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On Modernization of the LEE-75 Linear Electron Accelerator of the AANL (YerPhI)

L. R. Vahradyan*
Alikhanyan National Science Laboratory, Yerevan, Armenia
**e-mail: l.vahradyan@yerphi.am*

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Abstract—Briefly presented the scientific and technical state of the linear accelerator complex of the A. Alikhanyan National Scientific Laboratory. LUE-75 after renovation work carried out in recent years. The need for further modernization of the accelerator's main systems to ensure its long scientific life is substantiated. An analysis of the state of individual nodes and systems of the accelerator and calculations have been carried out, based on which modernization is proposed by the introduction of modern technology. The use of new-generation power electronics, vacuum equipment with a modern interface, and a thermostabilization system is offered.

Keywords: linear electron accelerators, modernization of particle accelerators, electron beams

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1. INTRODUCTION

Linear electron accelerator LUE-75 of the National Scientific Laboratory named after A.I. Alikhanyan (AANL, Yerevan Physical Institute (YerPhI)) served as an injector for the ARUS synchrotron. After the synchrotron is shut down, it operates in autonomous mode and provides electron beams and secondary radiation for experiments in the field of low-energy nuclear physics.

The linear accelerator operates in the electron energy range of up to 75 MeV with average beam currents of up to 10 μA. The accelerator must be constantly developed to meet the growing requirements for beam parameters. Without the introduction of new technology, the accelerator cannot have a long scientific life. To improve the quality of research and increase demand, it is planned to modernize the linear accelerator installation with the introduction of modern technology. The main attention is paid to vital systems: vacuum technology, thermal stabilization, cooling systems, and modulators of powerful amplifying klystrons. Modern measuring equipment will improve the accuracy and quality of experiments.

In this work, after a brief review of the scientific and technical state of the linear electron accelerator LUE-75, issues of modernization of this unique installation in Armenia are outlined.

2. ON THE LINEAR ACCELERATOR LUE-75

The accelerator complex consists of a linear electron accelerator and a parallel beam transport path. The accelerating structure contains a buncher (waveguide grouper) and three identical accelerating sections, which are round diaphragm waveguides operating in the S-band on a traveling wave. The electron source is a thermoelectric cathode placed in a diode gun with Pierce optics. The energy of electron injection into the buncher is 50 keV. In it, electrons are grouped into bunches and simultaneously accelerated to an energy of 3 MeV. The sections are powered by three klystron posts built based on powerful fly-by klystrons of the KIU-12 AM type. The first klystron operates in self-excitation mode, supplying the remaining klystrons with input power [1]. Part of the power of the 1st klystron is supplied to the input of the waveguide combiner using an adjustable directional coupler. LUE-75 is powered by a 0.1% stable three-phase electrical network.

LUE-75 provides acceleration of electrons in the energy range of 10–75 MeV at pulse currents of 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 energy spectrum width (FWHM) is about 2%. The proven modes make it possible to obtain intensities from tens to 5×10^{13} electrons per second.

Fig. 1. The typical oscillogram of the output pulse of a klystron modulator.

In recent years, some work has been carried out on the linear accelerator to improve its parameters. Let us note the main ones: the barium-nickel cathode was replaced by a metal-ceramic one with a relatively longer operating time, higher emission, and less susceptibility to oxidation; to reduce the background radiation level when the synchrotron is turned off, and the influence of electrical pickups and radio interference from operating linear accelerator systems on the measuring equipment in the synchrotron hall, an electron beam transport path with parallel transfer away from the LUE was built; The beam energy was increased from 50 MeV to the design value of 75 MeV [2]. These and other works expanded the capabilities of the accelerator and, accordingly, the range of scientific research planned by experimenters.

A technique for obtaining unique electron beams of extremely low intensity was developed and further improved [3]. Together with a scientific group from the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research (Dubna, Russian Federation), a technique for energy testing of elementary particle detectors with beams of extremely low intensity of several tens of electrons per second was developed and applied. This technique was used to study a prototype electromagnetic calorimeter for an experiment planned at Fermilab (FNAL, USA) Mu2e. Low-intensity beams can also be used to study individual events and diffraction problems, the emission of electrons in single crystals, the biological effects of ionizing radiation in low doses, the radiation resistance of semiconductor materials, and nanotechnology. The parameters of the linear accelerator complex, including the parallel transfer path, are presented in detail in [2, 3].

3. ISSUES OF MODERNIZATION OF LUE-75

3.1. Klystron Modulators: Power Electronics

The modulators produce pulses with an amplitude of up to 300 kV and a duration of 2.2 μs to power powerful klystrons such as KIU-12 AM. The quality of the electron beam, in particular, the width of the energy spectrum, largely depends on the shape of the modulating pulse (Fig. 1). The modulators use hydrogen pulsed thyratrons of the TGI1-2500/35 type, which are out of production now.

The task arose of replacing thyratron switches with modern ones. When selecting the type of switch, we proceeded from the approximate correspondence of technical characteristics, minimal design, and circuit changes in the modulators during replacement, operating time, and economic considerations. The closest electrical parameters turned out to be thyratrons of the CX1525A type from “e2v” Technologies and the new generation TGI-type thyratrons from Pulse Technologies LLC [4]. Installation of TGI-type thyratrons will require minimal changes in power supply and cooling circuits; their acquisition is more economical. The company also provides adapters when replacing TGI1-2500/35 with new-generation thyratrons. When using new thyratrons of the TGI1-5k/50 type, one can limit oneself to two series-connected thyratrons in each modulator instead of the three currently used.

The metal-ceramic design of these devices is safer to use compared to the currently used glass thyratrons TGI1-2500/35: the internal screen minimizes the level of X-ray radiation from the anode region. Table 1 shows some basic comparative characteristics of thyratrons.

It is expected that the use of new-generation thyratrons will lead to an improvement in the pulse: a decrease in the front duration, an increase in the flat part of the pulse – the working section, and therefore an improvement in the stability of the beam during the pulse.

Note that with high voltages and currents used at the accelerator, replacing gas-filled thyratrons with solid-state switches based on IGBT transistors will require serious design and circuit changes and is more expensive because of the complexity of the circuit. There are uncertainties regarding the service life of IGBT modules. At this stage, their use as switches is impractical.

Table 1. Parameters of the thyratron used and new generation thyratrons.

Parameter name	TGI1-2500/35	TGI1-5k/50	TGI2-3k/30
Filament voltage, V	6.3	5.0/6.5	4.0/6.5
Filament current, A	50–60	20–30	not more than 25
Pulse anode current, A	2500	2500	2500
Anode current pulse duration, μs	10	0.02–50	10
Anode current pulse frequency, Hz	250	200	300
Forward and reverse voltage, kV	not more than 35	not more than 50/20	not more than 30
Resource, h	500	no less than 3000	2000
Weight, kg	7	3.2	4

The powerful amplifying klystrons available at AANL will ensure the functioning of the linear accelerator for the coming years. However, in the future, when switching to a new generation of klystrons and replacing modulators with more compact modules, power consumption will be significantly reduced.

3.2. Thermostatic and Cooling System

For sustainable acceleration of the electron beam and stability of its energy and intensity, high stability of the natural frequency of the accelerating sections, as well as the frequency and power of microwave oscillation generators is required to maintain the phase relationships of the accelerating fields in diaphragm waveguides. To ensure the invariance of the geometry of resonant structures, it is necessary to ensure temperature stabilization of both accelerating sections and klystron generators.

The LUE-75 has two independent thermostatted and cooling circuits, built before the 90s. One of the circuits is used for thermal stabilization of the accelerating sections, the other is for klystrons with focusing coils and other components that require cooling.

Maintaining the required temperature within ±0.5°C of the set temperature is carried out using controlled heating of the supplied water at the inlet of each section. Signals from platinum sensors installed at the outputs of the sections are fed to control circuits (pulse-width modulation, thyristor units) located in the control room of the linear accelerator. Using the LabView program and CAMAC modules, the temperatures of the thermostatic water of the accelerating sections and water at the inputs and outputs of the klystrons are monitored. The cooling system for high-power fly-through klystrons does not contain heating blocks. The current thermal stabilization system is built on elements that have been discontinued, semiconductor electronics are aging, and parameters are deteriorating. It is necessary to create a new system using modern components and compact, highly efficient heat exchangers.

When the linear accelerator operated as a synchrotron injector, the same amount of energy and current was required. Currently, the accelerator operates in autonomous mode and provides experimenters with beams of varying energies and intensities within the limits given above. If it is necessary to quickly adjust the output parameters, the microwave power supplied to the sections changes. The thermal stabilization system has a large inertia and is physically outdated. Therefore, it is planned to develop a new system for temperature control of sections and cooling of accelerator units using PID control and a modular scheme, in which thermal stabilization of each section is carried out by its autonomous system, which will ensure automatic maintenance of the temperature of the sections within specified limits during long sessions, as well as efficiency and accuracy of setting section temperatures when changing linear accelerator modes.

According to the passport technical data, the total phase shift per accelerating section is 5.76 degrees. A systematic error in the cell sizes of the sections causes this shift. When the temperature changes, the dimensions of the accelerating waveguide change and an additional phase shift of electrons relative to the wave occurs. In the main sections, the bunches are placed at the top of the wave when tuning to obtain the greatest acceleration. If the temperature of the sections is not stabilized, then over time this will lead to a lack of energy and an increase in the energy spread of the electron beam.

The amount of energy decrease for small phase changes is equal to

$$\frac{\Delta E}{E} = \frac{(\Delta\varphi)^2}{6}, \tag{1}$$

where Δj is the phase shift. According to the reference book on diaphragm waveguides [5],

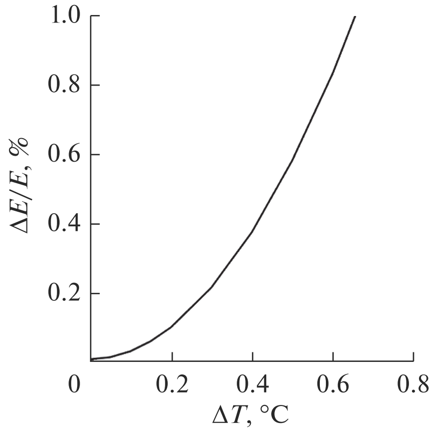

Fig. 2. Dependence of the relative change in the output beam energy on the change in the temperature of the accelerating sections.

$$\Delta\varphi = -\frac{2\pi}{c\beta_{\text{ph}}}\left(1 - \frac{f}{\beta_{\text{ph}}}\frac{d\beta_{\text{ph}}}{df}\right)L\alpha_T f\Delta T, \tag{2}$$

where β_{ph} is the relative phase velocity of the wave; f = 2.7972×10^9 Hz; L= 4.15 m is the active length of the diaphragm waveguide; when computing the change in beam energy at the output of a linear accelerator, one should take the total length of all three sections, $L = 3 \times 4.15$ m; α_T is the temperature coefficient of linear expansion of the waveguide material, for copper at 30°C (operating temperature of the section) $\alpha_T = 1.68 \times 10^{-5}$ K^{-1}; we find the dispersion coefficient of the diaphragm waveguide $fd\beta_{\text{ph}}/df$ from the expression for the group velocity β_{gr} [5]:

$$\beta_{\text{gr}} = \frac{\beta_{\text{ph}}^2}{\beta_{\text{ph}} - f\frac{d\beta_{\text{ph}}}{df}},$$

and we obtain

$$f\frac{d\beta_{\text{ph}}}{df} = \beta_{\text{ph}}\left(1 - \frac{\beta_{\text{ph}}}{\beta_{\text{gr}}}\right), \tag{3}$$

Substituting into (3) the data for the sections under consideration $\beta_{\text{ph}} = 1$ and $\beta_{\text{gr}} = 0.033$, let us find the dispersion coefficient $fd\beta_{\text{ph}}/df = -29.3$. Using expressions (1) and (2), it is easy to find the dependence of the output energy of the beam on the change in the temperature of the sections (Fig. 2).

Table 2 shows the energy shortfalls depending on the change in the temperature of the sections when the accelerator is pre-tuned to 75 MeV. When the temperature changes by 0.5°C, the average energy decreases by more than 0.4 MeV, and for many precision experiments the accuracy of 0.5°C is insufficient. The table shows that with a temperature stability of 0.2°C, the energy instability at 75 MeV is about 70 keV or less than 0.1%. Such accuracy of temperature maintenance is easily achieved using PID control, which is successfully used on other accelerators [6–8]. Ready-made PID controllers and controlled thyristor blocks of various capacities are produced by different companies.

When selecting chillers, heat exchangers, and charge pump capacities, knowledge of the cooling water flow or the temperature difference at the outlet and inlet of the cooled object is required. The relationship

Table 2. Dependence of the magnitude of the decrease in the average energy of the electron beam on the temperature change when adjusted to an energy of 75 MeV.

ΔT, °C	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
ΔE, MeV	0	0.017	0.069	0.156	0.277	0.432	0.623	0.848	1.107	1.401	1.73

between the flow and the temperature difference at the ends of the section is determined from the expression

$$\Delta T = \frac{\Delta P}{q\rho c}, \tag{4}$$

Here q, ρ, and c are the flow, density, and heat capacity of water, respectively, ΔT is the water temperature difference, and ΔP is the microwave power lost for heating the section [5]:

$$\Delta P = P_0\left[1 - \exp(-2\alpha L)\right], \tag{5}$$

where P_0 is the power supplied to the section input, α is the attenuation coefficient of the high-frequency field, and L is the length of the diaphragm waveguide. According to the passport data of the accelerating section, the RF power attenuation in the section, measured at an operating frequency of 2.7972 GHz is equal to 2.6 dB (according to technical requirements, no more than 3 dB), i.e., $\alpha \approx 0.07\ \mathrm{m}^{-1}$. Substituting the data into formula (5), we find that the power released in the walls of the accelerating waveguide is equal to $\Delta P = 0.45P_0$. Taking into account the fact that the average power supplied to the section input is from 1.5 to 2 kW in different modes, $\Delta P = 0.7–0.9$ kW. According to expression (4), this power will lead to an increase in the average temperature of the water passing through the section by the amount $\Delta T = (1.67 - 2.14) \times 10^{-4}/q$ or $\Delta T = (10 - 12.9)/q$, if the flow is measured in l/min.

The measured water flow pumped through the jacket of each linear accelerator section is approximately 20 l/min, which corresponds to a temperature difference at the ends of the section (0.5–0.65)°C. This temperature rise must be corrected using a temperature control system.

Note that the above computation is approximate and does not take into account the increase in room temperature when the accelerator is turned on, heat dissipation in supply pipes, etc. Therefore, when designing, the given values should be taken into account with a reserve and clarified during test work.

Klystrons lose more energy to heat. The average power coming from the high-voltage modulator is about 6 kW. The efficiency of the klystron used is (30–35)%, i.e. about 4 kW is converted into heat generated in the collector and in the walls of the klystron resonator block. The measured flow rate of water cooling the klystron is $1.85 \times 10^{-4}\ \mathrm{m}^3/\mathrm{s}$ (11 l/min). Substituting the data into formula (4), we obtain $\Delta T = 5.1$°C. This temperature must be compensated by the cooling system. According to the instructions for many modern chillers and heat exchangers, their effective operation is ensured when the temperature difference at the inlet and outlet of the cooled object is no more than $\Delta T \leq 4–5$°C. Therefore, when upgrading, you should increase the flow of water cooling the klystrons by installing a more powerful pump. We also note that experience with klystrons shows that they have sufficient temperature stability within ±0.5°C.

To quickly enter thermal mode when turning on a "cold" accelerator, as well as when transferring the system from one mode to another, the future thermal stabilization system of sections should ensure rapid adjustment of the temperature to the set value. The set water temperature at the supply to the accelerating sections must be reliably maintained with an accuracy of ±0.2°C during the multi-day operation of the accelerator. The setting, adjustment, and control of supply water temperatures must be provided from a PC in the control room of the LUE-75.

3.3. Vacuum System

At LUE-75, the pumped-out objects of which are the accelerating sections, there is a three-stage pumping system: low vacuum – with a forevacuum pump of the AVZ-20D type, medium and high vacuum – with a turbomolecular pump TMN-200 and magnetic discharge pumps (MDP) of the NEM-300 type; a working vacuum of no worse than 10^{-6} Torr is ensured. The three-stage system allows, after obtaining a working vacuum, to turn off all mechanical pumps except for MDP, which maintain a high vacuum not only during experiments but also during multi-day breaks between beam sessions.

The amount of leakage, according to the passport data of the accelerating section, is no more than 5×10^{-4} Torr/hour. Figure 3b shows a graph of changes in low vacuum in the LUE-75 accelerating system after turning off the fore-vacuum pump. The measurements were carried out using a PMT-4M thermocouple manometric transducer and a VIT-1A vacuum gauge. Using the calibration curve of the converter, which converts readings in millivolts (y-axis in Fig. 3) into pressure units in Torr, we find that in the first 10 days after the shutdown (steep section of the graph in Fig. 3b) the leakage is 2.6×10^{-4} Torr/hour, which, taking into account thermocouple measurement errors, is consistent in order with the passport value for the section. The time required to obtain a preliminary vacuum (Fig. 3a) in the system is at least one working day. This is caused by a decrease in pump performance because of physical wear and tear.

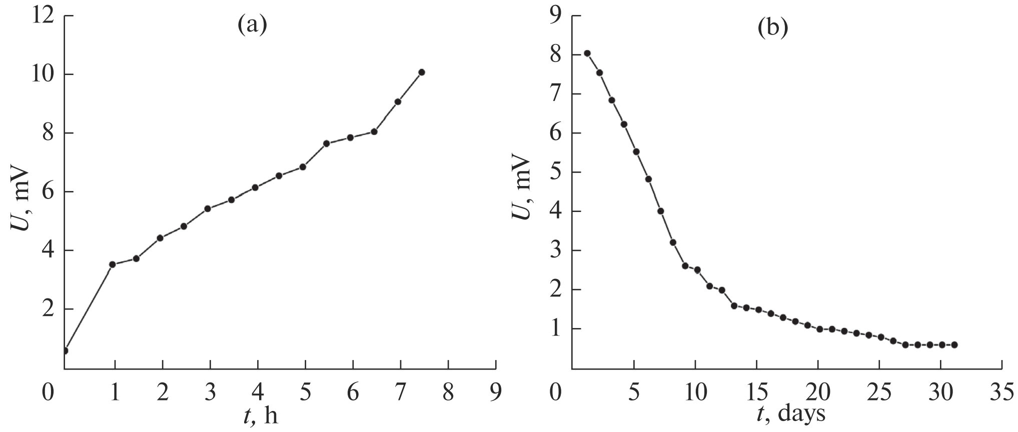

Fig. 3. Change in vacuum when (a) turning on and (b) turning off the forevacuum pump; *U* are the readings of the PMT-4M pressure meter.

A similar situation is observed in the high vacuum region. One MDP is installed on each section of LUE-75. Let us evaluate the required performance of high-vacuum pumps. The volume flow of pumped gas is

$$S = Q\,p, \tag{6}$$

where Q is the pump performance (pumping speed) and p is the operating pressure in the section. According to the technical specifications, for the used MDP Q = 250 l/s, operating pressure at the linear accelerator $p = 10^{-6}$ Torr. Substituting the data into (6), we obtain $S = 2.5 \times 10^{-4}$ Torr l/s. The volumetric flow of incoming gas, taking into account the above inflow value and taking the volume of one section with various outlets and chambers approximately equal to 20 l, is less than 2×10^{-6} Torr l/s. As one can see, the volume flow of the pumped gas is many times greater than the leakage into the section (either from the outside or caused by desorption from the internal surfaces of the section), which is a requirement for any vacuum installation. Thus, the indicated MDP pump capacities of 250 l/s for each section are sufficient to pump out the vacuum volume of the accelerating path.

The technical characteristics of MPH pumps have deteriorated over a long period of use and productivity has decreased. When disassembling the pumps, a failure of part of the electrodes is discovered (some titanium plates are pierced over the entire surface), which results in a loss of performance, and over time, failure of the pump. As the operation progresses, the time required to obtain a working vacuum increases, and electricity consumption increases accordingly. The brands of vacuum pumps used are not currently in production. Because of the above, there was a need to modernize the vacuum system.

When modernizing, it is necessary to make some design changes in circuits containing vacuum fittings. The configuration of the vacuum fittings (connecting pipes, vacuum valves, etc.) was made taking into account work in conjunction with the synchrotron. Because the linear accelerator currently operates in autonomous mode, design changes should be made, for example, a fore vacuum pump should be installed directly in the accelerator hall. The basic equation of vacuum technology has the form [9, 10]

$$\frac{1}{Q_o} = \frac{1}{Q_p} + \frac{1}{U}, \tag{7}$$

where Q_0 is the speed of pumping out the volume, Q_p is the speed of the pump, U = 1/R is the conductivity of the pipeline, and R is the hydraulic resistance of the pipeline. From equation (7) it follows that the pumping speed also depends on the hydraulic resistance of the pipeline. Hydraulic resistance, in turn, depends on the length and diameter of the pipeline. All MPR and turbomolecular pumps are connected to the system by short pipes with a diameter larger than the diameter of the sections. Therefore, we can consider the hydraulic resistance to be small and $Q_\mathrm{o} \approx Q_\mathrm{p}$ and the utilization rate of these pumps

$$K = \frac{Q_\mathrm{o}}{Q_\mathrm{p}} \approx 1.$$

The fore-vacuum pump is located away from the accelerating sections - this is an oil pump installed outside the accelerating room, which significantly reduces its utilization rate, $K < 1$.

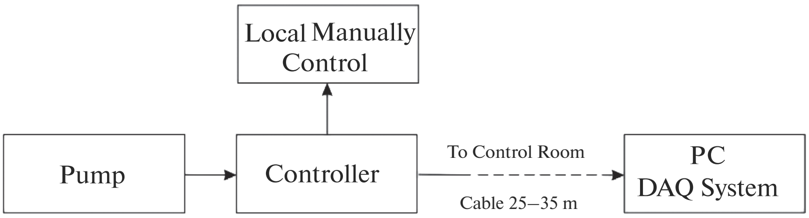

Fig. 4. Vacuum pump control circuit.

It is planned to replace the forevacuum pump with an oil-free type pump to prevent oil vapor from entering the accelerating system and install it directly in the accelerator hall.

During modernization, the ideology of the three-stage pumping system will remain. Out-of-production pumps and corresponding vacuum measuring equipment will be replaced with modern ones, equipped with controllers that make it possible to carry out computer monitoring and control directly from the control room (Fig. 4). This is important when working in a radiation environment and for creating a data acquisition system (DAQ system). The efficiency of the vacuum system will increase, its reliability will increase, time consumption will decrease, as well as the energy consumed.

4. CONCLUSION

As a result of the planned modernization, it is expected: an increase in the stability of the beam parameters—long-term energy stability during long sessions, and, consequently, intensity; saving energy consumed by the accelerator; reduction of time required to enter thermal and vacuum modes; it will become possible to use computer monitoring and create a data collection system as a necessary initial stage of automation, which will reduce the time required to detect and eliminate possible problems.

Improving the stability of the beam energy and its intensity will allow for precision experiments and will create the opportunity to detect and study rare decay processes in low-energy nuclear physics. As an example, we cite [11] and references therein, where, based on LUE-75 beams, AANL (ErPhI) researchers searched for the near-threshold formation of a four-neutron system in a photonuclear reaction ^{209}Bi (γ, 4n)^{205}Bi. For the first time, the reaction cross-sections of this rare process were determined. Research to establish the existence of a hypothetical bound state of neutrons (tetraneutron) can be continued, according to the authors, only with improvement in the stability of the energy and intensity of the beam.

This is also important in isotope physics, in particular, in the production and study of theranostic radioisotopes, where it is necessary to obtain a given isotope, excluding the formation of other reactions that are close in threshold.

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CONFLICT OF INTEREST

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SPELL: OK