COMPLEXES ON THE BASIS OF HIGH-CURRENT LINEAR INDUCTION ACCELERATORS AND PULSE NUCLEAR REACTORS

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In VNIIEF there were proposed and have been developed since the mid-sixties high-power pulse high-current induction accelerators (LIA) of electron beams called “ironless” because large ferromagnetic cores are not applied in them. The most significant peculiarity between LIA and direct-action accelerators consists in generating rotational electric accelerating field in the cavity between two segments of the common toroidal “grounded” metal surface of a single typical accelerator – inductor – or a group of them. Thus, all electrodes in the accelerator guide occur under “ground” potential. The accelerating system is formed by a consequent location of such inductors. The lack of full accelerating voltage does not provide principal limitations for the energy of particles acceleration. The real energy in LIA is defined only by the size and cost of the installation as well as by the solution of the problem of high-current beams efficient transportation over long distances.

The first experimental accelerator LIA-2 (2 MeV, 2-25 kA, 35 ns) was put into operation in 1967 [1,2]. The electric energy was accumulated in the circularly positioned capacitors (total capacity 60 nF, 50 kV) which formed together with a multi-spark gap and connecting disc-shaped conductors a primary low-inductive (~12 nH) contour of each inductor embraced by the secondary torus-shaped contour. At the capacitors discharge to the first contour inductance there was initiated the alternating magnetic flux closed around the accelerating area. The accelerating system 4 meters long was formed of 48 inductors of this kind; the switches were turned on with the scatter less than ± 2 ns as related to the initial pulse. To limit radial expansion of the beam in the accelerating guide there was created a longitudinal magnetic field of up to 0.5 T induction. The accelerator demonstrated stable and consistent serviceability at about 60 closures per shift and confirmed good prospects for the development of the above-type accelerators. The documentation for LIA-2 was transferred to ITEP (Moscow) where there was created a similar accelerator on which physics investigations have been performed within more than 10 years since 1973. More detailed information on LIA-2 can be found in [3].

In 1967 there was advanced a more powerful LIA with the inductors on radial lines (RL) where the decisive role was played by electromagnetic wave processes. RLs serve as energy accumulators and at the same time as a shaper of accelerating field pulses. In 1971 there was substantiated and initiated the development of LIA-30 accelerator (see below) and some time later – of LIA-10 accelerator (14 MeV, 40 kA, 20 ns); the latter was put into operation in 1977 as the first world example of such powerful high-current installation. It contained 48 inductors (16 blocks) with water-insulated RLs charged within 0.8 μs up to 500 kV. RL was commutated in each inductor with the scattering of ±1 ns by a circular switch composed of 8 trigatrons. The first four blocks served as power source for the electron beam injector. The consequent connection of blocks formed the accelerating systems with the single guide and the longitudinal magnetic field induction in it of 0.5 T. Additional information on LIA-10 is available in [3,4]. The accelerator of LIA-10 type was reproduced in NIIP (Lytkarino) and is being used for radiation researches.

In 1988 there was put into operation LIA-30 accelerator with the highest for the installations of this type electron energy of 40MeV. Along with the typical mode LIA-30 provides for the mode of generating two consequent high-power bremsstrahlung pulses per one operation cycle with the regulated boundary energies (their sum is ≤ 40 MeV) and inter-pulse interval of 0.2 – 2 μs. By changing the inductors switch-in time program the shape and duration of bremsstrahlung pulses vary in the accelerating pulse and, in particular, the short (~7ns) bremsstrahlung pulse with 3 ns increase obtained. There are elaborated and applied the promptly re-organized acceleration modes with boundary energies of 4, 6, 15, 25 and 40 MeV. The LIA-30 operation was investigated at its characteristics change within the following intervals: injected beam diameter - 100-300 mm, injection energy – 2-7 MeV, current amplitude – 50 – 180 kA.You may also find information on LIA-30 in [3, 5, 6].

It is proposed to apply in LIA stepwise forming lines (SFL) with discrete change of impedance to more efficiently use energy in inductor storages and to simplify high-voltage commutation systems. Through the wave processes realized in SFL the several-time increase of accelerating voltage in the inductor is provided as compared to the charging voltage. There is developed a set of low-energy installations with such SFL; they are: STRAUS (2.7 MeV, 15 kA, 40 ns), STRAUS – 2 (3.3 MeV, 50 kA, 40 ns), I – 3000 (3.5 MeV, 20 kA, 16 ns) [7], the new high-power accelerator LIA – 10M (1994, 20 MeV, 50 kA, 20 ns). It contains only 16 inductors, the number of trigatrons in them is decreased by 20% as compared to this value for LIA-10; the system of control voltage pulse shaping for the switches is considerably simplified as well. More detailed information on LIA-10M accelerator is given in [3, 8, 9].

After our publications there started the development of such LIA in the USA with reference to the priority of VNIIEF. In particular, in Sandia Laboratories there was created an accelerator called RADLAC-1; the parameters of its electron beam are as follows: 9 MeV, 25 kA, 25 ns [10].

Since the early sixties there had begun in VNIIEF the development of VIR – 1 aperiodic pulse nuclear reactor (PNR) with the soluble core and BIR – 1 reactor with the core of uranium-molybdenum alloy; these reactors were put into operation in 1964 and in 1965, correspondingly. Then, there were consequently created the following reactors: BIR – 2M, TIBR, BIGR, VIR – 2M etc., whose characteristics along with some investigation results are presented in review [11].

A large experience in operating such reactors predetermined the development of LIA – PNR complexes. The first complex of this kind (LIA – 10 – GIR) was put into the experimental operation in 1984. GIR reactor had a spherical core surrounded by the neutron reflector in the form of a cap with the walls 60 mm thick made of homogeneous mixture of polypropylene and cadmium oxide, what insured the increase of GIR gamma-radiation and reduced the core disturbance by external devices. To work with a beam of LIA-10 it was made in a reflector a through window 200 mm in diameter. In this window there is created a maximum fluence of neutrons in $\sim\pi/4$ solid angle as related to the core center. The lower half of the core represented a block of rough regulation of reactivity. A cylinder made of brass that displaced relatively to the core lower part surface served as a block of precise regulation. The pulse generation was implemented at the introduction of uranium rod displaced in the central axial channel of the core. The fuel occurred inside the pressurized jackets made of stainless steel. A more detailed information on GIR is given in [11, 12].

Two versions of neutrons initiating source realization have been experimentally studied:

- irradiation of the external relatively to GIR target by the electron beam what creates bremsstrahlung and photoneutrons in it; initiation of fissions in the core was realized through the neutrons from the external core as well as through the photoneutrons in the core itself affected by bremsstrahlung from the target;
- irradiation by the extracted electron beam of the external core surface directly and generation of photoneutrons in the core itself.

Over the period from 1984 to 1990 there were solved on the complex the basic science and technology problems and elaborated the problems of the installations joint stable functioning. The typical energy output per pulse constituted ~2 MJ (number of fissions in the core is $\sim 6{\cdot}16^{16}$). In the table there are generalized the characteristics of LIA-10-GIR complex.

In connection with the perfection of LIA-10 and its replacement by LIA – 10M accelerator there was also developed a new GIR2 reactor for LIA – 10M – GIR2 complex. Basic characteristics of the complex are given in table. The core was designed of hemispherical components in pressurized jackets of stainless steel. The upper part of the core is an immobile block, its external shell is made of $36\%^{235}U$ + Mo alloy while the lower one – of $90\%^{235}U$ + Mo alloy. Power control was implemented with the aid of two lower blocks displaced relatively to each other and to the upper part. Generation of a fission pulse was realized at high-speed pass of the pulse block from A1 in the central axial channel. The block parameters are as follows: diameter – 65 mm, length – 400 mm, flight rate – 15 m/s. The reflector of the core is of the same type as in GIR. Additional information on the complex is contained in [11, 13].

On the basis of LIA – 30 and BR – 1 reactor with a compact metal core which had been autonomously put into operation in 1978, there was created a complex and provided stable functioning of two intricate physics installations both in the mode of joint synchronous operation and in the mode of BR functioning as booster – multiplier. The core of BR-1 is made of thin-walled (≤ 15 mm) freely suspended and unfastened elements what makes it possible to increase specific energy output through the reduction in them of thermal stresses associated with the pulse character of loading and non-equilibrium space distribution of the field of temperatures. The pulse with the number of fissions equal to $4{\cdot}10^{17}$ was stated to be the maximum pulse for the operation, it corresponds to the jump of temperatures up to 700 °C in the hottest segment of the core.

At the core location on the axis of LIA accelerating guide there is provided at a distance of 0.9 m from the core center to the target a stable regulated functioning of the installations with their bringing to maximum autonomous parameters. The target device was designed of a composite W powder-based disc 3 mm thick and 430 mm in diameter giving rise to bremsstrahlung and the adjacent disc of ^{238}U dioxide (of natural isotopic composition) 40 mm thick and 300 mm in diameter in a thin-walled shell of stainless steel. The yield of neutrons from the target constituted ~ $1{\cdot}10^{14}$neut/pulse. As well as in autonomous mode, BR-1 generates a neutron pulse with the duration of ~60 μs (at half-height) with the energy output of $3{,}6{\cdot}10^{17}$ fissions in the core ($5{\cdot}10^{17}$ leakage neutrons).

Under booster mode of BR-1 there served as a target for bremsstrahlung generation only a composite disc 3.6 mm thick. The disc of UO_2 was missing. There was investigated BR-1 operation at the change of Q coefficient of the reactor system by prompt neutrons from 100 to 4500. Within this range the yield of Y neutrons per pulse will comply with the ratio $Y\approx 5{\cdot}10^{12}{\cdot}Q$, while the pulse duration on half-height – with the ratio $\tau\approx 10^{-2}{\cdot}Q$ (μs). For example, at Q=2570 there were experimentally found $\tau\approx 25$ μs and $Y\approx 1.4{\cdot}10^{16}$. You may find more information on LIA-30-BR-1 complex in [11, 14, 15].

A wide set of researches in insuring joint functioning of the installations in synchronous and booster modes as well as in studying short- and long-pulse effects of gamma- and neutron radiations to different objects was realized on the above complexes.

№	Characteristics	Complexes		
		LIA-10-GIR	LIA-30-BR-1	LIA-10M-GIR2
1	Year of putting into operation	1984	1991	1994
2	Core material	^{235}U + Mo alloy	90%^{235}U + Mo alloy	Components of 36%^{235}U + Mo and 90% ^{235}U + Mo alloys
3	Core mass, kg	64	176	178
4	Core shape	Sphere ∅ 200 mm	Cylinder ∅ 270 mm h=270 mm	Sphere ∅ 300 mm
5	Initial number of neutrons in the core provided by the accelerator	$(1\text{-}4)\cdot 10^{10}$	$\leq 10^{13}$	$2\cdot 10^{12}$
6	Duration of initial neutron pulses, ns	~15	~20	15; 30
7	Energy output per pulse, MJ	≤2	≤11	7
8	Number of fissions in the core	$\sim 6\cdot 10^{16}$	$\leq 4\cdot 10^{17}$	$2.7\cdot 10^{17}$
9	Neutron fluence on the core surface, neut/cm^2	10^{14} in the reflector window	$\leq 3.5\cdot 10^{14}$	10^{14} in the reflector window
10	Gamma-radiation dose on the external core surface, Gy	600	500	600
11	Neutron pulse duration (half-height),µs	300	≤60	300

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