HIGH-CURRENT PULSE ELECTRON ACCELERATORS BASED ON STEPPED FORMING LINES

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There presented is a brief review of I-3000, STRAUS, STRAUS-2 and LIA-10M accelerators produced in VNIIEF over the period from 1981 to 1994. All the installations function in the mode of single pulses. Their distinction consists in using the systems of forming high-voltage pulses on the basis of stepped forming lines. Such installations formed of line sections of a similar electrical length with a stepped character of impedance variance provide a high efficiency and as a result of wave processes increase for a several time the output voltage as compared to the charge voltage of lines. The limiting energy of accelerated electrons for the created accelerators lies within the range from 2.3 to 25 MeV, beam current amplitude – from 20 to 50 kA, current pulse width at half-height – from 16 to 40 ns. The basic characteristics of each accelerator are presented.
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1 INTRODUCTION

In VNIIEF developed are the electric circuits of multi-cascade generators of high-voltage pulses based on stepped lines (SL) ensuring as a result of transition wave processes a considerable – 5-10 times – increase of voltage, current or power [1-3]. At the corresponding relation of impedances of cascades possessing similar electrical lengths such facilities have – in ideal case – 100% efficiency. During the time period from 1981 to 1994 there were created on the basis of circuits with capacitive energy storage the following high-current electron accelerators: I-3000, STRAUS, STRAUS-2 and LIA-10M. The basic characteristics of these accelerators are presented in the table. The brief description of accelerators that are mainly used for bremsstrahlung (B) pulse generation is given below.

Table – Basic characteristics of the accelerators based on stepped lines produced in VNIIEF

Accelerator	I-3000	STRAUS	STRAUS-2	LIA-10M
Energy stored in Marx generators, kJ	12.5	10	24	180
Charging voltage of the forming line, kV	500	530	610	530-610
Number of switches in the forming system, item	60	13	21	341
Limiting energy of accelerated electrons, MeV	3.5	2.3	3	20-25
Current beam amplitude, kA	20	22	50	≤50
Current pulse width at half-height, ns	16	40	20-40	25
Bremsstrahlung dose, R : on the flange at a 1-meter distance from the target	2000 9	4500 9	10000 20	40000 750
Dose rate, R/s: on the flange at a 1-meter distance from the target	$1\cdot10^{11}$ $8\cdot10^{8}$	$1{,}5\cdot10^{11}$ $8\cdot10^{8}$	$5\cdot10^{11}$ $1\cdot10^{9}$	$2{,}7\cdot10^{12}$ $5\cdot10^{10}$
Bremsstrahlung pulse width, ns:	12	32	15-25	15
Diameter of irradiated spot (D_{max}/D_{min}=2) cm: on the flange at a 1-meter distance from the target	10 100	5 70	8 80	8.5 55

2 I-3000 ACCELERATOR

On the basis of two injector modules of LIA-10 [4] there was created in 1981 the I-3000 accelerator (Fig. 1) with the following overall dimensions: 3.5×3.7×2.3(h) m^3. The idealized electric circuit of a three-cascade double stepped forming line (DSFL) is presented in Fig.2, and the constructional scheme of the accelerator high-voltage section is in Fig.3. To increase the voltage generated by a group of six inductors there was used a high-impedance vacuum transmission line (TL). At the operation on the second pulse of accelerating voltage this made it possible to increase the limiting energy of electrons by a factor of 2.3. It should be mentioned that these are just the results of experimental research of the I-3000 facility that stimulated the development of SL theory in VNIIEF.

3 STRAUS ACCELERATOR

In 1982 the STRAUS accelerator was put into operation; it is the first accelerator on SL with the optimal relation of impedances [2, 5]. The view of the accelerator when studying the injection to betatron is presented in Fig. 4. In Fig. 5 shown are the electric circuit (a) and scheme (b) of the high-voltage accelerator unit. It is produced on the basis of a five-cascade DSFL. At such relation of impedances as Z_1:Z_2:Z_3:Z_4:Z_5 = = 1:3:15/4:5/4:15 it ensures in the matched mode of operation the increase of the output voltage by a factor of 3 while in the idle-running mode – by a factor of 6. In a cylindrical tank (∅0.8m, ℓ=2.9m) located is DSFL with the impedances of lines 1-5 equal to 1.1, 3.3, 4.1, 1.4 and 16 Ohm, respectively. At the external diameter of DSFL a triggered commutator formed of 12 gas-filled switches 6 was installed. The electrical length of water–insulated lines T_0=20ns. The accelerating tube is made on the basis of sectioned insulator 10. The cavity between the sectioned insulator and polyethylene tube 9 is filled with electrolyte 11 (water solution of NaCl). The space between the accelerating tube and polyethylene diaphragm 7 is filled with transformer oil. The diode assembly 12 is connected to DSFL through a one-channel triggered gas-filled pre-pulse switch 8.

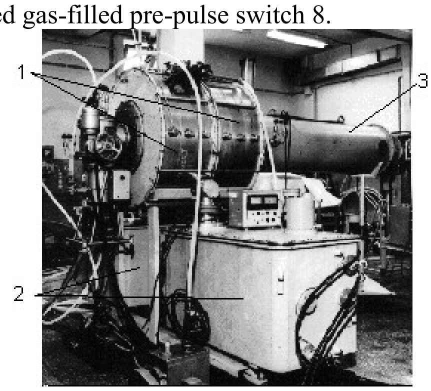


Fig. 1. General view of I-3000 accelerator: 1 – two injector blocks of LIA-10; 2 – two Marx generators GIN-500; 3 – vacuum TL.

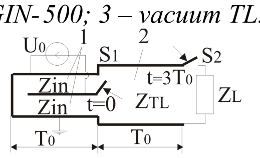


Fig.2. Electric circuit of load connecting to the inductor (group of inductors) (1) through a homogeneous TL (2).

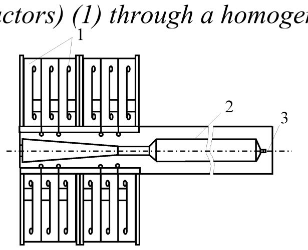


Fig. 3. Scheme of I-3000 high-voltage unit: 1– injector block of LIA-10 inductors; 2 – vacuum TL; 3 – cathode.

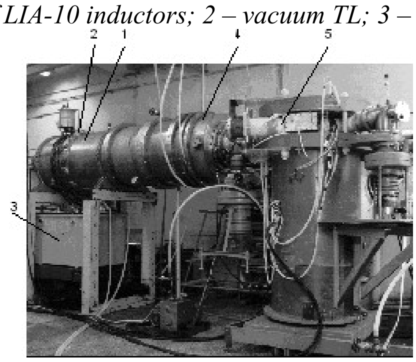


Fig. 4. General view of STRAUS accelerator:1 – DSFL body; 2 – DSFL switches; 3 – Marx generator GIN-500; 4 – body of accelerating tube assembly; 5 – iron-free BIM-234 betatron.

DSFL is charged to ≤500kV during 0.8μs. The pulse of diode current has the shape close to trapezoidal one at $t_{0.5}\approx$ 40 ns, $t_{0.8}\approx$ 20 ns. On Fig. 6 there are presented the oscillograms of diode current (a) and bremsstrahlung (b) pulses registered at the accelerating voltage of 2.3 MV. The accelerator characteristics are given in the table.

The results of the experiments confirmed completely the conclusions of the theoretical analysis made for pulse devices on SL. Along with high coefficient of voltage transformation the possibility of forming a pulse with a “flat” top was confirmed too. As compared to I-3000 the STRAUS accelerator has one Marx generator GIN-500 instead of two generators, the full number of switches in the forming lines is decreased from 60 to 13 and it is provided that the energy left in the forming system after the working pulse termination is scattered in the electrolytic load. As a result the reliability of accelerator operation increased noticeably.

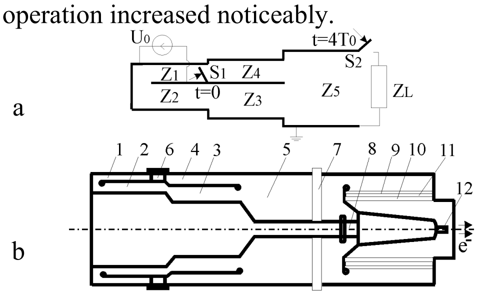


Fig. 5. Electric circuit (a) and scheme (b) of STRAUS high-voltage unit.

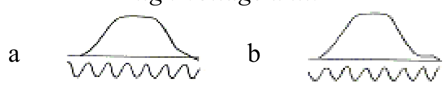


Fig. 6. Oscillograms of diode current (a) and bremsstrahlung (b) pulses. Frequency of marks is 100MHz.

4 LIA-10M ACCELERATOR

The accelerating system of linear induction accelerator LIA-10M (Fig. 7) is comprised of an injector, 16 accelerating modules and beam transportation track 4m long with a target assembly for bremsstrahlung pulse generation [2, 6]. The dimensions of the accelerating system without transportation track are as follows: 12x3.5x2.4(h) m^3. Beam acceleration and transportation is realized in a pulsed magnetic field of 0.5T. Being a modification of STRAUS-2 accelerator the injector is aimed at forming annular electron beam. It is produced on the basis of a five-cascade DSFL (T_0 =18 ns). The relation of impedances Z_1;Z_2:Z_3:Z_4:Z_5= = 1.0:2.4:4.0:1.1:22.5 is optimized for the modes of electron beam injection and bremsstrahlung generation. When charging DSFL to 0.63 MV the amplitude of the output voltage pulse of idle-running mode is as high as 4.1MV (U/U_0 = 6.5).

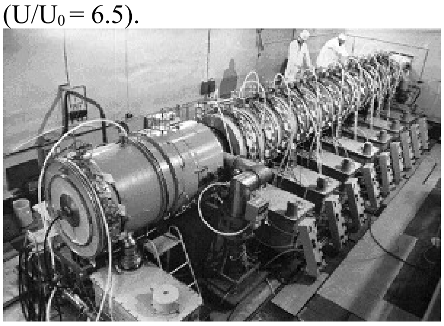


Fig. 7. General view of LIA-10M accelerating system.

In Fig. 8 presented is the scheme of the high-voltage injector unit. Water-insulated DSFL is commutated by 20 triggered gas-filled switches 6. The impedances of lines 1-5 are equal to 0.8, 1.9, 3.2, 0.9 and 18 Ohm, respectively. To decrease the length of DSFL, lines 1-4 are located in series by the radius within the limits of one axial size. The accelerating tube is formed of polyethylene tube 8 and sectioned insulator 9, cavity 10 is filled with electrolyte. The space between the accelerating tube and polyethylene diaphragm 11 is filled with transformer oil. DSFL is connected to the accelerating tube through a one-channel triggered pre-pulse switch 7. DSFL diameter is 1.2 m, its length with the accelerating tube assembly and output chamber being equal to 2.7 m. DSFL is charged over 0.51μs to the voltage of ≤ 700 kV by two six-cascade Marx generators with a total energy store of 24 kJ.

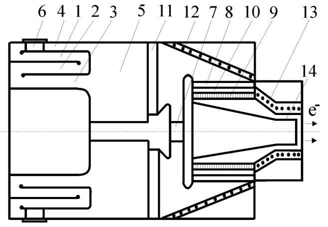
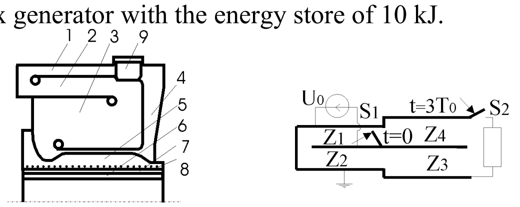


Fig. 8. Scheme of the high-voltage injector unit.

The inductor generating accelerating voltage pulses and Marx generator ensuring the inductor pulse charging are the basic assemblies of the accelerating module. The inductor is produced on the basis of four-cascade DSFL (Fig.9b) increasing the voltage by a factor of 4 in the idle-running mode. Three coaxial lines 1-3 (Fig. 9a) with the impedances equal to 0.55, 1.65 and 3.3 Ohm are displaced in series by radius, while the fourth one 4 (Z_4 = 1.1 Ohm) is produced in the form of a homogeneous radial line. The inductor diameter is 1.1 m while the axial size is 0.57 m. The commutation of DSFL is implemented by 20 switches 9. The lines are charged to ≤ 560 kV over the time of 0.8 μs by a five-cascade Marx generator with the energy store of 10 kJ.



a b

Fig. 9. Scheme (a) and electric circuit (b) of the inductor: 1-4 – water lines with Z_1, Z_2, Z_3 and Z_4 impedances, respectively. 5 – polyethylene tube; 6 – sectioned insulator; 7 – electrolytic load; 8 –solenoid; 9 – multi-channel switch.

The accelerating track of LIA-10M is formed by 16 sectioned insulators of inductors with 200 mm aperture and total length of 9.2 m. The accelerator whose characteristics are presented in the table was turned on ~1600 times. The electric characteristics of the inductor and injector are close to the calculated ones. The first and second voltage pulse amplitude of the inductor on 60-Ohm load is 1.2 and 2.0 MV, the duration by the basis was equal to 30 and 34 ns while at half- height this value is as high as 22 ns. At R_{EL} =60 Ohm and I_b = 50 kA the amplitude of accelerating voltage constitutes 1.6 MV at the tempo of acceleration equal to 2.8 MeV/m.

5 STRAUS-2 ACCELERATOR

The basic characteristics of STRAUS-2 accelerator are given in the table. As differentiated from LIA-10M injector, the STRAUS-2 solenoids aimed at magnetic field creation are missing and the cathode configuration is changed. The accelerator output voltage and current are regulated but most frequently realized is the mode of U≈3 MV, I≈ 50 kA, corresponding to the maximal dose when operating in the mode of bremsstrahlung generation. The pulse duration varied through the change of time of the pre-pulse switch triggering. The dose remains practically unchanged at $t_{B0.5}$= (15-25) ns, moreover, the dose rate is maximal at $t_{B0.5}$= 15ns and as compared to the mode of $t_{B0.5}$=25ns it increases by a factor of ~1.5. The dose permanence is provided through the growth of diode current and voltage (10-15%) with the reduction of pulse duration. The first model of STRAUS-2 accelerator on which there was made ~2000 pulses had been produced in 1989. After carrying out the investigations on beam injection and bremsstrahlung pulse generation it started being used as LIA-10M injector. Now in VNIIEF operate two more models of this accelerator as compounds of irradiating complexes LIA-10M-GIR2 and PUL'SAR [8].

6 CONCLUSION

In the course of I-3000, STRAUS, STRAUS-2 and LIA-10M creation and operation the high efficiency of the proposed schemes of generators on stepped lines was confirmed. For the first time a considerable scope of scientific and engineering information has been accumulated and the experience in developing and producing the systems of high-voltage pulses based on stepped lines has been gained.

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