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INTENSE RESONANCE NEUTRON SOURCE (IREN) — NEW PULSED SOURCE FOR NUCLEAR PHYSICAL AND APPLIED INVESTIGATIONS

V. D. Anan'ev [a], *A. R. Frolov* [c], *W. I. Furman* [a], *S. M. Gurov* [c], *V. V. Kobets* [a], *R. P. Kuatbekov* [b], *P. V. Logachev* [c], *I. N. Meshkov* [a], *V. M. Pavlov* [c], *V. G. Pyataev* [a], *G. D. Shirkov* [a], *V. A. Shvets* [a], *B. A. Skarbo* [c], *A. P. Soumbaev* [a], *I. T. Tretiyakov* [b]

[a] Joint Institute for Nuclear Research, Dubna
[b] Research and Development Institute of Power Engineering, Moscow
[c] Budker Institute for Nuclear Physics, Novosibirsk, Russia

An accelerator-driven subcritical system (200 MeV electron linac + metallic plutonium subcritical core) IREN is constructed at the Joint Institute for Nuclear Research (JINR) [1]. New pulsed neutron source IREN is optimized for maximal yield of resonance neutrons ($1-10^5$ eV). The S-band electron linac with pulse duration near 200 ns, repetition rate up to 150 Hz and mean beam power 10 kW delivers 200-MeV electrons onto specially designed tungsten target (an electron–neutron converter) situated in the center of very compact and fast subcritical assembly with $K_{\rm eff} < 0.98$. So a duration of fast neutron pulse is near 400 ns and total neutron yield achieves 10^{15} per second. A mean fission power of the multiplying target is planned to be near 15 kW. Current status of the project is presented.

В ОИЯИ создается управляемый ускорителем импульсный источник нейтронов ИРЕН — подкритическая система (электронный линак + W-конвертер + Pu-бланкет), оптимизированная для максимального выхода нейтронов в области резонансных энергий ($1-10^5$ эВ) [1]. Ускоритель инжектирует пучок электронов с энергией 200 МэВ, с длительностью импульса тока около 200 нс, частотой циклов до 150 Гц и средней мощностью пучка 10 кВт в вольфрамовую мишень-конвертер, расположенную в центре компактной быстрой подкритической сборки с $K_{\rm эф} < 0{,}98$. При проектной средней мощности делений размножающей мишени до 15 кВт интегральный поток нейтронов может достигать 10^{15} с$^{-1}$ с продолжительностью импульса быстрых нейтронов около 400 нс. Представлено текущее состояние проекта.

1. THE BASIC CONCEPTS

The IREN source [1] is intended for nuclear physics investigations by a time-of-flight method in a neutron energy region of up to some hundred keV. It is created on a place and in a building of the LUE-40 + IBR-30 installation removed from operation, thus the existing infrastructure of eight neutron beams with fly paths from 10 up to 1000 m, an experimental hall and measuring pavilions is completely used.

To achieve compromise between an energy resolution of time-of-flight (TOF) spectrometer, a brightness of neutron source and its operational cost, a booster scheme was accepted. New pulsed neutron source should provide a fast multiplication of initial neutrons produced by an electron beam in electron-γ-neutron converter. So its design has to ensure as short as possible time τ for one act of neutron multiplication ($\tau \leqslant 10$ ns) into a subcritical blanket, the total duration of a fast neutron pulse of about 400 ns with a repetition rate of 150 Hz, and a neutron yield at a level of 10^{15} s^{-1}.

The project of IREN source matches the two basic principles of nuclear safety: 1) in all designed modes of operation, including works on service of an active zone and possible emergencies, including external influences, nuclear failure should be excluded; 2) in all regimes of operation, including reloading of an active zone and possible emergencies, including extremely improbable, influence on the attendants, on the population and on an environment should not exceed the established regulations and should be at reasonably achievable low level.

The high level of nuclear safety of the installation is provided due to deep subcriticality of multiplying blanket — active zone ($K_{\rm eff} < 0.98$ in all modes of operation, including emergencies foreseen by the project) and a respective design of the whole booster.

The design of the installation should provide replacement of removable elements: the converter, the moderator, lateral reflectors, etc., allowing perspective improvement of a design.

The IREN source created now at JINR will be used as a neutron source of new generation for research of the broad spectrum of problems of fundamental and applied nuclear physics, actual for country-participants of JINR:

- search for the Time Reversal Invariance Violation effects in neutron–nucleus interactions;
- neutron-induced fission studies;
- fundamental properties of the neutron: mean square charge radius and electric polarizability;
- nuclear structure studies;
- nuclear data program.

The program of fundamental and applied research at the IREN source [1] was discussed at many international workshops. Respective experimental setups are being prepared now at JINR and at many nuclear centers of Russia and country-participants of JINR. It is planned that the IREN source will be open for outer users so proposals for new experiments at its neutron beams are welcome.

2. GENERAL DESCRIPTION OF THE FACILITY

The IREN source consists of two basic parts shown in Fig. 1: vertically located electron linear accelerator (LUE-200 linac) with the vacuum pipeline of transportation of a beam to the electron-γ-neutron converter with a membrane separating a vacuum system of the linac and helium gas cooling system (the first contour) which is situated in the center of the multiplying subcritical blanket, containing about 24 kg of highly enriched metallic plutonium (more than 95% of ^{239}Pu). Below a set of the converter and the blanket will be called multiplying target (booster).

The LUE-200 linac is located on the top and average floors of a building, and the electron transportation line, the multiplying target on the ground floor into a lower hall (target hall). The dimensions of this hall are $10 \times 10 \times 8.4$ m with two-meter-thick walls of heavy concrete. In the target hall the so-called target chamber measuring $10 \times 7 \times 3.3$ m is constructed, inside which the multiplying target itself and also internal and wall shutters are placed. The internal shutters are designed to ensure safe access into the target chamber. On the outside of the

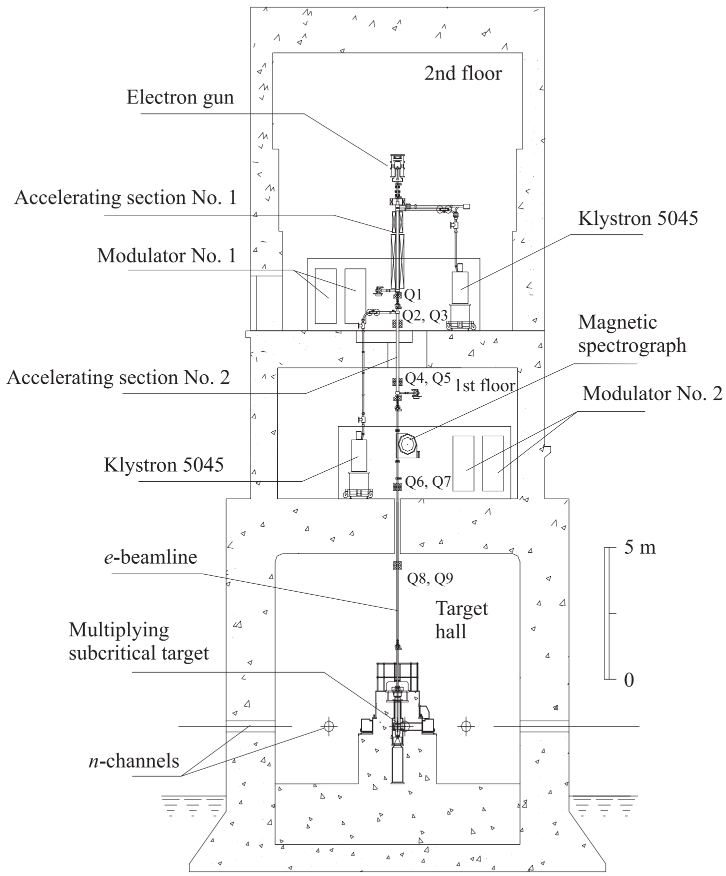

Fig. 1. Schematic layout of the IREN facilities

target chamber there is an adjoining dry temporary storage for fuel elements and activated replaceable constructive elements of the facility.

The IREN source is equipped with biological shielding; the cooling system providing a heat removal in all design modes of operation, including emergency; the control system; other necessary systems and the equipment providing reliable and steady functioning of the facility.

3. LUE-200 LINAC

The travelling wave electron linac is designed at the Budker Institute of Nuclear Physics (BINP), Novosibirsk [2, 3]. Its main characteristics are incorporated in Table 1.

The linac and its auxiliary systems are situated vertically on two upper floors of the IREN source building as shown in Fig. 1. Due to fixed height of accelerator halls the strict limitations for total length of the linac ($\leqslant$ 8 m) exist. A special vacuumed electron transport pipe penetrates the ceiling of the lower hall and the ceiling of the target chamber and enters the centre of the multiplying target ending just over the upper surface of the converter. This transport line is equipped with a separate focusing system and a vacuum pump as well as a beam position control device.

Table 1. **Main parameters of the LUE-200 linac**

Beam average power, kW	10
Electron energy, MeV	200
Pulse current, A	1.5
Beam pulse duration, ns	$\leqslant 250$
Repetition rate, Hz	150
Average accelerating gradient, MeV/m	~ 35
Operation frequency, MHz	2856
RF power amplifier	5045 klystron (SLAC)
Number of accelerating sections	2

The main elements of the linac are the following: a pulsed electron gun, an accelerating system, RF assembly on the basis of two 5045 SLAC klystrons, RF power compression system SLED, two klystron modulators, a focusing system, a beam diagnostic system and a wideband magnet spectrograph. The electron gun uses a 200-kV pulsed high-voltage transformer, thermoionic cathode, providing a pulsed current of up to 2.5 A with a pulse duration of 200–250 ns at a repletion rate of 150 Hz and an emittance of no more than 0.01 $\pi \cdot \text{cm} \cdot \text{rad}$. The accelerating system of the linac consists of the S-band buncher and two accelerating sections. Each section is powered by a 5045 SLAC klystron.

The shaping preamplifier forms the RF pulse of ~ 3.5 μs duration and an output pulse power at a level of 200–400 W for 5045 klystron excitation. The phase shifter provides the phase inversion at the operational frequency to ensure an operation of the power compression system. RF pulse of up to 60 MW power is transported from the klystron along the waveguide (72×34 mm) via the SLED-type power compression system to the accelerating section inputs. The RF pulse phase and amplitude can be varied by means of the attenuator and phase shifter.

Table 2. **Main parameters of accelerating sections**

Operational frequency, MHz	2855.5
Internal cell diameter $2b$, mm	83.75
Iris diameter $2a$, mm	25.9
Iris thickness t, mm	6
Period D, mm	34.99
Operational mode of oscillation θ	$2\pi/3$
Relative phase velocity β_p	1
Relative group velocity β_g	0.021
Section length L, m	2.93
Total number of cells	85
Unloaded quality factor Q_0	13200
Shunt impedance R_{sh}, MΩ/m	51
Time constant $\tau_{0a} = 2Q_0/\omega_0$, μs	1.471
Attenuation (by field) $\alpha = 1/(\tau_{0a} v_{\text{gr}})$, m^{-1}	0.108
Filling time $T_f = L/v_{\text{gr}}$, μs	0.465

The S-band traveling wave accelerating sections have a round disk-loaded waveguide of constant impedance. Its parameters are given in Table 2.

The temperature control of the accelerating structure is provided by the thermostabilization system. The operational temperature of accelerating sections is 30°C. The accuracy of temperature stabilization is ± 0.1°C.

The focusing system should provide electron beam transport from an exit of the electron gun up to a final membrane at the end of electron transport system near a tungsten converter situated inside the neutron multiplying blanket. This system consists of two parts.

For the first accelerating section a solenoidal focusing with very homogeneous magnetic field is used. The solenoidal focusing system is optimized to compensate for the space charge influence at the bunching step and at the initial stage of acceleration.

Two accelerating sections are manufactured at BINP, Novosibirsk, partly tested there and delivered to JINR. The technology of their fabrication should guarantee a reliable continuous operation of the devices with high accelerating gradient at the planned RF power level. The use of 5045 SLAC klystrons should provide a reliable linac operation during the period of at least 10 years (in mode of the IREN source operation 2000 h/y).

The accelerating system of the LUE-200 linac was tested at the VEPP-5 preinjector mounted at BINP [4–6]. The facility consists of an electron gun, a magnetic focusing system and two 3-m-long accelerating sections powered with RF assembly on the basis of one 5045 SLAC klystron (1st section powered about 27.5 MW and 2nd section powered about 13.8 MW).

The following parameters of the electron beam were measured while testing the sections:

- gun beam pulse current,
- total charge of the accelerated beam (total number of particles per one beam pulse),
- beam energy spectrum,
- beam energy content.

The energy spectra and energy contents of the accelerated beam were measured with increasing gun beam current from 1.63 up to 3.48 A. Energy spectra of the beam after acceleration in two sections for three values of the gun beam current are shown in Fig. 2.

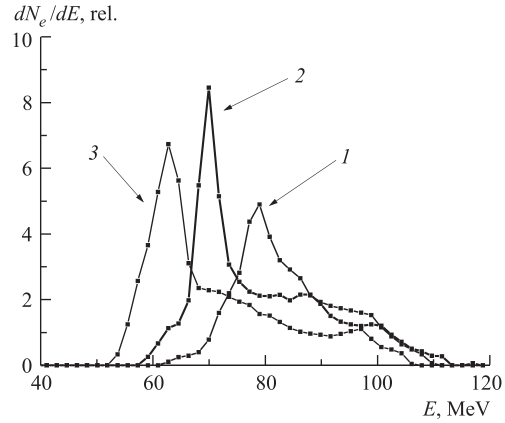

Fig. 2. Energy spectrum of the beam after acceleration in two sections at three values of gun beam current: *1* — $I_{\text{gun}} = 1.63$ A; *2* — $I_{\text{gun}} = 2.84$ A; *3* — $I_{\text{gun}} = 3.48$ A. Curve *2* shows the spectrum of the beam with maximum energy content

It is seen from Fig. 2 that at the increase in the current of the beam injected in the accelerating system, the energy of the beam and mean accelerating rate are reducing.

As shown in earlier experiments [5, 6], in accelerating section powered about 55 MW RF power the accelerating electrical field can reach more than 45 MV/m, and the average acceleration rate reaches more than 30 MeV/m.

These results give good evidence that the designed parameters of the LUE-200 linac could be achieved.

4. MULTIPLYING TARGET

The multiplying target (Fig. 3) is placed in a target chamber in mine of biological shielding which has «windows» in a direction of neutron beams, closed by internal shutters if necessary. Outputs of neutron beams in an experimental hall are equipped with individual wall shutters. The target chamber as a whole is separated from a rest part of the lower hall by a concrete shielding protecting personnel from direct «visibility» of any activated elements of the multiplying target at work in the lower hall on the stopped facility.

The subcritical blanket is equipped with 108 fuel elements from metallic plutonium in diameter on a stainless steel-tantalum cladding of 11.18 mm, which are placed on a triangular grid with step of 11.5 mm in the stainless steel case having shape of correct hexahedron at a level of an active zone. Fuel elements are incorporated in 18 sets containing three, seven or eight elements. In the central cavity of the blanket the electron-γ-neutron converter from a monocrystallic tungsten is installed.

The converter and multiplying blanket are jointed by the common closed contour of helium gas cooling system. A helium flow goes from the top down. The cooling system is designed to match all conditions of safety exploitation of fuel load at all operating modes of the facility, including possible emergency situations. Final heat removal in an environment is carried out from the second (water) contour of cooling.

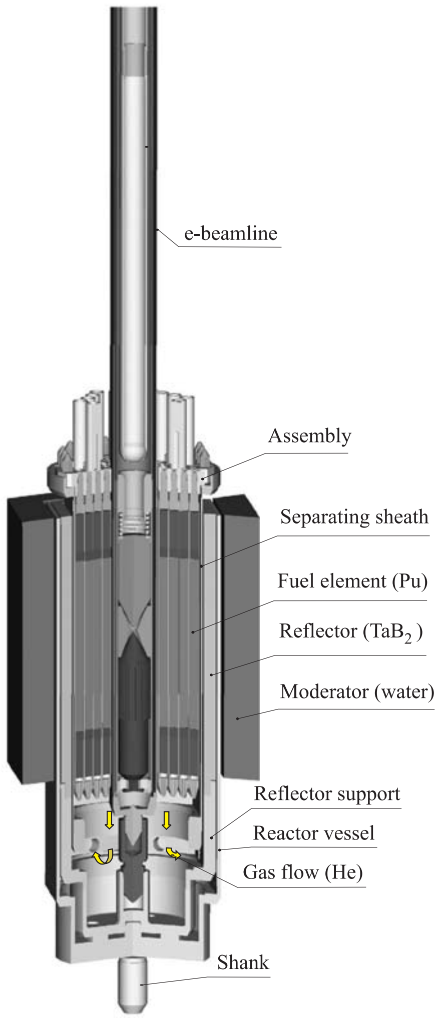

Fig. 3. Subcritical assembly core

To ensure as fast as possible multiplication of neutrons, an original idea was proposed for design of the blanket. Namely just outside of the blanket case a special lateral reflector from composite material $Ta(^{10}B)_2$ is installed. This reflector transmits and partly reflects fast neutrons born into the converter and the blanket but prevents back penetration of thermal neutrons produced in water moderators situated tightly around the reflector. Such a design allows one to obtain safe and extremely fast multiplying blanket — the time τ for one act of neutron multiplication is less than 10 ns. The «semiconducting» reflector and the moderators cover four sides of hexahedral case of the blanket directed onto neutron beams. From the two rest sides disconnected with beams the reflector from a tungsten alloy adjoins the case.

Some elements placed around the case (a lateral reflector, moderators) are cooled by air blown throughout of mine of biological shielding. In case of failure of the helium contour hermeticity or damage of electric supply, the air cooling system provides deheating of an active zone from residual energy release.

A subcriticity level of the assembly is supervised by three channels of control placed in the immediate proximity to the blanket. All the basic elements of the multiplying target (a part of fuel elements, reflectors, moderators, the case, and so forth) are equipped with means of the thermometry, allowing one to supervise a level of temperatures.

The basic characteristics of the subcritical assembly are resulted in Table 3.

A campaign of an active zone is designed 2100 effective days, which corresponds to a planned resource of facility operation during 25 years. Scheduled overloads of fuel are not

Table 3. **The basic characteristics of the subcritical assembly**

The characteristics	Description
Thermal fission power, kW	Up to 12
Electron beam power, kW	Up to 10
Fuel	^{239}Pu
External diameter of fuel element, mm	11.18
Height of a fuel active part, mm	180
Number of fuel elements, pieces	Up to 108
Maximal gain factor, K_{eff}	< 0.98
The heat-carrier	Helium
Reflectors:	
fuel element butt-end	$W(^{10}B)_2$
lateral	$Ta(^{10}B)_2$
Effective pulse duration of fast neutrons, μs	0.42
Total neutron yield, s^{-1}	10^{15}

provided. The need for an overload can arise only in case of emergency loss of hermeticity of one or several fuel elements. For this purpose, and also for final unloading of an active zone at full decommissioning of the facility, the transport-reloading device providing directing, capture, extraction and safe delivery fuel sets into the temporary storage placed in the lower hall is developed.

5. STATUS OF THE PROJECT

The creation of the IREN source is now (the end of 2003) at a rather advanced stage. A general engineering project in the part for approval in Russian authorities as well as a technological design of the multiplying target and the linac are completed. The fuel elements have been manufactured and certified. Main elements of the linac have been manufactured and delivered to JINR. Two accelerator halls placed on upper floors of the building designated for displacement of the IREN source have been released from old LUE-40 linac. Assembling of new LUE-200 linac has to start in these halls.

Full dismantling of the old reactor IBR-30 has to be completed by the end of 2003 and a deactivation and reparation of the lower hall will begin.

Table 4. **A time-table of the project implementation**

Planned activity	Dates of realization	Requested funds, K$
Creation and startup of the first stage of the IREN facility	2002–2005	1430
Test experiments and upgrade of facility for project parameters	2005–2006	310
Modernization of spectrometers for experiments at the IREN source	2003–2005	950
Data taking at IREN neutron beams	2006–2009	200

A time-table of the project implementation (Table 4) foresees a startup of the first stage of the IREN source (at 20% level of designed power) in the year 2005 if an approved plan of financing will be fulfilled.

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