TECHNICAL REPORT

LUE-200 Accelerator — A Photo-neutron Generator For
The Pulsed Neutron Source “IREN”

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ABSTRACT: This article reports about the construction and status of the accelerator facility at the
Laboratory of Neutron Physics (FLNP) in the Joint Institute for Nuclear Research (JINR, Dubna),
the driver of an intense pulsed resonance neutron source. The general scheme of the electron linear
accelerator and features of its basic systems are presented. LUE-200 consists of two accelerating
sections on a traveling wave with an operating frequency of 2856 MHz with RF power compression
systems of the SLED type. The pulse current of the beam at the output of the accelerator reaches
2 A with a pulse duration of 80–100 ns. At the average energy of beam particles from 60–65 MeV
and a cycle repetition rate of 50 Hz, the average beam power reaches ≈ 600 W. The integral neutron
flux from the non-multiplying target reaches ~ 10^{12} s^{-1}.

KEYWORDS: Accelerator Applications; Accelerator Subsystems and Technologies; Instrumentation
for neutron sources; Instrumentation for particle accelerators and storage rings - high energy (linear
accelerators, synchrotrons)

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1 Introduction

In 1992, the JINR Communication [1] formulated a proposal to construct a new research nuclear facility — a neutron source with the energy in the region of resonance neutrons based on a subcritical assembly — an active zone with external injection of photo-neutrons. The main purpose of this new source was to provide high-resolution time-of-flight spectrometers with pulsed neutron fluxes. The following parts were proposed to include in the new source:

- a modern electron linear accelerator as a driver with a beam energy > 100 MeV, current pulse duration of ~ 250 ns and average electron beam power of about 10 kW;
- a multiplying target — an e-γ-n converter made of heavy material (tungsten or uranium), surrounded by a blanket with a fast, deeply subcritical plutonium assembly which multiplies neutrons due to the photo fission of plutonium nuclei.

The above together with the driver, made it possible to obtain a short neutron pulse (up to 400 ns) with an average intensity up to $5 \times 10^{14} \text{s}^{-1}$.

The new facility was named IREN and designed as a time-of-flight neutron spectrometer with a developed network of experimental neutron channels. Achieving design parameters allowed JINR to become the owner of a modern pulsed neutron source for nuclear and applied physics with the parameters close to the best neutron sources in the world.

2 Accelerator LUE-200. Conceptual scheme

As a result of competitive selection to implement the project, the proposal of Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences [2] was approved to use a linear traveling wave (2856 MHz) electron accelerator as the neutron source driver based on Budker Institute developed accelerating sections powered by klystrons with SLED (Slac Linac Energy
Doubler) systems. The block diagram of the accelerating system is shown in figure 1. The scheme is based on the linear accelerator main elements of the for injector in the Budker Institute electron accelerator complexes. In the RF circuit, the power of each of the two accelerating sections with constant impedance is generated by pulse klystrons KL1 and KL2 with an RF output pulse power of several tens of MW. Each klystron is powered by its own modulators (M1 and M2). The excitation of klystrons is synchronized from a common generator with two output channels by using a phase shifter installed at a low level of RF power.

The buncher is docked directly with the first accelerating section without drift space and is powered by a branch from the RF feeder of the first accelerating section through a waveguide directional coupler with the 17 dB attenuation and an additional chain consisting of a phase shifter (0–350°) and a power regulator — attenuator (0–22 dB). Each RF feeder supplying the accelerating section includes power compression system consisting of two storage resonators and a 3-dB slot bridge. The SLED systems make it possible to increase the power injection into the accelerating structure and to accelerate short current pulses with high efficiency in accelerating structures in the stored energy mode.

The design output parameters of the accelerated beam were corrected while developing the project. In order to improve the energy resolution of time-of-flight neutron spectrometers, the pulse duration of neutron bursts and, therefore, the beam current pulse duration were reduced from 250 ns to 80–100 ns. The design average beam power, depending on the commercial availability of the klystrons, was also reduced to 2.6–3.3 kW.

Due to the fact that the developers of the IREN facility project at the stage of transition to the technical design had to give up the active zone and the status of a nuclear facility in general, the IREN facility was transferred into the category of sources generating neutrons by a photonuclear reaction initiated with brake gamma rays while irradiating the targets by electrons produced in the accelerator, i.e. to the category of the so-called ADS-type facility (Accelerator Driving System), where neutron generation ceases when the accelerator stops operating.

3 The main accelerator systems

The general layout of the accelerator and phototarget in a tower-type building is shown in figure 2. The main part of the accelerator with a total accelerating system length of about 10 meters is placed vertically in the two upper floors of the building of the former neutron source [1]. The phototarget is located in the lower hall (target hall). The beam, accelerated from top to bottom, is transported through the inter floor opening to the W converter located in the center of the lower hall at the intersection point of the axes of the neutron beam channels.
The accelerator uses a pulsed two-electrode electron gun with the Ø 12-mm oxide thermocathode powered by a 200 kV pulse transformer. The gun provides a pulsed beam current of up to 8 A with a pulse duration of 100 ÷ 300 ns and a cycle repetition rate of up to 150 Hz.

Optimal klystrons for the LUE-200 accelerator are the ones of the 5045 SLAC type [3] with an output pulse power of 67 MW, however, due to their commercial inaccessibility, the klystrons of the same frequency range available at the JINR are as follows: TH2129 Thomson with the maximum pulse power of 20 MW and E3730A Toshiba with the maximum output pulse power of 50 MW. To supply klystrons with high pulse voltage, we have used high voltage modulators with the maximum pulse power of 180 MW and the average output power of 180 kW [4]. The modulators are made on pulse forming network with a charge from the inverter-type high voltage sources and discharge by thyatrons to the primary windings of klystron pulse transformers.

The accelerator magnetic system consists of a complex of electromagnets that forms magnetic fields to transport the beam while being accelerated and transported to the target. The structure of the magnetic system is shown in figure 3. The following elements are presented in it: EG — an electron gun, RFB — RF buncher, AS1 — the first accelerating section, AS2 — the second accelerating section, BV1, BV2, BV3, BV4, BV5 — beam viewers, CM1, CM2, CM3, CM4, CM5 — beam current monitors (Rogowsky belts), T — target (W converter), ML1, ML2 — short solenoidal magnetic lenses, BC — short buncher solenoid, FS — focusing solenoid of the first accelerating section, SC1, BC1, BC2, SC2, SC3, SC4 — beam trajectory correctors, Q1/Q2, Q3/Q4 — doublets of wide-aperture quadrupole lenses, Q5/Q6, Q7/Q8 — doublets of quadrupole lenses, MS — magnetic spectrometer.

The formation and focusing of the beam in the area from the gun to the entrance of the buncher at low beam energy are carried out by short solenoidal magnetic lenses ML1, ML2. In the buncher and in the first accelerating section, the beam is transported by the continuously increasing magnetic field of the short solenoid coil (350 G) and then — by the long solenoid field (2800–3000 G). Quadrupole lenses are used to transport the beam after the exit of the first accelerating section and further — to the target. In the region of the second accelerating section we apply

Figure 2. The general arrangement of the accelerator and the target in the neutron source building: a — is a vertical section of the building, b — a plan of the target hall with neutron beams channels.
the doublets of wide-aperture quadrupole lenses Q1/Q2, Q3/Q4, and the doublets of quadrupole lenses Q5/Q6, Q7/Q8 to transport the beam from the second section exit to the target. The beam trajectory correction along the accelerating tract and transportation channel is carried out by dipole steering coils and bias coils.

As diagnostic and monitoring tools for the accelerated beam, we have used current monitors — Rogowsky belts, phosphor BPM — beam position monitors with CCD video cameras, and a magnetic spectrometer with beam bending by an angle close to 90°.

4 Startup and current status of the accelerator

Installation and commissioning of the accelerator at the Joint Institute were carried out after the head samples of the accelerating sections having been developed and tested at Budker Institute [5]. The testing experiments confirmed the fundamental opportunity of obtaining electron beams with a charge of up to 150–300 nC accelerated to the energy of 80–90 MeV in the accelerating sections for the LUE-200 accelerator [5, 6].

Start-up and adjustment of the accelerator were carried out in two stages. At the first stage, the accelerator was assembled of one accelerating section with one TH2129 Thomson klystron (KL1) using the RF power compression system. Due to the absence of a second klystron, a passive drift space tube was installed instead of the second accelerating section with two doublets of quadrupole lenses, which preserve the transverse size of the accelerated beam while being transported to the target. This scheme was defined as the “first stage of the LUE-200 accelerator” [7]. The first stage of the linac worked out several thousand hours for the experiments at the repetition rate of 10–25 Hz. The average power of the electron beam at the repetition rate of 25 Hz was equal to 0.13 kW for the beam with the average pulse current of 1.5 A and 0.2 kW — for the beam of 2.5 A. The “second stage” assumed the assembly of the accelerator consisting of two sections in the whole. The opportunity of implementing the “second stage” appeared when the Joint Institute purchased a new powerful E3730A Toshiba klystron [8].

Commissioning of the second section was accompanied by installing the second klystron (KL2), the second modulator (M2) and the feeder supplying RF power from the KL2 klystron together with the SLED2 system. When installing the second accelerating section, the feeding scheme of the sections by klystrons was changed: now the first (upper) accelerating section is powered by the E3730A Toshiba klystron. The TH2129 Thomson klystron was installed to supply the second (lower) section. Figure 4 shows the general view of the accelerator after mounting the second (lower) accelerating section.

Figure 5 demonstrates the first energy spectra of the beams accelerated in two sections in 2017 (Figure 5.a) [9], measured at different beam current from the gun (curve 1 — \(I_{EG} = 3.5\) A, curve 2 — \(I_{EG} = 1.2\) A) and the energy spectrum of the beam with the current of 2 A measured after long “training” of the accelerating and RF systems in December 2019 (figure 5.b). Figures 5.a and 5.b illustrate the increase of the both: the average energy of the beam and the energy content of the beam per cycle.

The results of energy measurements have shown a certain “lag” in the energy characteristics of the beam in comparison with the design estimates made for the beam with a current of 1.5 A [2]. It should be taken into account that the characteristics of the dynamics of the accelerated beam in the
electric field of the RF wave propagating along the \( z \) axis in the accelerating constant impedance structure are defined with the following formula:

\[
E_z(z) = E_0 e^{-\alpha z} - I_0 R_{sh} (1 - e^{-\alpha z}).
\]  

(4.1)

Here, the first term is determined by the field of the external generator: \( E_0 = \sqrt{2\alpha R_{sh} P_0} \), where
Figure 5. Energy spectra of the accelerated beam.

\( P_0 \) is the generator power, \( R_{sh} \) is the shunt resistance, \( \alpha \) is the loss coefficient in the structure. The second term in the equation determines the field induced in the accelerating structure by an electron beam with the average current \( I_0 \) and determines the content of the beam loading effect of the accelerating structure by the current of the accelerated beam.

The beam loading analysis of the accelerating fields [10] has shown that the current value of the accelerated beam (2 A) is less than the critical current for the accelerating structures of this type; therefore, the beam loading effect in the accelerating fields has a limiting, but not suppressing character. The measurements of the energy spectra performed with extremely small beam current at the RF power level taken from the klystrons of 35 MW (KL1) and 20 MW (KL2) have shown that fragments with an energy of more than 100 MeV are recorded in the accelerated beam (figure 5.c), that is consistent with the estimates.

There are, at least, two factors which prevent further increase of the beam energy and its average power: the insufficient electric strength of the accelerating structures and RF feeders, and the limiting capabilities of the klystrons used for the average output power. Further upgrading of the accelerator provides installation of E37340 Canon klystrons (maximum output power of 50 MW, maximum average power of 27.5 kW) operating with a cycle repetition rate of up to 150 Hz, which forms opportunities for increasing the average accelerated beam power to 2–2.5 kW. The problems of the electric strength of accelerating structures are well known both in the theory concerning the mechanisms of appearance and development of RF breakdowns in them and in accelerators with high accelerating gradients. There are no single and unambiguous methods for solving this problem, so at the moment this problem remains the most significant for the LUE-200 accelerator.

5 Non-multiplying neutron generating target of the IREN Source

Tungsten-based alloy was used as a converter material for a neutron-producing non-multiplying target in the IREN facility. The dimensions of the converter have been selected from the conditions of complete absorption of electrons and the maximum productivity of neutron photo production in the same converter in reactions of type \( ^{197}W(\gamma, n)^{196}W \). The target assembly is shown in figure 6.

The converter is a cylinder with a diameter of 40 mm, a height of 100 mm, placed inside an aluminum container with a diameter of 160 mm, through which the distilled water circulates from a closed circuit with an external cooler. The thickness of the water layer in the radial direction is
Figure 6. The scheme (a) and general view (b) of the non-multiplying target with the W converter.

50 mm. Water serves both as a moderator to form the neutron spectrum, and as a coolant for the target.

The integral (in $4\pi$ space) neutron flux from the target $N_n$ have been estimated in dependence of the neutron yield in photonuclear reactions on the electron energy. Figure 7 shows the calculated dependences of the specific neutron yield (per beam power unit) for thick targets from various materials [11]. Following the figure, $N_n \approx Y_n \cdot P_b$ (kW), where $Y_n$ is the neutron yield per second per kW of the beam power, and $P_b$ (kW) is the average electron beam power. For a tungsten target, the following numbers can be taken as estimates of the neutron yield for the first or second stage of the accelerator:

- at the electron energy of 35 MeV and beam power of 0.324 kW (first stage of the accelerator) $N_n \approx 2.0 \cdot 10^{12} P_b$ (kW) sec$^{-1}$ or $N_n \approx 2.6 \cdot 10^{11}$ sec$^{-1}$;
- at the electron energy of 60 MeV and beam power of 0.6 kW (second stage of the accelerator, 50 Hz) $N_n \approx 2.25 \cdot 10^{12} P_b$ (kW) sec$^{-1}$ or $N_n \approx 1.35 \cdot 10^{12}$ sec$^{-1}$.

Experimental estimates of the integral neutron yield were carried out at all stages of commissioning and adjustment of the accelerator by measuring the neutron flux density at a distance of 5 m and 10 m from the target using the $^3$He proportional gas detector, as well as measuring the neutron flux density using activation detectors on the outer surface of the target cooling container. The readings of these measurements were converted to $4\pi$ space, taking into account the geometric and physical efficiency of neutron registration by detectors. In this case, the geometric efficiency was determined taking into account the solid body angle, under which the detector from the “point” source was visible. The results of measurements of the integral neutron yield obtained by these methods are in satisfactory agreement with each other and have given values of $(3 \div 5) \cdot 10^{10}$ s$^{-1}$ at the stage of physical start-up of the first stage of the accelerator and up to $10^{12}$ s$^{-1}$ in the runs with the maximum neutron yield while the second stage of the accelerator with a cycle repetition rate of 50 Hz.

Figure 8 shows the energy spectra of neutron beams obtained in the first stage of the accelerator (2009–2015) and in the second stage of the linac operation (2016). The measured integral neutron
Figure 7. Neutron yields from infinitely thick targets of various materials, per kW of electron beam power as a function of electron beam energy $E_0$ [11, p. 87].

Figure 8. The spectra of neutron beams obtained in the first stage of LUE-200 (2009) and in the second stage of the accelerator (December 20, 2016).

flux from the target reached the values of $(3 \pm 5) \cdot 10^{10} \text{s}^{-1}$ in the first stage and $(5 \pm 6) \cdot 10^{11} \text{s}^{-1}$ in the second stage. The energy range of the measured spectra has confirmed that most of the generated neutron beams belong to the class of “resonance” neutrons.

6 Conclusion

The linear electron accelerator LUE-200 was made and put into operation at JINR as the driver of the new basic facility IREN [12] — a pulsed resonance neutron source with the integral neutron flux
values in $4\pi$ space $\sim 10^{12}$ s$^{-1}$, where dozens of experiments were performed [13]. From the above it can be concluded that the new basic facility IREN is a specialized ADS type (Accelerator Driving System) neutron source having its own niche in the neutron field of nuclear physics both: in applied research and in the field of methods and testing the detectors for nuclear and particle physics.

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