RESULTS OF LIA-10M ACCELERATOR INVESTIGATIONS

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There are presented basic results of experiments on the LIA-10M accelerator since its putting into operation (1994) till today. There were investigated various modes of accelerator operation and its output characteristics depending on the parameters of injected electron beam, number of connected accelerator modules, time program of inductors switch-in etc. There was obtained a large scope of experimental data that are of interest for LIA-10M accelerator practical use and for the development of new facilities of this type. The investigations that have been performed recently make it possible to considerably (half as much again) increase the output dose parameters of the accelerator as compared to the level achieved before: maximal dose (Si) and dose rate on the output flange constitute 400 Gy and $2.5\cdot10^{10}$ Gy/s, while at a 1 meter distance from the target they are equal to 7.5 Gy and $5\cdot10^{8}$ Gy/s, respectively.

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During the period beginning from the time of LIA-10M [1-3] putting into operation till now there have been made about 1800 work pulses. In the course of the accelerator experimental development there was performed a large scope of experimental investigations purposed at studying the peculiarities of its operation and aimed at achieving maximal dose parameters at the facility output. In the experiments the conditions of optimal injection, acceleration and transport of electron beam were investigated depending on its parameters (amplitude and current pulse duration of the beam, its diameter and injection energy), delay time of injected beam pulse as related to the accelerating voltage pulses of inductors and time program of inductors turn-on as related to each other.

One of the tasks at the initial stage of researches consisted in defining the optimal correlation between the pulse durations of injected beam current and the accelerating voltage formed by the inductors. In Fig. 1 presented is an oscillogram illustrating the shape of voltage pulses at the output of LIA-10M inductor in the idle mode. The inductor forms the group of pulses of alternate polarity with different amplitude and duration. To accelerate the beam there was used the second pulse (of negative polarity) with the amplitude of 2 MV and 22 ns duration at a half-maximum. The maximal duration (FWHM) of the beam current pulse formed by the LIA-10M injector [4] is approximately twice as large. However, there exists the possibility of its regulation within the limits from 20 to 40 ns through the change of the turn-on time of the controlled pre-pulse switch installed at the output of the injector forming system.

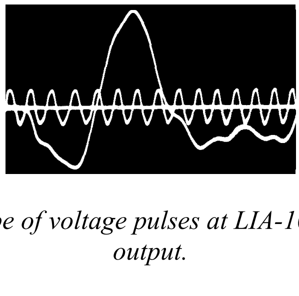

Fig. 1. Shape of voltage pulses at LIA-10M inductor output.

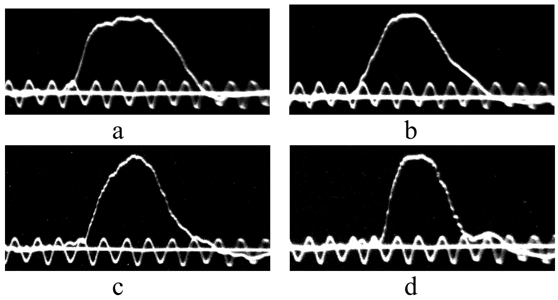

Fig. 2. Oscillograms of injected beam current pulses (duration at half-maximum: a – 40 ns, b – 35 ns, c - 30 ns, d – 25 ns).

In the experiments performed the duration of the injection current pulse varied from 40 to 25 ns with a step of ~5 ns. The obtained oscillograms of beam current pulses injected to the accelerating channel are given in fig. 2. At reducing the duration of pulse its shape was changed as well as the amplitude (towards the increase by 10-15% at pulse shortening). For each version of injection there was selected the optimal time of beam current pulse delay as related to the accelerating voltage of inductors. The criterion of optimality consisted in getting the maximal dose and dose rate of bremsstrahlung registered at the facility output. The unique conclusion on the fact that the best conditions for the beam acceleration are achieved at approximately equal duration of injected current and accelerating voltage pulses is the result of the investigations performed. Thus, in case of a shortened to 25 ns pulse of injection current the dose (Si) of bremsstrahlung at 1 meter distance from the target was 20-30% higher than in case of a “long” (40 ns) pulse. The advantage by dose rate was even more considerable and constituted 50-70% and in separate pulses it was close to 100%. This is conditioned by the decrease of bremsstrahlung pulse duration at the accelerator output (Fig. 3) in case of short-pulse injection (13-15 ns instead of 15-18 ns) at simultaneous growth of dose. The pulse of injected current can be even shorter by duration than the pulse of accelerating voltage, however, in this case the efficiency of accelerating system use decreases.

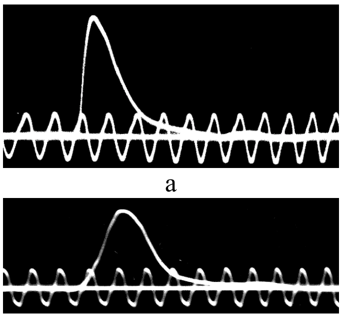

Fig. 3. Oscillograms of bremsstrahlung pulses corresponding to 25-ns (a) and 40-ns (b) duration of injection current pulses.

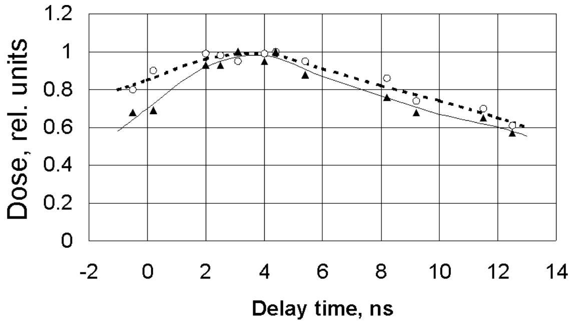

Fig. 4. Dependence of bremsstrahlung dose on the delay time of the injected current pulse as related to the accelerating voltage of the first inductor.

In Fig. 4 presented is the dependence of bremsstrahlung dose on the delay time of injected current pulse as related to the accelerating voltage of the first inductor of the accelerating system. The solid line corresponds to the dose at 1 meter distance from the target, the dashed one – to the dose at the output flange of the accelerator (~50 mm from the target). From the figure it is evident that maximal dose parameters are achieved at 3-4 ns delay time of pulse injection relative to the accelerating voltage pulse. The delay of the injected current is required to compensate inductive deceleration of electrons on the beam front by the accelerating voltage of inductors. It should be mentioned that the required delay time depends not only on the properties of the accelerating structure and characteristics of accelerating voltage pulse but on the injection current pulse parameters – its amplitude, duration, rise- and decay time. In each specific case it is selected individually.

The other task solved in the course of experimental accelerator development was to optimize time program of accelerator modules switching as related to each other. At the velocity of electrons close to the velocity of light in vacuum the time of their flight through a separate inductor (axial length – 0.58 m) of the accelerating track is equal to 1.9 ns. In the initial series of experiments the time shift of turn-on for each consequent inductor as related to the previous one corresponded to this value. However, at the accelerating structure input the velocities of electrons near the current pulse front and slope are considerably lower than the velocity of light while at short-pulse injection this group of electrons constitutes the noticeable part of the beam. Therefore later the program of accelerating modules turn-on was corrected in terms of this factor.

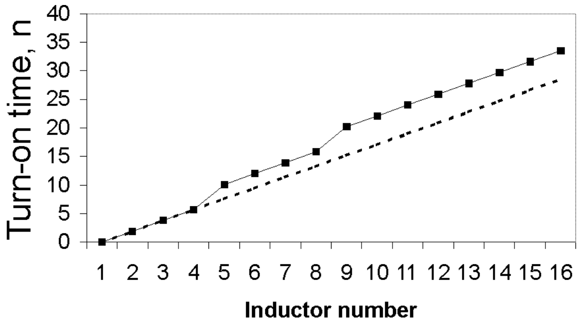

Fig. 5. Time diagram of LIA-10M inductors turn-on.

The time diagram of LIA-10M inductors operation is presented in Fig. 5 (solid line). The first 4 inductors turned on in accord with the velocity of light in vacuum (dashed line), the second group of inductors is additionally shifted in time by +2.5 ns as related to the first one. The last group of 8 inductors was delayed in run-up by 5 ns as related to the time schedule corresponding to the velocity of light. The time shift between the two neighboring inductors in each group is retained equal to 1.9 ns. Such program of inductors switching was selected basing on the results of experiments in a set of ~100 work pulses of LIA-10M accelerator what provided for getting sufficiently reliable statistics. Its realization made it possible to additionally increase by 15-20% the dose characteristics of the generated by the accelerator bremsstrahlung and finally achieve the dose levels of ~300 Gy (Si) at the output flange and ~ 5 Gy - at 1 meter distance from the target.

In one series of experiments there was investigated the dependence of the dose at the accelerator output on the number of the active accelerating modules. Here only n=0, 4, 8, 11 and 16 of the first accelerating modules were charged and they formed the pulses of accelerating voltage. The case of n=0 corresponds to the operation of a single injector (with no inductors turned on) while the case of n=16 – to the operation of the accelerator in a body. The chart of this dependence is given in Fig. 6. The dose curve can be approximated by the degree function $D_n \cong D_N \left(\frac{n}{N}\right)^{2.3}$, where D_n – dose at the facility axis at n number of inductors turned on, while D_N – dose value at the same point at all N=16 accelerating modules turned on. The obtained data make it possible to predict the bremsstrahlung dose at a definite point near the accelerator axis for the accelerator operation in any configuration. It is of particular convenience for the work with large-scale objects when the change of dose load to the object through its approach or moving away from the target does not always represent a simple task.

A considerable scope of investigations was connected with the study of LIA-10M accelerator at different-diameter electron beam injection and acceleration. With the increase of the number of its modules at a stage of tuning activities it was required - for the purpose of ensuring stable mode of electron beam transport to the target - to gradually decrease the cathode diameter from 120 to 80 mm. For the accelerator in a body we had to decrease as well the energy of injection from 3 to 2 MeV. It has been established later that the problem was associated with parasitic electron emission from the conical segment of the injector cathode what led to the fact that the beam injected to the accelerating structure was surrounded by a circular “aureole” of these electrons. Its diameter was sufficiently large, ~160 mm, that is comparable with the aperture of the accelerating channel (∅200 mm). In the course of acceleration there was observed the increase of cross dimensions of the beam and, correspondingly, of the “aureole” surrounding it. Finally, it led to the electrons hit on the accelerating tubes of several last inductors what initiated electric breakdowns on the surfaces of their insulators.

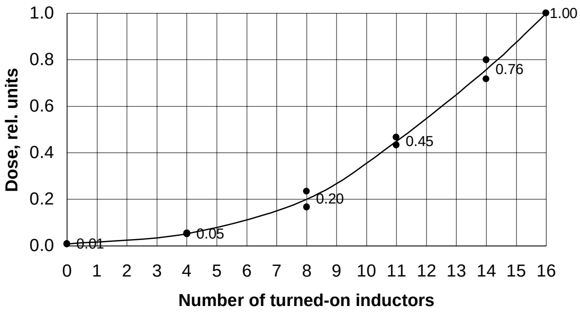

Fig. 6. Relative bremsstrahlung dose change on LIA-10M accelerator axis at different number of turned-on accelerating units.

Table 1. Dose parameters of LIA-10M accelerator depending on the cathode diameter

Parameter	Cathode diameter, mm		
	40	60	80
Bremsstrahlung dose at the output flange, Gy	250÷300	350÷400	300÷350
Bremsstrahlung dose at 1 meter distance from the target , Gy	4÷5	6÷7	5÷6
Dose rate at the output flange, Gy/s	$2\cdot10^{10}$	$2.7\cdot10^{10}$	$2.3\cdot10^{10}$
Dose rate at 1 meter distance from the target , Gy/s	$3.3\cdot10^{8}$	$4.7\cdot10^{8}$	$4\cdot10^{8}$
Diameter of irradiation spot with D_{max}/D_{min}=2: at a flange, cm	5.5	9	12
at 1-meter distance from the target, cm	50÷55		
Bremsstrahlung pulse duration, ns	14÷17		

For the purpose of this phenomenon elimination the configuration of the injector cathode was changed by decreasing the axial length of its conical segment at the corresponding increase of the cylindrical one. This had a positive effect and made it possible to carry out the investigations of the beam injection and acceleration with the use of cathodes of 40-80 mm diameter. We had not managed to do it before as the diameter decrease of the cylindrical cathode segment did not lead to the essential change of injection parameters: cross dimensions of the beam, its current and energy remained approximately the same as at 80-mm diameter. The parameters of bremsstrahlung at the output of the facility fixed in the experiments are presented in Table 1. The best results by dose are achieved at 60-mm cathode diameter. The injection current and energy in this case constitute 20 kA and 2.3 MeV, respectively. In this mode there are fixed record dose characteristics for LIA-10M. In a set of pulses the dose at 1 meter distance from the target was as high as 7.5 Gy (Si), while at the output flange it achieved 400 Gy at $5\cdot10^{8}$ Gy/s and $2.7\cdot10^{10}$ Gy/s, respectively. The results obtained by a dose are ~1.5 times higher than the levels that had been achieved before.

In the course of experimental investigations at LIA-10M accelerator there were made noticeable strides in increasing its output dose parameters. However, the reserves built in its design are not by far exhausted and one can expect to get the dose levels ~10 Gy and higher at 1 meter distance from the target. Both theoretical and experimental works are being performed along this line.

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