INCREASING THE VOLTAGE MULTIPLICATION FACTOR ON A DIRECT ACTION ACCELERATOR WITH AN INDUCTIVE ENERGY STORAGE AND A PLASMA OPENING SWITCH

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The conditions for increasing the discharge voltage multiplication factor k_{ind} on a small-sized direct-action electron accelerator with an inductive energy storage and a DIN-2K plasma opening switch are considered. The determinative influence of the discharge voltage of the main discharge circuit, its inductance and vacuum conditions are determined. It is established that the largest values of $k_{ind} = 8$ are obtained with a correspondingly selected balance of electrophysical and vacuum conditions, namely, an increased discharge voltage of the main circuit, under the conditions of its minimum inductance, with an increased number of symmetrically located plasma guns with experimentally selected discharge voltage values and at a vacuum less than 10^{-4} Pa. Technological possibilities for further increasing k_{ind} are considered.

PACS: 52.75.−d, 94.20.wc, 52.80 Vp, 52.70Kz, 29.30Ep

INTRODUCTION

The acceleration of charged particles with a plasma opening switch (POS) based on inductive energy storage (IES) has achieved wide development, which continues today, just like last year [1–7]. The direct-action electron accelerator (DAEA) with the inductive energy storage (IES) cell and plasma opening switch (POS) DIN-2K, shown in the Fig. 1, is used for those application fields that require small overall dimensions and appropriate weight characteristics of the accelerator that ensure its maneuverability and the possibility of placement on moving platforms. A wide range of industrial, defense applications and fundamental research confirms the demand for accelerators of this type and the interest in them among scientists around the world [1–14].

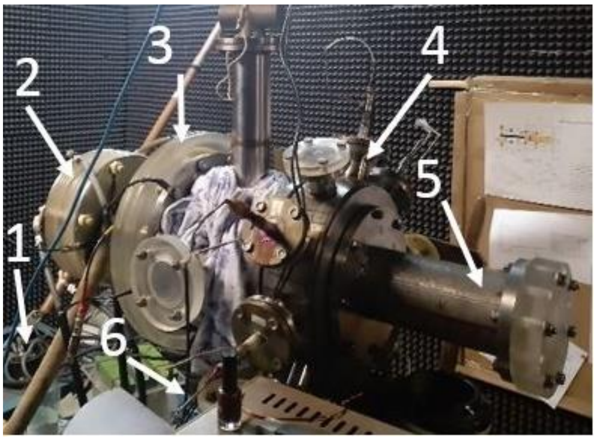

Fig. 1. General view of DAEA DIN-2K:
1 – pulsed low – inductive capacitor 50 kV/3 μF of the main discharge circuit which feeds the IES;
2 – high-current controlled atmospheric pressure discharger; 3 – high-voltage insulator between the cathode and the anode chamber; 4 – plasma guns block which creates the POS plasma; 5 – waveguide;
6 – diffusion vapor-oil pump

The DIN-2K accelerator is currently intended for the study of electron beams, virtual cathodes and phenomena associated with their occurrence [15–20].

The key factor influencing the possibility of explosive emission from the end of the cathode and, as a consequence, the electron beam, and then the virtual cathode, is the induced voltage.

Thus, the determination of the discharge voltage multiplication factor k_{ind} and as a consequence an increase the magnitude of induced voltage is an important scientific task that ensures the successful implementation of many technological processes.

The objectives of this research are to establish the ranges of discharge voltage of the primary circuit of pulsed current generator, the ratio of the discharge voltage of the main discharge circuit to the discharge voltage of the electric circuit of plasma guns and the influence of vacuum on the change in the discharge voltage multiplication factor k_{ind}.

EXPERIMENTAL PART

To determine the multiplication factor k_{ind} of the discharge voltage in each individual pulse, the system inductance was calculated. The inductance was determined by the geometric dimensions of the coaxial electrode system and the location of the conduction channel formed in the POS plasma. In each pulse, the conduction channel could differ both in size and in the location of the cathode-anode connection, which determined the difference in the L values. By the method of successive approximations, the front of the calculated curve was achieved to coincide with the front of the experimental I_{PCG} current oscillogram. The final inductance was determined by the Thomson formula:

$$L = \frac{T^2}{4\pi^2 C}, \qquad (1)$$

where L – inductance; T – oscillation period; C – capacitance of the capacitor in the main discharge circuit.

A steeper front corresponded to lower inductance values, the comparison was made by the angle inclination α of the front curve, see Fig. 2.

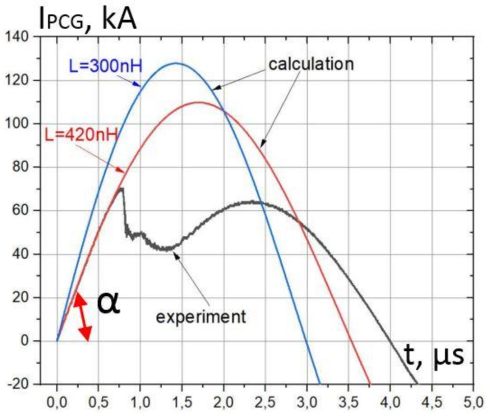

Fig. 2. General view of the characteristic experimental current curve and calculated curves created to determine the inductance of the energy storage device

Fig. 3 presents typical current oscillograms by which the parameters of the energy accumulation stage in the IES, the stage of the opening of the POS and the stage of releasing residual energy are determined.

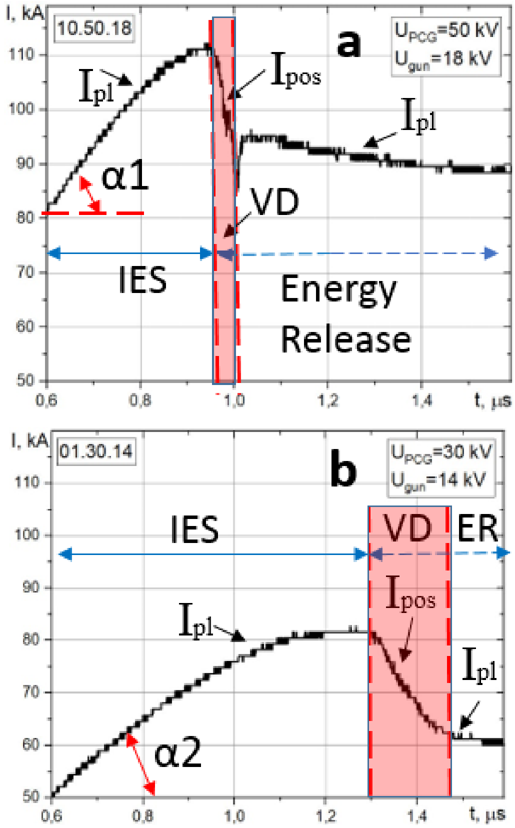

Fig. 3. Typical current waveforms, which determine the parameters of the energy accumulation stage in the IES, the stage of opening the POS, and the stage of releasing residual energy. a – U_{PCG} – 50 kV, U_{PG} – 18 kV; b – U_{PCG} – 30 kV, U_{PG} – 14 kV; at pressure $P = 10^{-3}$ Pa

As can be seen from Fig. 3, by selecting the discharge voltage of the main discharge circuit that feeds the coaxial electrode system and the discharge voltage of the plasma gun circuit, both the energy accumulation time and the energy that will be released in the load presented by the vacuum diode can be controlled. As can be seen from the oscillograms, at lower voltages the energy accumulation time increases, it can be up to 1.3 µs and more. The total current I_{PCG} that determines the level of accumulated energy in the IES is approximately 25 % less than at increased discharge voltages of the main circuit and the plasma gun circuit. The opening time decreases from 160 to 40 ns when the discharge voltages increase from 30 to 50 kV. In the case where α1 is less than α2, the inductance of the discharge circuit will be less.

The higher values of the discharge voltage of the main discharge circuit and the discharge voltage of the plasma gun circuit and corresponding ratio between them is established empirically:

$$2{,}5 \le \frac{U_{PCG}}{U_{PG}} \le 4. \qquad (2)$$

It is possible to achieve higher values k_{ind} of induced voltage and thus obtain higher k_{ind}. After opening of the POS and release of the energy accumulated in the IES in the load presented by the accelerating vacuum diode, there is a sudden increase in voltage. Provided that value of U_{ind} exceeds some critical value, then there is a further initiation of explosive emission of electrons with the formation of an electron beam from the end of the cathode. For reliable formation of an electron beam and additional phenomena associated with it, such as the emergence of a virtual cathode, it is necessary to have as large values of k_{ind} as possible [7].

The current flowing through the coaxial electrode system of the accelerator at the initial stage of the development of physical processes acts as a source that pumps the inductive accumulator with energy. At this moment, the current flows through the plasma formed by the plasma guns. During the opening of the POS, there is a sharp increase in the plasma resistance and a corresponding change in the current $\frac{dI(t)}{dt}$. The electronic component of the plasma is largely excluded from the current transport process and the current flows mainly due to the ionic component of the plasma. Ions have three orders of magnitude lower mobility and at this moment a sharp drop in current is observed on the oscillogram, while the plasma breaks and a vortex electromotive force (EMF) arises, which forms a voltage pulse. It is many times greater than the primary EMF. In the case of the formation of an electron beam, energy is spent on ensuring its acceleration and movement in the waveguide space. When the beam is compensated by plasma, the remaining energy is released and a periodic decaying discharge is observed. The process of energy distribution and the path along which the current flows can be schematically represented by schematic expression 3.

$$I_{PCG} = I_{PL} \xrightarrow{IES} I_{POS} \xrightarrow{ER} I_{beam} \xrightarrow{ER} I_{PL}\,. \qquad (3)$$

The induced voltage is determined by equation (4):

$$U(t) = -L\frac{dI(t)}{dt}, \qquad (4)$$

where L is the inductance of the primary circuit and $\frac{dI(t)}{dt}$ is the time derivative of the current.

Fig. 4 shows typical waveforms of current during opening of the POS, the current of the formed beam and the induced voltage calculated by (4). As can be seen, the increase in voltage begins simultaneously with the decrease in current, while the electron beam is not formed immediately, but only at a certain critical, suf-ficient value of the already induced voltage. In this case, this value is about 150 kV and the coefficient $k_{ind} = 3$.

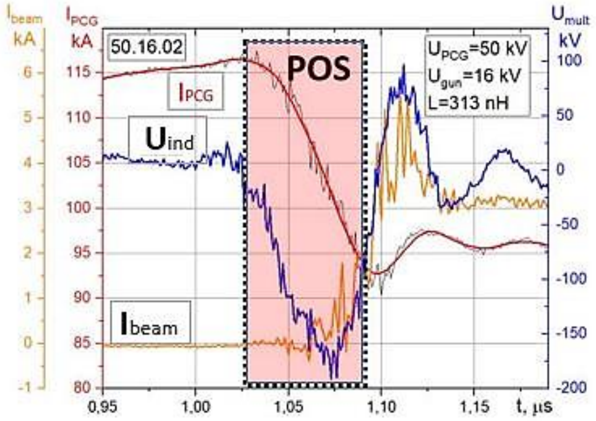

Fig. 4. Typical current waveforms during disconnection of POS – I_{PCG}, current of the formed beam – I_{beam}, Induced voltage calculated by formula (4) – U_{ind}

A series of pulses was prodused in the voltage range from 30 to 50 kV. From the analysis of a statistical sample consisting of 10 pulses at each of the values of the discharge voltage of the main circuit U_{PCG} an approximation curve was constructed in the form of a fourth-order polynomial, which allowed to determine the existence of two conditional zones.

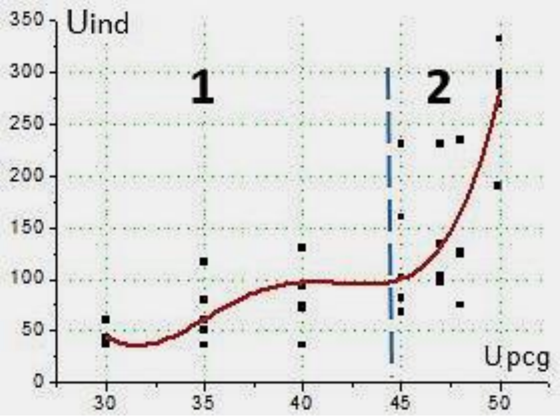

Fig. 5. Curve of the induced voltage versus the discharge voltage of the main circuit $P = 10^{-3}$ Pa

The first zone is where the *kind* coefficient does not exceed 3 and this is typical for discharge voltages less than 45 kV. The second zone is where k_{ind} ranges from 2.5 to 7.

Based on the statistical processing of experimental pulses at a pressure of $P = 10^{-3}$ Pa, a second-order polynomial approximation was constructed using the least squares method. It can be seen from Fig. 6, that there is an almost linear increase in k_{ind} with increasing discharge voltage.

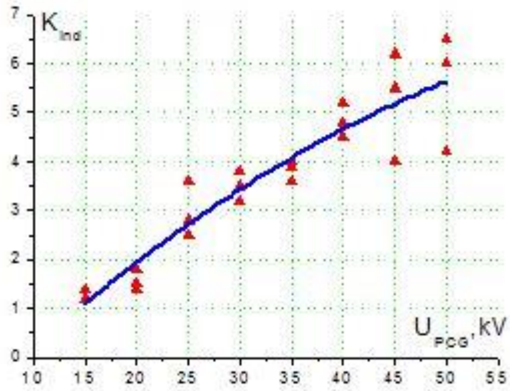

Fig. 6. Dependence of the multiplication factor of the discharge voltage on the discharge voltage of the main discharge circuit at a pressure of $P = 10^{-3}$ Pa

To determine the effect of pressure in the accelerator chamber on k_{ind}, experiments were conducted in the entire possible range of vacuum values from atmospheric pressure to high vacuum of $5 \cdot 10^{-5}$ Pa (Fig. 7).

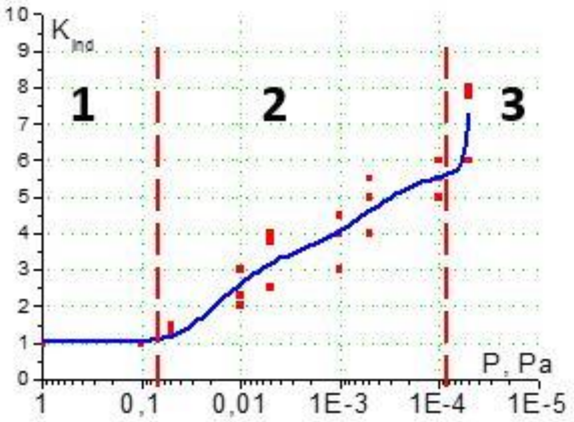

Fig. 7. Dependence of the multiplication factor of the discharge voltage on the values of the vacuum in the accelerator volume. For U_{PCG} – 45 kV and U_{PG} – 16 kV

It is possible to define three conditional zones where the multiplication factor of the discharge voltage k_{ind} behaves differently. The first zone with a vacuum worse than $7 \cdot 10^{-2}$ Pa, where the opening of the POS does not occur, or is unlikely and therefore the voltage increase does not occur. The current of the I_{PCG} discharge circuit flows through the plasma formed by plasma guns and as a result of a large amount of residual neutral gas, energy is spent on the ionization of neutrals and its heating. The second zone is characterized by an almost linear increase in k_{ind} and changes to pressure values of $9 \cdot 10^{-5}$ Pa in the range of values 1.4…5.5. When switching to vacuum values above $6 \cdot 10^{-5}$ Pa, a rapid increase in k_{ind} to 8 is observed.

CONCLUSIONS

During the experiments, the influence of the discharge voltage on the value of k_{ind} was determined. It was established that the dependence is almost linear and in the range of possible discharge voltages up to 50 kV, it is desirable to strive to produce pulses at higher voltages, which in turn imposes additional requirements on the insulation characteristics of the accelerator units.

The ratio range of discharge voltage values of the main circuit and the plasma gun circuit has been established, ensuring the highest values of k_{ind}.

It was determined that there is a synergy of using a discharge voltage of more than 45 kV in conjunction with vacuum conditions where $P \geq 5 \cdot 10^{-5}$ Pa, which allows to obtain discharge voltage multiplication factors from 4 to 8.

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ПІДВИЩЕННЯ КОЕФІЦІЄНТА МНОЖЕННЯ НАПРУГИ НА ПРИСКОРЮВАЧІ ПРЯМОЇ ДІЇ З ІНДУКТИВНИМ НАКОПИЧУВАЧЕМ ЕНЕРГІЇ І ПЛАЗМОВИМ КОМУТАТОРОМ СТРУМУ

Д.В. Вінніков, О.М. Озеров, В.В. Катречко, В.І. Ткачов, Б.О. Бровкін, С.В. Марченко, І.М. Оніщенко

Розглянуто умови підвищення коефіцієнта множення розрядної напруги k_{ind} на малогабаритному прискорювачі електронів прямої дії з індуктивним накопичувачем енергії та плазмовим комутатором струму DIN-2K. Визначено як визначальний вплив розрядної напруги основного розрядного контура, його індуктивності та вакуумних умов. Встановлено, що найбільші значення k_{ind} =8, отримуються при відповідно підібраному балансі електрофізичних та вакуумних умов, а саме підвищеній розрядній напрузі основного контуру, за умов його мінімальної індуктивності, зі збільшеною кількістю симетрично розташованих плазмових гармат з обраними експериментальним шляхом значеннями розрядної напруги та при вакуумі не гірше 10^{-4} Ра. Розглянуто технологічні можливості для подальшого збільшення k_{ind}.