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STATUS AND DEVELOPMENT PROSPECTS OF CHARGED-PARTICLE ACCELERATORS IN RFNC-VNIIEF

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Since the sixties of the twentieth century, a large experimental and test base of facilities and complexes have been developed in RFNC-VNIIEF. It allows studies of radiation hardness for electronic component base and electronic radio equipment (ERE), radiographic examinations of fast processes, nuclear physics researches. Experimental and test base of RFNC-VNIIEF is a federal importance base and provides needs of enterprises: state corporation (SC) “Rosatom”, Department of Defence, Department of Industry and Trade and SC “Roscosmos”. The base involves pulse high-current electron accelerators, pulsed nuclear reactors (PNR), linear resonance electron accelerators, electrostatic tandem accelerator EGP-10, plasma pulsed neutron radiation generators. Irradiation complexes are developed on the basis of linear induction electron accelerators (LIA) and PNR.

Accelerator LIU-30 [1-3], which is a basic facility for a multipurpose irradiation complex PULSAR [4, 5], was put into operation in 1988. The accelerator allows to produce accelerated electrons with the energy up to 40 MeV (record for its facility class) and beam current ~ 100 kA with pulse width ~ 20 ns. Furthermore, the facility is one of the most high-power sources of bremsstrahlung (BR) short pulses in the world. The common view of LIU-30 accelerator is given in Fig. 1.

Figure 1: Overall view of LIU-30 accelerator.

At present LIU-30 acceleration system is arranged as a 32-module structure with an independent power supply and module control for each module. Each module of the accelerating path contains one unit comprised of four inductors with on water insulated radial lines, possessing a common accelerating tube.

Besides 32 modules, the accelerator structure comprises transport system and output device with a target providing stable beam transport and BR field formation in the irradiation hall of PULSAR complex. The accelerating system length ~ 23 m, both with transport system ~ 30 m, width ~ 9.5 m, height ~ 4 m.

The most steady BR generation mode is optimized at beam current amplitude 70 kA, when BR dose per a pulse at a distance 1 m from the target is ~ 4.5 kR, average dose rate ~ $2.5\cdot10^{11}$ R/s at BR pulse half-height duration ~ 18 ns.

The system of electron beam compression at the output of the transport guide can be attached for a radial beam compressed by a magnet field enhancing along the axis, what allows generation of a dose ~ 240 krad (thermoluminescent detector) and BR dose rate ~ $1.5\cdot10^{13}$ prad/s in a spot with the area of ~ 100 cm^2 with irradiation heterogeneity 50 % at radiation pulse length $\tau_{1/2}\approx16$ ns [6].

In the period from 2006 to 2015 without stops in facility operation accelerating units of inductors and transport guide section have been sequentially upgraded; as a result the reliability and functioning steadiness of LIU-30 accelerator [7, 8] have significantly grown.

Basic facility of the irradiation complex LIU-10M-GIR2 is a linear induction accelerator LIU-10M [9, 10]. The accelerator is manufactured on the basis of VNIIEF developed step-like forming lines. As a result of wave processes, output accelerating voltage a several times higher compared to the line charge voltage. The accelerating system (Fig. 2) consists of injector, 16 typical accelerating modules, each involving one inductor, the transport electron beam guide of 4 m length and the output device with a target unit. Dimensions of the accelerating system without the transport guide – (12×3.5×2.4) m^3. Diameter of inductors – 1.1 m, axis dimension – 0.58 m.

At a 1 m distance from the target the BR pulse dose rate, generated by the accelerator is $4\cdot10^{10}$R/s at half-height duration from 10 up to 20 ns. At the electron beam compression mode near the accelerator target the obtained BR dose rate is ~ $4\cdot10^{12}$R/s in the spot of diameter 8 cm at pulse length (15 ± 3) ns. In this case BR dose approaches ~ 60 kR. Boundary energy of accelerated electrons and, respectively, BR quantum approaches 25 MeV.

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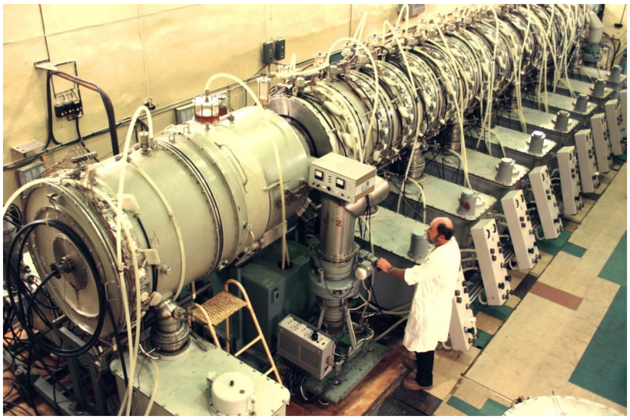

Figure 2: Overall view of LIU-10M accelerator.

For the purpose of providing a more full simulation of penetrating radiation effect, the both complexes are additionally upgraded by supplementary electric and physical facilities: pulse electron accelerator STRAUS-2 [11, 12] and small-size pulse electron accelerator ARSA [13], located in irradiation complex halls. Furthermore, the irradiation complex PULSAR is additionally rigged by two X-ray pulse generators ILTI-1, an X-Ray static facility URS and linear resonance electron accelerator LU-7-2 [14].

The accelerator STRAUS-2 was developed on the basis of a five-cascade double step-like forming line with water insulation and an outer diameter 1.3 m. The beam current amplitude is ~ 50 kA in the accelerator operation mode with ultimate electron energy ~ 3 MeV. The BR dose rate at a distance 1 m from the target is 10^9R/s, the one near the target – up to 10^{12} R/s at half-height duration ~ 20 ns. A specific feature of STRAUS-2 accelerator of PULSAR complex (Fig. 3) is the fact that all facilities are mounted on the platform moved by a crane.

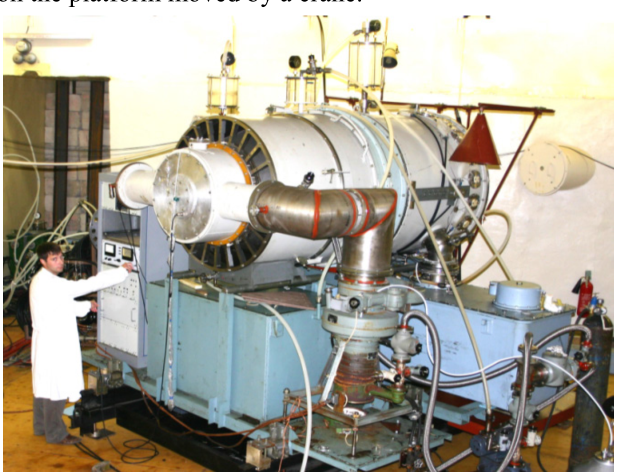

Figure 3: Overall view of STRAUS-2 accelerator of PULSAR irradiation complex.

The small-size accelerator ARSA (Fig. 4) is intended for simulation of a pulse gamma-radiation effect on ERE. Accelerator dimensions: diameter 0.2 m, length – 0.9 m. Synchronization accuracy with other electrophysical facilities ± 12 µs. A base of ARSA accelerator structure is Marx generator with a pulse charge of storage capacitors. A radiation source is a sealed-off accelerating tube with an edge cathode. The accelerating voltage amplitude – 1 MV. The electron radiation dose rate near the target – $1{\cdot}10^{14}$ R/s. Dose rate of the target – $3{\cdot}10^{10}$ R/s in the spot of 1 cm diameter at BR pulse length 4 ns. Productivity – up to 100 pulses per working shift.

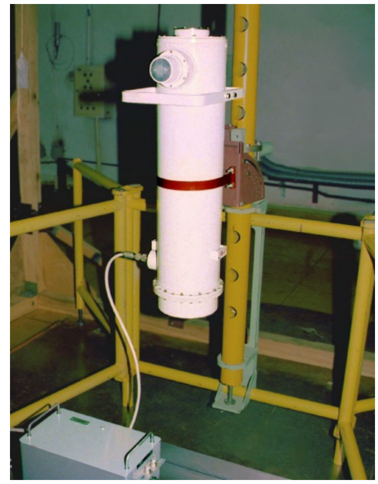

Figure 4: Overall view of accelerator ARSA.

The portable generator of X-ray high-power pulses – an accelerator ILTI-1 (Fig. 5) is intended for simulating a sequential effect of two or three BR pulses during joint operation with accelerators LIU-30 and STRAUS-2.

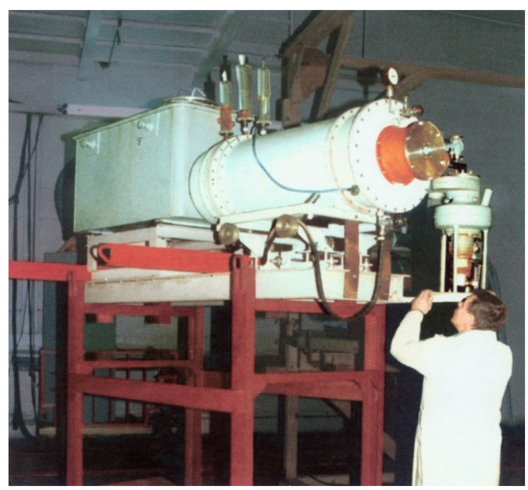

Figure 5: Overall view of accelerator ILTI-1.

In the independent operation mode ILTI-1 accelerator provides loading of individual devices by radiation with a softened spectrum due to a specially developed close-focus accelerating tube with radiation output from the back target semispace. As compared to a standard approach this allows an increase from 15 up to 50% of radiation energy fraction within the range from 10 up to 100 keV. X-ray yield angle is 60° in such geometry. At the accelerating voltage amplitude 700 kV the beam current is ~ 70 kA.

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a b c

Figure 6: Overall view of accelerators LU-7-2 (a), LU-10-20 (b) and LU-50 (c).

A transportable linear resonance electron accelerator LU-7-2, developed in the year of 2004, has started operation in a structure of PULSAR complex since 2007. LU-7-2 accelerator characteristics: electron energy – 6.5 MeV; pulse length – 4.5 μs; average electron beam power – 2 kW; average exposure dose BR rate – up to 25 R/s on the area 800 cm^2 with heterogeneity not worse than 30%; pulse repetition rate – 600 Hz. It is configured on the supporting platform and can be used in production radiation technologies and for flaw detection of objects with high mass thicknesses. Overall view of LU-7-2 accelerator is given in Fig. 6 a.

Along with accelerators described above, in order to simulate a gamma-radiation dose effect, LU-10-20 linear resonance accelerator [15], presented in Fig.6b, is used.

LU-10-20 accelerator characteristics: accelerated electron energy (regulated): 5 ÷ 9 MeV; average current – 1.3 mA; pulse length – 3.5 μs; pulse repetition rate – 10 ÷ 1000 Hz; rate of electron radiation absorbed dose near the outlet window – up to 5 Mrad/s; BR exposure dose rate at 1 m distance from the target on the area ∅ 0,36 m with heterogeneity not worse than 30% – up to 300 R/s. The average electron beam power is 10 kW. A system of electron beam scan and a transporting line allow irradiation of objects with width up to 700 mm, length up to 2000 mm and height up to 750 mm.

LU-50 linear resonance accelerator [16], developed jointly with Moscow Institute of Radio Engineering, is shown in Fig. 6c. LU-50 accelerator characteristics: accelerated electron energy – 55 MeV; average electron current – 0.24 mA; pulsed current – 10 A; average BR quantum energy ~ 6 MeV; pulse length – 10 ns. Beam average power – 10 kW. On LU-50 the pulse repetition rate of accelerated electrons can be adjusted from single ones up to 2400 Hz. This allows irradiation rate variation without accelerator tuning.

One of the main instruments meant to perform nuclear-and-physics studies at VNIIEF is an electrostatic tandem accelerator EGP-10 [17, 18]. A number of original developments provided the best indices for it among electrostatic accelerators in Russia. The accelerator permits to accelerate ions of hydrogen, oxygen, carbon. For protons the energy operating range is from 1.5 up to 12 MeV at maximum beam current – 1 μA. In this case monochromaticity of accelerated protons (at energy 9.345 MeV) is not worse than 1 keV.

During several last years for a pulsed radiography induction accelerator LIU-R-T was developed [10] (12 MeV, 20 kA, 60 ns), presented in Fig. 7, which dose parameters exceeded by an order the available native analogs and approached the best foreign such class facilities. Exposure radiation dose at a distance 1 m from the accelerator target approaches 300 R at X-ray pulse length 50 ns and source focus spot diameter 2.5÷5 mm. LIU-R-T accelerating system is built on the basis of a developed at VNIIEF technique of «air-cored» linear induction accelerators with water-insulated inductors based upon step-like forming lines with distributed parameters. This allows 2-times increase of acceleration rate and 5-10 times gain of electron beam current compared to the most high-power foreign X-Ray facilities (DARHT, AIRIX, Dragon), fabricated according to a scheme of classic LIU with ferromagnetic core inductors. Since 2015, LIU-R-T accelerator has been jointly operating with three betatrons BIM234-3000 as a part of a multi-beam X-Ray complex.

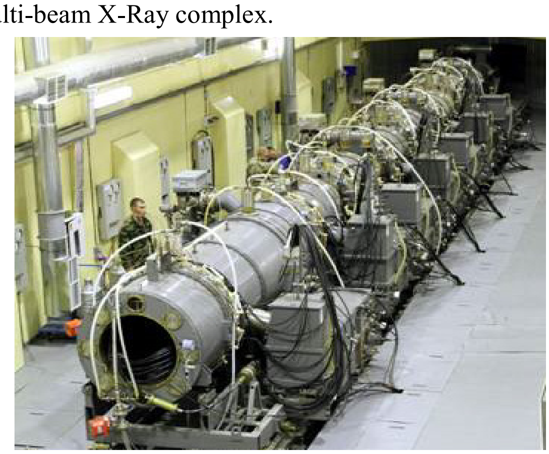

Figure 7: Overall view of accelerator LIU-R-T.

Within the frames of works on developing the experimental base a multi-terawatt electrophysical facility (2 MeV, 12 MA, 65 ns) [19] is being developed in RFNC- VNIIEF. A four-module facility [20], consisting of four pulse high-current electron accelerators (2 MeV,

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750 kA, 65 ns) has been created by present. An overall view of the four-module installation is shown in Fig. 8. The main destination of the facility is generation of BR pulses with maximal quantum energy up to 2 MeV.

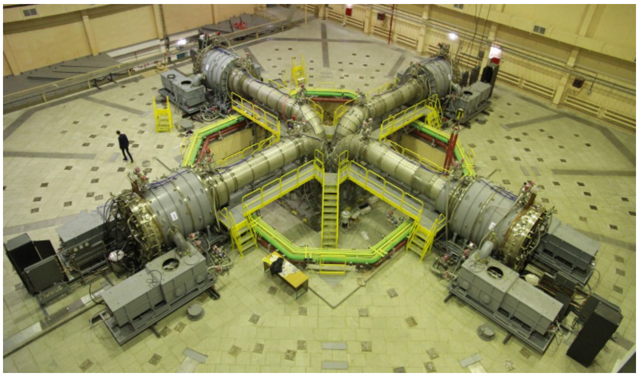

Figure 8: Overall view of a four-module facility.

The facility is planned to be used in two modes. In the first mode the facility modules are fully independent, and the load of each of them is a separate high-current vacuum diode. In this case diodes are placed close to each other, forming an array of four discrete irradiators. A radiation field, being formed by the facility, is a superposition of radiation fields of its individual modules. In the second mode it is planned to shunt the facility modules on the single diode load [21], in order to increase radiation energy density compared to the independent modules mode.

Also the facility operation is planned in the modes:

Generation of soft X-ray radiation (SXR) when operating on plasma load (wire liner). According to calculations the energy transmitted in a SXR pulse must be 75 kJ at a pulse length 5 ns;

Shock-wave and quasi-isoentropic materials compression by pressure up to 50 GPa.

As of today a resonance electron accelerator with a high average beam power is being developed in RFNC – VNIIEF [22, 23]. Its main element is an accelerating coaxial half-wavelength resonator, with operating frequency 100 MHz. The accelerator is intended for operation in pulse-periodic and continuous modes of beam generation. Development of such an accelerator allows generation of accelerated electron beams with energies – 1.5, 4.5 and 7.5 MeV in one common output device at average beam power up to 300 kW.

At present there is developed a operating accelerator full-scale test mockup, shown in Fig. 9, involving an accelerating coaxial resonator, RF injector, RF generator module, meant for 180 kW of average output power, RF transport guide, RF power input unit, technological systems, automated control system, as well as elements of magnetic transport system and electron beam output device.

Figure 9: Overall view of test accelerator mockup.

When high-frequency power equal to 160 kW is supplied into the accelerating cavity in single and double-passage acceleration modes beam with average electron energy 1.5 and 3 MeV, respectively, is generated at average current up to 100 μA. Further development foresees implementation of five-passage acceleration mode with a simultaneous gain of RF supply power up to 540 kW.

To specify time resolution of nanosecond detectors of electron and bremsstrahlung pulses, to certify and control measuring channel operability, a subnanosecond electron accelerator with a gas–filled shaper [24] is developed in RFNC-VNIIEF. The accelerator is created on the basis of a small-size accelerator ARSA with a gas-filled shaper of subnanosecond pulses. A double sharpening circuit allows generation of an electron beam with duration and amplitude of current pulses 0.25 ± 0.02 ns and ~ 1.5 kA, respectively at maximal electron energy ~ 850 keV.

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