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Status of Electron Linear Accelerator LUE-75 of the A. Alikhanyan National Science Laboratory and Stability of Electron Beam Energy

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Abstract—The scientific and technical status after renovation and restoration works of the linear electron accelerator LUE-75 of the Alikhanyan National Science Laboratory is presented, and some computed data on the effect of frequency, phase, and temperature changes in the high-frequency power supply path and the accelerating system on the stability of the electron beam energy, associated with the use of an additional accelerating station.

Keywords: linear accelerator, electron beam, beam energy spectra

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1. ON STATUS OF LUE-75

Electron accelerator LUE-75 of the A.I. Alikhanyan National Science Laboratory (ANSL, Yerevan Physics Institute—YerPhI) Foundation the proton medical accelerator—the C-18 cyclotron with the ability to conduct physical experiments, as well as the unique AREAL linear accelerator of the “CANDLE” Synchrotron Research Institute, allow the Republic of Armenia to remain a regional center for the application of accelerator physics and technology in the field of fundamental and applied scientific research [1, 2].

The resonant electron accelerator LUE-75 on a ten-centimeter traveling wave is the injector of the Yerevan 6 GeV synchrotron ARUS (Fig. 1), the operation of the annular part of which is currently suspended, functions autonomously as the only basic complex of the experimental department of the ANSL for studying urgent problems of low-energy nuclear physics in the energy range 10–75 MeV.

A thermionic gun with the Pierce optics is used as a source of electrons in the LUE-75, from the output of which a 50 keV beam enters the input of the waveguide buncher (in the injection section). In the buncher, in the process of autophasing, the electron flux uniformly distributed over the wave phases is grouped into bunches (is modulated in density) with a repetition rate equal to the frequency of the microwave accelerating field and is simultaneously accelerated to the energy of 3 MeV; further acceleration is carried out by three identical main accelerating sections (Fig. 2), which receive microwave energy from three powerful klystron posts. The first klystron operates according to the self-excited oscillator scheme proposed by YerPhI specialists back in the 70s [3], supplying the remaining klystrons operating in the amplifying mode with the input power. The advantage of the LUE-75 self-excited oscillator power supply system is its operational reliability, simplicity, and the absence of an expensive external driver. If necessary, it is possible to operate in the mode of external excitation of powerful amplifying klystrons.

When the synchrotron was operating, the linear accelerator as an injector was launched from the process control system of the electron-ring accelerator (ERA) synchronously with the supply frequency of the ERA electromagnets with a nominal pulse frequency of 47–49 Hz. In the autonomous mode, the synchronization system is powered and started synchronously from the same stable network as the high-voltage modulators of microwave generators and an electron gun, which prevents the occurrence of beats. The nominal trigger pulse repetition rate is 50 Hz. The pulsed mode of the accelerator results in double modulation of the electron beam. The temporal structure of the beam is shown in Fig. 3.

The accelerator provides experimenters with electron beams with an average current of up to 10 μA (without collimation), which corresponds to a pulse current of up to 150–200 mA, depending on the duration of the macropulse and energy. A collimated and well-bunched beam at nominal energies has an

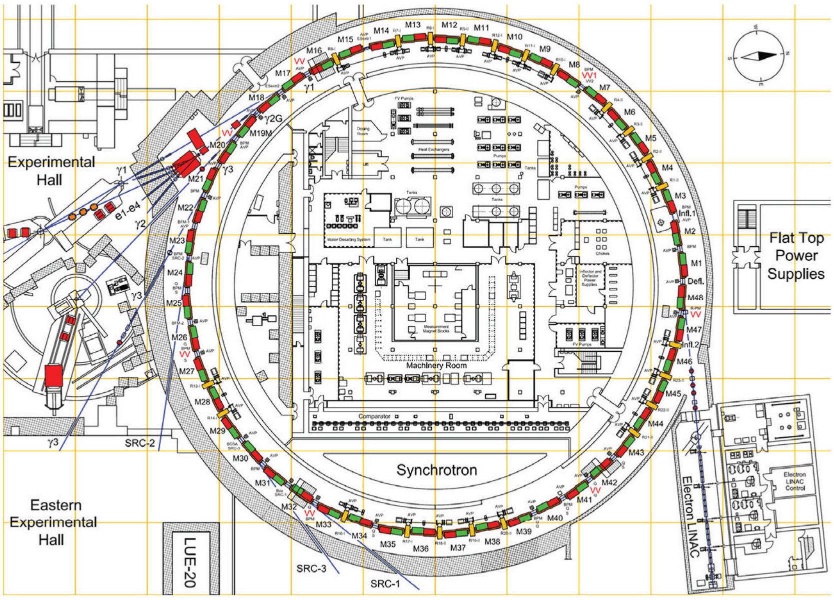

Fig. 1. The sketch of ARUS synchrotron ring.

Fig. 2. The accelerating sections of the LUE-75.

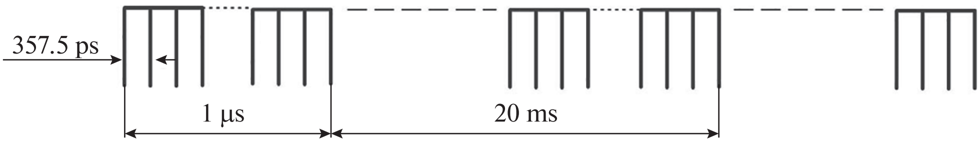

Fig. 3. The temporal structure of the LUE-75 beam.

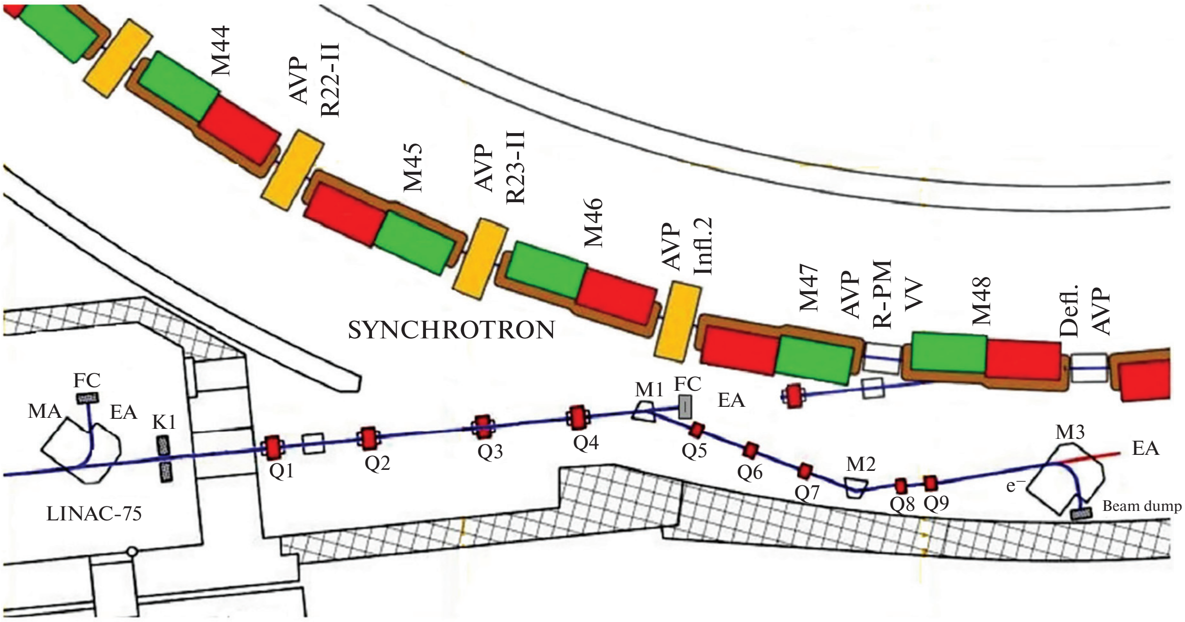

Fig. 4. The layout of the transport and parallel transfer path in the synchrotron hall. MA is the dipole analyzing magnet 90° at the output of the LUE-75; FC is the Faraday Cup; K1 is the collimator; M1 and M2 are the bending magnets of the parallel transfer; M3 is the beam dump, used to obtain photon beams; Q1...Q9 are the quadrupole lenses; EA is the experimental area.

energy spectrum width (FWHM) of about 2%. The LUE-75 linear accelerator complex parameters, which include the linear accelerator itself and the parallel transport path (Fig. 4) located in the annular hall of the synchrotron are presented in detail in [4–6].

In recent years, some renovation and restoration work has been carried out [4], in particular, the 3rd accelerating station which includes an accelerating section, was restored and put into operation, a klystron post with a waveguide path and a high-voltage pulse modulator, as well as systems for their support. Thanks to the work carried out, the electron energy at the output was increased up to 75 MeV, which made it possible to study photonuclear processes in reactions with a higher energy threshold, and the reliability of the functioning of the nodes was increased during long sessions.

The LUE-75 is a single-turn accelerator and, together with the parallel beam transfer path, has a length of about 45 m. The direction of the beam movement approximately coincides with the East-West direction, which is almost perpendicular to the magnetic lines of force of the Earth (Fig. 1). To eliminate the influence of the geomagnetic field on the beam, the extended correction coils were manufactured and installed on the newly activated accelerating section compensating for the displacement of the beam center of gravity in the horizontal and vertical planes; thereby also neutralizes the influence of the nearby ferromagnetic masses and different sources of fields.

The transport path with parallel beam transfer is located in the synchrotron hall far from the LUE-75 room behind its radiation-protective wall (Fig. 4), where, when the synchrotron is switched off, a significant decrease in the radiation background and the practical absence of the effect of electromagnetic influence and interference from electro-radio devices of the linear accelerator on instrumentation has created

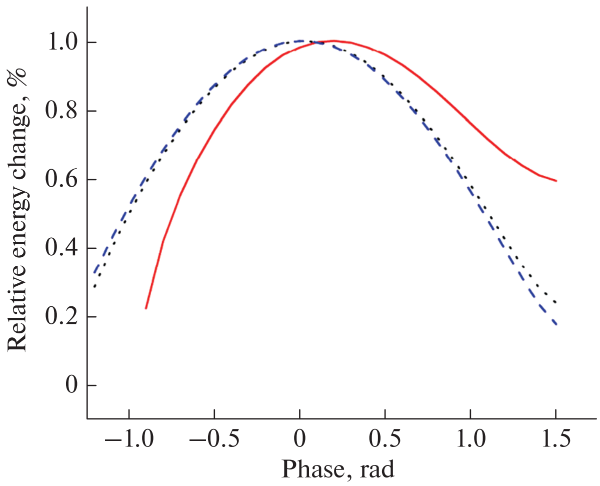

Fig. 5. The dependence of the relative increase in the output energy of electrons on the initial phase of the accelerating wave for the main accelerating sections of the linear accelerator; solid curve—at the input of the 1st section 3 MeV; dots—at the entrance of the second section 25 MeV; dashed line—at the entrance of the third section 50 MeV.

favorable low-background conditions for conducting precision experiments. The modernization of the elements of the magnetic optics of the parallel transfer path has been carried out.

A technique has been developed for obtaining unique beams of extremely low intensity of the order of tens of electrons per second in the energy range of 15—75 MeV. Such beams at LUE-75 were used as test beams with the number of single-electron events more than 70% for the calibration of crystal detectors of elementary particles within the framework of joint contractual work between ANSL/YerPhI (Yerevan)—JINR (Dubna) [4, 5, 7, 8]; beams of extremely low intensity can be used to study individual events, the biological effects of ionizing radiation in low doses, diffraction problems, etc. The possibility of obtaining photon beams using a deflecting electromagnet M3 at the very end (Fig. 4) of the path has also been created. During the execution of the work, the available technical and technological base of ANSL was mainly used.

The beam parameters and their stability, which determine the quality of the experiment, depend on various factors [9—12]. In connection with the inclusion of the third accelerator station with an additional section at the output of the accelerator, below we consider the influence of frequency, phase, and temperature changes on the stability of the electron beam energy at the output of the accelerating section of LUE-75.

2. ON THE STABILITY OF ELECTRON BEAM ENERGY

One of the important parameters of the electron beam is the stability of the energy and the energy spread of the beam estimated by the width of the energy spectrum, which determines the degree of monochromaticity of the beam. The acceleration stability depends on the initial conditions at the inputs of the accelerating sections.

Consider the dependence of the relative increase in the beam energy on the initial phase of the wave at the entrance to the accelerating section. To obtain the maximum acceleration, when the accelerator is tuned, the initial phase of the particles, that is the phase of the wave in which the particles find themselves at the beginning of each of the main accelerating sections, is chosen so that the bunches are near the crest of the main harmonic of the accelerating wave. A change in the initial phase results in a shift in the center of gravity of the bunches from the optimal position, which results in a shortage of energy at the exit of the section. With an increase in the phasing error, the energy spread of the beam increases. For a typical regime of the LUE-75, Fig. 5 shows the calculated curves of the dependence of the relative increase in energy on the initial phase at the same amplitude of the accelerating fields and a constant frequency of the field generator for three main sections, at the inputs of which the beam arrives with different energies. Depending on the kinetic energy of particles entering them, the optimal phases of the sections differ, but with an increase in the input energy, the curves practically merge, and the optimal value of the initial phase of electrons is close to zero.

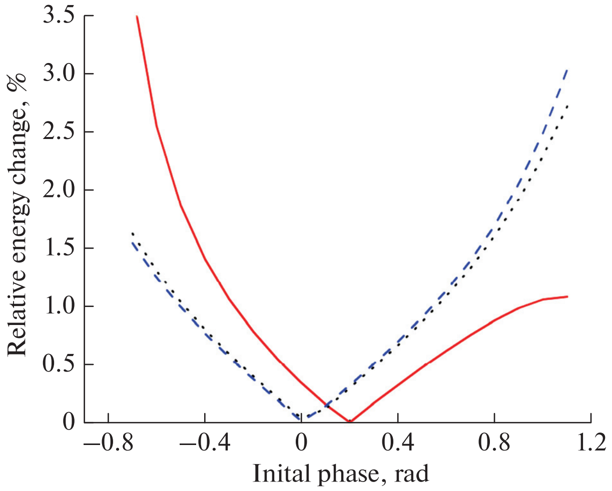

Fig. 6. The relative change in the energy of particles at the exit of the section when the initial phase of injection deviates from the set value by 1° for the main sections; the parameter is the energy of the particles at the inlet of the section: solid curve—at the input of the 1st section 3 MeV; dots—at the entrance of the 2nd section 25 MeV; dashed—at the entrance of the 3rd section 50 MeV.

For each section, with the small deviations of the initial phase from the optimal one, the relative change in the energy at the outputs is approximately the same, but with an increase in the deviation, the newly activated section, into which particles with the energy of 50 MeV enter, as well as the second section with the input of 25 MeV beam, are more critical regarding changes in the initial phase: for the same phase deviation, the energy shortage turns out to be greater than for the first section, into which electrons enter with the energy of 3 MeV. The LUE-75 is a traveling wave accelerator and from the point of view of microwave electrodynamics is a device of long-term interaction. With an increase in energy, the time of flight through the section—the time of interaction of the beam with the accelerating wave—decreases, and the same deviation from the optimal initial phase for whatever reason results in a greater shortage of energy at the output (compare the curves in Fig. 5). Similarly, one can explain the difference in the behavior of the family of curves given in [9], where the dependence of the relative increase in energy on the initial conditions is given, but at different amplitudes of the accelerating wave.

Deviations from the optimal value can be caused by incorrect phasing of the section. The effect of the initial phase of the particle on the energy can be shown more clearly by plotting the curves of the dependence of the relative change in the beam energy (change in the relative increase in energy) at the exit of the accelerating section from the initial phase with a slight deviation of the latter from the set one, for example, by 1°. The curves shown in Fig. 6 are plotted for three main accelerating sections at a constant frequency of the generator and the same amplitude of the microwave field at the inputs when the phase deviates from the set at 1°.

It can be seen from the graphs that the greater the phasing error, the greater is the relative change in the output energy of the particles when the initial phase of the electrons deviates by 1 degree from the set one, and with small phasing errors, the relative changes in the energy at the outputs of the sections are approximately the same, but with an increase in the error of the second and third sections become more critical in comparison with the first one, at the input of which a beam with much lower energy arrives. So, with the same phasing error of 50 degrees, a deviation of only 1° from set one results in a change in the energy at the output of the first section by 1%, and at the output of the third section by 2%. However, such a phasing error results in an instability of acceleration and is detected by the instability of the beam current measured after the magnetic analyzer, and the incorrect phase setting is eliminated by adjusting it.

Curves in Fig. 5 and 6 show that with small deviations of the initial phase from the optimal one, the energy spread of the beam is approximately the same for all three sections with different electron energies at the inputs; so, a phase change by ±8° from the optimal value results in a relative change in energy of ±1%.

The additional broadening of the energy spectrum also appears because of the dispersion properties of the waveguide path. During the operation of the accelerator, the frequency of the accelerating field generator can change under the influence of external factors such as supply voltages, temperature, which will result in a change of the phase velocity of the wave in the waveguide. The additional phase shifts will

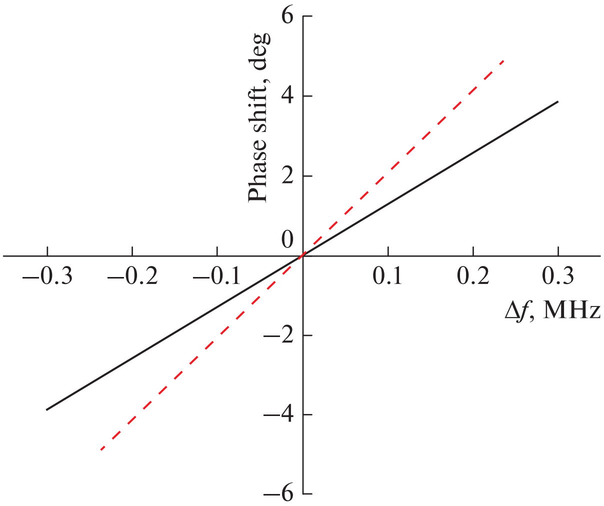

Fig. 7. The dependence of the additional phase shift (in degrees) because of the dispersion of the excitation lines of the klystrons on the generator frequency shift from the operating frequency: solid curve—between the 1st and 2nd sections; dots—between the 1st and 3rd sections.

appear at the inputs of the accelerating sections and the phase slip of electron bunches relative to the accelerating wave in the sections. The phase sliding of bunches results in an increase in the spread of electron energy, which is considered in the literature [9–12], for the LUE-75 – in [4]. Here we look for the phase shifts between sections because of the unequal waveguide transmission line lengths.

High power waveguide transmission lines from klystrons to accelerating sections have approximately the same length; therefore, the deviation of the frequency of the generator for any reason from the set at the time of tuning the same phase shifts occur at the inputs of sections. The excitation lines of klystrons assembled mainly from the rectangular waveguides with a cross-section of 72 × 34 mm^2 and laid from the 1st klystron to the other two have different lengths 7.2 m and 11.5 m, respectively. In the rectangular waveguide, the H_{10} fundamental wave is used. The small segments of coaxial lines with a TEM wave do not have dispersion. Figure 7 shows the dependences of additional phase shifts between the accelerating sections on the value of the oscillator frequency deviation Df arising from the dispersion of the waveguide lines of excitation of klystrons. With an increase in the length of the excitation line, the curve becomes steeper. For example, a deviation of the generator frequency within ±100 kHz (which is possible with long sessions) causes a change in the phase shift between the 1st and 2nd sections of ±1.3°, and between the 1st and 3rd (newly activated) sections ±2°, which contributes to the instability of the energy spectrum.

A phase shift also occurs when the temperature of the waveguide path changes owing to a change in its geometric dimensions. Figure 8 shows the computed dependence of the phase shift caused by a change in the temperature of the waveguide path of a high power level (with the total length of 30 m) for the fundamental wave in a rectangular waveguide with the cross-section of 90 × 45 mm^2 at a constant operating frequency. Computations show that within a wide range of the operating temperature of the waveguide channel, the phase shift is practically independent of the temperature value at which the accelerator was tuned, but depends on its change: a change in the geometric dimensions results in a change in the wavelength in the waveguide, which in turn results in a change in the electrical length of the waveguide path feeding the accelerating sections. It can be seen from the graph that a change in temperature by ±0.5°C results in a change in the initial phase ±1°. Such a deviation of the initial phase from the optimal one introduces an insignificant change in energy, about 0.014%.

The stability of the energy and current of the beam is also influenced by the stability of the frequency of triggering pulses synchronized with the stable network supplying the accelerator; the latter, in turn, works synchronously with the industrial network. Changing the frequency of the industrial network results in a change in the average current of powerful klystrons, which contributes to the instability of the beam. The change in the average current is eliminated by an appropriate adjustment. The instability of the frequency of industrial networks is rarely observed even with the continuous multi-day sessions.

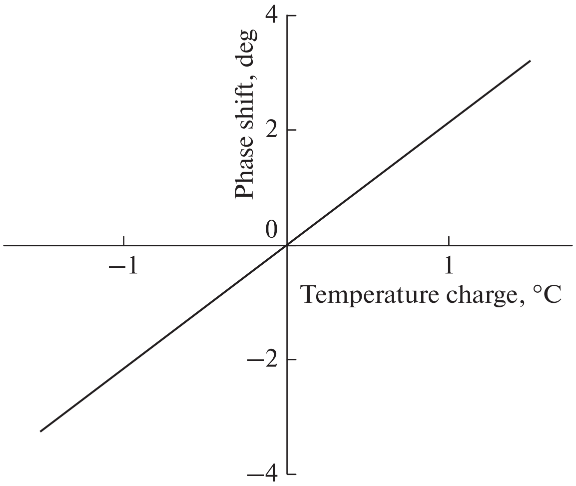

Fig. 8. The dependence of the phase shift on the temperature of the waveguide path.

3. CONCLUSION

The results obtained were taken into account when setting up and tuning the accelerator after the launch of the 3rd accelerator station. It was necessary to modify the phasing system of the newly activated accelerating section by including an additional variable waveguide phase shifter in the generator excitation line to establish and maintain limits the relative phase shift of microwave oscillations at the input of this section within the required. With the switching on of the modulator and the klystron station for operation in the 50–75 MeV mode, it was necessary to modify the cooling and thermostating systems.

The above-computed data and practical work on the accelerator show that with the inclusion of an additional accelerating section, the requirements for the stability of the generator frequency and phase relations increase, the optimal choice of which practically reduces the adjustment of the LUE-75, like any accelerator. Note that the instability of acceleration caused by a change in the frequency of the accelerating field is added to the instability from other factors. Requirements for the accelerator synchronous power supply system are increasing.

Although the experimental work carried out in recent years at the LUE-75 [7, 13–15] has shown its reliable operation, to improve the parameters, it is planned to develop a new system for thermostating the sections and cooling the accelerator units using the PID control and a modular stabilization scheme; such a scheme will provide not only the automatic maintenance of the temperature of the sections and generating units within the specified limits, but also the promptness and accuracy of setting the temperatures when changing the modes of the linear accelerator.

At present, the accelerator is in good working condition and provides electron beams for problems in low-energy nuclear physics and scientific and methodological research. The accelerator can also be used for educational purposes. It is planned to modernize the accelerator with the introduction of modern vacuum technology, power electronics, and a measuring base which will increase the quality of the beam, and hence the demand for the LUE-75 precision experiments. This will make it possible to expand the range of urgent research problems solved at the accelerator.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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