STATE AND PROSPECTS OF THE LINAC OF NUCLEAR-PHYSICS COMPLEX WITH ENERGY OF ELECTRONS UP TO 100 MeV

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The paper describes the results of the work on improvement of electron linac LUE-40. This linac has been designed for nuclear physics research in the electron energy range 40…100 MeV. The main purpose is to reduce the energy spread, emittance and long-term instability of the beam characteristics. For this purpose the system of klystron high voltage stabilization and the beam loading compensation system have been developed. The improved injector has been put into operation. A new DC power supply system of the magnetic spectrometer has been installed and tested.

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INTRODUCTION

One of the tasks of modern nuclear energy is creating the subcritical systems on the base of the powerful electron linac with energy of beam ~ 10^8 eV. For solving this task the experimental information is needed on the cross sections of photonuclear reactions, yield of multiplicity of neutrons and gamma-quantum for different isotopes, yield and cross sections of reactions of photofission of heavy nucleus. In the energy range of γ-quantum 40…100 MeV, many of the necessary experimental data are practically absent.

In the field of radiation medicine relevant is search for new promising isotopes and development of methods for their preparation. While conducting experiments on electron accelerators for the determination of reaction cross sections, select the desired beam parameters, test methods to improve the efficiency of photonuclear isotope is crucial. There are still a number of areas of experimental studies that require electron beams with energies up to 100 MeV.

To carry out these works the linac is needed with smooth regulation of energy, small energy spread of particles and high stability of all beam parameters. Thus average power of beam is not determining. In NSC KIPT the linac LUE-40 has been started in 2004 after a substantial reconstruction. Research facility for nuclear physics research was established on the basis of this accelerator [1].

The nuclear-physics experiments with different terms and requirement to the beam parameters are the stimulant factor for the continuous improvement of accelerating. In this article the research results are presented in this direction.

1. LINAC LUE-40

A linear accelerator LUE-40 consists of electron gun, injector system, two accelerating sections and ancillary systems (RF-power system, thermostatting, focusing system, synchronization, management, etc.). RF-power supply of the linac is carried out from two klystrons with maximal pulse power to 16 MW. The detailed description of linac is resulted in [1]. The linac is provided with the system of measuring of beam parameters. In the process of work there have been measured: the energy and energy spectrum of electrons, the change of particles energy during the pulse of current, pulse current, position of beam and spatial distributing of electrons in a transversal plane.

The basic parameters of beam on the linac output (on the status of January 2012) are presented in Table 1.

Table 1

Energy of electrons, MeV	35…95
Width of energy spectrum for 70% particles, %	2…3
Repetition rate, Hz	to 50
Pulse current, mA	70
Average current, μA	to 6
Diameter of beam, mm	3…4
Normalized emittance, mm·mrad	60

During the last years the researches of yield and cross sections of many-particle photo-nuclear reactions [2, 3], processes of photofission of heavy nucleus [4], mechanisms of origin of radionuclide of Be^7, methods of activating dosimetry [5], methods production of isotopes of the medical setting have been carried out on the linac [6]. At the same time the exploitation of the linac has shown the necessity to improve the parameters of beam and, above all things, to diminish the emittance, energy spread and of long duration instability of particles energy.

2. MODERNIZATION OF THE INJECTOR SYSTEM

At the reconstruction of the linac LUE-40 the injector based on five resonators system with evanescent oscillation [7], has been applied. In future we developed the improved injector system of such type, the resonators of which are optimized for more effective bunching [8].

Table 2

Working frequency, MHz	2797.15
Gun voltage, kV	25
Gun current, A	0.18
Current at the output of injector, A	0.14
RF-power, MW	1.0
Normalized rms emittance, x, y, mm·mrad,	9
FWHM energy spectrum for all pulse, %	9
Energy in the maximum of spectrum, keV	950

The substantial structural difference of this variant of injector from a prototype is the coaxial symmetric system for the input of RF-power. Two copies of such injector were made, one of which was set on linac of storage ring «Nestor», and the second has been mounted

on linac LUE-40. Characteristic beam parameters on the output of injector (Fig. 1), measured on a test stand, are resulted in Table 2.

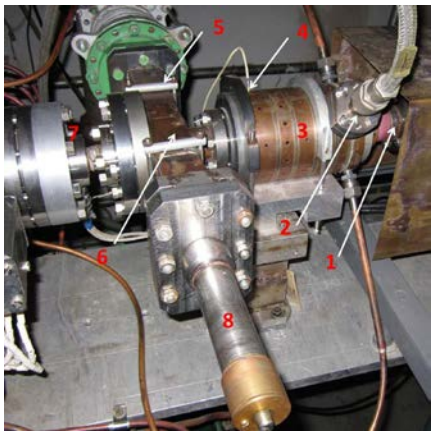

Fig. 1. New injector of linac LUE-40

In the picture it is marked with numbers: 1 – electron gun; 2 – control loop for measuring of the field in resonators; 3 – resonance system; 4 – thermocouple; 5 – connecting waveguide; 6 – coaxially-waveguide transition; 7 – inductive beam current monitor; 8 – device for tuning of transition.

The injector has been tested on linac at the beam current at the first section output of 40 мА. RF-power in the second section has not been supplied. To diminish the influence of the second section on the beam dynamics its temperature differed from working no less than 10°C. The energy spectrum of beam has been measured by a magnetic analyzer with resolution 0.2%. In a focal plane of 25° dipole magnet the slit collimator and Faraday cup have been set. Pulse signals from Faraday cup at the different values of magnetic field have been given in the PC of control system. It allows measuring a spectrum depending on time during the pulse of current. In experiments the scheme to obtain a special form of RF-power pulse has been used. The scheme is designed to diminishing of transient in a section, caused by the beam loading (in more detail this scheme will be described below). The measurements taken have shown that the replacement of injector had allowed to improve a energy spectrum (Fig. 2).

Thus, the width of the spectrum (at 0.09 of maximum intensity) in the steady state is almost three times less for the new injector (1.3 vs. 3.4%). The period of discretization of analog-digital transformers, applied at processing (50 ns) is much less than the filling time of resonators of injector and section (0.7 and 0.9 μs accordingly) with RF-power. Therefore, the spectrum measured at a given time is determined by the electron bunch length. Measurement of transverse emittance of the beam was performed by a known method using one of the quadrupole lenses established by the output of the second section, the moving slit collimators and Faraday cup. The preliminary measuring has shown that setting of new injector practically did not influence the value of the normalized transversal emittance of beam. Its value makes about 60 mm·mrad. It is substantially more both calculated value and the measured value on the injector system output. It indicates that the influence of asymmetry of the RF field in input element of injector substantially less causes the emittance change than other factors.

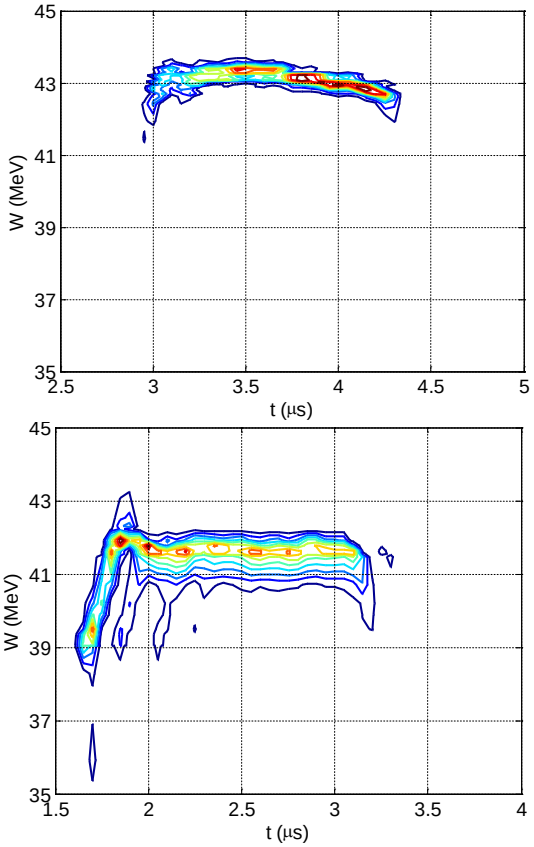

Fig. 2. Contour graphs of beam spectrum during the pulse of current. From above is a new injector, below is a previous injector. A dark blue contour corresponds 9% of maximal intensity

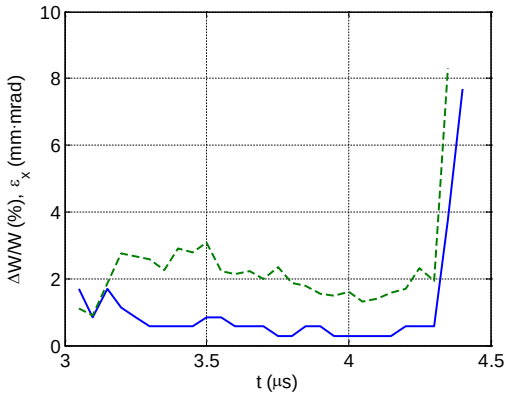

Fig. 3. Emittance of beam (stroke curve) and relative energy variation (continuous curve) from time during the pulse of current

Presumably, the particles of beam receive the additional transverse pulses in an accelerating section. The value of these pulses depends on the phase of the field. So, dependence of beam emittance on time during the pulse of current obviously correlates with analogical dependence for the width of energy spectrum (Fig. 3).

We plan to continue study the reasons for the emittance increase in acceleration system.

3. DIMINISHING OF ENERGY SPREAD AND INSTABILITY OF ELECTRONS ENERGY

One of the principle sources of energy spread of the particles is the beam loading of accelerating. Essence of this effect is to decrease energy of the accelerating particles due to a coherent radiation. The quantitative esti-

mation of the beam loading effect for different sections is a value of energy losses of electrons at the transmission of relativistic beam with a current 1 A in absent of external RF generator. For developed in NSC KIPT sections Kharkov-85, which are set on accelerator, this value is 67 MeV/A. Thus, even at the pulse current of 50 mA the energy loss of particles in the set mode in every section makes 6.7 MeV. Obviously, at filling time of 0.9 μs and current pulse widths a 1.5 μA, the beam loading effect is a basic factor which determines the width of energy spectrum. To diminish the influence of the beam loading we used the most widespread Δt-method. The essence of this method consists in that the injection of current pulse into the accelerating section is made in the moment of time, when a section is not fully filled with RF-power. Choosing the time of injection of current pulse, it is possible to improve a energy spectrum on the linac output. However, in the case of the two-sectional linac with considerable time of transients, this method works ineffectively (see Fig. 2 (below)). Therefore we have developed two schemes, realizing the most radical of the methods of diminishing the energy spread - method of modulation of the field amplitude. The increase of the field amplitude during time, exceeding or equal filling time in an accelerating structure allows practically fully removing the energy spread. By the simulation of particles dynamics in linac, an optimum form of the RF-pulse was certain. One of the schemes developed by us is based on amplitude modulation by a p-i-n diode RF-modulator. The modulator with a diode 2A520 is set in the chain of driving oscillator. Form of RF-pulse has been regulated by the change of amplitude and delay of managing pulse, given on the p-i-n diode of modulator. The work of this simple scheme has been tested experimentally. Measurements have shown performance of this scheme. As seen from (see Fig. 2 (top) and Fig. 4) influence the beam loading on the energy spectrum of the beam significantly decreased.

At the same time this scheme has a number of disadvantages. In particular it is the change of phase in p-i-n diode modulator, complication of forming the managing pulse of necessary form. In this regard, we have developed system in which the amplitude of the necessary form of microwave pulse and phase relationships is performed using the principle of I/Q modulation [9]. At the moment the system is under adjustment and test.

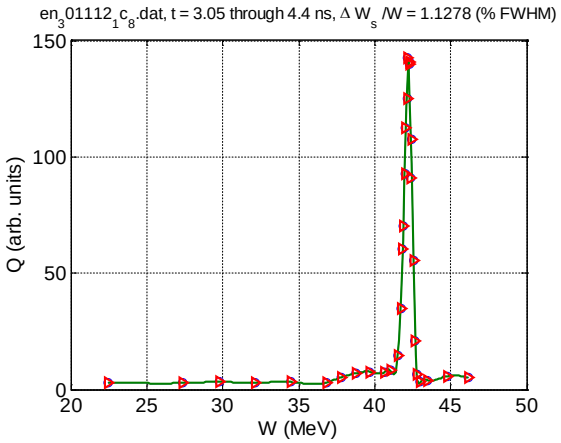

Fig. 4. Energy spectrum of beam with beam loading compensation

The research of photonuclear reactions requires high long-duration (a few hours) stability of beam parameters. The size of instability of electrons energy for some experiments must not exceed ±0.5%. One of basic destabilizing factors is the instability of high voltage of klystron amplifiers. In this connection the automatic system of stabilizing has been set on the linac and now successfully exploited [10]. The system includes the device which measures the average current of klystron on the base of shunt of class 0.1%, a microprocessor with a high-fidelity analog-digital transformer and managed element – a transformer of RTT-25/0.5. The stabilizing system supports the set value of average current of klystron with exactness 0.3%. It allows supporting the set value of electrons energy within the limits of ±0.25%.

To increase the accuracy of particles energy measuring, a new DC supply system of dipole magnet of spectrometer has been developed and created. General efficiency of source is 83%, and measured efficiency without the analog stabilizator is 93%. Stability of output current in a working range from 3 to 150 A is 0.005%. Structurally the source of current is placed in a block with sizes 50×50×30 cm, that substantially less, than motor-generator used before. In the range of energies of electrons (35…100 MeV), the change of current in the windings of magnet of analyzer on 30 mA corresponds the change of particles energy on a value, less than 0.1%. Management of the current source is executed remotely from a control room on RS485 or CAN with possibility to determine all the parameters of work. The mode of demagnetization of the magnet is realized automatically. The new system of magnet supply allows accelerating and fully automating the process of measuring of energy and energy distribution of the electrons.

4. OPTIMIZATION OF BEAM FOCUSING

During the research it is important to form the beam of necessary sizes on the linac output. The focusing system of accelerator consists of four quadrupole lenses.

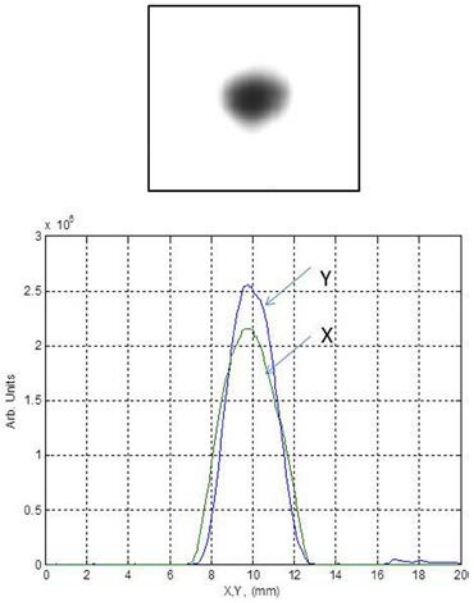

Fig. 5. Imprint of beam on glass (above) and distribution of electrons density

The lenses are set in the channel of transporting on an interval between second section and output devices. The computer model of beam transporting from the output of the first section to the target has been created. A model has been set directly on the computer of the linac control system. It enables to operatively find the modes of supply of quadrupole lenses at the change of particles energy. According to the results of modeling for a beam with energy 40 MeV and normalized emittance of 60 mm·mrad, the minimum beam size on a target (4σ) may be reduced to 2.4 mm. Experimental verification of calculation model has shown the accordance of calculation and experimental data. So, in Fig. 5 the typical imprint of beam on glass (sizes of frame of 10×10 mm) and proper distributing of electrons density have been shown directly after the output foil of a linac.

CONCLUSIONS

The linear accelerator LUE 40 is presently the unique in Ukraine source of electrons with energy to 100 MeV. The main purpose of the linac is the experimental researches, above all things, nuclear-physics experiments. As a result of the carried out works the beam parameters have been improved – energy spread of particles and sizes of beam on a target have been diminished, the stability of energy has been increased.

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СОСТОЯНИЕ И ПЕРСПЕКТИВЫ ЛИНЕЙНОГО УСКОРИТЕЛЯ ЯДЕРНО-ФИЗИЧЕСКОГО КОМПЛЕКСА С ЭНЕРГИЕЙ ЭЛЕКТРОНОВ ДО 100 МэВ

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Приведено описание результатов работы по усовершенствованию линейного ускорителя ЛУЭ-40, предназначенного для проведения ядерно-физических исследований в диапазоне энергий электронов 40…100 МэВ. Основной целью работы является уменьшение энергетического разброса, эмиттанса и долговременной нестабильности характеристик пучка. Для этого установлен и введен в эксплуатацию более совершенный инжектор. Разработаны системы стабилизации высокого напряжения клистронов и схема компенсации энергетического разброса, вызываемого токовой нагрузкой секции. Разработана и испытана новая система питания магнитного спектрометра.

СТАН І ПЕРСПЕКТИВИ ЛІНІЙНОГО ПРИСКОРЮВАЧА ЯДЕРНО-ФІЗИЧНОГО КОМПЛЕКСУ З ЕНЕРГІЄЮ ЕЛЕКТРОНІВ ДО 100 МеВ

М.І. Айзацький, В.І. Бєлоглазов, В.М. Борискін, В.М. Верещака, О.М. Водін, Р.М. Дронов, А.М. Довбня, В.Ф. Жигло, І.М. Зайцев, К.Ю. Крамаренко, В.А. Кушнір, В.В. Митроченко, О.М. Опанасенко, С.М. Олійник, С.А. Пережогін, Ю.М. Ранюк, О.О. Репіхов, Л.В. Реприндев, Д.Л. Стьопін, В.І. Татанов, В.Л. Уваров, І.В. Ходак, В.О. Цимбал, Б.І. Шраменко

Наведено опис результатів роботи з удосконалення лінійного прискорювача електронів ЛУЕ-40, призначеного для проведення ядерно-фізичних досліджень у діапазоні енергій електронів 40…100 МеВ. Основною метою роботи є зменшення енергетичного розкиду, еміттансу і довготривалої нестабільності характеристик пучка. Для цього встановлено та введено в експлуатацію більш досконалий інжектор. Розроблені системи стабілізації високої напруги клістронів і схема

компенсації енергетичного розкиду, що спричиняється струмовим навантаженням секції. Розроблена і випробувана нова система живлення магнітного спектрометра.