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Test Electron Beams Based on the Linear Accelerator Complex LUE-75 of A.I. Alikhanyan National Scientific Laboratory

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Abstract—Based on the linear electron accelerator LUE-75 of the A.I. Alikhanyan National Scientific Laboratory a technique for obtaining controlled primary electron beams with an intensity of (10–20) electrons per second in the energy range (15–75) MeV for elementary particle detectors calibration was developed and used. Joint work with the V.P. Dzhelepov Laboratory of Nuclear Problems (JINR, Dubna, RF) showed the efficiency of the technique.

Keywords: linear accelerator, low intensity beams, particle detectors calibration

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1. INTRODUCTION

The linear accelerator complex LUE-75 of the A.I. Alikhanyan National Science Laboratory (ANSL, Yerevan Physics Institute – YerPhI) Foundation until 2008 served as an injector for the Yerevan electron ring accelerator ARUS, at one time the largest electron synchrotron in the Soviet Union with energies up to 6.1 GeV. The LUE-75 continues successfully to operate currently in an autonomous mode. It is a four-section resonant accelerator on an S-band traveling wave. It provides acceleration of electrons in the energy range (10–75) MeV at pulse currents up to (150–200) mA, which corresponds to an average current of up to 10 μA (without collimation), depending on the macropulse duration and energy; at nominal energies the width of the energy spectrum (FWHM) is about 2%. The parameters of the LUE-75 linear accelerator complex, including the linear accelerator itself and the parallel transport path (Fig. 1), located in the ring hall of the synchrotron, are presented in [1] in detail. The LUE-75 is the only operating accelerator of this class in the region. The research groups of Armenia conduct experiments on it, as well as the joint projects, which are carried out with the scientific groups from other countries, to solve the fundamental issues of nuclear physics at low energies and apply the scientific and methodological problems [2].

In recent years, renovation and restoration works have been carried out with the purpose to expand the capabilities of the accelerator. In particular, a technique for obtaining the unique electron beams of extremely low intensity (10–20) e^-/s in the energy range 15–75 MeV was developed and further improved in 2014–2015. Such low-intensity beams can be used to study individual events, diffraction problems, the radiation of electrons in single crystals, the biological effects of ionizing radiation in low doses, and nanotechnology, etc. In 2015–2019, such beams were successfully used at LUE-75 as test beams with the number of one-electron events per pulse exceeding 70% to calibrate crystalline scintillation detectors of elementary particles in the framework of joint work of the ANSL (Yerevan) – JINR (Dubna). For the Mu2e experiment, which is being prepared at Fermilab (USA) [3], the testing of a prototype electromagnetic calorimeter in the form of a matrix of nine undoped CsI crystals has shown the effectiveness of the method. This collaboration served as a motivation for the problem, the solution of which is described below.

2. EXTREMELY LOW INTENSITY TEST BEAMS

Highly sensitive detectors cannot be investigated or calibrated with beams of high intensity to avoid radiation damage, an increase in the afterglow time, and the phenomenon of phosphorescence [4]. Low-

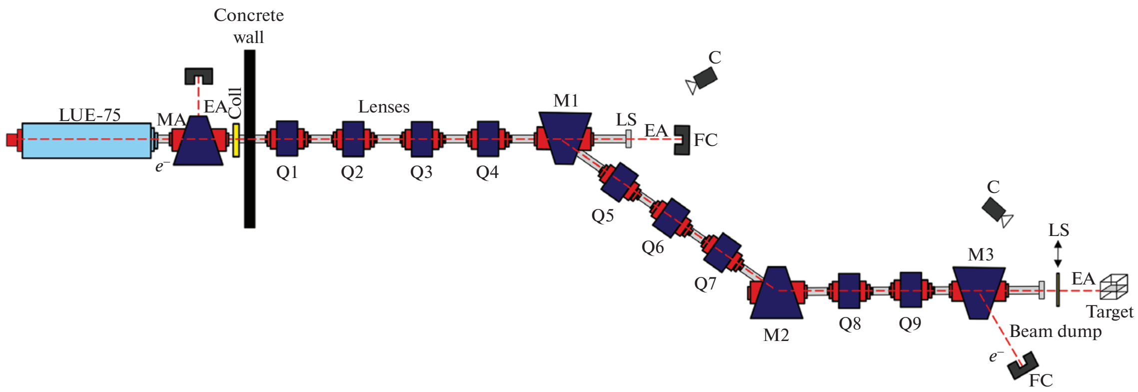

Fig. 1. Simplified diagram of the beam transport path with parallel transfer: FC is the Faraday cup; MA is the analyzing magnet; coll is the collimator at the accelerator outlet; M1, M2 are the parallel transfer magnets; M3 is the magnet-beam dump; Q1... Q9 is the quadrupole lenses; EA is the experimental area; LS is the phosphor screen; C is the camera.

intensity radiation from the sources of natural origin, radioactive isotopes, and cosmic rays are used more often as an indicator for testing the performance of both scintillation sensors and recording equipment at fixed particle energy. Cosmic muons are used not only for these purposes but also for assessing the temporal and spatial resolution of scintillation counters, as described in [5].

In recent years, at LUE-75, the methodical work on energy calibration of the matrix of CsI crystals by beams of intensity (10–20) e^-/s in the energy range of 15–75 MeV was carried out in cooperation with the research group from JINR (Dubna, RF). The controlled electron beams of extremely low intensity are obtained in several research centers [6, 7]. The needed range of electron energies from 10–15 to 75 MeV, which was necessary to calibrate crystals, was provided by the LUE-75 linear accelerator at the time of the described work.

Note that an extremely weak flux of single, in succession, flying electrons with an intensity of 4.2×10^3 e^-/s, accelerated in a transmission type magnetic electron microscope to an energy of 72 keV, was first obtained in diffraction experiments described in the well-known work [7].

Depending on the type, design, and capabilities of the accelerator, solutions to such a problem may be different. There are two ways to obtain such electron beams: the converter method and the direct production of a primary ultra-low intensity beam [5, 6].

In 2014, on the LUE-75 accelerator complex, the task was set to develop a methodology for obtaining the test beams of extremely low intensity based on using the available technical and technological base of the ANSL (YerPhI), without making significant changes to the design of the accelerator. it was decided to obtain the primarily controlled beams of extremely low intensity using the constructive capabilities of the accelerator complex favorable for the set goal - the presence of a transport path with parallel beam transfer located in the synchrotron hall far from the LUE-75 room behind its radiation-protective wall (Fig. 1). The study, carried out in the measurement area, showed that there is practically no influence of electromagnetic interference and interference from the electrical and radio engineering devices of the linear accelerator on the measuring equipment, which is important for conducting precision experiments.

Obtaining such low intensities is also complicated by the dark currents of the accelerator, which create problems for experimenters: an increase in the radiation background, and the heat release on the walls of the accelerating waveguides and the beam guide, the loss of a part of the useful beam because of the induced parasitic fields, etc. When receiving the beams of ultra-low intensities, the dark currents limit the intensity of the useful beam from below, therefore, the identification and elimination of the causes of their occurrence is of fundamental importance. They can appear for various reasons: because of the microwave breakdowns in the accelerating sections, the ionization of the residual gas in the sections when colliding with electrons, field emission from the surface of a metal vacuum chamber. Electrons arising in these processes can enter into the favorable phase of the accelerating wave and appear at the exit of the accelerator along with the useful beam. Unlike the latter, the dark currents are random and uncontrollable: their energy depends on where in the accelerating structure they originated.

Measurements of dark currents using electrometric equipment and a magnetic analyzer with a Faraday cup at the output showed that the main source of these currents was the initial part of the accelerator: their intensity sharply increased with an increasing microwave power in the injection section. Improving the

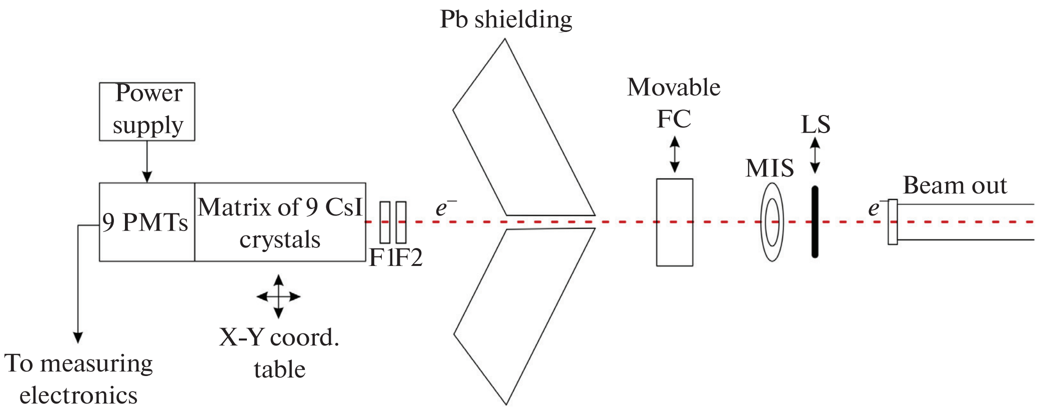

Fig. 2. Detector calibration area. Experiment scheme.

vacuum by almost an order of magnitude along the entire path and careful work to select the limits of changes in microwave power levels at the inputs of not only the injection but also all sections made it possible to exclude the appearance of dark currents at the outlet of the path – at the location of the tested samples. Subsequently, during numerous sessions on the calibration of crystals with beams of extremely low intensity in the energy range of 15–75 MeV, no dark currents were detected. Recall that the dark currents are the currents at the output when the gun is completely turned off. With a heated cathode of the electron gun, electrons at the exit of the transport path at the location of the crystals under study were also not detected by the recording equipment.

When receiving and adjusting the beam, we used a combination of the following methods of decreasing the intensity: lowering the temperature of the thermo-cathode – while the gun remained in the space charge mode; collimation of the beam; changing the duration of microwave pulses within a small range; regulation of the beam intensity by varying the high voltage at the electron source within small, predetermined limits, at which practically no change in the average flow energy is detected due to a change in the initial energy entering the injection section; adjustment of elements located in inactive areas of the accelerator, where there is no accelerating field. We have used different methods depending on the required output intensity and energy; for each required output energy of electrons, the predetermined parameters of the accelerator regime were set, which were then carefully adjusted to optimal values for a given average intensity of single electrons at the output of the channel.

On the Faraday cup behind the analyzing magnet MA (Fig. 1), the beam was preliminarily tuned to given energy with an intensity of several tens of nA. The beam was directed through a collimator with a 3 mm aperture to the transport path located at the exit of the LUE-75 itself. Using quadrupole lenses Q1– Q4 and correctors (not shown in Fig. 1), the forward beam current was measured with the Faraday cup behind the disconnected magnet M1. A clear image of the beam was obtained on the LS phosphor screen (a thin layer of phosphor material deposited on the Kapton output window). Then magnets M1 and M2 were switched on, and the beam was guided through the magnetic optics of the parallel transfer path previously adjusted by the laser beam.

Figure 2 shows a schematic diagram of the experiment in the area of the crystals under study. At the exit of the tract, a beam is formed with an average current of 2–3 nA and a beam spot diameter of 3–4 mm. This is the minimum current value at which visual registration of the beam profile is achieved on a movable phosphor screen mounted remotely in front of the beam exit window (Fig. 2). During tuning, the movable Faraday cup, in addition to measuring the current on the phosphor, protects the crystals from the hit of a high-intensity beam to avoid their overload and eliminate the influence of the afterglow. After the formation of the beam spot by the elements of the magneto-optical system, the beam intensity dropped to almost zero, the phosphor screen and the Faraday cup blocking the beam path were moved away remotely, and the flux intensity controlled by the measuring electronics was set to a given average value of 10–20 elec-

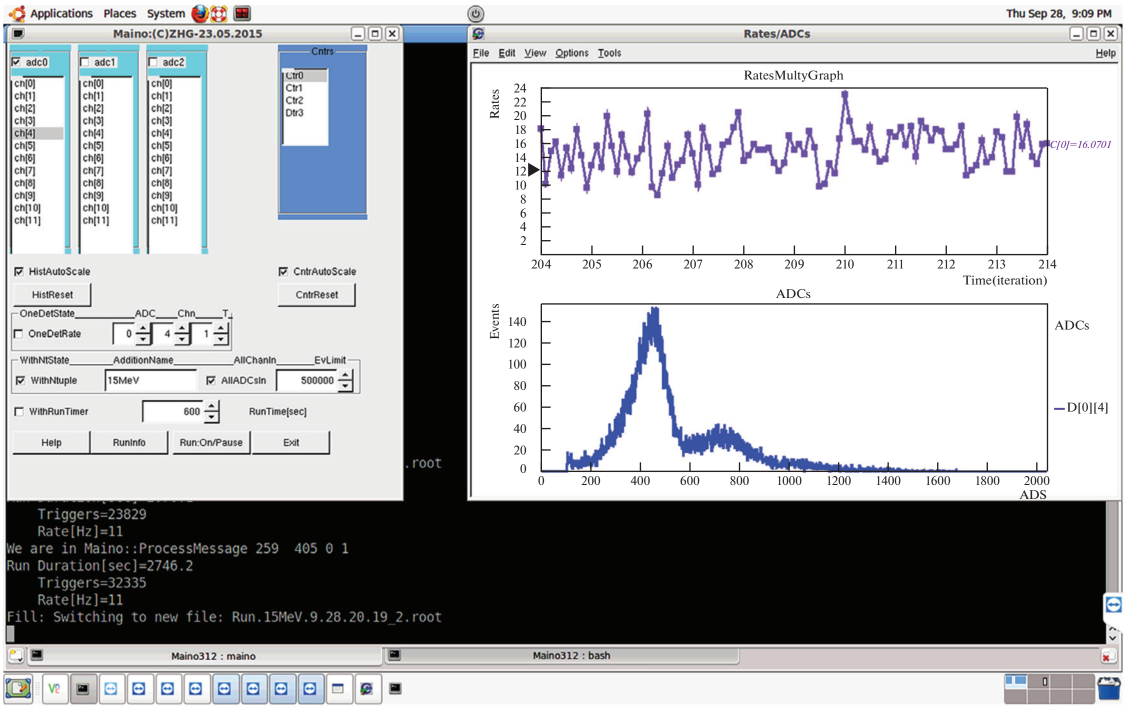

Fig. 3. Screenshot of the MAINO program interface. Right: upper ray is the line for reading single events, below is the histogram of the distribution of the number of events over the ADC channels with an average electron energy of 15 MeV.

trons per second. One of the criteria for choosing the intensity of the particle flux is to minimize the phenomenon of the signal pile-up. With an increase in the number of particles per unit time, the number of multielectron events per second increased. Consequently, the required output beam intensity required attenuation by at least 9 orders of magnitude.

To one degree or another, the energy and current of the accelerated electron beam depend on many tunable parameters of the accelerator. The beam energy mainly depends on the power level of the accelerating field. There is also a significant dependence on the magnitude of the pulsed beam current, expressed by the load characteristic, from which it followed that if the microwave power introduced into the section corresponds to a certain maximum output energy E_{max} (at $I = 0$), then with a preliminary set of the installation for a low current and a further decrease in the intensity to extremely low values, the change in the initial energy of the particles will be insignificant. So, when tuning to an average current of several tens of nanoamperes, and a further decrease in intensity, the change in the average electron energy does not exceed 0.1 MeV, which is within the permissible measurement error.

An additional powerful lead shield with a thickness of 20 radiation lengths shields the crystal zone from the bremsstrahlung generated when the beam is rotated by the parallel transfer magnets. A rather long collimator is built into the protective wall in front of the tested matrix of crystals, which limits the effect of natural beam divergence.

The investigated matrix of nine undoped CsI crystals (assembly 3×3) is equipped with photomultiplier tubes of the FEU-85 type (Fig. 2). The reception, processing, and visualization of data were carried out by program “MAINO” of one of the co-authors (H.Z.), which also allowed recording and storing the results for further processing (Fig. 3). The “MAINO” program was developed using classes from the ROOT Data Analysis Framework (https://root.cern) and ran on Linux. Remotely computer monitoring and control of the experiment were provided.

3. ABOUT OTHER WORKS RELATED TO SOLVING THE PROBLEM

The solution of the described scientific and methodological problem, however, like any other, required the creation of an appropriate infrastructure taking into account the features of the experiment, including elements of the structural diagram of the experiment, measuring equipment, software, etc. The imple-

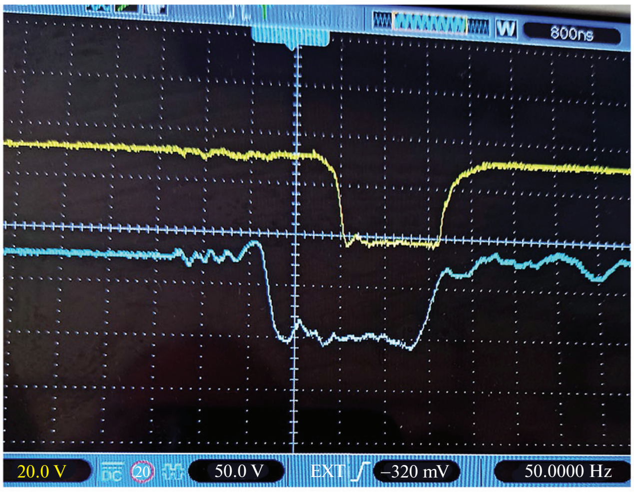

Fig. 4. The bottom beam is the modulator pulse; the upper beam is the microwave pulse envelope.

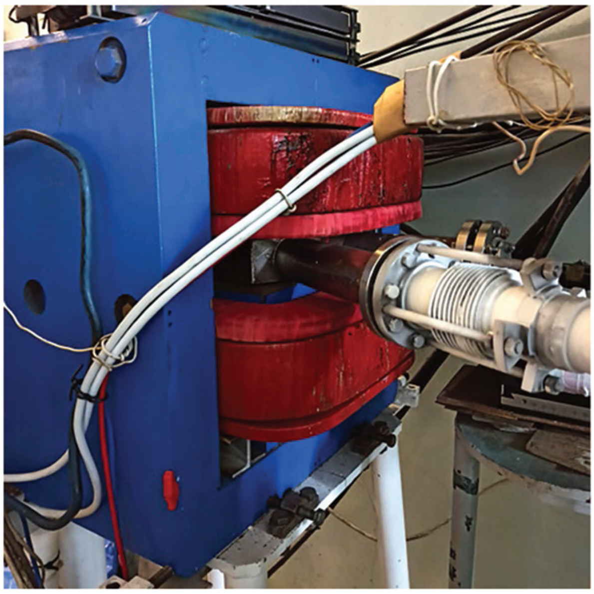

Fig. 5. Parallel transfer magnet with additional winding.

mentation of such an infrastructure makes it possible to assert that there is a stand for solving the set and similar tasks.

In connection with the energy range demanded of the work described above, the third accelerator station was restored and put into operation, due to which the electron energy was brought to 75 MeV [1].

Figure 4 shows the oscillogram of the high-voltage pulse of the klystron modulator and the envelope of the spent microwave pulse at the output of the accelerating section of the reconstructed third accelerating station.

It was also necessary to modernize the elements of the magneto-optical system of the parallel transfer path to operate with a beam in the energy range of 50–75 MeV. Figure 5 shows one of the identical bending magnets in the parallel transfer path after power rising.

Simultaneously with the work on increasing the energy to 75 MeV, problems were also solved on beam diagnostics. A calibrated magnetic analyzer (MA in Fig. 1) with the Faraday cup and a current integrator is used to measure the energy and intensity of the beam around the bend. Energy measurement in the

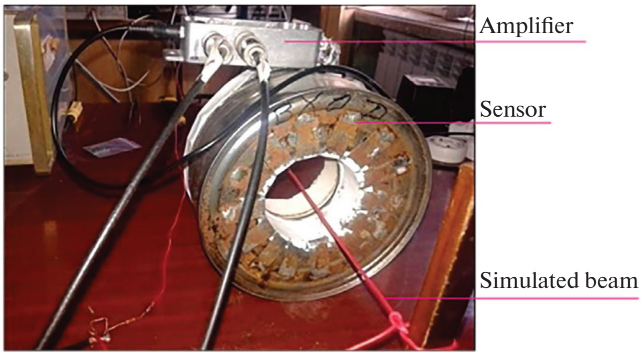

Fig. 6. Testing the sensor with simulated beam current.

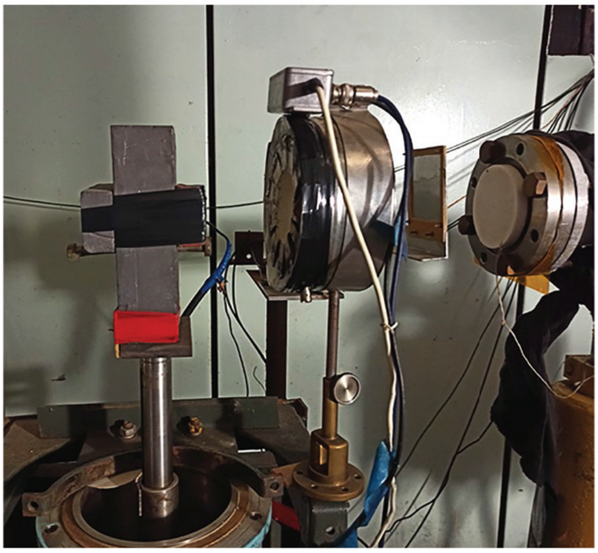

Fig. 7. Magnetic induction sensor with an amplifier at the output of the beam.

range of 50–75 MeV required an increased current through the analyzing electromagnet, therefore, the necessary changes were made to the power supply circuit, regulation, and stabilization of the electromagnet current, as well as to its cooling system to exclude the possible overheating of the windings with an increase in their current load.

In the course of the experiment, the possibility of non-destructive continuous monitoring of the intensity and shape of the output beam pulse was ensured. The target was installed in front of the 'straight beam' or behind the MA bending magnet between the LUE-75 exit window and the Faraday cup (EA zones in Fig. 1).

Magnetic induction sensors, consisting of a toroidal ferrite ring with two symmetrically wound windings on them were computed and designed. The signals from the beam directed to the windings are fed through two channels, which include two-stage amplifiers based on the low-noise high-speed op-amps, and the first stage of each channel is a differential amplifier at the output of which the common-mode noise is subtracted. The sensors are well shielded to prevent any interference. Thus, noise immunity and high sensitivity of the sensor are ensured. To test the sensors, a setup was assembled with the simulation of the beam current from a pulse generator (Fig. 6).

The sensors (MIS in Fig. 2) were installed in the sections of the beam exit into the atmosphere in the experimental zones (Fig. 7). Work with these sensors showed that their sensitivity is much higher than that of a phosphor screen, which facilitated the detection and adjustment of a low-intensity beam when guiding it along the path.

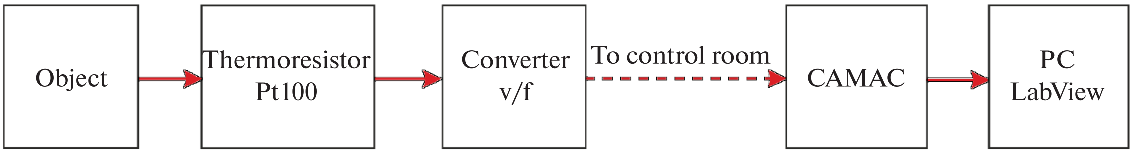

Fig. 8. Temperature measurement block diagram.

To ensure the stability of the beam parameters, the accelerating sections are thermostated with a temperature accuracy of ±0.5°C. For computer monitoring of temperatures of various systems vital for the accelerator, an electronic measurement, and control system was developed and implemented, taking into account the strong background of electromagnetic interference and interference in the premises of the accelerator (Fig. 8). The current through a platinum thermistor of the Pt100 type, linearly dependent on the temperature of the thermostating water, is proportionally converted into the pulse repetition rate transmitted via a coaxial cable to the LUE-75 control panel and arriving at the scaler in the CAMAC standard.

The temperature readings of the thermostating water of the accelerating sections and the cooling water at the inputs-outputs of powerful klystrons are displayed on a computer monitor, where information processing and visualization is carried out using the program LabView.

For irradiation with an electron beam, a coordinate table (Fig. 2) was designed to place a test matrix of crystals on it, and also software was prepared to control its movement. The coordinate table allows the high-precision scanning of the crystal assembly in the transverse plane with the use of a computer both in the accelerator hall and the experimental room, from where the experiment was controlled using one of the programs for remote access to the computer.

4. CONCLUSION

The presence of a parallel beam transfer path, a low level of dark currents, and the correct choice of operating modes of the accelerator systems taking into account the current load made it possible to create favorable conditions for obtaining electron beams of extremely low intensity.

The joint successful work of research groups of the Department of Experimental Physics of the ANSL (Yerevan) and the Laboratory of Nuclear Problems of JINR (Dubna) showed that the LUE-75 linear accelerator complex can serve as a source of test beams of extremely low intensity for calibrating elementary particle detectors. As noted in the Introduction, such low-intensity beams can be used to solve various problems in the field of low-energy nuclear physics. Works are known [9] on the irradiation of nanoparticles with radionuclides, but it is also interesting to test nanotubes with beams of low intensity for radiation resistance at higher energies.

The accelerator is currently working reliably. We consider it expedient to carry out work on the modernization of individual items and systems with the introduction, where is possible, of digital technology to further increase efficiency. First of all, this refers to the accelerator support systems: the thermostating and cooling system, electro-radio components, the vacuum system, and the control system.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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