient energy transport in dense matter by a collimated beam of fast electrons, which is relevant for many applications such as ion-beam sources and fast ignition inertial fusion.

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5-04

LASER ACCELERATOR OF PLASMA BEAMS FOR PLASMA-WALL INTERACTION RESEARCH

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An idea and a laboratory model of the laser-driven accelerator of plasma beams for research of interaction of plasma with materials, including the ones predicted for fusion reactors, is presented. The accelerator is based on the laser-induced cavity pressure acceleration (LICPA) scheme [1] and includes four parts: (a) the laser driver, (b) the plasma cavity where high-temperature plasma is created by the laser driver and a high plasma pressure is generated, (c) the acceleration channel where the plasma beam is formed and accelerated by the plasma pressure, (d) the beam guiding channel which enables us to control the plasma beam parameters (the beam fluence, intensity and duration). It is predicted that the accelerator employing a commercial nanosecond laser of energy 2...3 J would be capable of producing a plasma beam of controlled composition and the beam fluence up to 200 J/cm^2, the beam peak intensity up to 20 GW/cm^2 and the beam duration within the 10 ns...10 μs range. The accelerator has a potential to work with a repetition rate up to a few Hz (in a burst of ~ 50...100 shots) with the beam average intensity up to 1 kW/cm^2.

A laboratory model of the accelerator with a 0.5 J/4ns Nd:YAG laser driver was built and tested. A CH plasma beam of the peak fluence > 10 J/cm^2 and the peak intensity > 100 MW/cm^2 at the accelerator channel exit was produced with the laser-to-beam energy conversion efficiency approaching 15%. A strong surface damage of various metal samples by the beam was observed.

The proposed accelerator of plasma beams is a novel tool for materials research which seems to be particularly useful for testing materials proposed for future fusion reactors both the MCF and ICF ones.

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5-05

EROSION BEHAVIOR OF W-Ta FILMS IN PLASMAS OF STATIONARY MIRROR PENNING DISCHARGES

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Investigation is carried out of the influence of Ta (5…38%) admixture in W-films on an erosion behavior in plasmas of Penning discharges in different gases (Argon, Nitrogen, Helium and Hydrogen). The coatings were deposited on stainless steel substrate by argon ion sputtering of targets made from appropriate metals. For comparison it was investigated the erosion behavior single components: pure W and Ta films obtained by the same method.

5-06

ELECTRON BEAM FORMATION AND ITS EFFECT IN NOVEL PLASMA-OPTICAL DEVICE FOR EVAPORATION OF MICRO-DROPLETS IN CATHODE ARC PLASMA COATING

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Vacuum-plasma technologies of film deposition are now applied extensively [1]. Vacuum-arc method provides excellent adhesion of coatings to the substrate surface and high deposition rates. Cathode sputtering of vacuum arc by cathode spot determines the generation of flows of ions and micro-droplets. The micro-droplet component of erosion for the majority of metals is a significant part of a general loss of the cathode material in an arc, comparable with ion component. The micro-droplets in the formed ion plasma flow restrict the applicability of this method of film synthesis. Micro-droplets do worse properties of deposited films. Therefore for prevention of loss of substance and for prevention of influence of micro-droplets on a substrate it is necessary to eliminate micro-droplets. In [2] the conclusion has been formulated that micro-droplets cannot be completely evaporated in the arc plasma flow without additional energy source. Firstly attempt of micro-droplet evaporation without their removal was performed in [3]. In [4] it has been shown that in a discharge with hollow cathode the regime may exist with the double electric layer at the cathode and with high current density of fast electrons in the discharge volume, which is significantly larger than current density from cathode. Experiments [3] demonstrate the high efficiency of the novel plasma-optical system for evaporation of micro-droplets of dense arc plasma stream. The additional pumping of energy into arc plasma flow by the self-consistently formed radially directed beam of high-energy electrons for evaporation of micro-droplets is considered in the paper. The radial beam of high-energy electrons is self-consistently formed by double layer, appeared in a cylindrical channel of the novel plasma-optical system in crossed radial electrical and longitudinal magnetic fields. High-energy electrons appear near the inner cylindrical surface by secondary ion-electron emission at this surface bombardment by peripheral arc plasma flow ions. It is shown that high-energy electrons pump energy into arc ion plasma flow, which is sufficient for the evaporation of micro-droplets. It is shown that up to energy ε_m= 5.9 keV can be pumped by high-energy electrons during time of micro-droplet propagation through system and this energy ε_m is related to one atom, which should be evaporated.

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5-07

EXPERIMENTAL RESEARCH OF CLEANING RF DISCHARGES CREATED BY CRANKSCHAFT AND FRAME ANTENNAS

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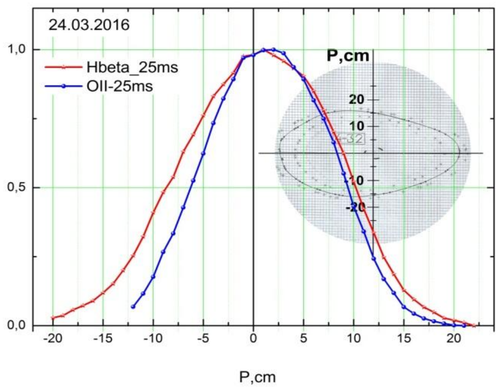
Vacuum chamber walls of the torsatron Uragan-2M are to be cleaned with RF and UHF discharges [1].

The study aims were: 1) to find optimal cleaning plasma regime (power output of RF and UHF generators, working gas pressure and magnetic field strength); 2) to measure plasma electrons density and temperature and to recover dimensional distribution of all mentioned parameters with the help of moving Langmuir probes and spectral diagnostics; 3) to determine how those parameters fit different cleaning regimes.

There are two main cleaning methods used at Uragan-2M device. They are chemical and physical cleaning. Chemical cleaning plasma is created by continuous RF discharge at frequency of 130 MHz (“UHF cleaning”). The source of RF power is the generator which works in continuous regime at frequency of 130 MHz and the power up to 3 kW. Physical cleaning plasma is created with two RF generators at frequency of ~ 5 MHz (Kaskad 1, K1, Kaskad 2, K2) and power up to ~ 50 kW. Every physical cleaning impulse lasts up to ~ 20 ms.

Spectrometer diagnostics data reveal the form and position of cleaning discharge plasma column inside of the device vacuum chamber.



Working gas and impurity distribution

Cycling of chemical and physical cleaning regimes allowed to decrease device vacuum chamber wall conditioning period down to one calendar month.

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5-08

ALLOYING AND MODIFICATION OF STAINLESS STEELS BY POWERFUL PLASMA STREAMS

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The successful implementation of the projects of International Thermonuclear Experimental Reactor (ITER) and DEMO as an efficient fusion source of electrical power strongly depends on selection of the structural materials. Stainless steels (SS) are one of main material for next step fusion devices. Nevertheless, the large sputtering rate under high energy partials is main disadvantage of SS as armour material. One of the potential ways of improving these properties is by alloying theirs surface layer with heavy elements [1]. One of possibility of alloying under pulsed plasma processing is by mixing previously deposited thin ($h_{coat} < h_{melt}$) coatings of different predetermined composition with the substrate and then subjecting to a powerful plasma impact [1, 2]

Presented studies are devoted to researches of properties the stainless samples coated by Plasma-Vapor-Deposition technique with thicknesses of tungsten layers of the below 3 μm. Such samples were exposited with powerful hydrogen plasma streams generated by powerful plasma accelerators QSPA Kh-50. The surface energy loads were 0.6 MJ/m^2 (i.e. near tungsten melting threshold). The plasma pulse shape is approximately triangular, pulse duration 0.25 ms. The sample surfaces have been examined with an optical microscope MMR-4 equipped with a CCD. X-ray diffraction (XRD) has been used to study structure, sub-structure and stress state of the samples. θ/2θ scans were performed using a monochromatic Cu-K_α radiation. Changes of phase state on the surface were obtained from XRD spectrum analysis. The analysis of diffraction peaks intensity, profiles, width (B), angular positions was applied to evaluate stress state, texture and coherent lengths. Residual macro-stresses (σ) and the lattice parameter in the unstrained state (a_0) were determined using a- $\sin^2\psi$-plots. Measurements of weight losses and precise measurements of the surface roughness with the Hommelwerke tester T500 were also performed.

The plasma streams exposures result in modification of steel-based structural materials and formation of re-solidified layers. Alloying of surface layer in result of the coating-substrate mixing allows achievement of desirable chemical composition in surface layers. The changes of substrate texture were also registered. Phase characterized by body-centered cubic lattice appeared due to recrystallization of affected material. Thus, the helpful conditions were created for penetration of tungsten in SS materials. Growth of lattice parameter was observed as result of plasma irradiation of coated samples. It indicated on penetration of tungsten into the depth of substrates. The erosion of modified layer alloyed by tungsten under high energy ion sputtering is also discussed.

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5-09

INFLUENCE OF KIND OF WORKING GAS ON PLASMA STREAM PARAMETERS, GENERATED BY MAGNETOPLASMA COMPRESSOR MPC

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Investigation of parameters and characteristics of plasma streams, generated by different types of plasma accelerators and magneto-plasma compressors, is one of actual and important from point of view basic plasma dynamics research and plasma applications in different technologists.

The present paper devoted to influence of kind of working gas on plasma stream parameters, generated by the MPC compact geometry. Such important parameters as energy density of the plasma stream, plasma density in compression zone have been studied. For analyze the dynamics of forming compression zone have been studied spatial distribution of currents flowing. All experiments were performed by magnetoplasma compressor MPC in mode operation in residual Helium and Argon with pressure 10 Torr and 1 Torr. Changing of kind of working gas and simultaneously by changing the initial pressure it possible to investigate the formation of the compression zone and plasma parameters are depending on the initial concentration at constant of integral mass rate.

Found that changing the initial concentration of working gas and constant values of mass rate leads to a change of the integral characteristics of discharge (VAC) and energy density of the plasma stream.

The reducing of the initial concentration, due to the transition from helium to argon, leads to significant change of current distribution, which flow in plasma stream with generation of toroidal current vortex, and displacement of the current from the axial area. Consequently, the spatial distribution of the Ampere force in the stream significantly changes. It leads to partial inhibition of the stream and its compression in the direction of the axis of system. The theoretical evaluations based on Bernoulli equation show increasing of a plasma stream density with decreasing of a working gas concentration in a vacuum chamber.

Nitrogen was chosen as the gas with intermediate atomic mass to verify the dependence of plasma stream parameters on the type of working gas. The integral characteristics of the discharge were measured. The comparative analysis of flow parameters for the three working gases was done.

5-10

MAIN DESIGN FEATURES OF THE QUASI-STATIONARY PLASMA ACCELERATOR QSPA-M

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The quasi-stationary plasma accelerators (QSPA) widely use for experimental simulation of ITER transient events as adequate reproduces of pulse duration and high energy density of ITER transient plasma loads. Thus the response of the plasma facing components to the plasma loads and the erosion effects at the actual plasma parameters are investigated with a large number of pulses. Quasi-stationary plasma accelerator QSPA Kh-50 generates high powerful plasma streams and injects into longitudinal magnetic field of several kGs. The main disadvantage of this facility is impossibility any further increase in the magnetic field value up ITER relevant magnitudes due to a fast rise of the energy and plasma particles losses.

Therefore, the novel powerful test-bed facility of the compact geometry QSPA-M was developed. A cathode unit of the new QSPA-M facility consists of cylindrical and ellipsoidal parts. The ellipsoidal part is formed by 12 rods-lamellas. The maximal diameter of this part is 160 mm, and its length is 300 mm. The anode of the squirrel-cage type (of 250 mm in diameter and 730 mm in length) is composed of 24 rods, each of 10 mm in diameter. For working gas supply into the acceleration channel are used 4 axial gas-feed injectors and one additional radial gas-feed injector placed inside the cathode unit region. Separate supply units allow the gas injectors to deliver different combinations of gases and their mixtures into the accelerating channel. The plasma accelerator is placed into a vacuum chamber of 340 mm in diameter. It is connected with chamber (diameter of 150 mm and length of about 3 m) provided transportation of plasma in magnetic field.

The magnetic system of the QSPA-M device consists of 21 coils producing the longitudinal magnetic field, and special corrected coils placed in different regions of the plasma accelerator and the target chamber. This system is able to create the magnetic field up to 2 T with a variable distribution along the z-axis, needed for the plasma magnetization and plasma streaming into the target chamber.

A power supply system for discharges in the QSPA-M facility constitutes the capacitor bank of the total capacity C = 1770 μF, which can be charged to U_{max} = 40 kV and store energy up to W ≈ 1.4 MJ. It is equipped with appropriate switching and synchronization units. The magnetic field system is supplied from another capacitor bank of the total capacitance C = 15.120 μF, which at the maximum charging voltage of 5 kV can store energy of W = 189 kJ. The third small condenser bank which supplies the gas injectors has the capacitance of C = 1800 μF and the maximum charging voltage of 5 kV.

Plasma parameters are varied by both changing the dynamics and quantity of gas filled the accelerator channel and changing the working voltage of accelerator QSPA-M. The characteristic of plasma stream injected and propagated in longitudinal magnetic field are discussed.

5-11

DIAGNOSTICS OF PLASMA STREAMS AND PLASMA-SURFACE INTERACTION OF ESSENTIALLY DIFFERENT DURATION OF PLASMA PULSES

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Spectroscopic studies main characteristics of the plasma streams generated by magneto-plasma compressor (MPC) and quasi-stationary plasma accelerator QSPA Kh-50 have been performed. Principal features of plasma interaction with surfaces have been also carried out in dependence on plasma heat loads, plasma density and pulses duration. Long pulse plasma streams energy density up to 2.4 MJ/m^2, pulse length of 0.25 ms created by QSPA Kh-50. The MPC generates short (plasma stream duration about 10 μs) compressed plasma streams with plasma density up to 10^{18} cm^{-3}, and plasma energy density varied in the range of 0.05…0.5 MJ/m^2. Helium, nitrogen, argon, hydrogen, xenon and different mixtures were used as working gases. Spectral analysis, particularly, shapes and intensities of spectral lines related to different ionization states was fulfilled. As result, temporal and spatial dependencies of electron density and temperature have been found. Special attention was paid to the dynamics of the spectral lines near surfaces of exposed targets. Estimation of number of particles of the target material in near surface plasma layers and distance of propagation of target particles from exposed surfaces were carried out. Performed studies of plasma-surface interaction also include measurements of plasma energy deposited to the material surface as a function of the impacting energy and kind of targets. It was experimentally found that shielding layers of cold plasma created near surfaces irradiated by plasma streams. Formation of such layer led to reduction of the energy density delivered to target surfaces. The resulting microstructure of the treated surfaces after dense plasma impacts is also discussed.

5-12

SURFACE TOPOGRAPHY AND DEUTERIUM RETENTION IN FERRITIC STEEL AND α-Fe EXPOSED TO LOW-ENERGY HIGH-FLUX DEUTERIUM PLASMA

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Current R&D activities on materials for fusion power reactors are focused on plasma facing, functional and structural materials. Candidate structural materials, as well as candidate plasma facing materials, have a chemical composition that is based on low activation chemical elements (Fe, Cr, V, Ti, W, Si, C) and include, in particular, reduced activation ferritic/martensitic steels, ODS RAFM and RAF steels. These materials will be subject to intense fluxes of energetic deuterium and tritium ions and neutrals. This implantation process leads to concerns about hydrogen isotope inventories after long-term deuterium-tritium plasma exposure and considerable erosion of near surface layers.

Surface topography and deuterium retention in 13Cr2MoNbVB steel and α-Fe under glow discharge hydrogen (deuterium) ions bombardment with energy ~1 keV at ion fluencies from $5\cdot10^{22}$ to 10^{25} D/m^2 and various temperatures have been examined. The methods used were scanning electron microscopy, thermal desorption spectroscopy and the D(^{3}He,p)^{4}He nuclear reaction.

During exposure to the D plasma blisters are formed on the surface. Both blistering and deuterium retention have showed significant dependence upon the exposure temperature and fluence. Two types of plasma-induced blisters were observed: large blisters with magnitude of greater than a few tens of microns and various shapes, and small blisters with size of less than one micron and varying dome. The thickness of blister lid (the blister cover) is larger than the mean projected ranges of D^+ ions. Deep cavities (holes or pits) were formed inside all of the small blisters, whereas void/crack along the grain boundary beneath surface was found for most of big blisters. The blisters on the surface of α-Fe showed a multilayered structure such as steps. These features is contrary to the conventional definition, in which blisters are considered as plastic dome-shaped buildings of the surface layer and a lenticular cavities are included between the blister lid and the bulk material.

The dependence of blister nucleation and growth on specimen deformation level was investigated at six levels between 5 and 95% introduced via cold-working. In deformed specimens the temperature range for blistering was extended to higher temperature, but the size distribution of blisters was strongly affected by deformation, with the low-temperature peak being suppressed by deformation and the high-temperature peak being enhanced.

As blisters developed there was a concurrent formation of cracks along grain boundaries far beyond the implantation zone. Significant deformation-induced changes in the size and distribution of cracks were also observed. In comparison with non-deformed alloy the size of concurrent cracks was several times higher in deformed steel. Post-irradiation measurements of deuterium showed that deuterium concentrations were relatively constant with depth and extended far beyond the implantation range. It was found that cracks up to 1 mm in length were formed in 95% deformed steel at depths reaching 500 μm.

6-01

ELABORATION OF PLASMA-DIELECTRIC WAKEFIELD ACCELERATOR*

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Theoretical and experimental investigations of the physical principles of dielectric wakefield accelerator based on the excitation of accelerating wakefield in the plasma-dielectric structure by a long sequence of relativistic electron bunches are presented. Enhancing the wakefield intensity is supposed to be achieved by using multibunch regime of excitation for the coherent summation of wakefields of individual bunches and resonator regime for wakefields accumulation. The acceleration of bunches in the total (plasma and dielectric) wakefields is realized by detuning of bunch repetition frequency relatively to the frequency of the excited wakefield. In such a way the sequence of bunches is divided into exciting and accelerated parts due to displacing latter part of bunches into accelerating phases of wakefield excited by a former part of bunches of the same sequence. The influence of plasma in the transit channel on the amplitude of excited plasma and dielectric wakefields and focusing exciting and accelerated bunches is investigated.

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6-02

TRANSITION RADIATION OF THE MOVING POINT CHARGE IN PLASMA AS A RESULT OF THE BACKGROUND PLASMA ELECTRONS' ACCELERATION

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Traditional method of calculation of the transition radioemission from the border of two media uses electromagnetic fields of the moving charge in these media presented in the terms of permittivity and permeability. These expressions are substituted to the boundary conditions together with the eigenmodes of the unknown magnitudes. Then these magnitudes are obtained from the set of algebraic equations obtained from the boundary conditions [1]. But it is not clear from such calculation that the radioemission source is the accelerated motion of the media electrons caused by the electric field of the moving charge. For subluminal velocity of the moving charge in the homogeneous media such emission is averaged into zero. For superluminal velocity in the homogeneous media one can obtain the Cherenkov radioemission [2–4]. For subluminal velocity in the inhomogeneous media one can obtain the transitional radiation [4]. This method of calculation makes possible to take into account effects described by the nonlinear terms in the equations of motion for the media electrons.

The aim of this work is to calculate the transition radioemission of the moving charge from the border of vacuum and cold isotropic plasma with the immobile ions using the abovementioned method. We solve the set of Maxwell equations and motion equation for plasma electrons in order to present vector potential in the background plasma. In the first approximation the charged particle's velocity is treated as the given value (i.e., it is steady and straight). Cold plasma is treated, only the motion of electrons is taken into account. Radiation pattern for the whole range of the possible frequencies and charge velocities was obtained. The data obtained coincide with the results of the traditional method of calculation.

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6-03

BREAKING OF ENSEMBLES OF LINEAR AND NONLINEAR OSCILLATORS

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Ensembles of oscillators are convenient models for analyzing the dynamics of various physical systems. Such systems can be charged particle bunches trapped in various potentials, a set of eigenmodes in oscillatory systems that are equivalent to resonators, and many other physical systems. Generally, the analysis of the dynamics of such ensembles is a complex task. However, there are important special cases, when the analysis of the dynamics of these systems can be carried out by analytical methods. In some cases the analytical methods are available for obtaining the most important characteristics of this dynamics. The key question here is the question about the stability of the ensembles. Such systems are, in particular, the linear ensembles of coupled oscillators. It is known that if the kinetic and potential energy of the ensemble are positively definite forms, then such ensembles exist, i.e., they are stable. Moreover, there are some common algorithms for finding the normal oscillatory frequencies of these ensembles. For ensembles of nonlinear oscillators, there are no general criteria for determining their dynamics.

In this paper some results on the analysis of the dynamics of ensembles of linear and nonlinear oscillators are presented. The most important results of these studies can be formulated as follows. It was found for an ensemble of linear oscillators, that if in this ensemble there are a number of identical oscillators and they can be grouped together, the ensemble of oscillators can be transformed into the ensemble of oscillators with a non-reciprocal connection. In such a case the matrix coefficients, describing the kinetic and potential energy of the ensemble, are no longer symmetrical, and different new dynamic processes can be realized. The most important of them is: the development of instability of such ensemble is possible. The criteria for the instability, as well as the elementary group of oscillators, which can lead to such dynamics, were found. The best known ensembles of nonlinear oscillators were investigated. This is the ensemble, where each of oscillators is described by the model of the mathematical pendulum, and the ensembles where each of oscillators is described by Duffing equation. The most important result of this study is disc of the fact that in the case when the dynamics is determined by the dynamic chaos, many vibrational characteristics, including stability of such ensembles, are determined by the value of statistical moments. Conditions are found when such ensembles do oscillate, and when breaking of such ensembles does occur.

6-04

JOINT WAKEFIELD ACCELERATION BY LASER PULSE AND BY SELF-INJECTED ELECTRON BUNCHES

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At the laser acceleration of self-injected electron bunches by plasma wakefield field (LPWA) it is important to accelerate bunches up to the high energy. In [1–5] it has shown that at certain conditions in blowout regime the laser wakefield acceleration by plasma wakefield with time is replaced by a combined joint LPWA acceleration and beam-plasma wakefield acceleration by first self-injected electron bunch. The purpose of this paper is to study some properties of self-injected electron bunches, which are accelerated by wakefield electron bubbles, excited by a laser pulse. Results of fully relativistic electromagnetic PIC simulation are presented. The laser pulse with a wavelength $\lambda = 0.8$ μm is injected into a homogeneous semi-infinite plasma. The plasma density is chosen to be equal to $n_0 = 1.8 \cdot 10^{19}$ cm^{-3}. The longitudinal and transverse dimensions of the laser pulse are selected to be smaller the wavelength. The length of the laser pulse at half-maximum equals to 2λ, and the width at half-maximum equals 8λ. The intensity of the laser pulse is equal to $I = 5.3 \cdot 10^{19}$ W/cm^2. It is shown that in the first and second wake bubbles of the electrons, excited by the laser pulse, first on one electron bunches are self-injected and accelerated under certain conditions, and then after these bunches the additional electron bunches are self-injected and accelerated. It has been shown that over time, initially self-injected bunches become driver- bunches, while additionally self-injected electron bunches are accelerated. Initially self-injected electron bunch in the second wake bubble after deceleration is self-cleaned due to defocusing by radial fields. Charges of initially self-injected electron bunches are several pC, and the charges of additionally self-injected and accelerated electron bunches with the largest energy are much less. It is shown that the energies of additionally self-injected and accelerated electron bunches in the first and second wake electron bubbles are larger than the energies of the bunches, originally self-injected in the first and second wake electron bubbles.

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6-05

STUDIES OF PLASMA PARAMETERS IN LOW PRESSURE DISCHARGE INITIATED IN COAXIAL WAVEGUIDE BY MICROWAVE STOCHASTIC RADIATION

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It was shown early, both theoretically and experimentally, that the phenomenon of anomalous penetration of microwave radiation into plasma, conditions for gas breakdown and maintenance of a microwave gas discharge, and collisionless electron heating in a microwave field are related to jumps of the phase of microwave radiation. In this case, in spite of the absence of pair collisions or synchronism between plasma particles and the propagating electromagnetic field, stochastic microwave fields exchange their energy with charged particles. In such fields, random phase jumps of microwave oscillations play the role of collisions and the average energy acquired by a particle over the field period is proportional to the frequency of phase jumps.

At presence of jumps of wave phase the curve of break-down in the area of low pressures. We will remind that at resilient collisions part of energy of radiation is lost. Therefore advantageous is work in area of low pressures (near-by the left edge of curve of break-down), as a contribution of collisions to the set of energy of electrons is small as compared to a deposit from the jumps of phase. Accordingly, to create an effective discharge by means of radiation with a bruising along phase, as be obvious from above-mentioned, expediently only at pressures near-by the left part of break-down curve. Because as far as the increase of pressure the losses of energy increase on elastic and non-elastic collisions, that reduces efficiency of discharge.

Characteristic times, for that electrons collect energy corresponding to a maximum of section of ionizing of air, are small as compared to a pulse width, therefore during an impulse there is substantial growth of plasma density to the values of 10^9 cm^{-3}.

First measured a plasma closeness in low pressure discharge initiated by a microwave radiation with the jumps of phase authors the articles developing the original technique of the use the double probes of Langmuir, separate source of direct-current, high-frequency transformers, digital oscillograph and least-squares method, for treatment of signals, using the special type of function of regression. As a result of experimental data we found that a plasma density made from $1{\cdot}10^9$ to $3{\cdot}10^9$ cm^{-3} at 6 kW.

It should be noted that there is a current and at a zero tension from motion of electrons in the poorly heterogeneous high-frequency fields due to forces of high-frequency pressure (like behavior of pendulum with the quickly hesitating of fixing point, first studied P.L. Kapitsa in 1951).

Some of the got results may be, also to use in connection with the additional plasma heating in thermonuclear devices, because heating of charged particles is collisionless.

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6-06

PECULIARITY OF THE CHARGED PARTICLES DYNAMICS AT THE CYCLOTRON RESONANCES

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Results of research of peculiarities of the charged particles dynamics in external constant magnetic field and in the field of plane electromagnetic wave are stated. The main attention is paid to dynamics of particles near cyclotron resonances, in conditions when nonlinear cyclotron resonances overlap, and also influence on this dynamics of additive and multiplicative fluctuations.

Briefly the main results can be formulated in such a way.

It is shown that in the case when the criterion of overlapping of the nonlinear cyclotron resonances doesn't work, chaotic dynamics of charged particles is possible. Such dynamics is due to the nonlinear interaction of a large number of non-resonant cyclotron modes. In this case, the processes in the small and large time can significantly differ. This is important in the investigation of stability of the charged particles flows in devices like gyrotron, cyclotron resonance masers (CRM) and cyclotron autoresonance masers (CARM) and in such devises with plasma.

The role of external additive and multiplicative fluctuations on the dynamics of charged particles at the cyclotron resonance is investigated. The dependence of the growth energy of charged particles in the field with additive fluctuations are investigated. It is shown that, as usual, the diffusive law of growth of energy of a particle takes place. A feature of this diffusion dynamics is that the diffusion coefficient is inversely proportional to the derivative of the resonance on energy, and when this derivative tends to zero (autoresonant condition) diffusion coefficient tends to infinity. Analysis of this peculiarities shows that for at the same time process usual diffusion with an exponent 1/2 ($\gamma \sim Dt^{1/2}$) in the space of energy is replaced by superdiffusion in which the exponent change to 3/2 ($\gamma \sim Dt^{3/2}$).

Note that in the regular mode of the charged particles acceleration in the conditions of autoresonant energy of the particles increases according to the law proportional $\sim t^{2/3}$. Influence of multiplicative fluctuations is even more significant. The presence of these fluctuations leads to the development of fluctuational instability at which the second moments grow exponentially, and all of the following moments are growing even faster

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6-07

FEATURES OF THE TRANSVERSE DYNAMICS OF ACCELERATED BUNCH IN THE PLASMA-DIELECTRIC WAKEFIELD ACCELERATOR

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Transverse dynamics of bunches of charged particles is the subject of researches in the powerful beam generators of electromagnetic radiation and particle accelerators. The most important characteristic of particle accelerators is the luminosity of the beam. Reducing the phase space of the beam can be reached by radial focusing a beam of charged particles by outside magnetic systems. Earlier in our studies the possibility of focusing of the accelerated bunch by filling the transit channel of the dielectric structure with plasma has been shown. It has been shown the possibility of obtaining simultaneous longitudinal acceleration and radial focusing of the accelerated bunch by the wake fields [1].

This work presents the analytical calculations of the transverse dynamics and numerical modeling of the behavior of the accelerated bunch in the plasma-dielectrictric wakefield accelerator (PDWA). It has been found that excessive focusing is dangerous by transferring in the nonlinear regime. A variant of solving the problem of excessive compression of the accelerated bunch inside PDWA, by separating the plasma-dielectric wakefield accelerating structures by vacuum space is proposed.

Also we study theoretically transverse dynamics of the bunch of charged particles with the finite emittance in the plasma-dielectric wakefield accelerator. Parameters of bunches are chosen the same as available from the 15 MeV Argonne Wakefield Accelerator beamline. Obtained results allow to determine the limits of the emittance of the bunch where dynamics of the accelerated particles remains stable [2].

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(http://www.sciencedirect.com/science/article/pii/S0168900216301334).

6-08

DYNAMICS OF THREE WAVE STOCHASTIC DECAYS IN NONLINEAR MATTER

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Stochastic decays in plasma are responsible for different important physical processes. In particular they allow to transform energy of regular oscillations into chaotic ones. In our previous investigations the decays of transverse electromagnetic waves into transverse one and electron oscillations in plasma were studied. It is interesting to investigate such processes when transverse electromagnetic waves decay into electromagnetic ones and plasma oscillations in which ion component of plasma take place. Excitation of such chaotic oscillations allows most effectively to heat just ion component of plasma. In this work results namely such investigations are described. Below we briefly will point out most important results of these investigations.

Analysis of such decay processes shown that matrix elements of nonlinear wave interaction in plasma may be abnormally large when frequency of LF wave (that is formed with ions) is close to ion cyclotron frequency. In this case matrix element of nonlinear interaction is inversely proportional to frequency difference of low frequency wave (for example, Alfven wave) and ion cyclotron one. In this case efficiency of nonlinear wave interaction essentially increases. Besides, conditions for realization of regime with dynamic chaos can be essentially reduce.

Preliminary analysis of investigation possibility of such processes in experiment is enough complicated. So other possibilities of realization of such decay processes were investigated. In particular, analysis shows that most simple nonlinear matter for experiment is ferrites. Analytical investigations of decay processes in ferrites were carried out. It was shown that main properties of decay processes in plasma and ferrites are analogous. It is needed to point out that only processes of nonlinear interaction of electromagnetic wave and magnetostatic ones were considered.

6-09

A STUDY OF THE MICROWAVE AMPLIFICATION IN MILO WITH THE FLAT INTERACTION SPACE

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Magnetically insulated transmission line oscillator (MILO) is a crossed field device designed to generate microwave power at the gigawatt level. We explored by a method of numerical simulation the microwave amplification in MILO with a flat interaction space of an electronic stream and a slow-wave structure field. The explored system represents a segment of a flat transmitting line of the infinite width. The slow-wave structure in the form of a comb is disposed on one of electrodes (anode). Other electrode (cathode) is the distributed electron-emitting source on the effect of explosive emission. Line areas at the left and to the right of a slow-wave structure are filled by an absorbent for prevention of wave reflection. After an applying voltage in a line the regime of magnetic self-insulation of an electronic stream is installed. One of comb resonators is exited by an external signal. Dependences of a transfer ratio, as well as dependences on a frequency detuning of a signal comparatively a structure principal mode are gained by results of examination of such model. Also spectral characteristics of output signals for various regimes of excitation have been estimated.

6-10

ARTICLE I. NUMERICAL SIMULATION OF WAKEFIELDS EXCITATION IN THE DIELECTRIC STRUCTURE FILLED WITH INHOMOGENEOUS PLASMA

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Results of numerical simulation of wakefield excitation in the dielectric structure filled with plasma created in capillary discharge are given. Wakefield was excited at injection of electron bunch in dielectric tube with relative dielectric permittivity 3.75 with outside and internal diameters of 1.2 mm and 1.0 mm, respectively, surrounded with cylindrical waveguide. Energy of bunch electrons was 5 GeV, bunch charge was 3 nC, its length was 0.2 mm, bunch diameter was 0.9 mm. The internal area of dielectric tube was filled plasma with density on axis 4.41×10^{14}cm^{-3}. Three different models of dependence of plasma density on radius were investigated: 1) homogeneous, 2) square and 3) the dependence offered by N.A. Bobrova [1], which is best describing the plasma received as a result of capillary discharge in waveguide.

The results of numerical simulation carried out by means of 2.5-dimensional code created by us have shown that amplitude (to 200 MeV/m) and frequency (372.2 GHz) characteristics of the longitudinal (accelerating) wakefield component weakly depend on what model of dependence of density of plasma on radius is used in calculations. At the same time the transverse (focusing) wakefield component significantly changes both amplitude, and frequency characteristics: in model of dependence of density of the plasma on radius offered by N.A.Bobrova [1] (3) amplitudes of transverse field is approximately twice more, and the frequency 1.4 times higher, than at homogeneous distribution (1). It should be allowed when elaborating the two-beam plasma-dielectric wakefield accelerator [2].

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6-11

HIGHER RADIAL MODES OF AZIMUTHAL SURFACE WAVES IN CYLINDRICAL WAVEGUIDES WITHOUT EXTERNAL MAGNETIC FIELD

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Both analytical and numerical studies of the dispersion properties of higher radial modes of electromagnetic surface type waves which propagate in cylindrical waveguides without external magnetic field which are partially filled by plasma along the small azimuth are carried out. These branches complement the previous results [1–3] obtained for the zero-th radial mode. Better conditions for these higher radial modes propagation are observed for the waves with larger azimuthal wave numbers in the waveguides with wider dielectric layer, and larger dielectric constant. Approximate expression (6) satisfactory describes the eigen frequency of ASW higher radial modes. Possibility of ASW higher radial modes propagation is proved for small values of effective wave number, i.e. in the waveguides with large radius of plasma column and plasma density. The demerit of the ASW higher radial modes dispersion properties is that a change in plasma waveguide parameters causes drastic change in ASW eigen frequency. This is in contrast to the possibility of getting advantage of smooth frequency tuning for the ASW zero-th radial mode.

The advantage of ASW higher radial modes is that their eigen frequencies are larger than those of the zero-th radial modes effectively studied earlier. In other words, ASW higher radial modes propagate with shorter vacuum wave length than the zero-th modes. Then the presented results promise to be of interest for the purposes of plasma electronics. Possibility of ASW irradiation from the narrow axial slot in the waveguide metal wall was demonstrated in [2].

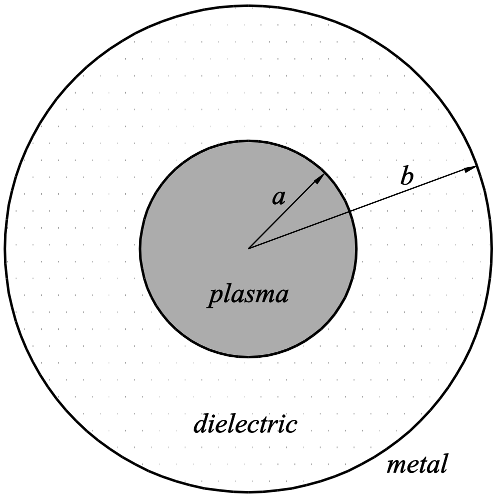

Fig. 1. Schematic of the problem

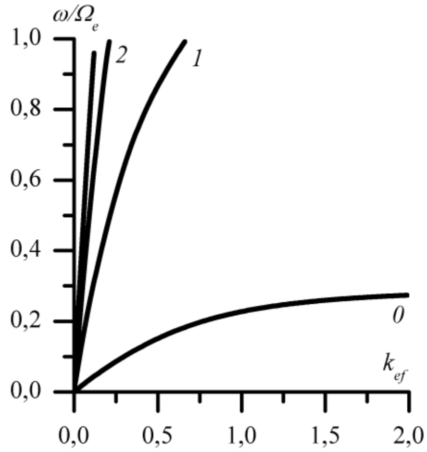

Fig. 2. Dependence of ASW eigen frequency normalised by Langmuir frequency vs effective wave number $k_{ef}=|m|c/(\Omega_e a)$. $\varepsilon_d = 4$, $(b-a)/a = 0.5$, $m = 1$. Numerals nearby the lines denote the numbers of the radial modes

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6-12

NUMERICAL SIMULATION OF HIGH CURRENT ION BEAM WITH ADDITIONAL ELECTRON BEAMS INJECTION IN THE DRIFT AND THE ACCELERATING GAP OF LIA

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The dynamics of the high-current ion beam (HCIB) in the system consisting of magneto-insulated accelerating gap and the drift gap (DG) of experimental model the linear induction accelerator (LIA) has been studied by means of three-dimensional fully relativistic electromagnetic code "KARAT". The current and partially charge compensation of the HCIB has been performed in the first half of the magneto-insulated gap by the accompanying electron beam with the same current density and the same cross-section. Both beams have been injected simultaneously. The ion beam was compensated in the rest part of the system by an additional electron beam injected radially in the middle of magneto-insulated gap with a certain time delay (so that the HCIB and additional electron beam met in the second part of the accelerating gap). To realize this injection value, configuration and location of the magnetic field have been selected in such a way that additional electron beam, moving along magnetic lines, "fell" on the initial HCIB cross-section and was accompanying the ion beam in second half of the accelerating gap and in the DG, i.e. substituted for accompanying the electron beam. At the same time appropriately selected: thickness of the additional electron beam, density and electron energy, time and location of the injection.

The optimization of the geometry of the magnetic field, location and time injection of the additional electron beam, as well as its transverse dimension, has been carried. It is shown that at the established parameters of beams, the external magnetic field, the injection of main and additional electron beams HCIB can be compensated (currents of HCIB and the additional electron beam practically equal to the initial values and are equal to each other). Thus at the exit of the system the parameters of the ion beam remain useful for a number of important technological applications.

6-13

FIELD EMISSION NEEDLE-LIKE CATHODE HEATING

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The usage of linear induction accelerators (LIA) for obtaining high-current ion beams (HCIBs) with the parameters required for different applications is perspective as LIA can operate at high pulse frequency, and can accelerate HCIBs of virtually any ions. Collective focusing techniques can significantly increase the ion beam current. In such kind of LIA, the ion beam space charge is compensated by electron beams, and the electron current is suppressed by magnetic insulation of accelerating gaps [1–5].

The charge and current neutralization of the HCIB by electron beams requires high-current electron beams. These beams can be generated by a high-current diode with a knife-like cathode which works in the regime of the field- or explosive emission [6, 7]. The field emission mode is the preferred. To show that the high-current diode operates in the field emission mode, the coupled system for thermal conductivity equation and continuity equation for the current density was solved numerically. The numerical model took into account Joule heating, Nottingham and Thomson effects, and thermal radiation [6, 8]. The temperature dependences of the resistivity, heat capacity, and surface emissivity were taken into account. The boundary conditions for these equations include Nottingham effect, which directly depends from the cathode emission current density, and thermal radiation from emitter surface. Computer simulations have shown that the required currents can be easily obtained in the field emission mode.

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6-14

SURFACE ELECTROMAGNETIC WAVES ON BOUNDARY BETWEEN LOSSY DIELECTRIC AND LEFT-HANDED MATERIAL WITH GAIN

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Till now mankind has been achieved a great progress in the experimental and theoretical research of new artificial materials (so called metamaterials). These metamaterials demonstrate interesting behavior and possess a number of unusual physical properties that are not exist in all natural substances. Such unique properties give the opportunity to create a lot of innovative devices. The characteristic feature of the metamaterials is fact, that the electric field vector, magnetic field vector and wavevector of the electromagnetic waves in such media form a left-handed system (so, such metamaterials are often called "left-handed materials", LHM) [1].

It is well known that the undamped surface electromagnetic waves can propagate along boundary between lossless LHM and lossless dielectric [2, 3]. The amplitude of these waves will decrease with propagation distance if we take into account the losses in the dielectric. Let us assume the existence of gain in the LHM to compensate the wave lossess [4].

In our work it was studied the propagation of the eigen electromagnetic waves along the planar waveguide interface between the lossy dielectric and the left-handed metamaterial with gain. The dispersion equation and expressions for spatial distribution of the eigen waves of such waveguide structure were analyzed. It was obtained the conditions for existence of the surface electromagnetic waves.

The results obtained in this work can be useful for the practical applications of metamaterials in science and technology.

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6-15

DIAGNOSTIC MODULE OF THE RADIATION-BEAM COMPLEX "TEMP"

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For the development of diagnostic measurement techniques has been developed and manufactured power module. It consisted of the high-voltage multiplier, block thyratron start arrester and arrester itself. Thyratron trigger circuit generates a short pulse of 15 kV, trigger the spark gap capacitor bank. The design of the arrester, which has low inductance, allows you to work over a wide battery voltage range. The maximum parameters of the module: the charging voltage to 90 kV; discharge current up to 50 kA; current rise front – 600 ns.

For the measurement of the charging voltage capacitors used high-voltage unit with galvanic isolation, which can significantly increase the noise immunity and safety when working with high voltage. Meter High Voltage is based on relaxation oscillator transistor in the avalanche mode, allows you to simply generate the voltage conversion rate. This conversion accuracy is up to tenths of a percent. The stability of the circuit is achieved by the automatic threshold voltage difference stabilization. To form a rectangular current pulse (amplitude – 120 mA, duration – 5 ms), passing through the LED, is used accumulative LC-line. Receiver light signals made on the phototransistor and the ASIC 1054 XA3, which forms a standard rectangular pulse. This pulse triggers a pulse repetition frequency converter into a voltage. The frequency converter is implemented on one-shot 155AG1 and measuring head with a current of 300 mA full deflection. This scheme allows you to measure voltage up to 80 kV.

7-01

OPTICAL EMISSION SPECTROSCOPY OF PLASMA OF UNDERWATER ELECTRIC SPARK DISCHARGES BETWEEN METAL GRANULES

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A nanoscaled state of matter in form of a colloidal solution obtained by method of electric spark dispersion is considered to exhibit excellent bactericidal and fungicidal properties and have numerous biological applications in various fields of human life. Moreover, the liquid state of colloid is the most convenient and natural for manipulation with life forms and use as mineral nutrients. In this paper we present an experimental study of plasma of underwater electric spark discharges occurring between granules of different metals during the process of colloid formation.

Implementation of low-voltage spark discharges was carried out on the technological unit, which consists of a pulse generator, control unit, discharge chamber, measuring and auxiliary devices. Supply of the voltage to electrodes caused a current flow along the chain of loosely arranged metal granules in the stochastic switching mode. Plasma emission registration was carried out by high-aperture compact SDH-IV spectrometer.

Series of experiments were carried out exploiting granules of Cu, Fe, Mn, Mg, and Mo. Optical emission spectroscopy techniques were applied in order to obtain the emission spectra of corresponding elements and perform the diagnostics of a such plasma. Excitation temperatures of plasma of underwater spark discharges between corresponding metal granules were determined using Boltzmann plot technique. Spectral sensitivity of the spectrometer was taken into account in experimental measurements.

7-02

EFFECT OF DUST PARTICLES ON ELECTRON ENERGYDISTRIBUTION IN GLOW AND AFTERGLOW PLASMAS

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The electron energy probability functions (EEPFs) are analyzed for glow and afterglow argon dusty plasmas, using numerical and analytical approaches. The EEPFs are obtained from the homogeneous Boltzmann equation for electrons. For a glow dusty plasma, the effect of nonuniform dust density and sustaining electric field on the EEPF, the ion and electron densities, and the dust charge are investigated by self-consistently solving the Boltzmann and the particle-balance equations. In particular, we study the effects of the dust grains on the EEPF and its transitions, and show that the dust particles can lead to electron thermalization (Maxwellization). We also derive analytical expressions describing electron energy probability functions in glow and afterglow dusty plasmas. The expressions for the EEPF in a glow discharge plasma are obtained neglecting electron-electron collisions, as well as transformation of high-energy electrons into low-energy electrons at inelastic electron-atom collisions. At large electron energies, the quasiclassical approach for calculation of the EEPF is applied. The electron energy distributions, which are obtained analytically, are compared with those calculated numerically by a finite-difference method taking into account electron-electron collisions and the transformation of high-energy electrons at inelastic electron-neutral collisions. It is shown that the analytical approach can be used for calculation of the EEPF and dusty plasma parameters for the case of the positive column of a direct-current glow discharge and when the RF frequency is not very large ($\leq$ 27.12 MHz). Considering the afterglow case, analytical expressions describing the EEPF are obtained assuming that the electron energy loss is mainly due to momentum-transfer electron-neutral collisions and due to deposition of electrons on dust particles. The study is carried out for different electron energy distributions in the steady state, including Maxwellian and Druyvesteyn EEPFs. The cases when the rate for momentum-transfer electron-neutral collisions is independent on electron energy, as well as the case when the rate is a power function of electron energy are considered. Effect of dust particles on the EEPF of argon dusty plasma is analyzed.

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7-03

PROPERTIES OF SECONDARY DISCHARGE IN PLASMA-LIQUID SYSTEM BASED ON ROTATING GLIDING DISCHARGE

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A formation of thin current channels is quite typical for self-sustained plasmas ignited at atmospheric pressures. In particular, this behavior is common for gliding discharges (GD) [1] and rotating gliding discharges (RGD) [2]. It can be considered as negative effect in case when a generation of larger plasma volumes (or treatment of larger surfaces) is considered, especially when treatment efficiency directly depends on the electrode area. This is one of the main reasons plasma-liquid systems did not find major application, while being successfully tested in laboratory scale for water purification and sterilization. To resolve this issue, the discharge area is moved in a certain volume or over a certain surface, which is a general concept for both GD and RGD discharge systems. The use of secondary discharge (at least at low pressure [3]) allows overcoming mentioned issue and making plasma spread over larger liquid surface to be treated. Using secondary discharge allows controlling value of the electric field inside liquid also.

In current work we present results of studies of the secondary discharge ignited in RGD plasma system at atmospheric pressure. Analysis of discharge photos (exposition time varied from 15 ms to 125 ms, see Fig. 1) showed that depending on a gas flow rate in the system, the secondary discharge can be either more filamentary or diffuse.

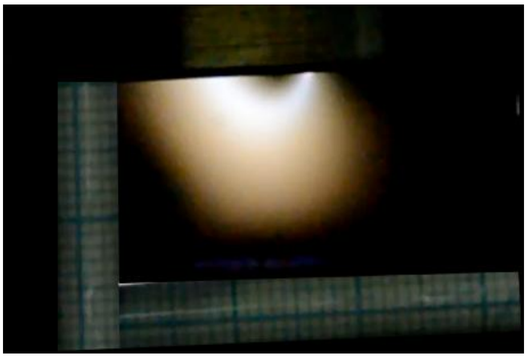

Fig. 1. Secondary discharge current – 80 mA, the gas flow (air) – 5 l/min at exposition time – 5 ms

For relatively low gas flow (5…10 l/min), diffuse discharge behavior and additional analysis of current-volt characteristics allowed us to classify it as a glow discharge.

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7-04

PROPAGATION OF ION PLASMA FLOW OF CATHODIC ARC DISHARGE IN HOLLOW CAHODE (STUDY AND THE FIRST RESULTS)

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Dense metal ion plasma flows generated by cathodic arc discharges are a subject of detailed studies due to their ability to provide high rates of various coating deposition with relatively low production cost. However, serious restriction in implementation of such technology consists in a presence of microdroplet fraction which follows the ion flow and degrades the coating quality. Among many technical approaches to the ion flow filtering, of a great interest are those with minimal losses of deposited substance, particularly, based on passing the flow through a plasma of the discharge in crossed electrical and magnetic fields inherent to electrostatic plasma lens configuration [1], with high efficiency provided by a principle of closed electron drift trajectories. Even simpler possible option, without magnetic field use, can be realized in hollow cathode discharge of low pressure in the presence of multiple oscillations of fast electrons across the discharge cavity.

This work presents the first experimental results of studying characteristics of repetitively pulsed cathodic arc plasma flow propagating through the pulsed hollow cathode discharge under low pressure of working gas argon. At that, the ion plasma flow originated from cathodic spots of vacuum arc discharge initiates hollow cathode discharge, which is self-sustained and continues its operation after the ion plasma flow blow out. This discharge was studied by electro-physical methods and by means of optical emission spectroscopy. Vacuum arc discharges with Cu and Ti cathodes were used in experiments. Power supply provided arc current pulses with 40…300 A amplitude and 0.1…1.0 ms duration. Specific power introduced into the hollow cathode discharge with 4…5 ms duration was varied in a range from a couple till tens W/cm^3 at the discharge voltage up to 2500 V and current up to 10 A. Studies of the discharge optical emission spectra were performed by means of CCD spectrometer SL-40-2-2048 in 200…1000 nm spectrum range. Optical system was composed of the spectrometer input waveguide with 0.4 mm core diameter located in a focal plane of quartz lens (F = 150 mm) with aperture varied in range 8…32 mm arranged coaxially with the hollow cathode and vacuum arc source. At that, influence of cathodic arc emission could be excluded by delayed start of the spectrometer exposure. For each recorded dataset of 128 exposures (4 ms each with 0.5 Hz repetition rate), statistical analysis was done based on dominating spectrum lines (213.6 nm for Cu^+, 324.75 nm for Cu and 750.4 nm for Ar). For the arc discharge only emission, typical relative standard deviations (RSD) are in ranges 50-70 % for Cu^+ and 25…30 % for Cu with good correlation of their variations. For the hollow cathode discharge only emission, RSD is 60…90 % for Cu and 15…20 % for Ar without correlation between them (at that Cu^+ emission is hardly distinguished from noise). These results, as well as wide Cu line intensity histogram, give evidence to evaporation process of Cu microdroplets in the hollow cathode discharge plasma.

The work is partly supported by the STCU-NASU Grant N 6059 and grant of NAS of Ukraine N Pl-16-32.

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7-05

THE MAGNETOPLASMA SEPARATION METHOD OF SPENT NUCLEAR FUEL

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At present the recycling of nuclear fuel (NF), i.e. its reuse, is implemented by using PUREX-process. However, it leads to increase of liquid radioactive waste (RW) volume, while the alternative methods of physical reprocessing, in particular plasma ones, do not require chemical reagents but use only electrical power. Currently, researches on plasma reprocessing of spent nuclear fuel (SNF) are carried out in the United States, Russia and Ukraine. In NSC "KIPT" it is offered the magnetoplasma reprocessing of SNF, which includes three stages (heating, ionization, magnetoplasma separation in rotating plasma), on which fission products (FP) are consistently separated from NF. Herewith the simulation of SNF separation should carry out in a multicomponent molecular medium. Calculated trajectories of ions with different masses, coinciding with experiment conditions and indicating the possibility of mixture separation, are obtained. Experiments for plasma Ar, N_2, CO_2, simulating spent nuclear fuel, upon combination of pulsed discharge with a stationary one with incandescent cathode are carried out. The oscillograms of discharge current and voltage at low emission currents and constant energy input show that energy is spent for other processes different from ionization. With an increase of emission current the nonlinear character of the discharge current and voltage, which may be indicative of the role of dissociation and vibrational levels in energy consumption, is observed.

7-06

MACROPARTICLES IN BEAM-PLASMA SYSTEMS

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The dynamics and phase states of the macroparticles (MPs) in beam-plasma systems are reviewed. The plasma in vacuum arc spots is always accompanied by a production of MPs. The presence of MPs in the form of micrometer-sized molten droplets of cathode material limits technical application of such plasma. The significant MP fraction in the plasma flow worsens the coating parameters and it is the critical problem of vacuum arc deposition [1]. The removal of MPs is typically done by guiding the plasma through magnetic filters in order to spatially separate plasma and MPs [2]. There are a number of ways by which this has been approached. Since the duct efficiencies are in general low, alternative approaches of obtaining clean vacuum arc plasmas are needed. The methods such as electron beam bombardment, negative substrate biasing, steering magnetic field seem to be most promising.

The charging of MP in the gaseous plasmas has been well studied [3]. The MPs are charged by the collection of the plasma particles flowing onto their surfaces. Because of the high thermal velocity of the electrons compared to the ions, MPs are negatively charged. Besides, the charge of the MP fluctuates around its mean charge because the currents collected from the plasma consist of discrete charges arriving at the particle at random intervals [4]. For beam-plasma systems, in addition to collecting thermal plasma particles, MPs are subjected to fluxes of energetic particles, which release the secondary electrons. If electron emission is large enough, the MP can be positively charged [5]. It can be useful for plasma processing, since particles are confined in a discharge only if they have a negative charge. Charge and energy transfers from the plasma particles and energetic particles to MPs are investigated. The energy and current balances of a MP are considered taking into account secondary electron emission caused by electron and ion impact. Both charging of MP in the plasma bulk and vacuum arc sheath are analyzed. The sheath model has been combined with the charging orbital motion limited theory in order to determine the interaction of the MP with the local potential and its subsequent effect on the dynamics of the MP. It was shown that MP traveling in the vacuum arc sheath acquires a charge which depends on the potential distribution, in contrast to MP charging in the quasineutral plasma. The random fluctuation around its mean charge is obtained. The drawing phase spaces of MPs show fraction of MPs which pass through the sheath and reach the substrate.

The results reported here are quite general and can be applied to the control of the MPs in plasma processing like plasma deposition.

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7-07

ROTATING GLIDING DISCHARGE SUBMERGED IN LIQUID

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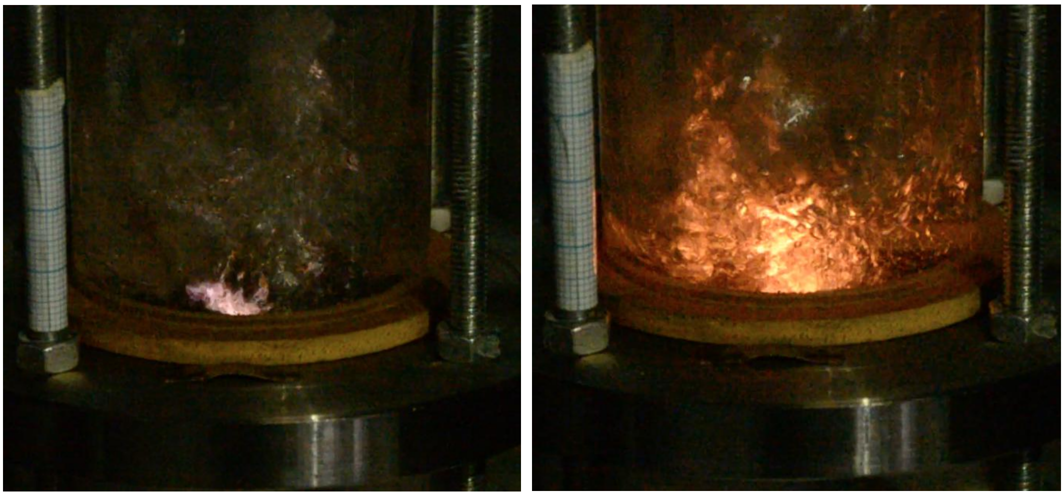
In the last years considerable attention has been given to the development of alternative approaches (plasma-chemical, chemistry, supercritical fluids, biological) and complex (plasma-catalytic, activation of plasma chemical processes) to create new technologies of gasification of different hydrocarbons – from fossil (coal, oil) to household waste. Particular interest presents a combination of traditional chemical technology with nonequilibrium plasma-chemical technologies. But the synthesis of synthetic liquid fuels from renewable hydrocarbons through synthesis gas practically not investigated, although his perspective, from the standpoint of environmental safety, is evident. For Ukraine as a country with great agricultural potential this area is strategic interest. In terms of efficiency, an interesting new approach is to obtain high-quality liquid fuels from liquid-phase hydrocarbon materials in plasma-liquid systems, in which long-chain hydrocarbons are converted into short-chain and oxygen-containing hydrocarbons with a low time of ignition delay [1].

Plasma-liquid system with rotating gliding discharge submerged in liquid for obtains of high-quality liquid fuels from liquid-phase hydrocarbon materials were studied. Electrical characteristics of the system, optical emission of discharge, composition of liquid and gas-phase products were studied. Distilled water and ethanol were used as working liquids. Air and argon were used as working gas. Photo of discharge represented on Fig.



Rotating gliding discharge submerged in distillate. I = 160 mA, Air = 20 L/m

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7-08

FEATURES OF PLASMA FORMATION AT IONIZATION STAGE FOR MAGNETOPLASMA REPROCESSING

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Earlier, [1–3] has considered the possibility of reprocessing of spent nuclear fuel (SNF) from fission products (FP) by means of three successive magnetoplasma reprocessing stages: heating, ionization and plasma rotating in crossed fields.In this paper the possibility of SNF treatment from PD in the ionization stage was evaluated. In view of the lack literature data on the cross sections of ionization and charge exchange of lanthanide oxides and oxides of nuclear fuel (NF), which will remain in the spent fuel after the heating step, carried out an extrapolation for the sought values of derivative values of the cross sections of ionization of alkaline-earth metals: Na, K and Li. These curves are close to the calculated curves for respective oxides, built by Thomson formula. With the help the obtained data carried out a rough calculation to create a plasma of oxides of the lanthanide and NF for a stationary process.

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7-09

THE CALCULATIONS OF TRAJECTORIES OF URANIUM AND LANTHANUM OXIDES AT MAGNETOPLASMA SEPARATION STAGE

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The physical principles of magnetoplasma method of spent nuclear fuel (SNF) separation, which consists of three successive stages: thermal heating, ionization and magnetoplasma separation in crossed ExH fields are investigated. The third stage, where mass separation occurs, is considered in detail. Trajectories of charged particles remained in SNF after thermal heating and ionization stages are calculated. Nuclear fuel (UO_2) is separated from certain fission products (with masses 106 a.m.u. and 160 a.m.u.) due to difference of these particles trajectories (particle with smaller mass moves along smaller radius trajectory than particle with greater one). The complication is lanthanide compounds such as La_2O_3 due to the fact that mass of this compound (324 a.m.u.) exceeds UO_2 mass (270 a.m.u.). The possibilities of UO_2 separation from La_2O_3 by changes in magnetic and electric fields components are investigated. There is additional segment of uniform magnetic field with induction 20, 40 and 60% greater than uniform magnetic field induction in axial distribution of magnetic field. Also the length of this segment is varied. The calculations show that these changes in distribution of magnetic field induction do not allow to separate effectively nuclear fuel from complex compounds such as La_2O_3.

The alternative variant of nuclear fuel separation from lanthanides is the addition of variable component to constant radial electric field. The amplitude and frequency of variable component are varied. Frequency was associated with the cyclotron frequency of UO_2 and La_2O_3. Calculations show that the addition of variable component with amplitude $0.6E_r$ and frequency equal to half of UO_2 cyclotron frequency to constant radial electric field leads to movement of UO_2 along trajectory with greater radius compared with La_2O_3. Thus it is possible to separate nuclear fuel from lanthanide complex compounds at magnetoplasma separation stage.

7-10

INFLUENCE OF NEGATIVE IONS ON ATOMIC OXYGEN PRODUCTION IN A HOLOW CATHODE DISCHARGE IN O_2/Ar MIXTURE

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Due to the large volume of plasma discharges with the hollow cathode is widely used for the generation of active species, especially atomic oxygen. One of the disadvantages of such discharges is a relatively low electron temperature. To increase the electron temperature and hence the production of the active particles, an addition of noble gases to the working mixture is commonly used. In this paper we investigated mechanisms of atomic oxygen production in the discharge with the hollow cathode and show that negative oxygen ions have great role in these processes under given conditions.

To determine the concentrations of the particles in the discharge chamber the kinetic model was developed. This model includes about 130 elementary reactions with the participation of 18 components. The rate constants of plasma-chemical reactions involving electrons were determined on the basis of the electron energy distribution function (EDF), which was taken from the solution of the Boltzmann equation.

It was found that the dependence of the atomic oxygen concentration on the argon percentage content in the plasma-forming mixture has a substantially non-monotonic character. The maximum amount of the atomic oxygen is in the case of pure oxygen and the concentration decreases with addition of the argon to the discharge. But after the argon fraction increases up to approximately 50% the atomic oxygen concentration in the discharge begins to increase and reaches a maximum at 80...90% of argon. This behavior is due to the different atomic oxygen production reactions are dominated at different oxygen concentration in the discharge. The main source of the atomic oxygen in most cases is reaction of dissociation: $O_2 + e \rightarrow O + O + e$. In our case its output has little change with the oxygen concentration variation. This is explained by the fact that with the increasing of the oxygen concentration simultaneously decrease the reaction rate constant due to the change of the EDF.

As a result of the low electron temperature in the discharge with the hollow cathode there are favorable conditions for the formation and preservation of negative ions O_2^-. As far as the concentrations of both positive and negative oxygen ions are linearly dependent on the content of neutral oxygen in the discharge, the rate of recombination has a quadratic dependence, and therefore, at high concentration of molecular oxygen reaction of recombination $O_2^+ + O_2^- \rightarrow O_2 + O + O$ gives the greatest income of the atomic oxygen.

Reducing of the oxygen content in the mixture leads to increase of high-energy electrons, which in turn results in one hand growth of concentrations of excited metastable oxygen levels ($O_2(a^1, \Delta_g)$, $O_2(b^1, \Sigma_i^-)$ and al.), and on the other hand to increase of rate constants of their dissociation. Thus, at the low oxygen concentration, the main mechanism of the atomic oxygen formation is the stepped dissociation. The combination of these three mechanisms explains the nonmonotonic dependence of the concentration of atomic oxygen on the composition of the working mixture. The shape of this dependence is in good agreement with experiment.

7-11

ATMOSPHERIC PRESSURE SECONDARY MICRODISCHARGE SYSTEM WITH VORTEX GAS FLOW

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This work presents atmospheric pressure plasma-liquid secondary discharge system with low power DC microjet in vortex gas flow (as the primary discharge). The photo of working system is shown in Fig.

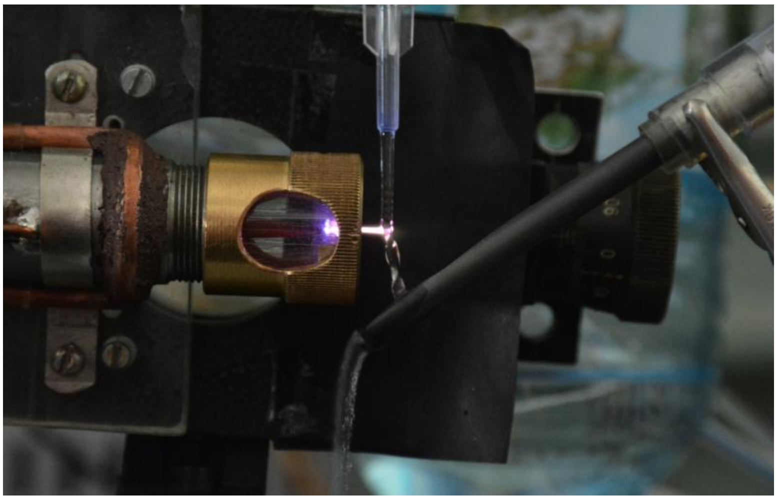

Photo of the atmospheric pressure secondary microdischarge plasma-liquid system with vortex gas flow

The system contains two electrodes: internal high-voltage electrode and external/grounded electrode (external copper enclosure with quartz glass). The internal high-voltage electrode was copper wire (d ~ 3.5 mm) with rounded cone-shape ending (d ~ 0.5 mm and high ~ 13.0 mm). The jet was blown over from the primary microdischarge system through the outlet (d = 1.0 mm) in grounded electrode by the vortex gas flow. The working gas was fed through the input channel tangentially to the internal dielectric (quartz cylinder) wall, thus forming a reverse vortex flow in dielectric camber. Plasma jet can rotate under the influence of the gas flow, gliding over the surface of the grounded electrode. Either air, N_2, Ar or CO_2 were used as the working gases. The primary microdischarge system can work horizontally, vertically or any other position/angle.

The third electrode was working liquid. This secondary microdischarge plasma-liquid system can be used for treatment of liquids with different conductivity. The studied secondary microdischarge system could be used for various applications as, for example, pollutants destruction, wastewater sterilization or nanoparticle synthesis in case of treatment of noble metal solutions [1]. The plasma-liquid system was diagnosed using current-voltage characteristics, photo registration, electron energy distribution functions and emission spectroscopy methods. Treated liquid was diagnosed also. The relation between nanomaterials production and plasma properties will be presented and briefly discussed.

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7-12

SPATIAL DISTRIBUTION OF CONTINUUM RADIATION FROM PLASMA OF PLANAR CAPACITIVE RF DISCHARGE IN ARGON AT 1 ATM PRESSURE: PHOTOMETRIC STUDY

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In the past decade atmospheric pressure discharges with non-thermal plasma attract increasing attention from viewpoint of their technological applications. Such discharges have the following advantages: 1) devices on their basis do not require expensive vacuum equipment; 2) specific power introduced to such discharges can reach hundreds W/cm^3. It enables plasma generation with concentration of active species several orders of magnitude higher than that in case of low pressure plasma.

In spite of wide enough variety of types of atmospheric pressure discharges, use of planar capacitive radio-frequency (RF) discharges is the most optimum choice for technological applications, particularly, for treatment of large square surfaces. Advantages of such discharge type are low ignition voltage and ability to create dense uniform plasma in relatively large volume.

It should be noted, however, that up to now physical processes occurring in low-temperature plasma of atmospheric pressure discharges remain not fully understood. An essential reason for that is complexity of measurements of the most critical plasma parameters, first of all, electron density n_e and temperature T_e. One of the most attractive, from viewpoint of simplicity, methods of determining n_e and T_e spatial distributions is neutral bremsstrahlung based one. Neutral bremsstrahlung is the main source of continuum radiation from the plasma of non-thermal atmospheric pressure discharges in wavelength range ≈ 450…650 nm with intensity

$$\varepsilon_{ea} \propto \frac{n_e n_a}{\lambda^2 T_e^{3/2}},$$

where λ is radiation wavelength.

However, use of this approach in case of spatially extended planar RF discharges encounters a number of obstacles. In particular, preliminary researches have shown that, even in case of the discharge glow in γ mode as a whole, local areas in the discharge gap exist with spatial distribution of radiation intensity inherent to α mode. Thus, at determining correlation between the discharge glow modes and spatial distributions of n_e and T_e one should take this fact into consideration.

Due to that, the first stage of our work was devoted to determining spatial distribution of continuum radiation integral intensity in wavelength range ≈ 480…580 nm by means of photo camera Canon EOS 350 D. For that purpose, RAW data arrays from the camera sensor were used. Dependencies of spatial distributions of radiation from the discharge gap with one pixel resolution (≈ 6.3 μm) were obtained, and tendencies of their variations were determined at gradual transition of RF discharge glow from low-current α mode to high-current γ one.

7-13

EFFECT OF ARGON CONTENT IN AR: O_2 MIXTURES ON O^-, O_2^- CONCENTRATIONS IN NEGATIVE GLOW PLASMA OF LOW PRESSURE DISCHARGE

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Discharges in oxygen are widely used in plasma technologies, particularly, for photoresist etching, modification of surface features of materials, deposition of thin oxide films, etc. Main role in these processes is performed by atomic oxygen. Instead of pure oxygen, $Ar+O_2$ mixture is often used as working medium. Although it provides rate increase of the plasma-chemical reactions, mechanism of argon effect on the rate of oxygen formation is not completely clear for now. Preliminary numerical modeling has shown essential influence of negative oxygen ions on [O] formation rate in the discharge plasma on $Ar+O_2$ mixture.

The present work is devoted to experimental study of argon admixture effect on concentration of oxygen negative ions in the plasma of low pressure hollow cathode discharge. For determining concentrations of negative ions, method proposed in [1] was used, which is based on comparison of ratios of ion and electron saturation current values in pure argon plasma and those on $Ar+O_2$ mixtures.

It is determined that concentration of negative ions possesses non-monotonous dependence on gas mixture content $[Ar]/([Ar]+[O_2])$. As well, dependencies of plasma electron density and mean electron energy values on argon fraction in the mixture are obtained.

Comparison of experimental data with calculation results is carried out.

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7-14

MODELING DOPING EFFECTS ON THE CATALYST-ASSISTED GROWTH OF CARBON NANOTUBES IN REACTIVE PLASMA ENVIRONMENT AND THEIR CONSEQUENT FIELD EMISSION PROPERTIES

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Carbon nanotube (CNT) growth assisted by catalyst in a reactive plasma environment is realized through modeling. The model incorporates the effect of doping with heterogeneous atoms such as nitrogen and boron on the growth kinetics of CNT on catalyst-substrate surface. The different growth processes like adsorption, desorption, thermal dissociation and dehydrogenation, diffusion, and accretion among others are accounted in the present model. The result of the present study suggest that the nitrogen doping results in reduced growth rates of CNT whereas doping with boron enhances growth rates of CNT. The field emission characteristics of CNT have been proposed in the present study. The CNTs doped with nitrogen have greater field enhancement factor than those doped with boron. The results of the present study may find applications in field emission devices, vertical transistors, and field ionization devices among others.

7-15

ION MOTION IN CROSSED FIELDS AND SEPARATION MECHANISM IN "ARCHIMEDES PLASMA MASS FILTER"

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"Archimedes Plasma Mass Filter" (APMF) [1] was suggested, constructed and explored to solve a problem of nuclear waste processing. The authors [2] stated that APMF allows to separate light mass component of a waste (low level radioactive) from heavy one (high level radioactive) in a single-pass. They reported [2] about high throughput of APMF. Designs of plants on nuclear waste processing [3] with APMF as the separating unit were considered. The possibility of APMF utilization for the solution of a similar problem – reprocessing of spent nuclear fuel – was also discussed [3–5].

It seems, that separation process of light mass ions and heavy ones takes place in APMF not quite how it is declared by its developers [1, 2]. Not all light mass ions produced in a volume of plasma in crossed fields, are confined in plasma and as a result get on a face collector. The light mass ions produced on periphery of plasma, under the action of positive radial electric field, should fall outside plasma and get on a radial collector together with heavy ions. This should lead to essential decrease (in times) of a separation degree. In present report this factor is studied.

The general solution of a problem about the ion motion in crossed fields is analyzed in the report within the whole range of electric field strengths. It is noticed that in a critical radial electric field $E_r = E_r^{cr}\ m_i\ \equiv m_i \omega_{ci}^2 r / 4e_i$, the general solution has the form distinct from the solution at other values of a field and the ion motion generally speaking is infinite on radius. The particular solution, that is finite on radius, is possible. It describes the ion rotation on an azimuth with frequency $-\omega_{ci}/2$. This solution is called "Brillouin's regime" [6].

Trajectories of ions produced in crossed fields due to ionization of neutrals (atoms, molecules) by electronic impact, as it occurs in APMF, are analyzed in the report. These ions are supposed to be produced in a state of rest. It is shown that for such ions the Brillouin's regime of rotation in the critical radial electric field is unrealized. The ion motion is infinite on radius.

The condition of confinement of ions in a volume of plasma cylinder in the positive radial electric field $0 < E_r < E_r^{cr}$ is determined. The ion production radius r_0 should be less than the confinement radius b_i. The ions, produced on larger radii $r_0 > b_i$, fall outside the plasma radius and get on a radial collector together with heavy ions.

Expressions for ion currents from plasma on radius (on a radial collector) and along a device's axis (on face collectors) are derived for a single-pass through APMF and for the second pass through the filter of the substance which have settled after the first pass on a radial collector. The conclusion is made about the impossibility of the total separation of light mass and heavy mass components of a waste in a single-pass in APMF.

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7-16

EFFECT OF COLD PLASMA ON THE CHARACTERISTICS OF DPPC LIPOSOMES

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Recent progress in atmospheric plasmas has led to the creation of cold non-thermal atmospheric plasma (CAP). CAP is an ionized gas that has tremendous applications in biomedical engineering and is used as a possible therapy in dentistry and oncology. The aim of plasma interaction with tissue is not to denature the tissue, but rather to operate below the threshold of thermal damage and to induce chemically specific response or modification. Liposomes are used as models for artificial cells. This report therefore investigates the effect of cold plasma on 2-dipalmitoyl-sn-glycero-3-phosphocholine (DPPC) liposomes prepared by thin film hydration method which are used as a model for lipid bilayer membrane. DPPC liposomes were exposed to cold plasma 2, 3 and 5 minutes, respectively. The effect of cold plasma on DPPC characterization parameters such as size, charge, FTIR absorption spectrum, UV spectrum and phase transition temperature were investigated. The present study revealed that CAP could alter the molecular structure for DPPC liposomes as depicted in the change in the FTIR absorption peaks at 3439 and 1687 cm^{-1}. In addition, CAP affected the phase transitions for the DPPC by shifting it to higher temperatures. Moreover, CAP led to the increase of DPPC liposome size. 2 min exposure to CAP resulted in rapid coagulation of liposomes as depicted from the low zeta potential value obtained. However, the UV absorption spectrum for DPPC liposomes was not altered by CAP exposure. Hence, this work highlighted that CAP may modify the physical and chemical characteristics of DPPC liposomes.

7-17

FEATURES OF COATINGS DEPOSITION IN COMBINED STATIONARY-PULSED OPERATION MODE OF THE MAGNETRON SPUTTERING SYSTEM

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The paper presents the results of studies of the combined stationary-pulsed operation mode of the longitudinal planar magnetron sputtering system (MSS) with magnetically insulated anode with an additional high-current high-voltage pulse power supply [1, 2].

Deposition of copper coatings on slides during the 90 *s* of burning of permanent magnetron discharge with parameters U_p = 375 V, I_p = 0,5 A under pressure of Argon $p = 7\cdot10^{-3}$ Torr was carried out in the experiment. Single voltage pulse had the value of U_{imp} = 1,1 kV and the duration of τ_{pulse} = 1, 2, 3, 4 or 5 ms. It was applied between cathode and anode of MSS during stationary voltage of burning of magnetron discharge. The discharge current under high-voltage pulse reached the value of I_{pulse} =6…7 A and exponentially decreased while pulse was going on. Simultaneously oscillogramme of floating potential of insulated substrate holder was measured. Identification of the mass-transfer efficiency of copper was made by balancing of slides with deposited coating on the analytical scales.

Experimental results showed that at the initial moment of voltage pulse the substrate holder had been charging up to U_{sub} = +20…30 V. After 200 … 300 μs the substrate holder potential became negative ($U_{sub} \approx -10$ V) and had such a value during the pulse of voltage. Average current of the pulse ($\bar{I}_{pulse}(A)$) and a mass stream of deposited copper ($j(g\cdot s^{-1}\cdot \text{cm}^{-2})$) with the increasing of the duration of the impulse from τ_{pulse} = 1 ms to τ_{pulse} = 5 ms decreased at about 5 times. Whereas value mass-transfer ($\rho(g\cdot\text{cm}^{-2})$) with the increasing of the pulse duration at first rose and reached maximum value at τ_{pulse} = 3 ms and then decreased.

To sum up, under combined stationary-pulsed operation mode of the MSS the processes of deposition and sputtering by working gas ions of coating occurred simultaneously. With the increasing of the pulse duration the intensity of sputtering rises.

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7-18

INVESTIGATIONS OF THERMAL PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN COMPOSITE Ag-C ELECTRODES

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Composite materials on silver base are widely used for contacts and electrodes in switching devices for the electrical engineering industry. Mass transfer of electrode’s materials inside discharge gap determines exploitation efficiency of switching devices. The amount of metal vapours in a discharge gap affected by mutual interaction between electrode’s material and electric arc plasma, which appeared during switching. Therefore, investigations of such plasma can be useful for optimization of new composite materials, their composition and fabricating technologies.

Investigations of electric arc plasma between composite electrodes usually are performed by optical emission and absorption spectroscopy. Because of the discharge spatial and temporal instability, the method of the single tomographic recording of the spectral line emission was used. A spectral device with 3000-pixel CCD linear image sensor (B/W) Sony ILX526A accomplished fast scanning of spatial distribution of radial intensity.

The arc was ignited between non-cooled electrodes in air atmosphere. The discharge gap was of 8 mm, arc current – 3.5 and 30 A. The pulsing high current mode was used to avoid metal droplet appearing: the current pulse 30 A was put on the "duty" low-current (3.5 A) discharge. The pulse duration ranged up to 30 ms. This paper deals with results of experimental spectroscopic investigations of plasma of electric arc discharge between composite Ag-C electrodes. Temperature distribution was measured by Boltzmann plot method using spectral lines of Ag I: 405.5, 447.7, 466.8, 520.9, 768.8 and 827.4 nm.

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7-19

INVESTIGATIONS ON THE PARAMETERS OF MULTICOMPONENT GAS-METAL PLASMA FORMED IN THE MIXED MOLECULAR GASES

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The plasma generated in the reflex discharge takes place in the crossed electrical (**E**) field and magnetic (**B**) field where the electron- and ion-plasma components are rotating. So, the reflex discharge is one of the expected variants for the development of devices with the rotating plasma [1]. The use of the devices with the rotating plasma for solving the problems of material separation into the mass groups and elements [2] is one of the purposes to investigate this plasma.

Previously, for example in [3, 4], experiments were carried out to investigate the multicomponent plasma generated by the pulsed reflex discharge in the working material medium containing the gas component (H_2, Ar, 88,9%Kr-7%Xe-4%N_2-0,1%O_2) and the metallic component coming into the discharge due to the Ti cathode material sputtering.

The present paper reports the results of the experimental investigation on the multicomponent gas-metal plasma formed in the working material medium containing molecular gases, e.g. nitrogen and oxygen and Ti metal component. The multicomponent gas-metal plasma was investigated by the microwave methods of plasma diagnostics, namely, by the microwave interferometry method and by the microwave signal cutoff. These methods were used to measure the average plasma density as a function of time, the microwave signal cutoff duration (lifetime of the plasma density of $N \geq N_{cr.} = 1.7 \cdot 10^{13}$ cm^{-3}), and the average plasma density lifetime within the range of $10^{12} \ldots 1 \cdot 10^{13}$ cm^{-3}. To measure the discharge current value and its time a Rogowski loop was applied.

The elemental and charge composition of the plasma was determined by the passive contactless method of optical emission plasma spectroscopy. The linear plasma spectrum record was carried out in the spectral range from 214 to 673 nm. In the spectrum of the emission from the reflex discharge plasma we have observed the lines of: excited Ti II ions (cathode material); molecular N_2 and N_2^+ (igniting gas); excited H atoms; excited C II ions; OH and CH radicals (products of H_2O, CH_y, C_xH_y dissociation), cyanogen CN radical (results of plasma-chemical reactions). Also there are the lines in the spectrum which can be referred to the TiN lines, though in this case it is difficult to identify them as TiN lines. After the discharge pulses were conducted, the vacuum chamber surface obtained a golden color characteristic for TiN coatings.

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7-20

TRIBOLOGICAL PROPERTIES OF VACUUM ARC Cr-O-N COATINGS IN MACRO- AND MICROSCALE

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The wear of the tool, particularly premature failure is a serious technical and economical problem. The solution to this would be to modify the tool surface by deposition of a thin hard coating. Such treatment greatly improves the mechanical and especially tribological properties of the tool. The application of transition metal nitrides can significantly improve their durability. Due to the good tribological and mechanical properties: high hardness and adhesion to the steel substrate, low coefficient of friction and excellent wear and corrosion resistance transition metal nitrides deposited by PVD methods are used in industry as protective coatings. Users requirements often exceed the possibilities of their use caused by the properties of a two-component coatings. Two-element systems not always can fulfill all requirements of users. Due to it two-element systems are extended into three or more element systems to increase hardness, thermal stability, wear and corrosion resistance.

Cr-O-N coatings are interesting as protective coatings because of their resistance to oxidation and wear, but also due to photo-thermal conversion of solar energy as a solar selective coating of the absorber, or as a decorative coatings because of their different colors. The main topic of interest was the structure and morphology of coatings and their mechanical and tribological properties was not a major subject of investigations.

Friction and wear are the main characteristics of coatings resistant to abrasion. The investigations of the properties of thin coatings with a thickness of 1÷3 μm require correction to the relatively soft steel substrate. Here may be helpful the atomic force microscopy (AFM) method, who meets high requirements for testing the vacuum deposited thin films on polished steel substrates.

In this paper the tribological properties of Cr-O-N coatings deposited using vacuum arc plasma flux in macro- (sphere-on-disc test) and microscale (AFM – atomic force microscopy) are investigated. The Cr-O-N deposition process was performed by unfiltered vacuum arc plasma flux method using "Bulat" system. A deposition process was performed at parameters: substrate bias voltage of -150 V, arc current of 90 A, nitrogen pressure of 1.8 Pa. In case of Cr-O-N coatings gas mixture (N_2+O_2) with different relative oxygen concentrations $O_2(x) = O_2/(N_2+O_2)$ where x equals 0, 5, 20 and 50% were used. The deposition time was kept at 45 min in all cases to obtain about 7…8 μm thick coatings. It was found that: the hardness of Cr-O-N coatings increases and critical load Lc_2 decreases with relative oxygen concentration increase. Specific wear rate determined in AFM measurements (micro scale) is approximately 2 orders higher than the macroscale. This is probably due to much higher Hertzian contact stress.

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7-21

STRUCTURE AND PROPERTIES OF VACUUM ARC Cr-V-N AND CrN/VN COATINGS

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Hard protective coatings based on transition metal nitrides deposited by PVD techniques are widely used in various industrial applications because of their good chemical, mechanical and tribological characteristics. Chromium nitride (CrN) can form a hard, chemically inert, thin film coating which performs well in corrosive environments and in sliding wear applications. However, high coefficient of friction makes it difficult to use in some cases. Vanadium nitride (VN), a ceramic compound has high mechanical properties and low friction coefficient at elevated temperatures caused by the formation of surface oxide phases, so called Magne´li type oxides, which may act as selflubricants [1]. Therefore, combination of these metal nitrides in three-element or multilayer systems could provide coatings with improved wear resistant properties.

The objective of these studies is to determine the effect of vanadium nitride additives on the structure and mechanical properties of the chromium nitride coatings.

The Cr-V-N deposition process was performed by unfiltered vacuum arc plasma flux method using "Bulat" system from two opposite chromium and vanadium cathodes with planetary rotation on HS6-5-2 steel substrates. A deposition process was performed at nitrogen pressure of 1.8 Pa and substrate bias voltage of -150 V. The concentration of elements in CrV_xN coatings changed by varying the ratios of the currents of the cathodes. In the case of the deposition of multilayer coatings (bilayer period-600, 400, 200, 100 and 50 nm) arc currents of 70 A were equal to each cathode. The coatings thickness was ~3 μm in all cases.

It was found that: obtained coatings are stoichiometric nitrides with the nitrogen concentration ~ 49…50 at.%, the hardness of CrN coatings slightly increases with vanadium addition (19…28 at.%) from 20 to 22.5 GPa, for multilayer coatings maximum hardness ~ 30 GPa obtained for bilayer period of 200 nm and for pure VN hardness and Young's modulus are 35 and 500 GPa respectively. Also in the work the influence of the concentration of elements and the thickness of the bilayer on the surface roughness, adhesion, coefficient of friction and wear of coatings were investigated.

Acknowledgement

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7-22

HIGH-VOLTAGE GAS-DISCHARGE CURRENT LIMITER-INTERRUPTER USING HIGH-DENSITY GLOW DISCHARGE

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Gas filled discharge switches are widely used for high voltage pulse generation in pulse radiolocation techniques, for laser pumping and electromagnetic (including X-rays) radiation generation, in an electrophysical apparatus, technological facilities for material treatment, plasma-chemical systems and powerful ozone generators, due to their best relevant features. Extant devices, however, are not capable to resolve all actual problems of power pulse generation, so a development of new switches with enhanced features is required.

The most actual is improvement of gas discharge switches with full control, i.e. closing and opening devices. The opening devices are capable to interrupt electrical current with simultaneous sharp voltage rising up to high values and the most known devices of such a kind are the tacitron type thyratrons with a grid control. However, the usual tacitrons contain the hot cathode with well known demerits, therefore the development of tacitrons with a cold cathode is the vital problem. The cold cathode may provide long lifetime, high radiation resistance, low cost, etc. This work deals with development and investigation of the tacitron type cold cathode device which can not only interrupt the current but limit this current, too.

The device employs the hydrogen high density glow magnetron discharge (~ 1 A/cm^2) maintained within a cylindrical hollow cathode immersed in an axial magnetic field, generated with a permanent magnet. Two microstructured grids are placed between the open end of the hollow cathode and a flat main anode of the device. The first grid serves as an anode of the glow magnetron discharge. The second grid serves as control one for regulation of anode current. The hollow-cathode effect together with the axial magnetic field provides beautiful conditions for gas ionization by secondary cathode electrons and generation of dense discharge plasma. The plasma surface in the openings of the first grid serves as an electron emitter for the anode part of the device. The products of gas pressure p and gaps d between the grids and between the second grid and the anode are very small (d ~ several millimeters); that is corresponding to pd values at the left of the left branch of Paschen curve. Hence, the self-maintained discharged within the gaps is impossible (as in vacuum) and we have the combination of gas discharge part with vacuum one. However, some gas ion generation by electrons emitted through the first grid and ion compensation of electron space charge in the gap occur. This provides low electrical impedance of the gaps.

The given work considers some features of control over such cold cathode device with two grids under the high anode voltage (10…20 kV). There are three operation modes: thyratron, tacitron, and limiting current modes. In the first thyratron mode the device works only as a closing switch. In the second tacitron mode the device works as a closing/opening switch (therewith the anode current pulse duration is defined by the width of positive voltage pulse applied to the second grid), so the device works as a current interrupter. In the third mode device works as a closing/opening switch but additionally the value of anode current is set up by the second grid voltage, so the anode current value is regulated by the second grid voltage and the device works as a vacuum tube. In the last mode in the case of shortage of the anode load the current value was limited by our device. The limited current values were tens of amperes. Some guidelines on development of devices with enhanced time and energetic parameters are formulated.

7-23

SPECTROSCOPY OF ELECTRIC ARC DISCHARGE PLASMA WITH ADMIXTURES OF W, MO AND CR

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Composite materials on a base of copper with addition of refractory metals are widely used as electrode or contact materials in electric industry applications (e.g. relays, commutators, circuit breakers etc.). Plasma emission spectrum of electric arc discharge between such materials contains spectral lines of Cu (which are well studied) and refractory metals (W, Mo and Cr). So such plasma can be used as spectroscopic tool for analysis and selection of W I, Mo I and Cr I spectral lines and their spectroscopic data.

In order to apply diagnostic techniques of optical emission spectroscopy, first, it is required to select 'convenient' spectral lines for plasma analysis, which must meet following criteria: these lines are supposed to be isolated in the emission spectrum and to be intensive enough for their guaranteed registration. Moreover, the difference between excitation energies of their upper levels must be as large as possible, since it allows determining the temperature with minimal error.

Due to, the emission spectrum of copper is well studied, so one can use plasma of arc discharge between composite copper electrodes to carry out the selection of spectral lines and corresponding spectroscopic data of other elements, which are present in plasma. Boltzmann plot method was considered as a tool for selection of W I, Mo I and Cr I spectral lines and their spectroscopic data. When plasma is in local thermodynamic equilibrium (LTE), then the slopes of Boltzmann plot lines corresponding to each spectroscopic plasma component must be the same. This slope depends on the excitation temperature of thermal plasma. In such manner, values of oscillator strength for W I, Mo I and Cr I spectral lines, which are in the best correspondence with the slope determined by intensities of Cu I spectral lines in Boltzmann plot, can be chosen.

It should be noted that spectroscopic investigations of electric arc discharge plasma, which contains vapours of more than one chemical element, require accurate selection of spectral lines for diagnostics. Particularly, Mo I, W I and Cr I spectra contain the large number of closely-spaced spectral lines with commeasurable intensities. In case of spectral device with low resolution capability, such lines can be registered as one non-separated line.
Such problem can be solved by accurate account of each component's contribution into the total intensity of non-separated spectral line, or by application of device with high spectral resolution for investigation of spectral lines' profiles, for instance, device for preliminary monochromatization with cross dispersion.

7-24

NORMAL MODE OF DC DISCHARGE IN ARGON, HYDROGEN AND OXYGEN

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Direct current glow discharges are widely applied in dc diode sputtering systems, gas discharge lasers, surge protectors/transient voltage surge suppressors. A number of papers talk on the opportunity to apply the glow discharge for isotope separation. The dc glow discharge can also be used for plasma sterilization of medical tools and equipment. Plasma nitration of iron-based alloys is one of the most important technological processes employing the dc glow discharge.

The dc glow discharge may exist in two different modes. In the normal mode the discharge spot occupies only a part of the cathode surface, and the current increase is accompanied by the growth of the area the discharge covers on the cathode. It is assumed conventionally that the ratio of the current density to the gas pressure squared j/p^2 and the voltage across the current sheath remain constant in the normal mode. When the plasma covers the total surface of the cathode the discharge experiences a transition to the abnormal mode in which the current and voltage increase simultaneously.

However, in papers [1, 2] it has been shown that the similarity parameter j/p^2 experiences weak changes only at sufficiently high gas pressure, but lowering the pressure involves a remarkable j/p^2 growth. Note that these data have been obtained for nitrogen [1] and N_2O [2]. It is of interest to study the j/p^2 behavior in other gases at low as well as higher pressure.

This paper reports the current-voltage characteristics and the j/p^2 similarity parameters determined in argon, hydrogen and oxygen in the pressure range from 0.1 to 10 Torr. Experiments have been performed in the discharge tube of 56 mm inner diameter and with stainless steel electrodes. Anode diameter was 55 mm whereas the diameters of the cathodes employed were 55 mm and 12 mm. The j/p^2 parameter has been shown to remain constant only at the gas pressure above 1 Torr. Its values comprise $j/p^2 = 0.1 \pm 0.02$ mA/(cm^2 Torr^2) for argon, $j/p^2 = 0.07 \pm 0.02$ mA/(cm^2 Torr^2) for hydrogen and $j/p^2 = 0.35 \pm 0.05$ mA/(cm^2 Torr^2) for oxygen. On lowering the pressure (below 1 Torr) the j/p^2 parameter grows fast and at the pressure of 0.1 Torr it may be two orders of magnitude higher than one at 1 Torr. One may attribute such behavior of the similarity parameter j/p^2 to the escape of charged particles out of the normal mode plasma column due to ambipolar diffusion. The ambipolar diffusion coefficient is inversely proportional to the gas pressure. Therefore at low pressure the ambipolar escape of charged particles is high, and to sustain the stationary discharge burning the voltage across electrodes and current density grow. At large pressure the diffusion loss decreases, the similarity parameter j/p^2 saturates and it depends on pressure no longer.

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7-25

CHILD-LANGMUIR LAW FOR CATHODE SHEATH OF GLOW DISCHARGE IN CO_2

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Direct current glow discharge in CO_2 is widely applied for pumping carbon dioxide-based gas discharge lasers. In recent years a growing attention is devoted to plasma conversion of hotbed gases of which carbon oxide is dominant (its presence in Earth's atmosphere is the most important for ambient medium) to the compounds such as methanol (CH_3OH) or synthesis gas (CO/H_2). They are of interest to chemical industry or they may be used as a fuel for internal combustion engines. As the cathode sheath is the most important portion of the direct current glow discharge, one has to study its characteristics in CO_2 to optimize plasma technology and devices.

This paper reports the simultaneous measurements of current-voltage characteristics and cathode sheath thickness of the glow discharge in carbon dioxide in the wide range of pressure and discharge current values. The aim has been to clarify which of the Child-Langmuir law versions (collision-free one or one of two collision-related versions – with the constant mean free path or the constant mobility of positive ions) may be applied for the cathode sheath description in carbon dioxide. Experiments have been performed in short tubes in which the discharge consists only of the cathode sheath and a small portion of the negative glow. Therefore the voltage drop across the cathode sheath has been approximately equal to the potential difference between the electrodes this difference being easy to register. We have revealed that in the total range of discharge conditions we studied (in the pressure range from 0.05 to 1 Torr and with the discharge current values up to 80 mA) the cathode sheath characteristics obey only the Child-Langmuir law version with the constant ion mobility.

The cause of this phenomenon may be associated with a substantial conversion of carbon dioxide molecules in the cathode sheath and the negative glow. It is supported with optical spectrum of radiation we have measured in glow discharge in CO_2. We have demonstrated that the atomic oxygen radiation line OI 777 nm is the most intense line (in the range between 400 and 1000 nm) near the cathode surface. Its intensity is tens of times higher than the line intensities of carbon monoxide, carbon dioxide and those of their ions, but it is decreasing fast when we move away from the cathode. In the negative glow the line intensities of different atoms, molecules and ions are comparable in value. Probably the O^+-ion rather than the CO_2^+-ion (as is usually assumed) is the dominating positive ion in the cathode sheath, and the charge exchange between O^+-ions and CO_2 and CO molecules may be impeded. In this case O^+-ions will move through the cathode sheath with the constant mobility (but not with the constant mean free path what might occur when the resonant exchange happens to affect the ion motion substantially).

7-26

FORMING A UNIPOLAR PULSED DISCHARGE IN NITROGEN

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At present pulsed gas discharge devices are widely applied in most diverse branches of science and technology – as light sources, in lasers, electron erosion machines, welding apparatuses, plasma display panels, as well as during plasma nitration, reactive magnetron coating etc. Many devices are now operating in a pulsed mode – plasma chemistry reactors, MHD-transformers, plasma injectors and accelerators. But presently medium-frequency discharges are studied much less than radiofrequency or direct current discharges what impedes the progress in this area substantially. Therefore the processes taking part in forming a unipolar pulsed discharge of low pressure have been the subject of this paper.

We have studied current and voltage oscillograms of the pulsed discharge in nitrogen within the frequency range from 20 to 300 kHz, the duty cycle has been from 0.15 to 0.85 for two pressure values of 0.1 and 1 Torr. We have found that the current oscillograms of the glow pulsed discharge possess a plasma phase and an afterglow phase.

We have observed the following stages of the plasma phase: 1. A pulse of the capacitive current with the duration of 0.5…1 msec; 2. A stage of current growth which duration depends on the gas species, the plasma phase duration and the pressure; 3. A stage of current decrease with the duration of tens microseconds to the level corresponding to the discharge with the constant voltage. The first stage is the same for all pressure values – this is the pulse of the capacitive current. Duration of this period is the same - about 0.5 μsec, it is related to the period of voltage growth at the cathode to its maximum value. This current pulse approaches (20…30) mA (at the nitrogen pressure of 0.1 Torr with the duty cycle of 0.5 and the applied voltage of 700 V). A current growth accompanying the discharge formation takes place at the second stage. At the indicated nitrogen pressure value the duration of the second stage amounts to about 0.2 μsec. At the third stage of the plasma phase formation we observe the decrease of the discharge current in time with moderate oscillations, and the current practically approaches saturation at the value of 10 mA.

Probably, the charged particles having left from the preceding plasma phase play a considerable role at the initial time period of the discharge formation. During the afterglow phase they fill the cathode and anode sheaths due to ambipolar diffusion, the sheaths possessing very low concentrations of electrons and ions. At the start of the subsequent voltage pulse ions and electrons escape quickly into the cathode and anode, respectively, what leads to the discharge current increase at the first and second stages. Perhaps, after the completion of the second stage, the charged particles which have arrived to the electrodes after the afterglow are lost at their surface, and the cathode and anode sheaths formed as a result are depleted of charged particles thus leading to the decrease of the discharge current during the third time period.

7-27

POSITIVE COLUMN CONTRACTION OF THE GLOW DISCHARGE IN NITROGEN

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The positive column of the glow discharge may exist not only in the stratified and uniform modes but also in a contracted one. Contraction is a plasma column transformation into a filament under conditions of the pressure increase and current growth. Conventionally the contracted mode is observed at high gas pressure (order of 100 Torr and above) and for considerable discharge current values (hundreds milliamps). On one hand, the discharge filamentation leads to the disruption of laser generation limiting from above the power introduced into the active medium. On another hand, separating the discharge from the tube walls in the devices for spectral analysis of gas mixtures enables one to reduce the introduction of impurities into the plasma. Therefore the processes in the contracted positive column require additional studies. As the phenomenon of contraction has been studied conventionally at high gas pressure, it seems expedient to find the threshold pressure and discharge current values characteristic for its onset.

This paper clarifies the dynamics of plasma parameters changes in the positive column depending on the discharge current and gas pressure variation during the transition from the uniform (diffuse) mode to the contracted one. At low pressure the positive column in the diffuse mode shines rather brightly even at low discharge current values but it becomes dark at the pressure values above 1 Torr. At the pressure of 0.5 Torr the reduced electric field decreases uniformly on the average with the current growing. But already at the pressure of 0.6 Torr with low current values before the discharge extinction the reduced electric field E/p experiences an abrupt decrease, it approaches the maximum with the current increasing and then it lowers. Such a E/p behavior remains at higher nitrogen pressure values (up to 1.5 Torr), i.e. the reduced electric field E/p remains to be invariably small at low current values and with the pressure growing it becomes lower. Starting with the nitrogen pressure value of 1.5 Torr, one observes not only the diffuse mode but also the contracted one. The weak current mode existing before the discharge extinction is transformed into the diffuse mode with high E/p values. During the discharge transition from the diffuse mode to the contracted one a filament of the contracted positive column develops starting from the anode to the cathode side. The filament occupies only a portion of the tube cross section and it is accompanied with the voltage increase across the electrodes and even a moderate decrease of the discharge current in the case of wide gaps. After the contracted positive column achieves its maximum length for the given pressure value, one observes the subsequent increase of the discharge current on lowering the voltage across the electrodes. The current-voltage characteristic assumes a negative tilt, i.e. it becomes a falling one.

The electron temperature T_e demonstrates a similar dynamics with the growth of the current and gas pressure. At low current and moderate pressure values the T_e quantity is small but with the current growing it increases, achieves a maximum and then decreases. At the pressure values above 1.5Torr one observes separately the diffuse (with the low T_e) and the contracted (with the high T_e) modes with a step-like transition between them. Note that in a brightly shining contracted mode the electron temperature is approximately 1.5…2 times higher than in the diffuse dark positive column.

7-28

STUDY A HALF LIFE OF OZONE IN THE ORGANIC IMPURITIES IN CHANGE OF TEMPERATURE AND HUMIDITY

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Paper presents the method of measurement of half-life of ozone τ (h) in air with impurities of ammonia, carbon dioxide and other pollutants.

This method allows simulating the conditions of ozone generation during sanitizing of farms. The decay of ozone is corrected in depending on temperature and humidity. The generation of ozone was performed in the closed volume of 0.125 m^3 by ozonizer based on dielectric barrier discharge [1, 2]. Measuring of concentration of ozone in the volume of the chamber and its output was controlled by automated meter spectrometer and ozone meter, respectively. Measuring of concentration of organic contaminants was fulfilled by means a gas analyzer "Dozor–C–P_V". The results of measuring of half-life period of ozone are obtained at temperatures in the volume of the chamber at 10, 24 and 40 ^{0}C and humidity – φ ~ 10, 50, 80%.

For chamber filled by air, the half-life of ozone has decreased by 23% with increasing of temperature from 10 to 24 ^{0}C. Further a rise of temperature from 24 to 40 ^{0}C leads to reduction of half-life on 30%. In the presence of ammonia vapor and at growth of temperature from 10 to 40 ^{0}C, the half-life of ozone decreased by 40% at humidity of 10%. At conditions minted above, the half-life of ozone is reduced on 50 and 59% at a humidity of 50 and 80 %, respectively.

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7-29

ACOUSTIC METER OF OZONE CONCENTRATION

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The paper describes an acoustic measuring ozone concentration at the outlet of the compressor of ozonizer type [1–4].

This instrument of the ozone concentration measuring principle is based on property changes the speed of sound in gas environ of different densities. By increasing the density of the gaseous environ the speed of sound will decrease, for example, the speed of sound in oxygen – 316 m/sec, in air – 331 m/s, in lightweight hydrogen – 1268 m/sec. If in a closed volume to excite resonant vibrations of the environ, the resonance frequency is inversely proportional to the density, in which the sound propogates. Thus the pressure of the analyzed gas mixture occurs fluctuation, he value of which depends on the nature of the gas and its concentration. Because ozone is heavier than oxygen in 1.5 times the sound speed decreases as ozone concentration increases.

Applying high-Q sound resonator, a highly stable reference crystal oscillator, and a multiple averaging of measured values by a microprocessor as well, it became possible to measure ozone concentrations from 1 to 100 g/m^3 and above.

The advantage of this device is that this method allows to measure the concentration of various gases in the air, using a same sensor. This requires to input a calibration characteristic for the selected gas in microprocessor. The choice of gas is given by corresponding code: 0–N_2, 1–CO_2, 3–CH_4, etc. Another important advantage – the relative cheapness of the device, because it does not contain an expensive components.

The small size and high reliability make it possible to use the meter for monitoring ozone concentrations of other gases in the atmosphere, and to monitor gas concentrations in working zone of various industries.

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7-30

MICROPROCESSOR DEVICE FOR MEASURING THE CONCENTRATION OF OZONE OCM-003

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The paper describes the meter of ozone concentration in the gaseous environment with microprocessor control. Presented device belongs to the type of spectroscopic measuring devices. Its principle of operation is based on measuring the absorption of ultraviolet radiation at a wavelength of 254 nm. Measurable concentration range is 0.1…100 mg/l. The Ozone meter is controlled by a microprocessor-based controller PIC18F25K80 manufactured by Microchip Technology [1–5].

Ozone technology, widely used at present in industry, medicine, agriculture and households, require the development and production of instruments for measuring the concentration of ozone.

If in laboratory tests one can limit by the use of expensive stationary spectrometers for mass usage it is necessary portable devices for measurement of high , medium and small (at MAC level) levels of ozone concentrations. The most widespread portable measuring instruments available on the market, are based on the principle of UV absorption measurement continues to improve in the direction of increasing the accuracy and reliability of measurement.

At the Institute of Plasma Physics KIPT designed portable ozone meters in a gaseous environment, including those based on the principle of absorption of ultraviolet radiation measurements with a wavelength of 254 nm.

The measurement system is a 2-channels analyzer of differential signal value containing information about the concentration of ozone in the gas.

The double-beam photometer light from an extended source of UV radiation passes through two identical lines (channels). One passes through the cuvette with the measured gas, and the other – through the cuvette filled with gas (air or oxygen) which don't contain the measured component ("zero gas").

Signals from the photo detectors input to the convertor current-voltage, differential logarithmic amplifier and further – to an analog-digital converter of the microcontroller. Thermal gradients between the cavettos were lowered due to their installation on the common metal plate made of aluminum alloy.

The measuring device is equipped by serial port RS-232. This option allows to visualize and archive results of ozone concentration measurement on the computer.

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7-31

OZONE DECAY IN CHEMICAL REACTOR WITH THE DEVELOPED INNER SURFACE

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The ozone decay in the refrigerated container for the transportation of perishable products was investigated. The loaded container can be considered as a chemical reactor with a developed inner surface on which the ozone dissociates or absorbs. Ozone is synthesized in the barrier-free streamer discharge ozonizer with the high-speed air-flow [1, 2]. Only a given part of the circulating cooling air flow is passed through the ozonizer. After switching ozonizer off, the ozone concentration in reactor decreases with time as a result of the ozone decay in the volume and on the inner surfaces of reactor. Ozone concentration behaves differently with time depending on where mainly decays ozone - in the volume or on the reactor surfaces. If ozone mainly decays on the reactor surface, the ozone concentration decreases with time proportional to $\exp(-at)$, where a is determined by the decay process at the inner surface of the reactor and its total area. If ozone decay occurs primarily in the volume, the ozone concentration decreases with time as $1/(1+bt)$, where b is determined by the common process of ozone decay in the volume [3–5]. The analytical expressions for ozone concentration in the reactor have been obtained as function of time and parameters, such as the initial ozone concentration, the reaction rate constants, temperature, humidity, the reactor volume and its inner surface. It is shown that the analytical results are in good agreement with the experimental data.

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7-32

A SIMPLE DATA ACQUISITION SYSTEM BASED ON ARDUINO PLATFORM FOR NON-SELF-SUSTAINED GAS DISCHARGE PLASMA DIAGNOSTICS

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One of the most important parts of plasma diagnostics equipment is digitizing and storing data of measurements. An industrial data acquisition systems produced by many companies, such as LabView, usually have a high price. However, nowadays, there is a possibility to build simple and low-cost system on the basis of independent embedded Arduino platform or similar.

Several works in different fields have been done for data acquisition using Arduino. For example, Coelho E.T. et al. [1] present an application in the scenario of controlling the information processing and communications between sensors and actuators onboard of an autonomous flying robot, in a "fly-by-wireless" approach. Krishnan J. et al. [2] present application in medical field. It serves as a remote monitor for measuring and analyzing along with logging of data from patients. Jenifer T.M. et al. [3] developed a mobile robot which is used for autonomous temperature measurement, as an early detector of fire in forest and also as a sensor kit in warehouses, hospitals, etc. We have not found any information about application of Arduino-based wireless data acquisition system in plasma diagnostics. Also we understand that the limitations of this system (due to low acquisition speed) could be the reason for its failure in plasma diagnostics. However, in the case of stationary plasma, i.e. in our case, the system shows good results.

Our data acquisition system based on Arduino Nano platform is developed for testing the concept. Bluetooth wireless protocol is used for data transmission. The process of data visualization and recording can be done on an ordinary Android OS device with the developed application. The system was successfully applied for acquiring data of Langmuir probe measurements in the non-self-sustained discharge with a hollow anode. The results of measurements show that our system can be applied for data acquisition of Langmuir probe measurements in stationary plasma.

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7-33

INVESTIGATION OF GAS DISCHARGE BURN CONDITIONS IN A PENNING GEOMETRY IN GRADIENT MAGNETIC FIELDS

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Gas-discharge plasma formed in the Penning cell is used in many technical devices being widely applied for solving the physical and applied problems, e.g. in the charged particle sources [1], ion pumps and vacuum manometers [2] and others. Depending on the pressure and magnetic field values, the Penning discharge (reflex discharge) has a number of performances [3]. Under low gas pressure ($p \leq 1.33 \cdot 10^{-2}$ Pa) in the interelectrode space a negative volume charge is dominant. Under higher gas pressure ($p > 1.33 \cdot 10^{-2}$ Pa) the whole interelectrode space is filled with plasma. Under pressures higher than $p > 1.33 \cdot 10^{-2}$ Pa the reflex discharge is used more frequently as a base for creating plasma sources. When investigating the reflex discharge and developing the reflex-discharge based devices uniform magnetic fields are generally used [4]. There is a few of studies aimed to the investigation of the reflex discharge in gradient magnetic fields. Therefore it is of interest to arrange and to carry out experimental investigations on the reflex discharges in the gradient magnetic fields for the purpose of obtaining additional information about the magnetic field gradient influence on the discharge burn conditions, and the expansion of the range within which the reflex discharge parameters are changing, as well as, to determine the field of this charge application.

This paper reports on the investigations of gas discharge burn conditions in a Penning geometry in the gradient magnetic field of a mirror configuration with a mirror ratio of ~ 3.17 [5]. The geometry of the discharge gap was a hollow cylinder-plane system. The first electrode was composed of two electrically coupled hollow cylinders having the internal diameter of 95 mm made of stainless steel. The second electrode was made in the form of a copper disk of 80 mm in diameter. We have investigated two discharge burn conditions with a different polarity of the electrode system feed. Depending on the electrode polarity either the Penning discharge was ignited or the discharge comprising the hollow cathode. The experiments were carried out under the following initial conditions: working gas-air under pressure of 1…250 Pa, value of the magnetic field induction $B \leq 0.023$ T, discharge voltage to 610 V.

The values of the ignition voltage and volt-ampere characteristics of the gas discharge were measured as a function of working gas pressure in the absence and in the presence of a magnetic field. There determined are the values of the power liberated in the discharge cell and the values of gas-discharge plasma conduction.

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7-34

EFFECT OF SUBSTRATE BIAS VOLTAGE PARAMETERS ON SURFACE PROPERTIES OF TA-C COATINGS

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The surface of material plays a basic role in determining of various processes such as dyeing penetration, chemical absorption, biocompatibility and others. Surface material properties – composition, roughness, topography, wettability can influence events at material interface. The surface free energy (SFE) is one of the basic surface material properties and very important for various advanced applications. Modern techniques are widely used for surface parameters modification. The aim of the study was the comparative analysis of the structural and surface properties of ta-C coatings depending on the substrate bias voltage, in the range of -25 to -200 V.

Experiments were performed on a modernized industrial vacuum arc device C55CT produced by the German company INOVAP GmbH for diamond-like carbon (DLC) coating deposition.

The cathodes of the arc sources used for coating deposition, 70 mm in diameter, were made from pure carbon and chromium. Cr cathode, with a DC-arc current of 100 A with high-current arc pulses of 1500 A, was used for deposition of the chromium inter-layer. Two graphite cathodes, with a DC-arc current of 50 A, high-current arc pulses of 1400 A, were used for carbon (ta-C) deposition. The pulse duration was set to 300 μs and the pulsing frequency was fixed at 100 Hz.

The effect of the substrate bias voltage parameters on the micro structure and phase composition of ta-C films were analyzed by Raman and X-ray photoelectron spectroscopy. The surface properties of ta-C films such as roughness and topography were investigated using a profilometer and SEM methods. Advancing contact angles were measured by Wilhelm's method (Kruss K12) at temperature 20 ^{o}C. The standard liquids with well-known values of surface tension, component of dispersion and polar interaction were used. The surface free energy SFE and its polar and dispersion parts estimations were made by Owens-Wendt-Rabel-Kaeble' method for liquid system: α-bromonaphthalene- formamide-ethylene glycol-diidomethane-glycerol-water, Van Oss and Fowkes methods.

The results of the structural analysis of coatings show characteristic changes in the content of the diamond-like sp3 fraction on the substrate potential. The highest content of sp3 bonds, of about 63 %, was obtained in the coating deposited at the substrate bias potential of -100 V, which also showed the minimum surface roughness. The SFE energy values were in the range 40…45 mN/m ,polar part was grown depending on the bias increasing from 4.79 mN/m to 8.49 mN/m for substrate bias potential of -100 V.

The results demonstrate the principal possibility to modify surface parameters of ta-C coatings by changing technological parameters and the substrate bias voltage adjustment. The changing of surface roughness, surface free energy and polar parts is very challenging for many ta-C coatings industrial applications.

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OZONATORS BASED IN THE DIELECTRIC BARRIER DISCHARGE

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Two types of ozone generators with high-frequency power supplies and reactors (tubular and plate) based on dielectric barrier discharge are presented in this article.

Plate-type reactors with glass-coatings ($\varepsilon \approx 5$) and the following parameters P_{max} = 30 W, U = 10 kV, f = 0,5 kGts are used in the first type ozonizers.

The Peltier element is used for reactor cooling.

Ozonator is equipped with built-in sensor based on the spectroscopic measuring method of ozone concentration.

The obtaining of ozone concentration from 0 to 40 mg/l is provided by adjusting the air flow through the reactor (0…1 liters/min) and power supplied to it plates (0…30 W) in ozonizers with this type of reactors.

Air flow, $\frac{l}{min}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Concentration O_3, $\frac{mg}{l}$	35	30	27	24	20	17	15	14	13	12

The results of ozone concentration dependence from air flow are shown in the table.

The bloc of coaxial cylindrical electrodes is apply in ozonizers with the tubular type reactor. The following parameters of such reactor: P_{min} = 44 W, P_{max} = 240 W, U = 5 kV, f = 13 kHz, the air flow 180 m^3/h.

The cooling reactor tubes process occurs forced by air flow.

Ozonizer productivity of 10 g/hr with a concentration of 40 mg/m^3 to 20 g/hr with a concentration of 80 mg/m^3, respectively.

Ozonizers of this type are equipped with a microprocessor control unit that allows to regulate the ozone productivity.

The productivity of 0.36 g/hr with a concentration of 6 mg/m^3 in the ozonizer with a single cylindrical tubular type reactor. Microprocessor unit of this device allows to maintain the ozone concentration at the level of MPC and up depending on the room size.

7-36

SEPARATION OF NEGATIVE HYDROGEN IONS FROM PENNING DISCHARGE WITH METALHYDRIDE CATHODE

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The natural division of excitation hydrogen molecules H_2 areas and region of H^- ions formation ensures the attractiveness of Penning discharge application as a source of negative ions with bulk generation. Using the effect of metalhydride hydrogen activation significantly improves its performance. The main mechanism of the negative ions formation there is a dissociative attachment of thermal electrons to vibrationally excited hydrogen molecules H_2^* desorbed from a metalhydride cathode by the action of the discharge current. However, desorption of H_2^* from the active metalhydride cathode significantly changes the properties of the discharge. For instance, there is an additional operation discharge mode at high-voltages, which dramatically changes the emission properties of the unit. Namely, there is an output negative current in the axial direction of the discharge, associated with primary electrons yield [1, 2]. Exactly that fact was the basis for the idea of a negative hydrogen ions source creating with longitudinal extraction. The problem that arises here is the necessity for separation of H^- ions from the total flux of particles emitted along the magnetic field. So it was designed and manufactured electromagnetic filter that will be installed behind the passive copper cathode of the discharge. Calculation of filter coils and magnetic field topology was made in the program Femm4.0© basing on the trajectories of charged particles, which have been identified by a numerical solution of the paraxial equations of motion by the Runge-Kutta fourth order in MathCad© package.

As a result of numerous calculations a model was built that allows choosing the best external parameters for efficient separation of H^- ions from the axial flow of charged particles. Experimental verification of the model was carried out by loosening the axial electron beam in the formed magnetic field. Good agreement between the experimental and calculated data showed the possibility of using the model for the interpretation of following experiments.

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7-37

LONGITUDINAL EXTRACTION OF H^- IONS FROM PENNING DISCHARGE WITH METALHYDRIDE CATHODE

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Interest in the negative ions of hydrogen H^- is due to the high efficiency of its neutralization in the range of medium and high-energies. Therefore, the application range of the sources is determined mainly with charge exchange technology. The most attractive and promising method of H^- generating is the formation at plasma volume due to the process of dissociative attachment of vibrationally excited hydrogen molecules to thermal electrons. Applying a metal hydride cathode opens one of the possible ways of vibrationally excited hydrogen molecules injection with following greatly increase of the H^- formation efficiency. It's common to extract H^- ions across a magnetic field. On the other hand, detected by authors electron emission in the axial direction from a Penning discharge with a metal hydride cathode makes it possible to significantly simplify the construction of the source and extract H^- along the magnetic field [1]. The aim of this study is to investigate the possibility of creating a source of negative hydrogen ions based on a Penning discharge with metalhydride cathode with extraction of H^- ions along the magnetic field.

Based on experimentally carried out ability of the Penning discharge with hydrogen-saturated metalhydride cathode to emit negatively charged particles along the magnetic field, the authors have shown the following. Due to the metalhydride hydrogen activation the efficiency of the negative ions H^- formation increases and opens the way to extract them along the magnetic field. Separation of negative ions from the flow of extracted charged particles has been done by electromagnetic filter. The efficiency of the filter was studied experimentally and the optimum external parameters for the H^- separation were determined. The experimental data of the extraction of negative ions along the magnetic field from the Penning discharge with metalhydride cathode were carried out. The influence of external magnetic field on the beam current of extracted ions H^- was established. The obtained maximum current of H^- ion beam was about 3 mA. The described method of H^- ions formation and extraction is of interest in high-vacuum devices where one wants to inject beams of negative hydrogen ions of continuous type.

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7-38

MAGNETIC FIELD INFLUENCE ON THE PARAMETERS OF THE TWO-STAGE DISCHARGE GAS-METAL PLASMA SOURCE

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Earlier [1] the project of the two-stage discharge gas-metal plasma source was presented and the requirements to the source was defines. The possibility of using source for separation techniques in particular for the regeneration of spent nuclear fuel (SNF) was considered [2]. Results of a study discharge source parameters are now. Particular attention paid to the magnetic field influence on the discharge parameters, since in further operation of the source in strong and gradient magnetic fields is presupposed. The vacuum-arc modes of the plasma gas and plasma metal are investigated. Distribution of the floating potential, the distribution of the deposited streams in different modes, voltage-current characteristic of the discharge, current characteristic for the reflective electrodes and the target are presented. The dependence of the discharge parameters of the pressure in the range of 10^{-4}…10^{-5} Torr is investigated. The magnetic field strength at the maximum up to 300 Oe, the discharge voltage is 30…150 V, discharge current up to 20 A. For gas discharge was used the air, copper was used for discharge in the metal vapor. The obtained evaporation rate of copper is at 20 g/h. Studies have shown a significant deviation of the distribution of the deposited streams on the chamber walls from cosine law describes evaporation in vacuum, which indicates a significant degree of ionization of metal vapors.

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THE FORMING SYSTEM SIMULATION FOR REACTIVE GAS ION SOURCE WITH DECREASED NEUTRAL GAS INLEAKAGE

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This report is devoted to research possibility of acceleration N ions with original system of ions extraction and acceleration. The simulation of its electrode geometry for nitrogen ions acceleration are described. The parameters of its optimization for nitrogen ions acceleration are described. Comparison of the simulation results with the experimental dates were done.

7-40

OBTAINING SILICON CARBIDE VIA CHEMICAL VAPOR, PLASMA-CHEMICAL AND SUBLIMATION METHODS

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Due to unique combination of physical and chemical properties of SiC-ceramics resides in great demand in the nuclear, defensive and metallurgical industries, as well as in the engineering of the first wall and blanket of fusion reactors. Issues in obtaining and examining the SiC-ceramics are in focus of researchers and engineers, both in Ukraine and abroad.

This paper presents the results of research on production of silicon carbide by chemical gas phase, plasma-chemical and sublimation techniques. Obtaining of silicon carbide via chemical vapor and plasma-chemical methods was performed on a flow-type reactor. Silicon tetrachloride $SiCl_4$, toluene C_7H_8 and hydrogen H_2 was used as the precursors, Mo, Zr1%Nb and NbTa were the substrates.

The thermodynamic of Gibbs energy was calculated for the reactions:

$$7SiCl_4 + C_7H_8 + 10H_2 \rightarrow 7SiC + 28HCl,$$

$$7SiCl_4 + C_7H_8 + 20H \rightarrow 7SiC + 28HCl$$

was showed that in the environment of the atomic hydrogen, in the plasma-chemical deposition, reaction of reduction of silicon tetrachloride $SiCl_4$ and C_7H_8 toluene occurs at a lower temperature rather than in chemical vapor deposition.

The temperatures of condensates growth and ratio of $SiCl_4/C_7H_8$ in the gas phase were found. The kinetics of SiC growth rate of the condensates in chemical vapor deposition and plasma was studied. Was shown that, the growth rate of SiC for PCVD higher than the growth rate for chemical vapor deposition, what can be explained by the stimulation of the process via excited and charged particles of the plasma.

Micro-X-ray-spectrum studies showed uniform distribution of Si all over the sample surface. The morphology of the surface has no defects.

Sublimation source, that was produced by chemical vapor, and which is the SiC coating with thickness of 40 microns on the NbTa substrate with size 60×10×0,3. Thin films of SiC was deposited, from the obtained source (NbTa), by the sublimation method via resistive heating (NbTa) on a high-vacuum assembly. Source temperature (NbTa)SiC was 2200 °C, the substrate temperature was varied in range of 300-500 °C, pressure in the chamber was $2 \cdot 10^{-6}$ mm Hg, deposition rate was 3 μm/h.

Micro-X-ray-spectrum studies showed uniform distribution of Si all over the sample surface. The morphology of the surface has no defects.

7-41

STRUCTURE AND PROPERTIES OF THE (Cr, Al)N COATINGS DEPOSITED BY PIII&D METHOD

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Multicomponent nitride vacuum-arc coatings have high hardness, thermal stability and oxidation resistance. Deposition from the filtered vacuum-arc plasma by PIII&D (Plasma immersion ion implantation and deposition) method under high voltage pulsed substrate bias allows to improve coatings characteristics. The aim of the present work was to study the structure and mechanical properties of Cr-Al-N coatings, deposited from filtered vacuum-arc plasma by PIII&D method, as well as to study the influence of the value of the bias potential amplitude on the coatings characteristics.

Coatings with thickness of about 2 μm were deposited onto substrates of polished X6Cr17 steel by using the vacuum-arc filtered plasma source with the cathodes of $Cr_{0.5}Al_{0.5}$ made by powder metallurgy method. During deposition the nitrogen pressure was of 0.1 Pa, the pulsed potential of negative polarity with the amplitude A_U of (0…2.5) kV, pulse duration 12 μs and repetition frequency 12 kHz was applied to the substrate.

Under specified deposition parameters the (Cr,Al)N coatings with a cubic structure of NaCl type are synthesized, the ratio of the metal components in the coatings corresponds well to that of the cathode. High voltage pulse potential bias causes formation of the coatings structure with fine grains (6...7 nm) and strong axial texture [110]. Residual compressive stress σ varies nonmonotonously from 2 to 7 GPa when the amplitude of the pulses increases from 0 to 2.5 kV. The resulting coatings are characterized with surface roughness Ra of 40…50 nm, low coefficient of friction μ, high hardness H 30...36 GPa and Young's modulus of about 400 GPa. High values of the parameter H / E in the range of 0,08...0,09 confirm good resistance of the coating to plastic deformation. The adhesion of coatings to the substrate was evaluated through scratch testing. The critical values of L_{C1} and L_{C2} loads at which the first cracks appear and delamination occurs, respectively, are listed in the Table. Evidently, the coatings begin to break at sufficiently low values of the critical loads, that is their adhesion to the substrate is low. Primarily, this is because all the coatings are very thin, and under load deformed easily with the soft steel substrate, hardness of which is only 2.5 GPa. The friction coefficient increases slightly since the beginning of the destruction of coatings, however, it does not exceed 0.3. It was found that one way to limit the residual stress in the coatings at optimal level, increase adhesion to the substrate and improve their performance properties is proper choice of the temperature regime during deposition.

Table. Characteristics of (Cr, Al)N coatings

№	A_U, кВ	Nanoindentation			XRD	FRT	Revetest		
		H, GPa	E, GPa	H/E	σ, GPa	R_a, нм	L_{C1}, H	L_{C2}, H	μ
1	0	29.6	404	0.073	2.0	38	9.0	12.4	0.15
2	0.5	33.4	390	0.087	6.1	36	5.5	7.6	0.10
3	1.0	33.1	385	0.086	7.0	56	6.5	9.8	0.10
4	1.5	36.2	436	0.083	6.1	45	5.9	10.2	0.10
5	2.0	30.5	385	0.079	3.9	50	4.0	6.8	0.10
6	2.5	30.2	373	0.071	5.3	52	1.2	2.2	0.10

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SYNTHESIS OF THIN-FILM TA_2O_5 COATINGS BY REACTIVE MAGNETRON SPUTTERING

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The results of investigation are presented of optimal conditions for synthesis of thin-film tantalum oxide dielectric coatings using the cluster multipurpose setup comprising a DC magnetron, an ICP plasma source, and a medium-energy ion source. Tantalum oxide was deposited by reactive magnetron sputtering using DC magnetron in atmosphere of argon and oxygen. The oxygen flow was activated passing trough the ICP plasma source. The described equipment allows independent control of the flows of metal atoms, of reactive particles, and of ions of rare and reactive gas. We measured the current-voltage characteristics of the magnetron discharge, and dependencies of the current and voltage on the argon pressure and flow of oxygen used as the reactive gas. TA_2O_5 coatings were deposited in various conditions, while the optimum mode of deposition of tantalum oxide was chosen as follows: argon pressure $8 \cdot 10^{-4}$ Torr, 30 sccm oxygen flow, voltage 500 V, discharge current 6 A. Ion bombardment of the growing film during the process of synthesis allows obtaining the unique properties of coatings, in particular electret properties of tantalum oxide films.

7-43

PLASMA ASSISTED DEPOSITION OF TaB_2 COATINGS BY MAGNETRON SPUTTERING SYSTEM

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Last decades the plasma assisted deposition of complex compound composites is actively investigated. The ion and electron fluxes with different energy allows to control the film grows parameters.

In the present paper the results of TaB_2 coating deposition in cluster set-up comprising a low pressure planar magnetron and an inductive plasma source are presented. The system allows to control independently the fluxes of the deposited Ta and B atoms from the sputtered TaB_2 target, and the fluxes of argon ions and electrons from the inductive plasma. Low argon pressure in the chamber allows the deposition process in the collisionless regime, providing the composition of the deposited film which is very close to the stoichiometry of the sputtered target. In the basic deposition regime the argon pressure was $8 \cdot 10^{-4}$ Torr, voltage was 585 V, discharge current was 5.6 A. The correlation of the TaB_2 coating structure with the substrate voltage in the range from -100 to +100 V and with the ion current density is demonstrated.

7-44

CATHODE DIRECTED STREAMER DUMPING NEAR AND FAR FROM CATHODE

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The numerical simulations of the cathode directed streamer propagation in the atmospheric air at the constant voltage applied to the discharge gap are carried out. The obtained results help to connect the phenomena observed in experiment with the corresponding processes.

If the streamer dumps far from the cathode then the total current time dependence has only one peak. If the streamer crosses the discharge gap then two peaks of the total current are observed. The first peak is connected with the temporal enhancement of photoemission when the streamer comes up to cathode and with subsequent decrease of the displacement current. The second peak is connected with increase of the positive ion conductivity current at the cathode and with some propagation of the ionization wave over the cathode surface with temporal formation of the structure somewhat similar to the cathode layer of glow discharge. During this propagation the conductivity current approaches its value determined by the normal current density value and by the volt-ampere characteristic of the power supply source. If the conditions for the electron emission from the cathode surface provide the keeping up of the structure in the quasi-stationary state then, as a rule, the discharge evolution leads to the spark formation through the thermal instability. If the conditions for the emission are not so favorable, and the cathode layer is destructed with the positive ion density increase just near the cathode, then the potential redistribution along the discharge gap leads to the considerable field strength decrease in the small space near the cathode and to some field strength increase in the greater part of the streamer channel. And the total ionization intensity either decreases through the diminution of the space, the field strength level in which is sufficient for the intensive impact ionization and for the radiation of the photons able to ionize gas, or gradually increases through the thermal instability, which leads to the spark formation.

There are two circumstances, in connection with which it is natural to expect that the streamers either do not arise or cross the whole discharge gap, depending on the applied voltage value, and it is almost impractically to stop the streamer near the given point of the discharge gap far from the anode. First, the possibility of the quasi-stationary streamer propagation in the electric field with the given average strength disappears rather sharply with the decrease of the average strength to some values. Secondly, before the streamer start the strength values in the different points far from the needle anode are not very different. And so, the possibility to ensure the streamer stopping near the given point of the discharge gap symmetry axis achieved in the experiments indicates an existence of some factors, which make the dependence of the stopping point coordinate on the applied voltage not very sharp. One of such factors is the decrease of the streamer channel conductivity through the process of electron attachment, which leads to the near-anode field strength increase and to the field strength decrease in the space of intensive ionization in front of streamer. Another such factor is the spatial distribution of the negative ions, which are formed in the previous streamers, as these ions can give the electrons initial for the impact ionization avalanches.

7-45

ON THE EQUATION OF STATE AND PROPERTIES OF THE PLASMA IN UNDERWATER DISCHARGES

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The underwater discharges are studied intensively in connection with its various technological applications. In arcs and electrical pulse discharges in liquids a high-density non-ideal plasma column contacts with limiting it condensed medium. The processes on the contact interface are essentially for the properties of the discharge as a whole. The most important influence on plasma of electrical pulse discharges in liquid (EPD) have the processes in a zone of its contact with condensed medium [1, 2].

At the initial phase of EPD small-scale irregularities of heat flow distribution were detected on a surface of channels. Development of such perturbations was accompanied by space modulation of an irradiation intensity, strain of a surface of channels, drop of conductance of plasma. One from reasons it is established further by comparison of a strain of a surface of plasma channels of EPD with outcomes of simulation on the basis of a solution of the task to development of Rayleigh-Taylor instability (RT-instability).

The irregularities have caused the turbulent mixing of ionized gas-vapor-liquid mixture in the channel of discharge. Because of that the plasma consists of a number of various components at high pressure. In the paper the equation of state and transport properties (electrical and thermal conductivities, viscosity, diffusion coefficients) of multicomponent plasma are studied for the conditions of underwater discharges.

The non-ideal plasma are known to occur in underwater discharges. The non-ideality corrections to equation of state are made according to [6–8]. In this way it may be obtained a wide-range equation of state for the plasma in discharges.

The most important factors determined the properties are the following: gaseous and plasma non-idealities, multicomponent contents. To include the factors into consideration the combined calculation procedure is used on the base of the Grad's method [3, 4] and Lee-More theory [5]. The obtained results are compared with the previous calculations based on the Lorentzian theory [9].

A number of processes lead to the appearance of impurities in the plasma channel of discharge. The calculations are carried out, and it is shown that a small amount of metal causes the essential changes in the values of transport coefficients in comparison with the case of pure water mixture. Also, It is considered the problem of difference between both the Lee-More theory and the Spitzer-Härm theory in application to transport properties.

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7-46

CAVITY WITH DISTRIBUTED DIELECTRIC COATING FOR SUBTERAHERTZ SECOND-HARMONIC GYROTRON

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Dielectric-coated waveguides and cavities [1] are actively studied both theoretically and experimentally for use in electronics and various techniques of particle acceleration, including wake-field acceleration. In particular, such cavities have found applications in gyrotrons [2].

The gyrotron relates to the class of oscillators based on cyclotron maser instability of weakly relativistic electrons gyrating in an external magnetic field. Nowadays it is the most powerful radiation source in the range of millimeter waves (30…300 GHz). However, very strong magnetic field (above 12 T) and thus very cumbersome and expensive magnetic systems are required to reach higher frequencies. In this connection the higher harmonic operation capable of reducing the above-stated requirement is of prime interest for sub-THz and THz gyrotrons. As a rule, such operation, however, suffers from severe mode competition with the first cyclotron harmonic modes. Therefore, of vital importance are the possible means of alleviating the problem of harmonic mode competition.

One of them is the coating of metallic cavity walls with dielectric layer of variable thickness. As has been shown in [3], such coating acts effectively as additional wall shaping and thereby changes the diffractive losses in the cavity. This in its turn has effect on oscillation threshold for the cavity modes. More importantly, such effect depends on mode frequency and is stronger for higher frequency modes. Thus the generation of high cyclotron harmonic modes may be favored by the proper distribution of dielectric coating.

In the present study we have considered the metallic cavity with distributed dielectric coating for the 0.4 THz second harmonic gyrotron. Scattering matrix formalism [4] has been extended to include hybrid modes into consideration and to investigate adequately the electromagnetic properties of the dielectric-coated cavity. This differentiates our study from that [3] performed within single-mode treatment. Numerical calculations have been performed with respect to different parameters of dielectric coating. It has been found that the distributed coating is responsible for mode conversion phenomenon in the cavity. This phenomenon tends to diminish the above-discussed positive effect of dielectric coating. Nevertheless, this effect is still distinct for certain parameters of dielectric coating and makes such coating feasible as a tool for selective suppression of low-frequency competing modes in harmonic sub-THz and THz gyrotrons.

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7-47

THE SIZE EFFECT AND X-RAY FLUORESCENC SPECTRA OF METALLIC NANOPARTICLES

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This paper presents the results of research of X-ray fluorescence spectra of metallic nanoparticles with reference to their size. It is known that changes of sizes and shapes leads to a change in the electronic structure of nanoparticles and their properties. Experimentally it was observed the dependence of the intensity of the photoluminescence of gold clusters on the number of atoms in a cluster [1]. Also were studied Raman spectra of nanocrystals Si (with the size of 5 nm) [2]. It was obtained the X-ray shifts for manganese K lines observed in nanoparticles oxides MnO, Mn_3O_4 and MnO_2 relative to the respective of macro material [3]. However, the aforementioned as well as many similar works studied electromagnetic properties of small particles whose size was less than 10 nm.

This work is aimed at the study of X-ray fluorescence spectra of metallic nanostructures with reference to the size and to compare them with the spectra of macro materials.

In order to form nanoparticles, we used an electrothermal plasma accelerator with axial geometry, whose electrodes are made from a material of obtained particles [4]. The discharge was produced in a narrow dielectric channel under atmospheric pressure. Synthesis of nanoparticles of Al, Ti and Cu was carried out at the expense of non-equilibrium condensation of supersaturated metal vapor (gas–plasma clot) flowing out of the accelerator nozzle at supersonic speed. Particles were precipitated on a glass substrate. By means of electronic microscopy and by using statistical processing, the sample means values of the particle sizes were determined: 14; 30,1; 85,9 nm.

To study the X-ray fluorescence spectra of Al, Ti and Cu, the X-ray fluorescence spectrometer ARL OPTIM′X-0335 (rhodium anode) was used. For fluorescence excitation the radiation lines Rh ($h\nu \approx 20213$ eV) and Rh ($h\nu \approx 22767$ eV) was used.

It is determined that the fluorescence spectrum of the aluminum nanoparticles is experiencing an energy shift relative to the spectrum a macro material. Offset for the line equals $\approx 0{,}35$ eV, and for line it equals $\approx 3{,}81$ eV. It is noteworthy that a similar offset is absent in the spectra of titanium and copper nanoparticles of a bigger size. Thus, the observed shift demonstrates the presence of "the size effect". This change results from deformation of the "spanning" energy levels (K, L and M-levels) of aluminum atoms during the formation from these atoms' nanoparticles. Thus, one could argue that the offset of X-ray fluorescence spectra of nanostructures depends on their size. In our case the energy shift is not observed for nanoparticles with dimensions exceeding the ~ 10…15 nm.

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7-48

PECULIARITIES OF PROPERTIES OF THE PULSE PLASMA JET

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The interaction of the plasma jet with material leads to a various chemical reactions in plasma. Creating a plasma medium in the optical laser cavity and subsequent extraction of the infrared radiation it enables accurate geometric processing of the material by focusing the infrared radiation. [1] This way leads to the minimization of chemical activity in plasma.

On the basis of the detonation of the fuel cycle is considered the possibility of a flat pulsed plasma jet is designed to feed into the optical resonator of a TEA laser to the heat pump [2]. There is a schematic diagram of a device for the production of flat plasma jet. It is shown that the use of detonation fuel cycle leads to greater population inversion of the upper levels, allowing you to perform a TEA laser, combining high average and peak power.

Impingement jets of supersonic radial cold mixture entering the fuel cavity causes the formation of a shock wave, which travels to the bottom of the cavity resonator, and is reflected by it focuses at the center of the resonator. In this area, due to the Hartmann–Sprenger effect it is local increases in temperature and pressure sufficient to self-ignition of fuel-air mixture. The detonation combustion is created, and the products of the combustion form the plasma jet. The pressure and temperature of the combustion products are increased and the detonation wave containing the plasma with a frequency up to 30 kHz is transformed into a reflected shock wave. With large speed it flows into the nozzle device, carrying combustion products and creating a cavity in thermal vacuum required for subsequent cycles. The frequency of pulsations is determined by the geometrical parameters of the thermal cavity, which is usually done in the form of a hemisphere [3].

The high exhaust rate can be due to lack of intake and exhaust valves and fuel pre-decomposition into components having explosive nature of combustion. The device is realized most economical fuel cycle close to the constant volume cycle. The supersonic velocity of the combustion products necessary to maintain the stability of the plasma environment in the cavity is achieved without the use of the Laval nozzle. Carbon black and various other compounds reduce the efficiency of the laser in the plasma environment is missing.

Thus, the pulse plasma environment it may be used for the plasma cutting of any materials in the ablation mode.

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INVESTIGATIONS ON THE EFFECT OF DIFFERENT CARBON SPECIES ON THE GROWTH AND FIELD EMISSION PROPERTIES OF PLASMA GROWN GRAPHENE SHEET

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The effect of different carbon species (i.e., hydrocarbon and fluorocarbon) on the plasma-assisted growth and field emission properties of the graphene sheet has been theoretically investigated. Two different plasmas constituting electrons, neutrals of CF_4/CH_4 and positively charged ions of CH_4^+/CF_4^+ are considered in the present investigation. Numerical calculations for the effect of CH_4 and CF_4 carbon species on the thickness of graphene sheet have been carried out for typically glow discharge parameters. It is found that CH_4 plasma favors the growth of thinner graphene sheets as compared to CF_4 plasma. The field emission of electrons from the graphene surface is also higher for the CH_4 plasma. Some of the results of the present investigation are in compliance with the experimental observations.

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THEORETICAL INVESTIGATION OF THE IMPACT OF VARIOUS PLASMAS ON THE CATALYST NANOPARTICLE SIZE FABRICATED FROM CATALYST THIN FILM

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The theoretical model is formulated to examine the impact of etching gases on the formation of catalyst nanoparticles from thin films. The model accounts the thermal and energy balance on the film surface placed over substrate, heat radiations, energy fluxes of various plasma species (i.e., electrons, positively charged ions, and neutrals). In our investigation, it is found that particles with lesser diameters are formed when hydrogen + nitrogen plasma is utilized than the pure hydrogen plasma. In addition, we found that number of catalyst particles per unit area increase when hydrogen + nitrogen plasma is used. The theoretical predictions are in concurrence with the experimental observations.

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DEVELOPMENT OF NEGATIVE HYDROGEN ION SOURCE WITH COMBINED DISCHARGE

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The negative ion sources are widely used in scientific investigations and high-tech applications. Previously we designed and tested original source with combined discharge and cesium adding to produce a moderate energy cylindrical negative ion beam. The discharge in crossed magnetic and electric fields operates near emission slit of the source. Another discharge of hollow cathode type is ignited in series with one mentioned above, and is located further from the emission region [1–3]. The source creates a negative particle beam in wide range of discharge parameters with very low noise current. But the beam was highly divergent and was in need of an improvement of its formation quality. Here we present development in the source design and the beam formation. With the emission electrode redesign, we obtain better formed particle beam. The new design of emission electrode also improves the discharge stability and voltage proof of the discharge gap. The new unit consisting of two parallel slits, each of 1 cm width, separated by 3 cm distance is added to the measurement setup previously composed of a set of ring electrodes. The new measurement setup with magnetic field turned on allows more precise separation of electron and ion components of the beam. The full negative particles current is up to 1,5 A for the discharge with 100 A current and 150 V potential. The measured mean current density for negative ion beam is up to 40 mA/cm^2 at a distance of 8 cm from the emission electrode. Calculated current density of negative ions at the emission hole is up to 4 A/cm^2. Current values of accompanying electrons and hydrogen negative ions originated from the source grow up with increase of the discharge power, which is confirmed by the measurements near the source aperture, as well as at 50 cm distance from the source. Total value of negative ion current at minimum discharge current of 30 A is about 150 mA and grows up more than twice at 100 A discharge current. Nevertheless, the problem of wide enough propagation angle of the beam still exists, and will be presumably solved in the future by the beam focusing system which is now developed.

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7-52

VAPORIZATION OF METALLIC MACROPARTICLES IN THE HIGH TEMPERATURE TECHNOLOGY PLASMA

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Cathodic arc deposition or Arc-PVD is a promising method of depositing thin films. It is actively used to synthesize extremely hard film to protect the surface of cutting tools and extend their life significantly. Arc-PVD deposition technique in which an electric arc is used to vaporize material from a cathode target. The vaporized material then condenses on a substrate, forming a thin film. Solid and liquid micron-sized particles (macroparticles or MP comparatively with ions and electrons) during the operation of vacuum arc due to erosion of the cathode are generated. Purification of plasma generated by vacuum-arc plasma sources from MP is an actual problem. At present, there are a lot of filters, based on the separation of trajectories of a plasma flow and the MPs by a magnetic field to prevent direct visibility for the MPs and as a result the MPs are deposited on the walls of the filter. The disadvantage of this type of filters is that the part of the plasma flow is deposited on the filter as well and, consequently, the efficiency of plasma sources is reduced [1–3].

In this work we studied the possibility of vaporization of metallic micron-sized particles during them passage through the area of magnetized plasma with hot electrons with a Maxwellian speed distribution. For example, it is shown, that copper MPs in plasma with density $10^{10}\,\text{см}^{-1}$ are heated up to the boiling point at a temperature of electrons $T_e \approx 30$ eV. The dependence of vaporization time of the MPs on the plasma density and its temperature are obtained. For example, it is shown that the vaporization time t_{vpr} of the MP with a radius $a = 1\,\text{mkm}$ during of its passage through the plasma with density $10^{10}...10^{12}\,\text{cm}^{-1}$ and temperature $100\,\text{eV}$ is $2\cdot10^{-1}...2\cdot10^{-3}\,\text{s}$ respectively, that corresponds to the MP speed $1...100\,\text{m/s}$ at passage of distance $l = 20\,\text{cm}$. The estimation of ionization possibility of vaporized atoms of the MP substance has been made. It is shown that part of ionization of vaporized atoms of the MP substance can reach 100% depending on the plasma density. Thus, creation of the plasma region with hot electrons, for example as a result of RF heating, allows to vaporize MP at short distances, as well as to ionize the vaporized atoms of the MP substance. These mechanisms could form the basis of effective filters of MPs that not only does not reduce the intensity of the plasma flow, but also provide an additional source of the metallic plasma due to ionization of vaporized atoms of MPs substance.

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7-53

DECAY OF LIQUID METALLIC MACROPARTICLES IN PLASMA-BEAM SYSTEMS DUE TO RAYLEIGH INSTABILITY

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Metallic macroparticles (MP) are present in most plasma devices. They are formed as a result of operation of plasma sources, as well as due to erosion of the vacuum chamber surfaces. In most cases they affect negatively on characteristics of these devices. In particular in the cathodic arc deposition or Arc-PVD due to operation vacuum-arc as a result of cathode erosion solid fragments and molten droplets of cathode material are formed that leads to reduce of quality of treated surfaces [1, 2]. In our previous work [3], we have studied the effect of vaporization of the MPs due to their heating by the electron beam, but the size of vaporized MPs was limited by the time of passage through the region of plasma with the electron beam.

The purpose of this work is the studying of possibility of reducing of number of liquid MPs in plasma by creating conditions for developing of Rayleigh instability and subsequent decay of MPs due to them charging by the electron beam.

It has been shown that as a result of charging MP by the electron beam, Rayleigh instability can be developed when the drop charge exceeds a critical value $Q > Q_{cr}$, that leads to a cascade decay of the MP into smaller droplets, which then can be vaporized.

Sizes of the MPs which are destroyed under instabilities may reach 50 micrometers or more depending on the energy of the electron beam. For decaying of droplet the sum of the charging time t_{ch} up to critical value Q_{cr} and the time of developing of instability t_{inst} has to be less than warming time t_h up to a temperature when the MP starts being discharged due to thermionic emission, that is $t_{ch} + t_{inst} < t_h$. It is shown that the characteristic time of the MP vaporization can significantly exceeds the time of developing of instability for MP with the same size. Thus electrodispersion of liquid MPs at low temperatures may be more efficient mechanism of reducing of number of MPs than their vaporization and this effect can be used for developing perspective filters of the MPs.

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7-54

NUMERICAL SIMULATION OF NANOPARTICLES COAGULATION IN RF-DISCHARGE

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Low temperature plasmas containing dust particles are widely studied for fundamental research as well as technological applications [1]. Plasmas present exciting opportunities for nanoparticle synthesis. Such nanoparticles could find applications in medicine, materials science, in the production of nanostructured materials if the formation, growth and transport of nanoparticles in plasmas can be controlled. In order to control the morphology, composition and transport of the particles in the above mentioned and other existent and future technological applications a better understanding of the particle formation mechanisms and their influence on plasma is needed.

The coagulation of dust particles in low-pressure plasma has been studied by numerous researchers [2, 3]. In particular, the formation, the growth and transport of nanoparticles studied in capacitively coupled radio-frequency discharge. In these reports, densities and charge distributions are calculated in the frame of one-dimensional hydrodynamic model, but the influence of particle charging on coagulation frequency not taken into account. In addition, hydrodynamic model is not applicable to describe the discharge at low gas pressures.

In this paper, we model the RF discharge with dust nanoparticles in argon gas at low pressures (p<1 Torr) using PIC/MCC method. At the same time, we neglect the diffusion of dust particles and take into account their coagulation using the sectional model [4]. This model was self-consistently coupled to a plasma PIC/MCC model. Charge distributions were calculated within each section, and the effect of particle charge on coagulation was considered. The fact that the time for particle charging is typically much shorter than the typical coagulation time allowed us to separate the problems of charging and coagulation from each other. The spatiotemporal evolution of the system was calculated as particles grew to several tens of nanometers in diameter.

It has been shown, that coagulation is a main reason of decrease in dust particle density as particles grow to larger size. The coagulation frequency is lower in the central part of inter-electrode gap that near the sheaths, because the charge distribution of nanoparticles significantly differs from one another. In the center of discharge gap, we can observe mainly negative dust particles, but in the sheaths, there is an essential fraction of positively charged particles. Consequently, the coagulation of the nanoparticles is more effective in the sheath, since in this region there are dust particles of opposite charge.

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7-55

INTRINSIC STRESSES IN MULTICOMPONENT NITRIDE COATINGS PRODUCED BY PLASMA IMMERSION ION IMPLANTATION

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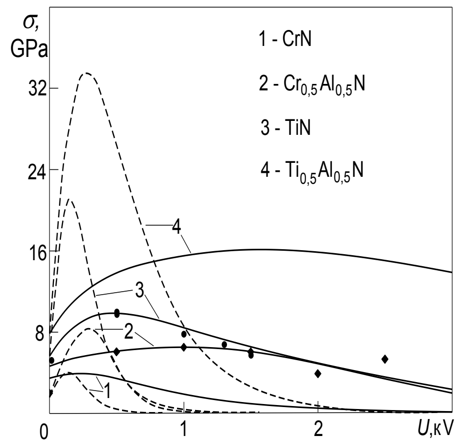
The coating based on nitrides of Ti and Cr with improved operational characteristics (hardness, wear, corrosion and radiation resistances) are formed mainly by vacuum-arc and plasma-ion deposition. During deposition process there are intrinsic stresses that cause destruction of coatings. Determination of intrinsic stresses and their dependence on deposition parameters, thermal characteristics of coatings are necessary conditions for selecting the optimum deposition mode and quality control of the forming coatings.

The theory of intrinsic stress σ calculation based on model of the nonlocal thermoelastic peak (NTP) of the ion is proposed in [1].The formula for calculating the value of the intrinsic stresses in the multicomponent coatings was obtained in NTP model [2].



Dependence of compressive intrinsic stress in coating based on nitrides of Cr (curve 1, 2) and Ti (curve 3, 4) on substrate bias potential in DC (dotted lines) and pulse (solid lines) modes. Black symbols – experi-mental data [3–5]

The paper presents the results of investigation intrinsic stresses in coatings CrN, $Cr_{0.5}Al_{0.5}N$, TiN, $Ti_{0.5}Al_{0.5}N$ deposited by vacuum arc method from ion beams Cr^+, $Cr^+_{0.5}Al^+_{0.5}$, Ti^+, $Ti^+_{0.5}Al^+_{0.5}$ in pulsed potential mode and direct current mode and comparing with experimental data.

Fig. shows the dependence of intrinsic compressive stresses in deposited coatings CrN, $Cr_{0.5}Al_{0.5}N$, TiN, $Ti_{0.5}Al_{0.5}N$ on bias potential *U* (curves 1–4) in direct current (dotted lines) and pulse (solid lines) modes. As can be seen from Fig. 1, increase of the Al content leads to increased stress and peak of stress shifts towards higher value of bias potential *U*. Analysis has shown that the best agreement with the experimental data for the TiN coating (solid curve 3) [3, 4] and $Cr_{0.5}Al_{0.5}N$ coatings (solid curve 2) [5] is obtained for the curves of stresses calculated at the activation energy of defect migration u = 0.75 eV. For $Cr_{0.5}Al_{0.5}N$ (TiN) coating maximum stress σ_{max} = 6.5(10) GPa is achieved at U = 1 (0.55) kV. For coatings TiN and $Ti_{0.5}Al_{0.5}N$ (CrN and $Cr_{0.5}Al_{0.5}N$) calculation parameters of pulse deposition and deposited coatings at temperature deposition T_0 = 473 K were followings: pulse duration t_p = 5 (12) ms, repetition frequency f = 24 (12) kHz, Young's modulus E_Y = 400 (450) GPa, Poisson's ratio υ = 0.23 (0.3).

The analysis shows that maximum stress in TiAlN (CrAlN) coatings grows with increase of Al content, and ratio between stresses arising at constant and pulsed potential on substrate at fixed deposition temperature essentially depends on Al content.

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7-56

DYNAMICS OF DUST PARTICLES IN A PLASMA JET

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The application of nanoparticles is rapidly growing in nanoscale science and engineering. During the last years many techniques for nanoparticles synthesis have been developed, particularly several research groups worldwide apply plasma processes for the synthesis of particulate matter [1]. One of the most promising methods of coating is spraying using plasma jets [2, 3]. Coating quality depends on the physical parameters such as the velocity of sputtered particles, their charge and temperature. In this regard, the study of the dynamics of dust particles in the plasma jets that can be used for transportation of dust particles to the substrate is of considerable interest. Unlike gas jets with dispersed phase, where the drag force determines the movement of dust particles, dust particles are charged in plasma and the electric force acts on them too. The purpose of this work is to study the charge distribution of dust particles in the plasma jet and influence of the electric field on their dynamics.

In this paper carry out the computer simulation of the plasma jet with dust particles, which expands in rarefied neutral gas. It was believed that the jet came out through a round hole in which plasma parameters were considered a given. We used equations of two-fluid hydrodynamics to describe the motion of dusty plasma. The simulation also takes into account the coagulation of dust particles in the framework of the sectional model [5]. Also, we take into account the plasma recombination in collisions of electrons and ions with dust particles and three-particle recombination. The charge of dust particles was determined on the theory of limited orbital motion. Solution of the problem was carried out using a numerical method of "large particles" [4].

Calculations performed for different ionization degree of plasma and various densities of dust particles on inlet. The spatial distributions of plasma parameters and dust components obtained at different time points after injection plasma jet. It is shown that at the large ionization degree of plasma ($\alpha > 0.001$) velocity of the dust particles significantly increased compared to the case of weakly ionized plasma stream. This result can be explained by the increasing role of electric force to accelerate dust particles with increasing concentrations of electrons and ions. It was also established that with a decrease in the concentration of dust particles their velocity increases due to the laws of conservation of energy and momentum.

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7-57

INVESTIGATION OF ELECTRIC ARC DISCHARGE PLASMA BETWEEN ONE-COMPONENT Cu&Ni AND COMPOSITE Ag-Ni ELECTRODES

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Switching devices are widely used in electrical industry for interruption of electric circuits. These devices have a significant drawback – arc discharge destructs the surface of contact materials. Arc erosion decreases life of electrical contacts. Nowadays, this is an essential problem. Such electric erosion of contacts depends on their composition [1] and manufacturing technology [2].

Electrical contacts are usually produced from composite materials by powder metallurgy. The advantage of such materials lies in a combination of high erosion resistance and satisfactory thermal and electrical conductivity. Development of contact composite materials cannot be improved without careful examination of electric arc influence on working layers of electrode surfaces. Therefore, it is important to study influence of arc plasma on erosion properties of such composites in order to be able to measure and control plasma parameters during such kind of investigations [3].

Free burning electric arc was ignited in air between the end surfaces of the non-cooled electrodes. Discharge gap was 8 mm, and the arc current was 3.5 or 30 A. One-component Cu&Ni and composite Ag-Ni were investigated. Electrodes were positioned vertically: upper electrode – Ni or Ag-Ni (cathode), the bottom electrode – Cu or Ag-Ni (anode).

Radial temperature distributions of arc discharge plasma between one-component Cu&Ni electrodes and composite Ag-Ni electrodes at current 3.5 A were determined. Radial distributions of electron density of plasma of electric arc discharge between the same electrodes at current 30 A were investigated as well.

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7-58

SUPPRESSION OF MICRODROPLETS FRACTION IN PLASMA FLOW OF ARC PLASMA SOURCE

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Vacuum arc sources are widely used in production of coatings with desired functional properties and synthesis of precision, including nanoscale structures [1]. The presence of microdroplet fraction severely limits the application of high erosion plasma sources in today's high-tech. Various methods of suppressing the microdroplets are known. Is quite effective the method for providing high speed motion of the cathode spot on the working cathode surface. But, when using cathodes made from non-refractory material such as aluminum, this method is not effective. Film deposition rate significantly decreases due to the mechanical removal of microdroplets if curvilinear plasma-optics systems applied. A new approach to the elimination of microdroplets without loss of the plasma productivity was first proposed in the article [2, 3], which describes the high technology of plasma-optical filter.

In this paper the features of passing the dense plasma of metal ions from the plasma source across the plasma-optical filter are considered, depending on operating gas pressure in the filter and potential on the central electrode of the filter. Nonself abnormal glow discharge in the filter in the crossed EH fields was initiated at passage of the ion-plasma flow at operating gas (Ar) pressure about Pa. The voltage on the central discharge electrode was 200 V and the discharge current was up to 5 A. The quality of the coatings deposited onto substrate was analyzed by scanning electron microscopy. The experimental results showed that the maximum size of the microdroplets in the ion plasma flow was reduced with increasing the nonself glow discharge power in the filter volume. Plasma flow was efficiently cleared from the microdroplets of the largest size more than 3…5 microns when passing zone of the glow discharge, under power of the plasma arc discharge up to 1.5 kW, and there the film deposition rate is reduced by no more than 20…30%.

The method of suppressing a microdroplet fraction in a plasma flow of an erosive plasma arc source by using a plasma-optic filter with a nonself glow discharge in crossed EH fields could be used in high-tech synthesis of the qualitative coatings and films.

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7-59

THE PAIR INTERACTION FORCES AND THE DIFFUSION COEFFICIENTS OF PARTICLES IN MOMENTUM SPACE

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We consider diffusion processes in momentum space in the systems containing a large number of particles satisfying the laws of classical mechanics. We derive the diffusion coefficients basing directly on the dynamics of individual particles motion under action of the pair interaction forces from each of them. Such approach describes both the change of a mean-square momentum of particles at an initial stage of system evolution, in the case of pre-Brownian motion of particles, and diffusion of particles in momentum space at the kinetic stage of system evolution, when motion of particles is completely random. This method allows to investigate the process of a radiative relaxation of the beam of initially monoenergetic ultrarelativistic electrons, moving in a spatially periodic static magnetic field of the undulator. In addition, it is possible to investigate the process of diffusion in momentum space at the collision of the charged particles in the absence of external fields. The results of such consideration for the kinetic stage of system evolution will be agreed with the results which are obtained with the help of kinetic equations with corresponding collision integrals.

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PLASMA EXPANSION INTO GAS

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An initial problem of low-temperature plasma expansion in an unbounded gaseous medium is theoretically examined. It is assumed that the plasma had been created locally in the gas by a source of ionization which acts during small enough time interval. So, the electron distribution function is formed to initial moment of time, but the ambipolar diffusion hadn't started yet. The ions have a temperature of the background gas, the ionization degree is small and the macroscopic fluid dynamics is neglectable. Timing dependencies of the plasma density and the electron distribution function for different background gases and initial electron mean energies are obtained. Also excited states dynamics of neutrals was considered. The problem can be interesting in the plasma afterglow studies and for the tasks of laser pumping by a short pulse.

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EVOLUTION OF MICROPLASMA BARRIER PULSE DISCHARGE INSIDE THE DIELECTRIC CELL

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Microplasma barrier pulse discharges appear in various laboratory and industrial applications so investigations of their behavior are quite important. In particular, those discharges are frequently used as UV radiation source in the small-sized plasma systems like plasma display panels (PDP, [1]). As those systems are quite complex and, in the case of PDP cell, microscopic, numerical simulation is practically only method for their adequate theoretical investigation. This work devoted to the computer simulation of evolution for microplasma barrier xenon-neon pulse discharge inside the dielectric cell. Our original 2D electrostatic PiC-MC code [2] was applied for the 500x500x200 μm cell, 500 Torr total pressures for 90% Ne and 10% Xe gas mixture. Electrodes are aligned in coplanar geometry with two bus electrodes at the upper side of the cell and one address electrode at its lower side. About 250 V of discharge voltage was applied to the coplanar electrode C1 at initial moment, while other two electrodes were at zero potential. Simulation results include the temporal evolution for system parameters as well as discharge spatial distributions. For the initial moment, the electric potential distributed according to the applied voltage, but at later stages, when both spatial charge density and wall charge sufficiently increase, potential distribution becomes practically flat. During that stage, discharge current has a maximum, and at later stages it decreases and almost vanishes at the time when the driven voltage pulse ends. UV radiation from discharge continues to increase after the maximum of discharge current and form a longer pulse. Electron energy distribution for most dense part of discharge is not Maxwellian for initial stages but becomes Maxwellian for the later discharge stage after the maximum of UV radiation pulse.

Electrons are driving out of the C1 electrode with negative potential, producing Ne^+ and Xe^+ ions as well as excited Ne and Xe atoms (also can be ionized later by another electron impact). Positively charged particles move to that electrode and inflict the secondary ion-electron emission that increases the electron density near the C1 electrode, making discharge current to grow faster during the discharge current forefront. Most dense discharge region also moves toward the negative coplanar electrode C1 during that stage. As a result, region with sufficient electrostatic field becomes smaller and, at later stages, potential distribution becomes almost flat. Excimer ions (like Xe^{2+} or $NeXe^+$) are mostly generated in this region when discharge current is close to maximum. At the discharge pulse back front, those ions producing the UV radiation, but their concentration decreasing slower then one for atomic ions. When the plasma concentration reach its maximum, most dense region of discharge is located along upper coplanar electrodes near the center of dielectric cell.

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7-62

PLASMA-CATALYTIC REFORMING OF ETHANOL: INFLUENCE OF AIR ACTIVATION RATE AND REFORMING TEMPERATURE

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Chemicals and fuels produced from the fossil hydrocarbons are the lifeline of modern chemical and energy industries. Thus, it is no surprise that current emphasis on the green technology and sustainable development places the replacement of fossil hydrocarbons with the renewable alternatives among the humanity's top priorities. Traditional hydrocarbon conversion methods are designed and optimized with fossil hydrocarbons in mind, which do not have as complex and varied composition as renewable hydrocarbons. High temperature during the thermo-chemical reforming (gasification) leads to undesirable gaseous by-products and results in negative gross electrical efficiency. During catalytic reforming, the large amount of impurities in biomass feedstock diminishes the product yield and poisons catalysts.

Plasma-catalytic reforming is an emerging alternative to the traditional conversion technologies, which uses active species generated in plasma to initiate the chain reactions of hydrocarbon conversion into synthesis gas. This conversion approach can maintain high conversion efficiency at lower temperatures and produce less gaseous by-products than both gasification and catalytic reforming. In addition, using plasma-generated active species instead of catalyst allows maintaining of the high selectivity at reduced operation costs. However, plasma-catalytic reforming systems require additional study in order to be able to optimize the parameters of the process and predict the composition of reforming products.

In order to investigate the plasma-catalytic reforming we performed the conversion of ethanol into synthesis gas in a system with a plasma source based on the rotating gliding discharge. The system features separated discharge and reaction chambers that are connected via the aperture. The plasma is generated by passing the stream of air through the discharge gap. Produced active species are injected through the aperture into the reaction chamber together with the rest of plasma. During the experiment, the mixture of ethanol and air was introduced into the reaction chamber as a vortex flow alongside the chamber wall and interacted with the injected plasma. This interaction led to the initiation of reforming chain reactions and conversion of ethanol into the mixture of synthesis gas and light hydrocarbons.

During the experiment, we varied the ratio between the plasma-activated air and the non-activated air (air activation rate) injected together with the hydrocarbon in order to determine its influence on the composition of the gaseous reforming products and on the overall reforming efficiency. The initial quantities of supplied ethanol and air corresponded to the reaction of ethanol partial oxidation by air. Additionally, we studied the change of product composition and conversion efficiency in the temperature range between 150 and 350 ^{o}C. We analysed the composition of gaseous reforming products using gas chromatography and mass spectrometry and used obtained results for the calculation of the reforming efficiency.

Our study showed that the conversion efficiency of the plasma-catalytic reforming of ethanol into synthesis gas depends on the reforming temperature and has a maximum of approx. 90 % at 250 ^{o}C in the temperature range of (200-350) ^{o}C. High reforming efficiency was reached without conventional catalysts at lower temperatures than during the gasification (> 700 ^{o}C) or catalytic partial oxidation (approx. 500 ^{o}C) of ethanol. We obtained the dependence of gaseous reforming products composition on the air activation rate in the system. Additionally, we calculated the energy yield of produced hydrogen and compared it with other experimental systems for the plasma-assisted conversion of an ethanol.

7-63

AMPLITUDE OF VORTICAL TURBULENCE IN CROSSED FIELDS IN SEPARATOR OF SPENT NUCLEAR FUEL AT OPTIMUM PARAMETERS

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It is well known from numerous numerical simulations (see, for example, [1]) and from experiments (see, for example [2]) that electron density nonuniformity in kind of discrete vortices are long-living structures. In experiments [2] a rapid re-organization of discrete electron density nonuniformity has been observed in the spatial distribution of vorticity in pure electron plasma when a discrete vortex has been immersed in an extended distribution of the background vorticity. In plasma lens [3–5] for high-current ion beam focusing a vortical turbulence has been excited in crossed radial electrical and longitudinal magnetic fields by unremovable gradient of external magnetic field. This turbulence is a distributed vorticity. In this paper the amplitude of the vortex saturation in cylindrical radially inhomogeneous plasma in crossed radial electric and axial magnetic fields in the separator of spent nuclear fuel [6] for the optimal parameters are investigated theoretically. It is shown that as the parameters tend to the optimal ones the amplitude of excited vortices tends to zero. This allows to specify a range of parameters of the experimental setup for which the vortical turbulence is suppressed [7].

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7-64

DEPENDENCE OF THE NONEQUILIBRIUM RADIATION OF A PULSED DISCHARGE IN WATER IN THE VISIBLE RANGE FROM THE ELECTRIC FIELD

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The radiation of pulsed discharges in water (PDW) is one of the most important sources of information on the plasma parameters in the discharge channel. The radiation from the PDW channel is a non-equilibrium [1, 2], and the brightness temperature of the plasma channel measured at different wavelengths can differ substantially. The radiation of nonideal plasma (NP), resulting in the erosion magnetoplasma compressor type, also non-equilibrium [3]. The degree of equilibrium deviations from the absolutely blackbody (ABB) radiation increases with increasing electric field. This explains by the appearance of ultrafast non-Maxwellian electrons, which lead to an increase in the radiation intensity having a high energy photons [4].

In [2, 5] nonequilibrium radiation of NP in PDW explained by the influence of the temperature gradient of the outer layers of the plasma channel and by output of short-wave radiation from the deeper layers of the plasma. There the temperature is higher than in the outer layers of the plasma channel. But at the initial stage of the discharge the most intense line of hydrogen Balmer series the H_α (656.3 nm) not been observed (even in the absorption spectrum). Parameter M of a hydrogen plasma inhomogeneity, according to [6], for the H_α line is M = 0.95 (for a continuous spectrum M = 0.91 to λ = 600 nm). Therefore, the influence of non-uniformity of the plasma channel in the plasma emission intensity of hydrogen, according to [6], should be negligible.

The difference in brightness temperatures measured at wavelengths 400 and 700 nm, may differ twice [2], especially at high rates of energy input into the PDW channel.

In this paper we present the results of studies of the effect of electric parameters of plasma channel on nonequilibrium radiation of NP. It is found that the variations of radiation intensity value from the plasma channel are not correlated with the power input to the channel. But the value of the degree of nonequilibrium $\Delta T/\Delta\lambda$ K/nm correlated with fluctuations in power. The highest degree of nonequilibrium is almost always coincides with the first peak current. It was also studied the dependence of the maximum value of the degree of nonequilibrium from: the initial electric field in the discharge, the maximum current in discharge, the electric field in the first current maximum, the length of the discharge gap at a constant initial battery voltage. Possible mechanisms of the observed effect are discussed.

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7-65

APPLICATION OF CONDUCTIVE, DIELECTRIC AND PROTECTIVE COATINGS ON INSULATORS WITH USING ARC DISCHARGE AND HF BIAS SOURCES

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In this article was shown the usage of combined high frequency and arc plasma sources for applying conducting, dielectric and protecting coverings onto different dielectric substrates at low temperatures (50…250 ^{o}C).

The variety of combined sources usage regimes was also studied. The aim of the study was to find the most optimal technological regime of deposition depending on the substrate material. This method provide high deposition rate and gives an opportunity to operate with heat sensitivity substrate such as plastic, glass etc. Plasma filter with open architecture was used to decrease droplet fraction which is the main problem of obtaining high-quality coatings. Assisting high frequency bias played the primary role in deposition process. In case of dielectric as a substrate material there is a problem of accumulated surface charge and usage of the HF bias can handle it.

Experiment was performed on vacuum installation with multi arc plasma sources "BULAT-6M" and high frequency generator. The deposition process divides in two parts: HF-cleaning and deposition itself. HF-cleaning performed under argon atmosphere, at pressures of P_{ar} = 1…5*10^{-1} Pa and bias voltage U_{HF} = -(0,4…1,2) kV. The application of the coating was carried out with feed of negative HF bias on the turntable U_{HF} = -(20…350) V. With different substrates the temperature were controlled to keep in 50…250 ^{o}C. For preventing overheating the impulse regime was used (spattering phase-cooling phase).

Using this method there were obtained: coverings on detectors of ionizing radiation, optically transparent protecting coverings for plastic glasses, connecting coverings on mica for ultra frequency emitter**.** Coverings that were obtained have good adhesion, due to the fact of substrate failure during the tensile test instead of detachment conductor adhesions site.

7-66

KINETICS OF PYROLYSIS OF ETHANOL-AIR MIXTURE

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Currently plasma chemistry provides two main approaches to the reforming of liquid hydrocarbons into synthesis gas: plasma and plasma-catalytic. During plasma reforming, the conversion occurs due to the plasma-chemical conversions that happen in the plasma itself. The feature of the plasma-catalytic approach is the use of plasma only as a catalyst for chemical reactions occurring in high-temperature chemical reactor.

A lot of experimental research was conducted on the technology of plasma-catalytic reforming, but in the most of them, the only controlled parameter was the composition of the plasma-generating gas reagents on the inlet and outlet of the system and only the measurement of plasma emission spectrum was carried out. Thus, the experiment does not give a complete picture of what is happening in the bulk of chemical reactor. This raises the need for conducting the numerical simulation of kinetics for a more complete understanding of the physical and chemical processes in the plasma-catalytic systems.

This work proposes the splitting of the volume in which the reforming takes place into the separate areas in order to simplify the numerical simulation. These areas are the zone of high temperature pyrolysis, the zone of the "activation" of the oxidant by plasma, and the zone of the main processes of the reforming.

Additionally, we conducted the numerical simulation of high-temperature pyrolysis zone (pressure 1 atm, temperature 1100 K). An investigation was conducted on the pyrolysis of the mixture of ethanol and air at the ratio of 1 to 4. Modeling was performed using ZDPlaskin software package.

An analysis of the obtained results can be used to make conclusions about the stages of the pyrolytic reform process. In the first stage, the active radicals are produced by the reaction of C_2H_5O with oxygen. A rapid decrease of oxygen concentration can be considered as a second stage, which can be characterized as the beginning of oxidation (dry) reform. As a third stage, we can consider the period after almost complete disappearance of oxygen during which enough water is produced to indicate possible beginning of a steam reforming.

7-67

REFRACTION OF MICROWAVES IN AN INHOMOGENEOUS ROTATING PLASMA

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Experimental investigations of the plasma in crossed **E×B** fields are of interest for a wide range of physical and applied problems of plasma physics. In particular, it is the investigation of a multicomponent gas-metal rotating plasma being generated in the facilities with crossed E×B films, e.g. in a reflex discharge (Penning discharge) [1]. Among the methods of plasma diagnostics widely used are the microwave methods [2], including the methods based on the microwave refraction in the plasma [3]. The microwave refraction is used to measure properties of the plasma in the plasma column cross-section with an oblique incidence of a probing microwave ray. For this the tilt angle of a horn antenna relatively to the plasma should be varied within a wide range that is not always can be realized. On the other hand, the horn is emitting rays which propagate and pass through different plasma layers. It is possible to use in principle this effect for plasma diagnostics.

So, to extend the possibilities of microwave-based diagnostics for multicomponent gas-metal rotating plasma it is expedient to consider the opportunity of using the refraction of electromagnetic waves in the peripheral layers of the plasma column.

Experiments on the microwave refraction in the plasma were carried out using the device MAKET [1]. In the device a high-power impulse reflex discharge was realized. The horn antennas were mounted in the diagnostic ports, the design of which does not provide the variation of the antenna tilt relatively to the plasma. In this connection we have performed preliminary calculations on the angle of deflection of the ray from the angle of its incidence onto the inhomogeneous plasma using some model functions of plasma density distribution. The calculation results show that in this case the phenomenon of microwave refraction can be used in principle for plasma diagnostics. The average plasma density was measured with a microwave interferometer. A scattered microwave signal was recorded simultaneously with interferometric measurements. In our experiments the microwave scattering at angles of ~ 60º and ~ 120º was observed. Analysis of experimental data shows that in the case of $N_p \geq N_{cr}$ the observed scattered signal is related with the microwave ray refraction in the inhomogeneous plasma. When $N_p < N_{cr}$ the received scattered signal is, from the one side, due to the microwave scattering in the plasma fluctuation, and, on the other hand, due to the probable reflection from the discharge chamber wall.

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8-01

SPECTROSCOPY AND PROBE DIAGNOSTICS OF DC SPHERICAL GLOW DISCHARGE

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There are only few studies devoted to experimental investigations of a spherical glow discharge at the present time (see [1]). Nevertheless, such type of discharge is widely applied for technological processes of nitriding of metallic constructional products surfaces [2]. That is why their study is of special interest. The detail numerical modeling and study of glow discharge in a spherical geometry is fulfilled in the recent paper [3].

The principal feature of a spherical discharge is an absence of the positive column.

The objective of this work is comparison of experimental (probe and spectroscopic) and numerical modeling results that obtained in a glow discharge at pressures up to 150 Pa. The nitrogen and argon plasma was studied since a mixture of nitrogen and argon is used for technological processes of nitriding (nitrogen for surface treatment of materials and argon for improving process efficiency).

The applicability of the Langmuir's probe model was specially identified (according to [4]) in this case up to mentioned 150 Pa. The part of probe investigations of plasma at pressures in the range from 10 to 150 Pa was done in nitrogen and argon in a spherical discharge conditions. Single and double tungsten and stainless steel Langmuir's probes was used. Furthermore, spectral investigations of the emission radiation of plasma were done using a tomographic spectrometer equipped with a high-resolution two-dimensional Hamamatsu Photonics sensor.

The spatial distribution of density and temperature of electrons was defined as well as distribution of an electric field in the electrode gap using probe methods. The radial and spectral radiation intensity distribution was obtained using tomographic spectrometer. The last data were processed using coronary model that allows obtaining the temperature and the density of electrons in plasma and their distribution function at low pressures.

The obtained results were compared with the ones of the theoretical study of the discharge. The character of distribution of the electron density and the electric field shows good agreement with the experimental data, which is indicative of adequacy of proposed in [3] model.

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8-02

HEAVY ION BEAM PROBING-A TOOL TO STUDY GAM, ALFVÉN EIGENMODES AND BROADBAND TURBULENCE IN THE T-10 TOKAMAK AND TJ-II STELLARATOR

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HIBP, the unique diagnostic for core plasma potential, operates in the T-10 tokamak (a = 0.3 m, R = 1.5 m, B_t = 1.5...2.4 T, I_p = 140...330 kA, P_{ECRH} < 1.2 MW) and TJ-II flexible heliac (< a> = 0.22 m, < R> = 1.5 m, B_t = 1 T, $P_{ECRH} \leq$ 0.6 MW, $P_{NBI} \leq$ 1 MW).

The time evolution of the radial profiles from Low Field Side (LFS) to the High Field Side ($-1<\rho<1$) is routinely observed in TJ-II with 127 keV Cs^+ ions in a single shot, while LFS ($+0.2<\rho<1$) profiles are observed in T-10 with 300 keV Tl^+ ions.

Multi-slits energy analyzers provide simultaneously the data on plasma potential φ (by beam extra energy), plasma density (by beam current) and B_{pol} (by beam toroidal shift) in 5 poloidally shifted sample volumes. Thus $E_{pol} = (\varphi_1\text{-}\varphi_2)/x$, x ~ 1 cm, and the electrostatic turbulent particle flux $\Gamma_{\boldsymbol{E}\times\boldsymbol{B}}(t) = 1/B_t\ \tilde{n}_e(t)\ \tilde{E}_{pol}(t)$ are derived. The density oscillations cross-phase produces poloidal propagation velocity of perturbation or plasma rotation.

The fine focused (< 1cm) and intense (100 μA) beams provide the measurements in the wide density interval $n_e = (0.3–5)\times10^{19}$ m^{-3}, while the advanced control system for primary and secondary beams provides the measurements in the wide range of the plasma current in T-10 and magnetic configurations in TJ-II, including Ohmic, ECR and NBI heated plasmas.

Low-noise high-gain (10^7 V/A) preamplifiers with 300 kHz bandwidth and 2 MHz sampling allows us to study broadband turbulence and quasi-coherent modes like Geodesic Acoustic Modes (GAMs) and Alfven Eigenmodes (AEs). The mode spatial location, poloidal rotation velocity and mode numbers for GAMs and AEs were studied in the core plasmas.

The work is a result of the long-term trilateral cooperation between participating institutes.

8-03

NEW CAPABILITIES OF PLASMA POTENTIAL AND DENSITY MEASUREMENTS USING A DUAL HEAVY ION BEAM PROBING (HIBP) DIAGNOSTIC IN THE TJ-II STELLARATOR

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Dual Heavy Ion Beam Probing Diagnostic (HIBP) which was installed on TJ-II stellarator [1] and at the moment is well-adjusted and tuned, give us an opportunity to study the temporal and spatial evolution of density and plasma potential profiles and its fluctuations, along with theirs poloidal and toroidal characteristics. The unique advantage of such aggregation towards HIBP diagnostic is to expand the investigation of multi-scale plasma properties from the edge to the core.

The results reported here mostly concern to the measurement of density and potential correlation in different operating regimes of the TJ-II stellarator. These are pure ECRH or pure NBI heating mode as well as their combinations with varied switch on sequence. We have also investigated the influence of the external biasing voltage applied to the plasma using both HIBPs. The reaction of the plasma potentials versus biasing voltage was analyzed with respect to the asymmetry of potentials, their correlation and coherency.

The Long Range toroidal Correlation (LRC) of potentials from HIBP1 and HIBP2 was observed in the ECRH plasma heating phase at low plasma densities ($\leq 0.5\cdot10^{13}$ cm^{-3}). Moreover the LRC level (coherence between potentials with frequencies less than 20kHz) was pronounced on the potentials ($C_{\varphi1,\varphi2} \leq 0.6$), but not on the total currents (plasma density) ($C_{I1,I2} \leq 0.2$).

In other hand, the poloidal short-range correlation between the slits of each HIBP's shows significant level of coherence for potentials and much higher for total currents. The phase shift between total currents indicates the poloidal plasma rotation velocity.

In ECRH low density regime the potential profile is in electron root (positive plasma potential) and the level of potential fluctuations is high. This fact can describe high level of plasma turbulence and low values of confinement time.

In NBI high density regime the potential profile is in ion root (negative plasma potential). The formation of LRC in pure NBI heated plasma is not so pronounced and it appears quite rare. Some evidence of increase the level of LRC is observed in the transition from Low to High confinement state. During this bifurcation, the plasma almost immediately changes some of its properties. The hydrogen emission drops while the total stored energy is starts to grow. There could also take place the changes in the shape of profiles for the density and temperature, the gradient on the periphery becomes stiffer. During the H mode it was possible to observe the increasing of the potential LRC level in the outer plasma column (Rho ~ 0.6…0.8 LFS) for the both HIBPs in the local point measurement positions as well as between adjacent HIBP´s plasma and probe's floating potential.

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8-04

ESTIMATIONS OF PLASMA POTENTIAL AND DENSITY BY THE HEAVY ION BEAM PROBING DIAGNOSTIC (HIBP) ON THE URAGAN-2M TORSATRON

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By means of the Heavy Ion Beam Probing Diagnostic (HIBP) on Uragan U-2M torsatron were done first estimations of plasma electric potential and density [1]. The HIBP is an unique tool for local plasma potential and density measurements [2]. The measurements were held at torsatron magnetic field value of B_0 = 3.9 kG with Cs ion probing beam energy of 70 and 69.2 keV, ion beam current was 55…65 μA. The plasma potential estimation gives the negative potential value of -90 V. This result has a good correlation with Langmuir probes measurement of plasma floating potential. This potential value is significantly different from positive plasma potential at TJ-II stellarator with ECRH plasma heating with rather small density. But the negative plasma potential was registered at TJ-II with NBI plasma heating [3]. The experimental values of the secondary ion beam current are correlated with average plasma density measured by radio-interferometer ($1{,}25\ldots2.5\cdot10^{12}$ cm^{-3}). The oscillations of the secondary beam current were observed. These oscillations were caused by fluctuations of the torsatron magnetic field.

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8-05

A NEW CONTROL UNIT FOR PROBING ION BEAM FORMING IN HIBP DIAGNOSTIC SYSTEMS

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This paper describes the new modification of control unit for ion beam formation in the heavy ion beam diagnostic system (HIBP). This electronic unit was developed, manufactured and tested on HIBP system of Uragan-2M torsatron [1]. Some new schematics were implemented in this system. These schematic solutions were created on the base of long operations with various feeding and control systems of HIBP for different fusion devices [2]. As a result the new type of electronic control unit that has some advantages was created. It can independently control and measure the emitter heating current and power, extracting and focusing voltages and power supplies currents, the accumulator current and voltage. Independent regulation of the extracting and focusing voltage gives ability to vary focal length of a probing beam, without changing his intensity. This very important property provides both good locality, and considerable size of a secondary signal in experiments. Without having a possibility of such adjustment of primary beam the problem of number restoration plasma density from secondary current practically not solved.

The unit controlling is provided by USB computer port and optical cables which provides the galvanic insulation of high voltage emitter unit of beam injector. This feature allows the implementation of the control unit to any HIBP system.

The system of current control and stabilization based on high frequency (~ 100 MHz) pulse converter with synchronous straightening. This system leads to high efficiency (up to 85%) in the wide range of current control (up to 20 A). This feature is determine the accumulator battery capacity (weight and size) for providing the necessary injector working time with determined emitter heating power during the working day.

This unit is rather small (the computer power supply box with 2 optical ports). It can be easily placed inside any types of electrostatic screens under high voltage injector potential for any HIBP system.

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8-06

STUDY OF GAMS AND TURBULENT PARTICLE FLUX DYNAMICS WITH HIBP IN THE T-10 TOKAMAK

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The new finding in the behaviour of geodesic acoustic modes (GAMs) and turbulent particle flux dynamics on the T-10 tokamak are described. The broadband oscillations of plasma electric potential and density in Ohmic and ECRH regimes are measured by Heavy Ion Beam Probe (HIBP) in the core plasmas. At the periphery, at $r/a > 0.8$, the dominated GAM peak with frequency ~ 14 kHz, and noticeable peak of quasi-coherent oscillations with frequency 40…100 kHz and HFHM ~30 kHz are observed. The noticeable GAM peak is also seen on the frequency resolved turbulent particle flux measured by HIBP and probes. It was found that in the high-density ($n_e \sim 4\times10^{19}$ m^{-3}) discharges during ECRH pulse, causing the energy confinement degradation, the level of broadband fluctuations measured by correlation reflectometry and HIBP decreases. At the same time the amplitude of GAM oscillations of plasma potential increases. The bi-spectral analysis of potential oscillations shows the statistically significant auto-bicoherency at the GAM frequency at the periphery, $r/a > 0.8$, indicating existence of three-wave interaction between GAM and broadband turbulence up to the presently studied frequency band 250 kHz, that points to quadratic character of nonlinearity in GAM generation, e. g. owing to Reynolds stress. This also holds for the cross-bicoherency of potential with density and poloidal magnetic field. For the plasma periphery, the two-fluid model of nonlinear interplay between GAM and small-scale drift turbulence, excited by the dissipative trapped electron mode is proposed. The model includes collisional damping of GAM due to parallel ion viscosity. The modelled GAM amplitude scales with density as $1/n_e$ that is consistent with the experimental observation.

8-07

INFLUENCE OF THE FRAME-TYPE ANTENNA ON THE RF-DISCHARGE PERIPHERAL PLASMA PARAMETERS IN TORSATRON URAGAN-3M

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In $l = 3$, $m = 9$ torsatron Uragan-3M with open helical divertor, the hydrogen plasma is produced and heated by RF fields with use of the unshielded frame-type antenna.
It is known [1], that far away from antenna, the potential, which induced in peripheral plasma by RF antenna, is small. This potential doesn't affect noticeably the plasma parameters. However, near the antenna the essential variation of potential, temperature and density of electron was revealed.

The Uragan-3M frame-type antenna may be regarded as a probe with RF potential applied.
Specifics of probe measuring in magnetic field were investigated earlier in many works, for example, [2–3]. Analysis of RF fields and currents rectification effect on nonlinear conductivity of spatial charge layers in low-pressure RF discharges was presented in works [4–5].

This report deals with qualitative evaluation of the potential of self-consistent electric field, together with stationary distributions of the hydrogen ion and electron densities in the vicinity of the RF antenna.
The results of this work give better understanding and further inquiry of processes, which take place in torsatron Uragan-3M in direct closeness from the frame-type antenna.

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8-08

BEHAVIOR OF SUPRATHERMAL ELECTRONS AT THE URAGAN-3M TORSATRON AFTER RF HEATING OFF

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The microwave radiometry is a well-known diagnostics to obtain the information on temporal evolution and radial profile of the electron temperature at Uragan-3M (U-3M) torsatron plasma experiments. However, under low plasma density we observe the high level of electron cyclotron emission at the frequencies that match the second and third harmonics of the extraordinary mode after RF heating pulse off. This effect could be explained with the production of the suprathermal electrons in U-3M plasmas. Study of the behavior suprathermal electrons is of great importance because: (a) suprathermal electrons significantly distort or make it impossible to measure the electron temperature; (b) such electrons influence the ionization process, the excitation of the plasma ions and may lead to the occurrence of several plasma instabilities.

The occurrence of the suprathermal electrons in U-3M plasmas not only restricted by RF heating pulse time, but at the ramp-up (rump-down) of the main magnetic field. It was found that maximum intensity of the ECE observed on the rising edge of the magnetic field pulse. For this condition electrons go over to a state of continuous acceleration since their dynamic friction force is less than the force exerted by the electric field. To investigate of this dependence on varied magnetic field we deliberately shift the RF heating pulse to the beginning of decay stage. This is led to significant increase in the afterglow radiation, observed by ECE. Moreover it was found a clear correlation in the behavior of signals from 140 GHz interferometer (line electron plasma density), SHR/HXR emission, spectroscopy (H_α) and plasma current (Rogowski coil).

The temporal traces of the different diagnostics show clear correlated peaks which could attribute as the impact of the suprathermal electrons on construction elements with subsequent ionization ejected impurities. The effect of working gas ionization by the suprathermal electrons has been registered as well.

Further detailed studies of suprathermal electrons dynamics in U-3M plasma will be carried out during next experimental compaign at the magnetic field rump-up phase.

8-09

FIRST MEASUREMENTS OF LINE ELECTRON DENSITY IN URAGAN-2M PLASMAS VIA 140 GHZ HETERODYNE INTERFEROMETER

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At any plasma fusion experiment it is always desirable to have diagnostics which can provide reliable data requiring a minimum of interpretation. Interferometry is such a diagnostic for the measurement of the electron density, since the phase shift depends only on the electron density. At the beginning of the last Uragan-2M (U-2M) experimental campaign (March 2016) 140 GHz (2 mm) super-heterodyne interferometer has been installed for the 'routine' line density measurements on 'every shot' basis. For the U-2M plasma conditions theoretical and practical problems arising in the application of microwave interferometry to density measurements on transient plasmas are discussed. This interferometer has a very low level of the phase fluctuations of the output signal. This feature has been achieved by utilizing IMPATT diodes in the high order multipliers and up-converters. To avoid the influence of signal fluctuations on the accuracy of the phase measuring there used the quadrature processing on the intermediate frequency and the amplifiers with automatic gain control system. The phase drift of the output signal modulo does not exceed 1 degree and a dynamic range for receiving signal is about 40 dB.

The sensitivity of the interferometer allows to operate at low plasma density ($10^{10}…10^{11}$ cm^{-3}) and detect timing of the RF heating plasma 'breakdown'.

Experimental data from different U-2M operational regimes are presented. In the case of the plasma conditioning discharges at low magnetic field ($B_0 = 0.01T$) and low density strong (amplitude modulation of 60…80 %) 'saw-tooth like' fluctuation has been observed. In the 'standard' U-2M discharges with higher magnetic field, and $B_0 = 0.35T$ the quasi-coherent density fluctuations from 3 kHz to 24 kHz are observed.

All those fluctuations at the various plasma densities are well correlate with the modulations of the signals from H_α and SXR diagnostics, which are measured corresponding emissions along different chord lines in different plasma crossection.

8-10

THE QUALITATIVE ANALYSIS OF THE COMPOSITION OF THE PLASMA RF DISCHARGE BY MEANS OF MASS-SPECTROMETRY

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Plasma in gases, which contain halogens in pure form or in admixtures with other gases, is widely used for plasma-chemical processing of different semiconductor materials. The mixtures of the gases containing halogens most often used with the addition of oxygen (O_2). The chemical processes occurring in PCR are multivariate and extremely complex. Probe techniques do not allow to fully understand the component composition and to determine the main parameters of chemically-active of the plasma of high- frequency discharges.

The mass spectrometry is one of the most effective methods of the control of plasma-chemical processes that occur in the PCR. This method of analysis of the plasma environment allows determining the qualitative composition of plasma and choosing the most effective operating conditions of the discharge processes for optimum etching of technological layers.
Researches of chemically-active plasma were performed on the plasma-chemical reactor with the closed electron drift. The mass spectrometer MX-7304 was used to obtain mass spectra of chemically active gases formed in the reactor chamber. In this work we used the following gases: Sulfur hexafluoride (SF_6), Freon-14 (CF_4), Freon-218 (C_3F_8) in a mixture of oxygen (O_2).

Analysis of the mass spectrograms shown that common to all is the presence of residual gases. Depending on the oxygen content in the PCR chamber was observed decrease in the intensity of the primary product of the working gas reactions, which talks about an increase in the number of oxidation reactions.

The research of freons showed the presence of carbonyl radicals and their decrease depending on the oxygen content. The toxic substances were found which could threaten human health. The gas composition and regimes of discharges were selected under which harmful substances are practically not observed.

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