ABOUT THE ROLE OF INJECTIONS TIMING OF AN ELECTRON BEAM INTO THE ACCELERATING STRUCTURE OF THE LUE-200 ACCELERATOR WHEN USING AN RF POWER COMPRESSION SYSTEM

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The results of measurements of the energy characteristics of the electron beam with a change in the time of beam injection into the accelerating structure of the LUE-200 accelerator - the driver of the IREN facility, a pulsed photoneutron source of the Joint Institute for Nuclear Research (Dubna) are presented. It is shown that when using a microwave power compression system of the SLED type, the choice of the moment of beam injection into the accelerating structure is an important means for forming and optimizing acceleration modes.

INTRODUCTION

Microwave power compression systems of the SLED type [1] are widely used in traveling-wave electron accelerators. However, in the vast majority of cases they are used to supply microwave power to structures accelerating "short" beams or even individual bunches, the current pulse duration of which is comparable to the oscillation period of the accelerating microwave wave, i.e. significantly less than the decay time constant of the microwave power envelope step propagating in the structure after "switching on" the compression (phase reversal of the microwave power introduced into the SLED). In this case, the beam particles are injected into the structure under conditions of a slightly changing value of the accelerating field, and it is possible to form a narrow energy spectrum of the accelerated beam. With an increase in the duration of the bunch current pulse (the duration of the beam current pulse), the beam particles are injected into the structure during a time interval in which the value of the accelerating field can change significantly. In this case, the particles located in the beam "head" and "tail" acquire different energies, the energy spectrum of the beam particles becomes significantly wider, and the specific energy characteristics of the beam depend on the position of the beam injection time relative to the moment of phase inversion of the microwave power at the input of the SLED compression system. For the purposes of this paper, the timing of electron beam injection into the accelerating structure is called the procedure of sequentially changing the injection time of the accelerated beam into the accelerating structure relative to the moment of phase inversion when introducing microwave power into the SLED system. In [2, 3], analytical and experimental studies of SLED-type microwave power compression systems used to power accelerating structures on a traveling wave of the 10 cm range (frequency 2856 MHz) with an oscillation mode of 2π/3 and a constant impedance, developed at the Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences for linear electron accelerators were carried out. Structures of this type operate in the INP accelerator complex (VEPP5 pre-injector) [4], and in the LUE-200 accelerator of the Joint Institute for Nuclear Research [5], as well as in the SKIF injector linear accelerator [6].

The work [7] presents beam energy spectra measured during beam injection timing at the stage of bench testing of the first accelerating section of the VEPP 5 pre-injector of the Budker Institute of Nuclear Physics SB RAS. These measurements demonstrate the existence of an optimum in injection time corresponding to the maximum energy content of the accelerated beam.

This report, in continuation of the studies performed in [8], considers the issues of the efficiency of the accelerating system of the LUE-200 linear accelerator, which uses SLED-type compression systems to increase the level of microwave power injected into the accelerating structure and its optimization for various beam acceleration modes.

ACCELERATOR LUE-200. ANALYTICAL ASSESSMENTS

The driver of the pulsed neutron source IREN [2] accelerator LUE-200 has a set of parameters that provide acceleration of a high-current beam with a duration of 100 - 200 ns by the accelerating system, fed from microwave power sources through SLED systems. The structural diagram of the LUE-200 is shown in Fig. 1. The accelerator consists of an electron gun, a buncher, two accelerating sections on a traveling wave of the 10 cm range (2856 MHz) with a constant impedance [3], fed from klystrons KL1 (E37340 Canon) and KL2 (TH2129 Thomson). The source of electrons of the accelerator is a two-electrode gun with a cathode supply of a pulse voltage of 200 kV and a beam current of 3-4 A with a duration of 200 ns at half-height of the pulse. The vacuum waveguide feeders for the microwave accelerator sections include compression systems SLED1 and SLED2, respectively.

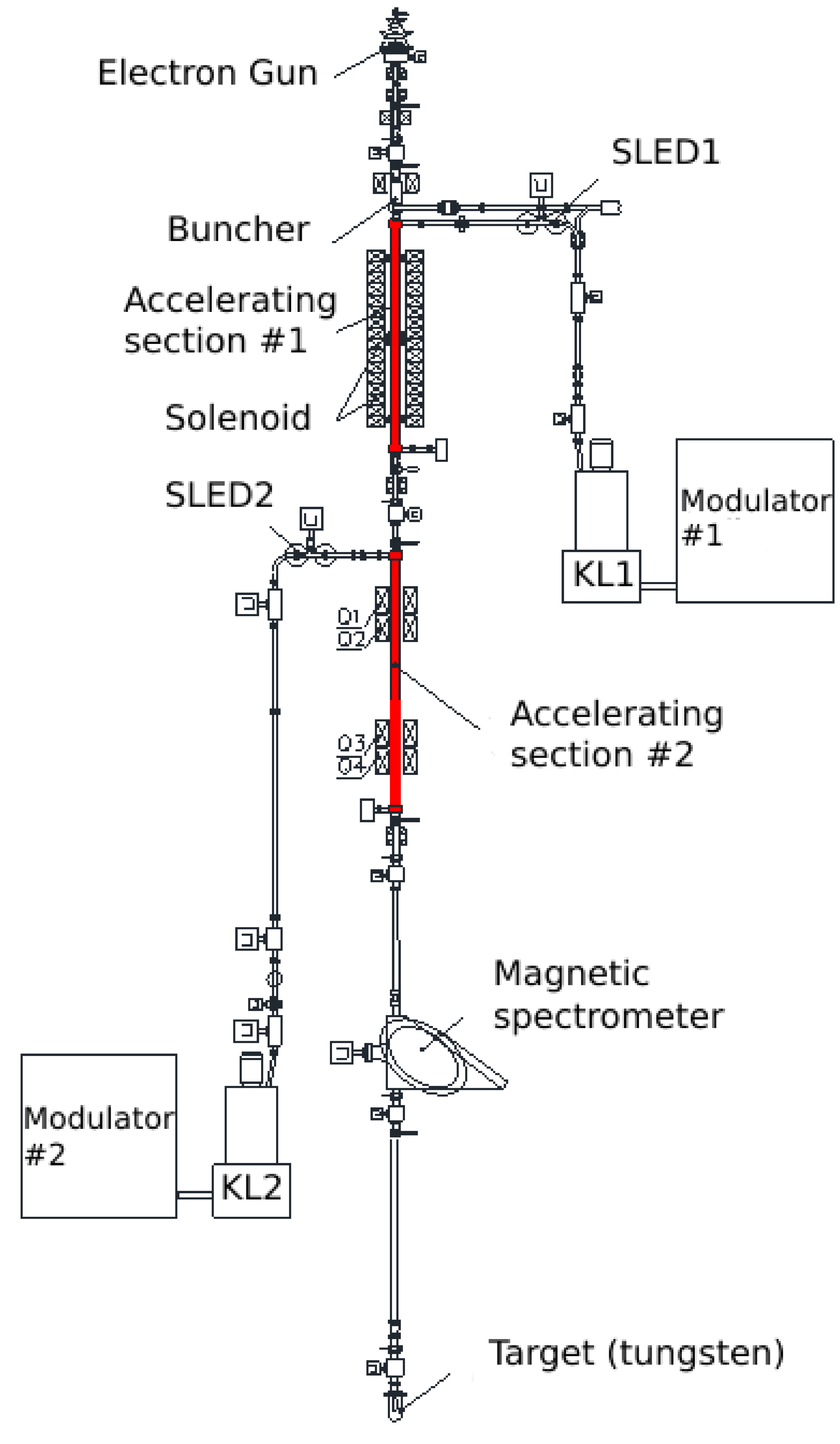

Fig. 1. Structural diagram of the LUE-200 accelerator. KL1 and KL2 are klystrons, M1 and M2 are modulators, SLED are microwave power compression systems

A magnetic spectrometer [9] is used to measure the beam particle energy. It consists of a rotating magnet, a vacuum chamber, and a position-sensitive detector. When the spectrometer magnetic field is switched off, the beam is conducted along an evacuated electron guide to the target. The neutron-producing nonmultiplying target material is ВНЖ-90 alloy based on tungsten.

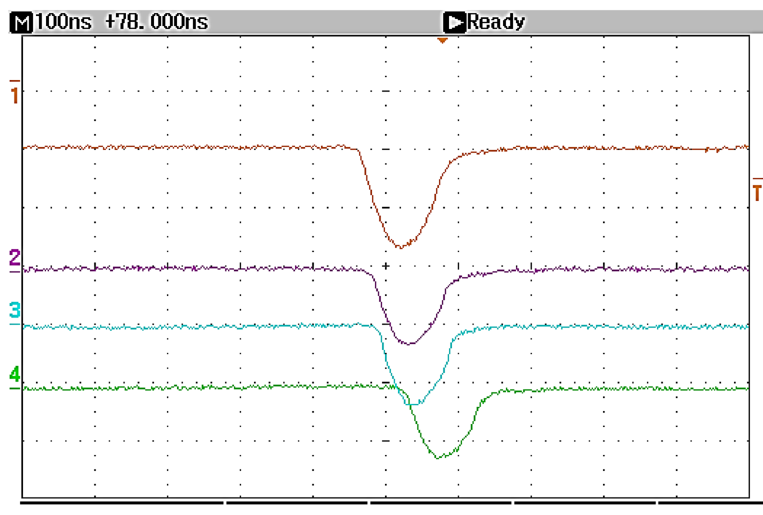

Fig. 2. Beam current oscillograms measured at the control points of the acceleration cycle: 1 - after the 1st section, 2 - after the 2nd section, 3 - after the magnetic spectrometer, 4 - before the target. Oscilloscope sweep -100 ns/div, sensor sensitivity 1 A/V

Klystrons generate microwave power pulses for accelerating sections with the following parameters: output power level of the first klystron is 35 MW, output power level of the second klystron is 20 MW. Klystron microwave pulse duration (3.5 µs) should exceed the filling time of SLED resonators with microwave power of the incident wave, which is 3 µs. After this time, the F1800 phase shifters in the generator of the working frequency of 2856 MHz perform a 180 degree flip of the microwave excitation phase and the SLED systems begin to emit microwave power of an increased level into the accelerating sections with a gain factor equal to the ratio of the microwave power level of the wave reflected from the SLED system resonators to the power level of the incident wave [2, 3].

Fig. 3 shows the oscillograms of the microwave power envelopes measured by the couplers installed at the output of the accelerating sections before the final microwave load. From Fig. 3 it is evident that for the LUE-200 accelerator the power gain factors for both sections are approximately equal and reach ≈ 3.

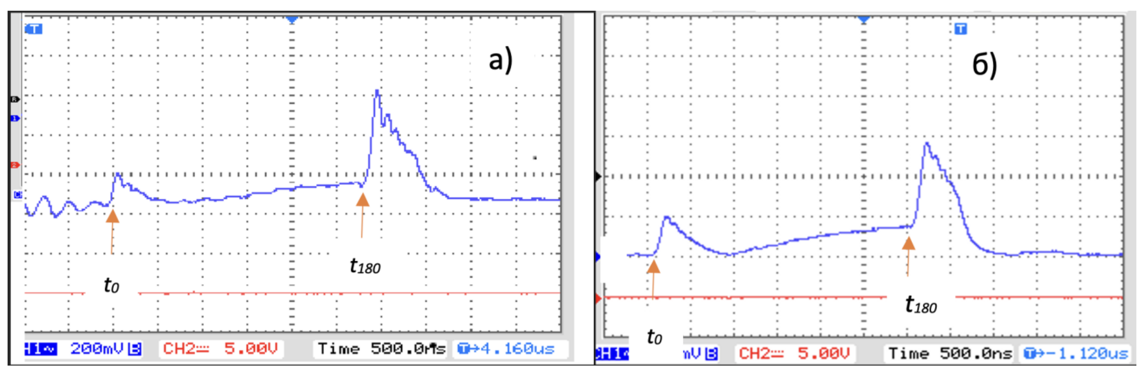

Fig. 3. Oscillograms of microwave power envelopes at the output of the accelerating sections when operating without a beam: a) – for the first section, b – for the second section. t0 – start of microwave power supply to the accelerating section, t180 – switching on the phase reversal of the microwave excitation of the klystrons

For efficient use of the microwave power stored in the accelerating section, beam injection into the section is usually performed after the section is completely filled with a microwave power pulse $t_{in} > T_f = L/V_{gr}$, where T_f = 0.476 µs is the time of filling the section with microwave power, L is the length of the accelerating section, and the group velocity of the microwave wave in the section is V_{gr} = 0.021 s. In the case of using the SLED power compression system, beam injection is performed after the phase flip in the excitation system. In [10], it was analytically shown that, due to the fact that the beam current pulse duration (≈ 100 ns) is commensurate with the duration of the microwave power rise front in the section after the microwave phase flip at the SLED input (≈ 40 ns), there is a certain range of beam injection times relative to the phase flip moment, in which the beam acceleration occurs in fields corresponding to the maximum microwave power levels transmitted to the accelerating section by the SLED system. Figure 4 shows the calculated gain in particle energy during the flight of one accelerating section powered by generators – klystrons with different powers (17 MW, 30 MW and 67 MW) using the SLED system with a power gain of 3 [10]. It is evident from the figure that the maximum energy gain in any case occurs during injection ≈ 0.47 µs after the phase flip. For the klystron configuration implemented at the accelerator (the power of the first klystron is 30 MW, the second klystron is 17 MW), the maximum total energy acquired by a particle in two sections can be ≈ 77 + 58 MeV = 130 MeV.

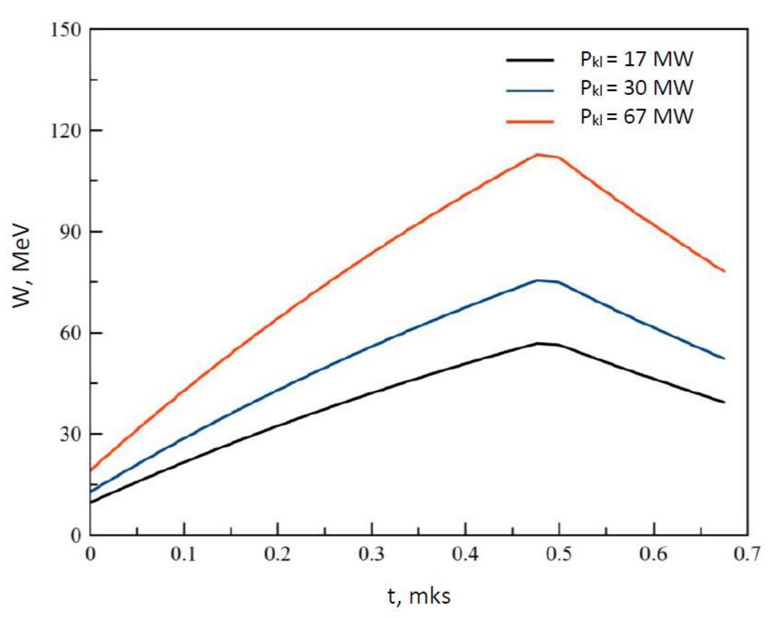

Fig. 4. Calculated gain of particle energy during the flight of one accelerating section, powered by generators – klystrons with different powers when using the SLED system with a power gain factor of 3 [6].

Calculations performed taking into account the loading of the accelerating field by the beam [10] show that for a beam with a current of 1.0 - 1.5 A it is possible to obtain a maximum particle energy of 130 - 135 MeV, and ≈ 90 - 96 MeV at the maximum of the spectrum.

FEATURES AND RESULTS OF TIMING

In the process of beam injection timing on the accelerator, the injection time corresponding to the optimal accelerator setting (with the maximum neutron yield) at the end of a long cycle was taken as the starting point ("0"). The step of changing the beam injection time into the first accelerating section was selected based on the width of the beam current pulse at the base after passing the first accelerating section, and was taken to be 0.15 µs.

To assess the effect of the accelerator setting on the neutron yield, a "neutron monitor" was used, based on a plastic scintillator in combination with a micropixel avalanche photodiode, which was placed in the target hall and recorded both neutrons and gamma quanta generated in the target.

The monitor is not a device for measuring the absolute number of neutrons, but serves to record the relative change in the neutron yield level when the accelerator setting is changed. The results of measurements of the main parameters of the accelerator during the experiment are presented in Table 1 and in Figures 5, 6, 7.

Table 1. Main parameters of the accelerator when changing the beam injection time into the first accelerating section

Injection Time Offset (ns)	-450	-300	-150	0	+150	+300	+450
Current amplitude at the output of the 2nd section (A)	0	0,37	1,25	1,25	1,1	1,3	0
Neutron monitor readings (imp/min)	0	3328	5335	6330	4768	3772	0
Maximum energy of electrons (MeV)	0	51	77	94	95	68	0
Spectrum peak energy (MeV)	0	51	72	90	91	68	0
Spectral width at half maximum (MeV)	-	2	8	8	17	3	-

Figure 5 shows the beam energy spectrum in the "optimal setting" when performing beam injection timing with a current of 1.25 A.

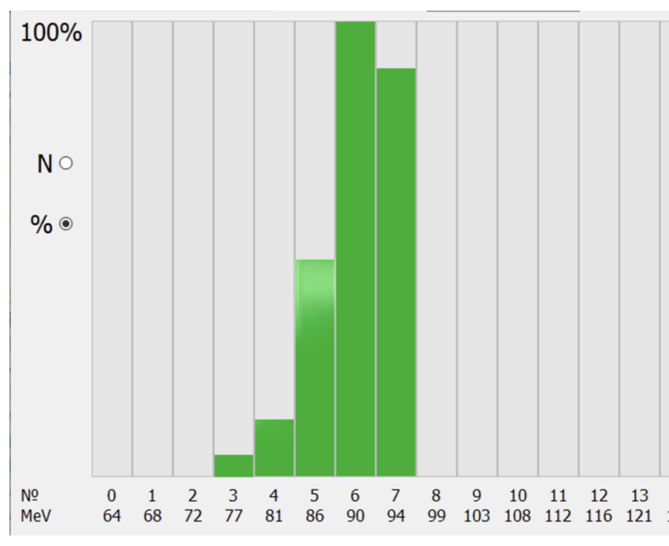

Fig. 5. Beam energy spectrum in the "optimal setting" when performing beam injection timing with a current of 1.25 A.

It can be seen that the deviation of the injection time from the initial point ("0") literally by several steps from the optimum leads to zero beam passage through the accelerating path. Despite the fact that the beam current amplitude at the output of the second section in the iteration with an injection time shift of +0.3 µs becomes slightly larger, the shape of the current pulse is significantly distorted and becomes smaller in the particle integral.

Figure 6 shows the energy spectrum of the beam accelerated in two sections with an injection time of "-300". Despite the fact that the beam passage through the accelerator has decreased (only 0.37 A), such a beam setting may be of interest to users as a source of electrons with a narrow energy spectrum.

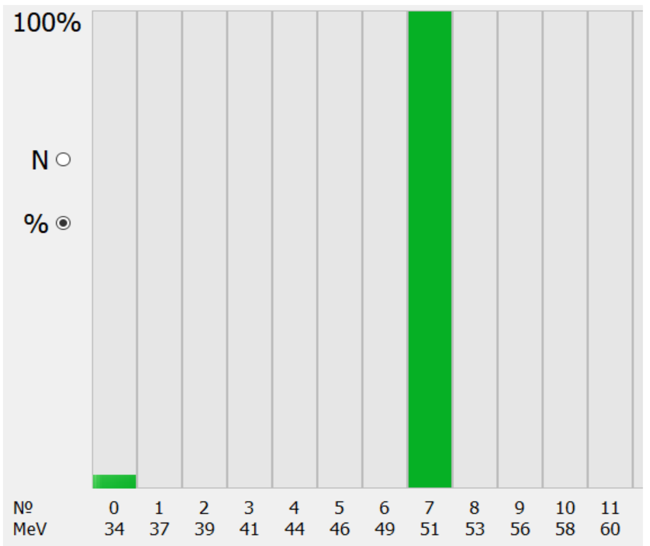

Fig. 6. Spectrum of the beam accelerated in two sections in the "without switching on microwave power compression" SLED" mode. Ib = 0.37 A

Figure 7 shows the beam energy spectrum obtained as a result of complex adjustment of the accelerator, including the selection of the injection time and the frequency of the master oscillator of the microwave excitation of the klystrons [8] in order to obtain maximum energy while maintaining an adequate beam transmission level (1.3 A at the target).

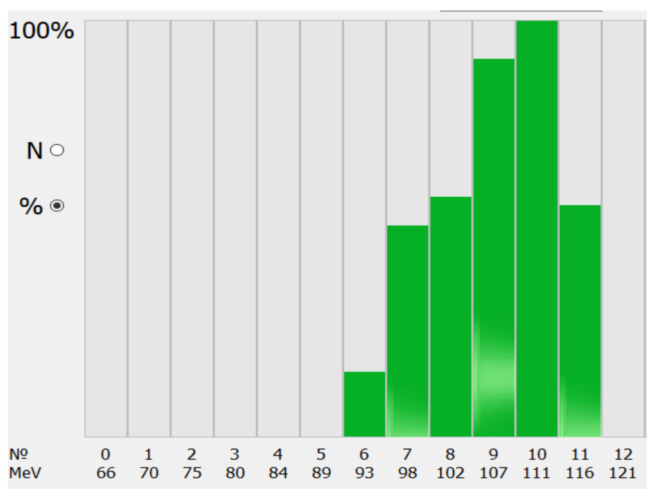

Fig. 7. Spectrum of the beam accelerated in two sections in the "microwave power compression on" mode. Ib = 1.3 A

From the obtained data, it is possible to draw a conclusion about the correct choice of the beam injection time "0", "productive" from the point of view of the neutron yield, about specific boundary cases that allow obtaining a narrow spectrum of the accelerated beam (Fig. 6). It seems possible, in the case of a combination of different approaches to accelerator adjustment (changing the microwave power, the pulse width of the injected beam, the injection time), to obtain high average energies and the maximum neutron yield, while maintaining a low energy spread.

CONCLUSION

In the LUE-200 accelerator - the driver of the ADS type photoneutron source, beams are accelerated whose pulse duration is approximately equal to 1\5 – 1\10 of the microwave power envelope decay time constant. In this case, the "head" and "tail" of the beam are accelerated in fields that differ for the "head" and "tail" particles, which in turn affects both the shape of the accelerated beam current pulse, primarily the amplitude (i.e. with the loss of particles), and the energy spectrum of the beam. As a result of the timing of the beam injection into the accelerating system in combination with the matching of the natural frequencies of the accelerator microwave system components, the energy characteristics of the beam were obtained that are close to the calculated ones for the implemented configuration of the microwave system. For the LUE-200 accelerator, the main parameter of the accelerated electron beam is its power, determined by the values of the energy and current of the beam. The choice of the moment of beam injection into such a system becomes a convenient means of changing and optimizing acceleration modes and depends on the intended use of the LUE-200 accelerator, either as a driver of a photoneutron source or as a source of a high-current electron beam for applied purposes.

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