FUNCTIONING OF LIA-30 ACCELERATOR IN THE MODE OF GENERATING BREMSSTRAHLUNG PULSES SHORTENED TO SEVERAL NANOSECONDS

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Deceleration of electrons and further transformation of the beam current lead to the ~2-times increase of the pulse amplitude, self-excited acceleration of electrons at the cutoff and shortening of 15…20 Gy bremsstrahlung pulse.

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INTRODUCTION

LIA-30 linear induction accelerator of electrons is a basic irradiating facility of RFNC – VNIIEF [1]. In the list of its potentialities there is available a mode of generating bremsstrahlung pulses of short duration τ_γ~5ns with a peak bremsstrahlung dose power $P_\gamma \sim 5\cdot10^9$Gy/s and integral dose up to D_γ ~15 Gy. The mode by itself is interesting both from the point of view of its physical realization and for simulating some aspects of nuclear burst injurious effects.

As differentiated from high-current (~100kA) direct-action accelerators a 36-module structure of LIA-30 is a convenient instrument for realization of different functioning modes. This can be fulfilled through the possibility of changing the number of enabled modules by means of some moderate variations in configurations of high-voltage electrodes contained in a vacuum track and through varying delays of voltage appearance in the accelerating gaps of one or another group of modules [2].

In the experiments aimed at forming high currents of relativistic electron beams (REB) $I_п$ ~ 100 кA much attention was paid to the shape transformation of REB current pulses when the beam was accelerated in LIA-30 modules. Fig.1a, b gives for different time dependencies of current at the accelerating system input $i_{inp}(t)$ further changes of its shape in the cross-sections of modules No 10, 20, 36. To make the picture more demonstrative the oscillograms of currents were synchronized in terms of time delays of currents appearance in the blocks specified. In correlation with the observed "peaks" of current amplitude $i_{36}(t)$ there were registered at the accelerator output the pulses modulated with high-frequency oscillations and shortened as a whole by duration $P_\gamma(t)$. It was clear that at a definite time dependence of current $i_{inp}(t)$ there can be realized the conditions of REB acceleration in subsequent modules to get a short pulse of bremsstrahlung. However, this was a difficult task as a whole because of the lack of a calculation model of REB space-time location needed to measure its current pulse in the accelerating structure of LIA-30.

Under these circumstances there was selected an experimental method of finding conditions for the realization of the accelerator operation mode with bremsstrahlung shortened pulses generation. For this purpose it seemed expedient to use the accelerator of the system of pulse currents and voltages registration available almost in each accelerator module.

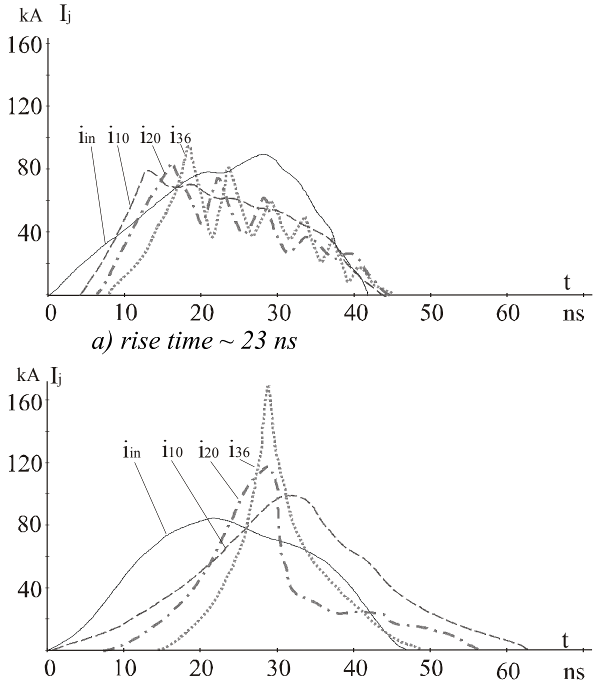


Fig.1. Time dependence of REB currents pulses in LIA-30 modules No 10, 20, 36 at gently sloping and drastically growing front pulse of the injection current i_{inp}

SOME PHYSICAL ASPECTS

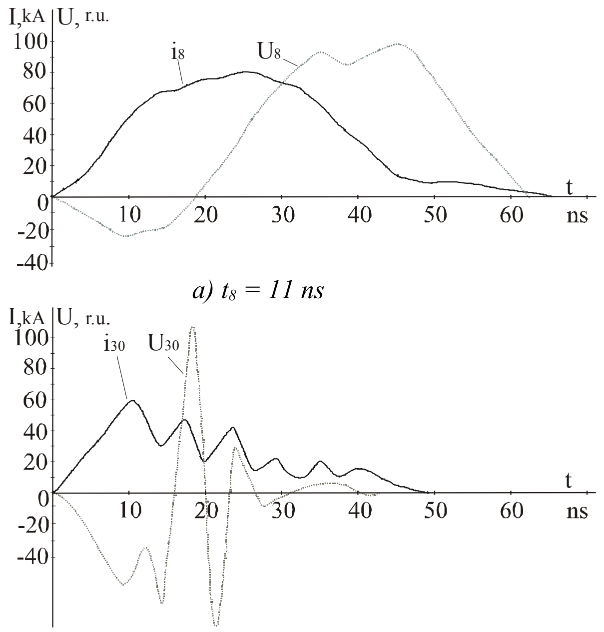
Simple calculations of transition processes in inductor blocks demonstrate that owing to the availability of inductively resistant output impedance of accelerating gaps (~6 Ω as stated in terms of one module on the main operation frequency f ~ 10 MHz), when passing the current pulse of ~100 kA amplitude and standard duration of ~50 ns, there takes place the induction decrease and increase of accelerating voltage values at the front and trail of its pulse, respectively. The total change of voltage in the gaps of 10 modules may constitute a sufficiently high for acceleration – deceleration value Δ U~ 6 MV. More precise calculations in terms of LIA-30 accelerating track electric parameters per unit length [3] lead to variations of the total induced voltage in N-accelerator modules in the following form:

$$\Delta U = N\cdot (I_{REB}\cdot W + L\cdot d\, I_{REB}/dt),$$

where W~2,8 Ω is the total wave resistance of the connected module; L ~ 110 nH is the inductance of torus shaped cavity between the block inductors and REB boundary (∅ ~ 250 mm). They point to even higher possible values of ΔU > 14 MV at N=10 and considerable abruptness of current rise dI_{REB}/dt > 10 kA/ns.

The use of this physical peculiarity forecasted effective deceleration – acceleration of electrons at REB front (trail) and, finally, shortening of current pulses and bremsstrahlung. Fig.2 presents for different current pulse shapes the examples of voltage (in relative units) changes in 8 and 30 modules at an additional delay of their switching for the following cases, respectively:

a) t_8 =11 ns and б) $t_{30}\to\infty$ (passive condition of module).



б) $t_{30}\to\infty$

Fig.2. Voltage changes in the accelerating tracks of the 8th and 30th module depending on the passing current of the beam during delayed modules switching

As is well seen from the oscillograms in the accelerating gaps of modules there actually induce additional negative and positive potentials depending on the delay of module switching and abruptness of current pulses time dependence. For the current pulses of >100 kA these potentials were registered to be even more increased.

Deeper understanding of the processes follows from space-time apprehension of REB. An appreciable current pulse transformation occurs if a considerable share of electrons notably fall behind high-energy electrons moving at a rate $\upsilon\approx c$. In the course of deceleration low-energy electrons with c $\upsilon<<c$ generally pass from inner to outer trajectories. At a constant azimuth density of currents a large electron charge can be dislocated just in the outer annular layers of the tubular REB. Moreover, electrons leaving the process of acceleration collide with the track walls causing intrinsic leakage currents of modules what was observed in reality. Later it leads to an abrupt reduction of acceleration tempo for all electrons. This is and important limiting point for the realization of current pulse transformation with no loss of bremsstrahlung dose and power.

To prevent shunting of accelerator gaps there was proposed in one of operation versions to discharge the remaining electrons by means of local decrease of the leading longitudinal magnetic field. On the other hand it followed from the experiments that transformation of current pulses can be easier realized for the beams of large diameters (>150 mm). In this case there appeared a proposal to use for space separation of electrons a separate outer beam injected simultaneously with the chief one with the aid of additional coaxial emitter especially because the amplitude of the total current could be considerable due to additional outer layer of electrons.

INVESTIGATION RESULTS

The first experiments were performed for the accelerating track configuration presented in Fig.3, i.e. step-by-step coaxial cathode possessing 100 and 150 mm-diameter annular emitters to form two simultaneous beams. The emitters provided REB injection with relatively low for LIA-30 current i_{inp}=50…70 kA (through disconnecting of a share of inductors of 1-4 modules). To decelerate the beams there was installed a program of advance injection according to which modules No 5,6,7,8 were connected with the following delays, correspondingly: t_5=4 ns, t_6 =4 ns, t_7=3 ns, t_8=3 ns. The total delay of the 8th model switching as related to the 4th module constituted 14 ns.

The establishment to cathode-anode gap of three diaphragms with the aperture of ∅ 210…240 mm and at a distance of 0,1…1,0 m from the cathode trail (Fig.3, dotted) made it possible to increase through the decrease of anode-cathode gap the input current up to 100 kA, cause effective pulse transformation and essential shortening of τ_γ. However, the operation mode was not stable enough because of the fact that the beams were too close to each other. Constant shift of beams by ~60 mm from the axis caused by some engineering peculiarities of magnetic field realization on the accelerator track hampered the mode realization as well.

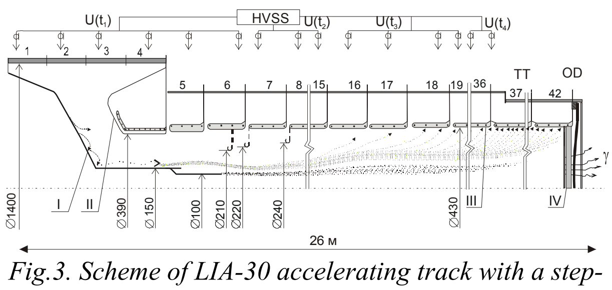


Fig.3. Scheme of LIA-30 accelerating track with a step-by-step two-emitter cathode:
1, 2, 3…36 – serial number of modules; $U(t_1)$, $U(t_2)$, $U(t_3)$, $U(t_4)$ – starting voltages;
TT – transportation track ; OD – output device; HVSS – high-voltage system of modules synchronization.
I, II – cathode-anode electrodes; III – drift tube with solenoid; IV – target

Finally the mode was elaborated in the configuration presented in Fig.3, where the emitters 135 and 245 mm in diameter were used instead of the available ones. The

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axial distance between the ends of emitters constituted ~1 m. To keep sufficiently high current of injection I_{inp} =90 kA the blocks from 7…15 and from 16…36 were connected 4 and 8 ns earlier, respectively. For the purpose of local dump of decelerated particles to the walls of the accelerating track the magnetic field in the 12th module was decreased from 0.5T to 0.4 T. As a result there was achieved a required transformation of REB current pulses and decrease of τ_γ to the value of <4 ns at the bremsstrahlung integral dose D_γ = 19 Gy and peak dose rate of bremsstrahlung $P_\gamma \sim 5 \cdot 10^9$ Gy/s. However, after some pulses had passed there took place a breakdown of a solenoid of the leading magnetic field in module 15 because of failure of its coils insulation resulting from their irradiation with locally dumped electrons.

To somehow disperse the dumped electrons the magnetic field was reduced by a lower value (from 0.50 to 0.45 T) simultaneously in three modules: No 10,11,12. Finally the shortening of current pulses was not so efficient and the value of τ_γ was higher- ~6 ns.

Fig.3 presents transformation of the REB current pulse in the accelerating operation mode at which the injection current was additionally increased to the amplitude i_{inp} = 100 kA. The magnetic field was kept at a level of 0.5T by the entire accelerator length. A more regular dump of scattered electrons was implemented through their deceleration in some disconnected modules (No 12,14,17,21,36). In this case there took place the reduction of bremsstrahlung parameters to the level D_γ = 15 Gy, $P_\gamma \sim 3 \cdot 10^9$ Gy/s the shortening of pulses remaining equal to τ_γ = 5 ns.

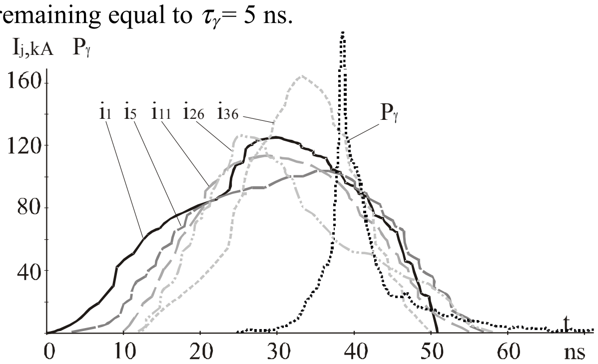

Fig. 4. Time dependence of current beam pulses in accelerator modules 1, 5, 11, 26, 36 and bremsstrahlung dose rate at the LIA-30 output

The characteristic peculiarity of bremsstrahlung was reduction of its spot diameter (as compared to the available in the standard mode of operation) by >20% because in the generation of bremsstrahlung at electron deceleration in the target there basically participates an internal beam ~135 mm in diameter.

CONCLUSIONS

The performed experimental investigations of the process of REB current pulse transformation made it possible to realize generation of shortened - by duration - bremsstrahlung pulses with the following parameters: τ_γ = 5...10 ns, D_γ = 15...20 Gy, P_γ up to $5 \cdot 10^9$ Gy/s. Of course, to increase the levels of D_γ and P_γ with keeping $\tau_\gamma \sim 5$ ns unchanged one must perform more optimization of selecting amplitude, shape of current beam pulse $i_{inp}(t)$ and program of accelerator modules connection. The maximum dose and dose rate could be realized in case of total joining of all the accelerator modules due to the lack of modules shunted by intrinsic leakage currents initiated by transformation electrons spreader by the current pulse, with axial REB shift elimination**.** Most probably at that time we managed to implement the distributed dump of electrons from $\upsilon << c$ in the available prolonged (≈ 4 m) transportation magnetic track connecting the last accelerator module (No 36) with its output assembly and target.

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РАБОТА УСКОРИТЕЛЯ ЛИУ-30 В РЕЖИМЕ ГЕНЕРАЦИИ ИМПУЛЬСОВ ТОРМОЗНОГО ИЗЛУЧЕНИЯ, УКОРОЧЕННЫХ ДО НЕСКОЛЬКИХ НАНОСЕКУНД

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Торможение электронов на фронте и последующая трансформация тока пучка приводят к увеличению амплитуды импульса в ~ 2 раза, к автоускорению электронов на срезе и укорочению импульса тормозного излучения с дозой 15…20 Гр.

РОБОТА ПРИСКОРЮВАЧА ЛІП-30 У РЕЖИМІ ГЕНЕРАЦІЇ ІМПУЛЬСІВ ГАЛЬМОВОГО ВИПРОМІНЮВАННЯ, УКОРОЧЕНИХ ДО ДЕКІЛЬКОХ НАНОСЕКУНД

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Гальмування електронів на фронті і наступна трансформація струму пучка приводять до збільшення амплітуди імпульсу у ~ 2 рази, до автоприскорення електронів на зрізі й укороченню імпульсу гальмового випромінювання з дозою 15…20 Гр.