Pulsed Neutron Source IREN at Frank Laboratory of Neutron Physics, JINR

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Abstract

The IREN facility is pulsed Intense Resonance Neutron source operating in Frank Laboratory of Neutron Physics of Joint Institute for Nuclear Research in Dubna, Russia. The predecessor of the IREN facility was the IBR-30 reactor, which was located in the same building and was dismantled 13 years ago. The IREN facility is developed for fundamental and applied investigations in neutron nuclear physics by precision neutron spectroscopy methods in a neutron energy range from eV to hundreds of keV. The IREN is based on an electron linear accelerator (LUE-200) with an S-band travelling wave accelerating structure. A massive target made of a material with high atomic number (tungsten or uranium) serves as a source of neutrons. The electron beam produced by the LUE-200 linear electron accelerator hits the target and undergoes there a conversion into neutrons (e-γ-n reaction). The full-scale IREN project comprises a 200 MeV electron linear accelerator with repetition rate up to 150 Hz and mean beam power up to 10 kW and subcritical multiplying target. Realization of project is conducted in several stages. At present time main efforts are directed on the development of the LUE-200 accelerator.

1. IREN Structure

Iren facility consists of linac, non-multiplying target and seven experimental channels. Linac LUE-200 is located vertically into two halls (Fig.1). Under the linac is a target hall, in which is mounted a target.

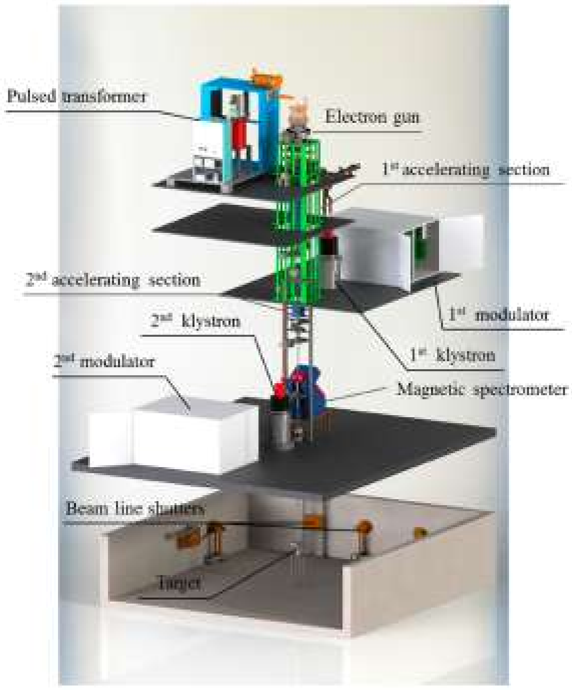


Fig.1. Layout of Linac LUE-200.

Experimental channels have intermediate experimental flight bases at a distance of 10 to 500 meters from the target (Fig.2).

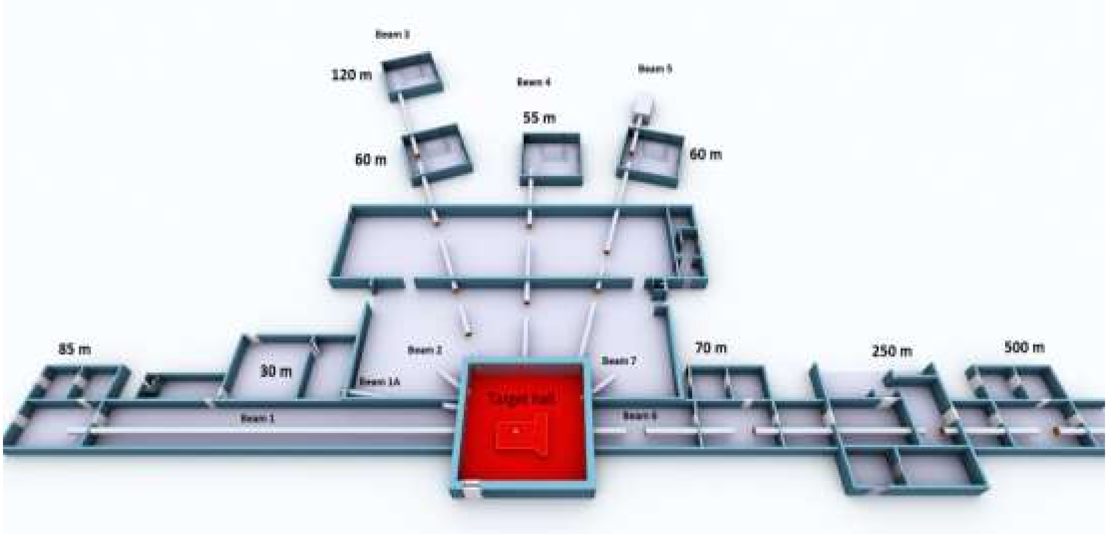


Fig.2. Layout of experimental channels of IREN.

Table 1 shows design and the current parameters of the linac. The implementation of the linac was divided into 2 stages. First stage is working with one accelerating section and one klystron. In the second stage, the second accelerating section and the second klystron were installed. New klystron modulators with a pulse power of 180 MW and maximal repetition rate of 120 Hz were purchased and installed. As you can see on the table, to date the installation has not yet reached the design parameters. The increase in beam power and electron energy continues. Now we have electron energy of about 50 MeV and a beam current of about 1.5 amperes at the target. The pulse repetition rate is 50 Hz and is limited by the capabilities of klystrons. Beam power is 400 W, neutron flux is $(1 – 2) \cdot 10^{12}$ s^{-1}.

Table 1. Parameters of linac

Parameter	BINP project 1993	1^{st} stage realization of LUE-200, 2009	2^{nd} stage realization of LUE-200, 2016
Quantity of the accelerating sections	2 sections (2 klystrons)	1 section (1 klystron)	2 sections (2 klystrons)
Type of klystron power	5045 SLAC 67 MW	TH2129 Thomson 20 MW	E3730A Toshiba 50 MW + TH2129 Thomson 20 MW
Maximal energy of electrons	212 MeV	35 MeV	50 – 55 MeV
Peak current	1.5 A	1.5	1.5
Electron pulse duration	250 ns	100 ns	100 ns
Repetition rate	150 Hz	25 – 50 Hz	25 – 50 Hz
Mean power of beam	≈ 11.2 kW	0.13 kW	0.4 kW
Neutron yield	$2 \cdot 10^{13}$ s^{-1}	$5.4 \cdot 10^{10} – 10^{11}$ s^{-1}	$(1–2) \cdot 10^{12}$ s^{-1}

As an electron injector, is used a diode 200 kV electron gun (Fig.3). Thermal emission is achieved by supplying high voltage to the heated oxide-barium cathode. The gun modulator (Fig.4) allows to form a beam pulse with a duration of 350 ns and a current of about 6 amps.

The repetition rate of the modulator is from 1 to 150 Hz. Under the electron gun there is a buncher that pre-forms the electron bunches before their acceleration.

Fig.3. Electron gun.

Fig.4. Gun modulator.

After the buncher, the beam passes through the first and second accelerating sections (Fig.5), where it is accelerated to relativistic values and receives an increase in the energy of electrons. Each section is a standard accelerating structure of the SLAC-type on the running wave, with constant impedance. The average accelerating gradient of each section is about 35 MeV per meter. For better beam focusing, the first accelerating section is surrounded by a focusing solenoid. Focusing of the beam in the second accelerating section is carried out with the help of quadrupole lenses. The main parameters of the accelerating section and the solenoid are shown in the Table 2.

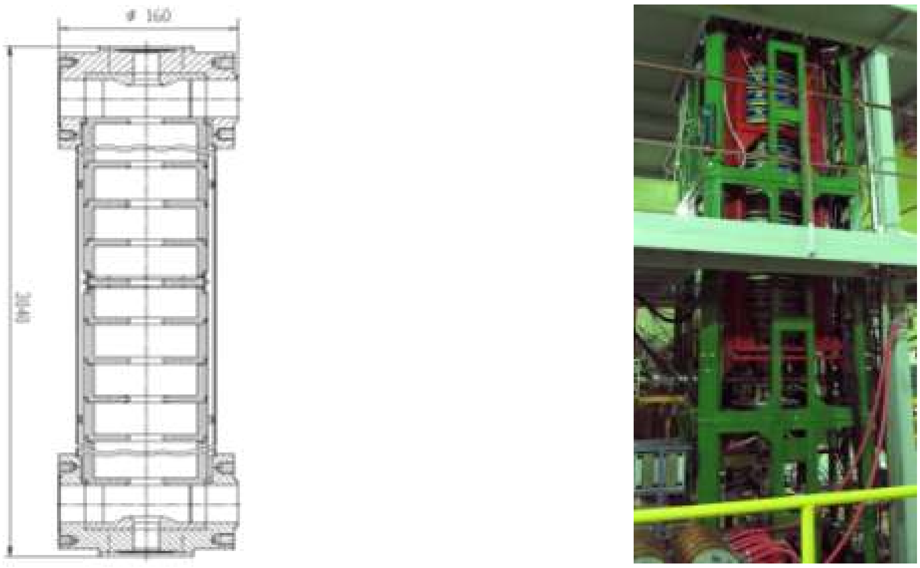


Fig.5. Accelerating section with focusing solenoid.

Table 2. Parameters of accelerating section and solenoid

Parameters of accelerating section	
Frequency (MHz)	2855.05
Accelerating gradient (MeV/m)	35
Type of fluctuations	$\theta=2\pi/3$
Filling time (μs)	0.471
Internal diameter of cells (mm)	83.7
Number of cells	83+2
Length (mm)	2930

Parameters of solenoid	
Number of coils	16
Nominal current (A)	300
Max. current (A)	400
Magnetic field at 350A (Tl)	0.28
Required power at 400A (kW)	51.2
Length (mm)	2700

The analyzer of energy (Fig.6) is the integral part of the linac. The magnetic spectrometer consists of an analyzer chamber and a bending magnet. The analyzer chamber has a triangular shape, on the edge of which there are sensors. When measuring the energy of electrons, a bending magnet is approaching the chamber, the field of which is directed perpendicular to the electron beam. As the field in the magnet increases, the electrons deviate from their axis and enter the sensors of the analyzer chamber. Electrons with less energy get to the near sensors, and electrons with more energy get to the longer sensors. Thus, by receiving signals from sensors it is possible to estimate the energy spectrum (Fig.7).

Max. magnetic induction	1 Tl
Magnetic rigidity of magnet	0.166 – 0.7 Tlpm
Number of coils	2
Max. current in a coil	500 A
Sectional of a pole	2500 sm²
Angle of rotation of a beam	90°
Number of sensors	32
Weight	1500 kg

Fig.6. Magnetic spectrometer and its parameters.

Also on the linac LUE-200 by means of visual and magnetic induction diagnostics of the beam position in the electron guide are used. All along the linac are beam-viewers that represent vacuum chamber within which the movable reflector is coated with phosphor and axis marking. The Fig.8 shows an example of a beam spot after the second accelerating section. Also on the prints shows the effect of the magnetic field of quadrupole doublets.

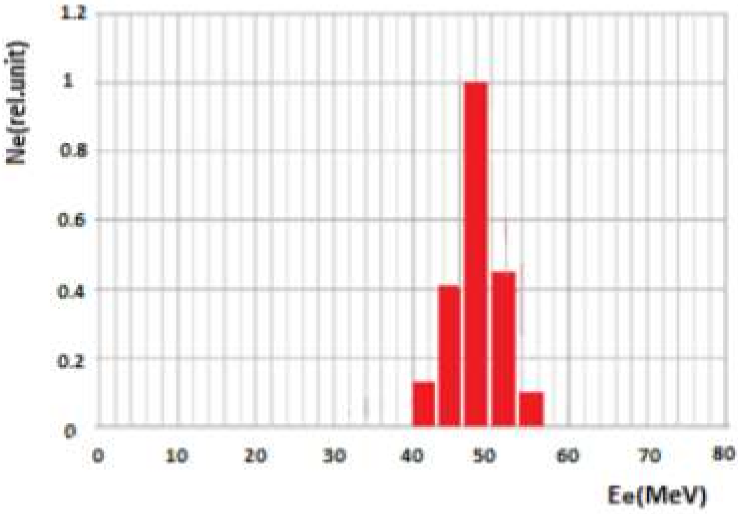


Fig.7. Spectrum of electron energy after 2nd accelerating section.

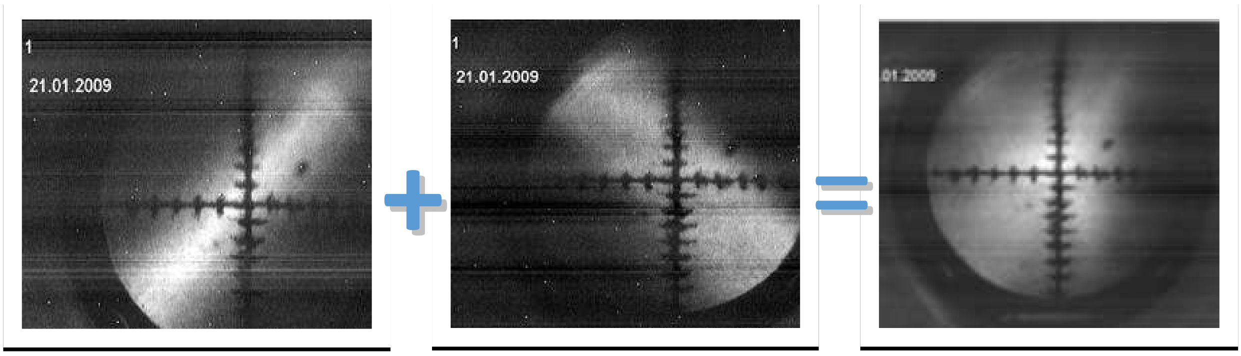


Fig.8. Beam spot on luminescent screen in front of the target: quadruple lenses doublet effect.

Magnetic induction current monitors located along the LINAK are used to measure the beam current. Its sensitivity is 1A/V.

At the end of the electron guide there is a target (Fig.9). The target is a tungsten cylinder immersed in a sealed container with distilled water. Water is both a cooler and a moderator of fast neutrons to resonant energies. As one of possibilities to increase the neutron output of the IREN facility is the replacement of tungsten target at the target from natural uranium, the measurement with a prototype of the uranium target was performed and neutron outputs were compared.

Fig. 9. Targets.

2. Experiments and scientific program at IREN

The comparison was conducted on the yield of the reaction (n, γ) resonances of tantalum sample in the energy from 4 to 1200 eV. Event detection was performed by a large 6-section liquid scintillator detector at 60-meter flight base. The results of measurements and analysis are shown in the graph (Fig.10). Measurements were made with the same parameters of linac. Calculations were carried out in the programs GEANT and FLUKA. An increase of the neutron flux by 2.5 times was experimentally recorded.

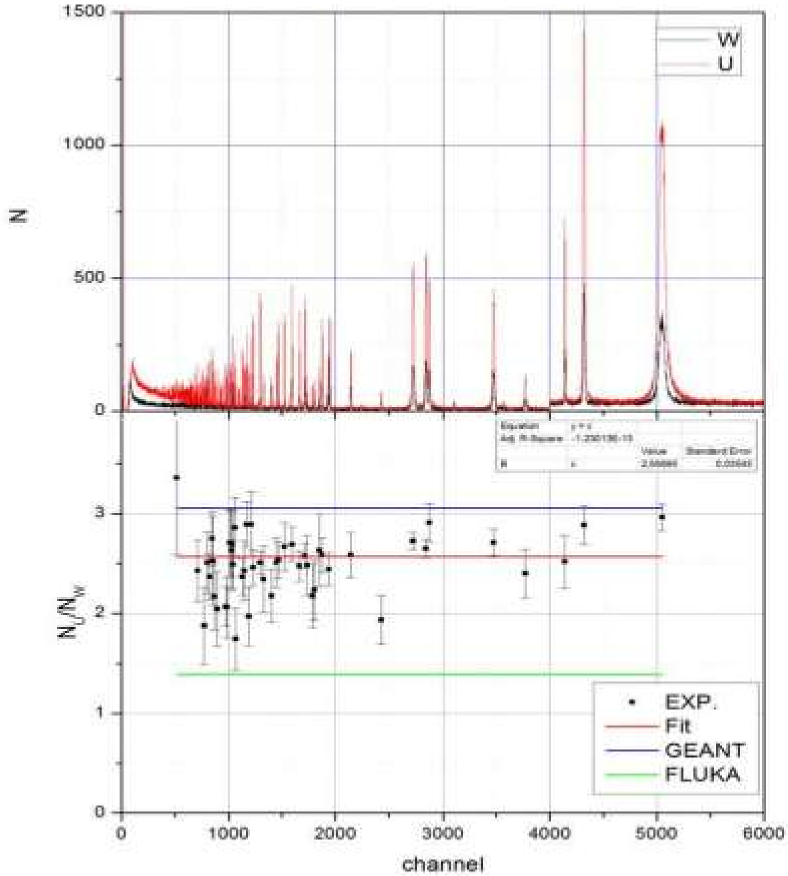


Fig.10. Results of measurements.

The graph (Fig.11) show the comparison of the neutron flux output during the first stage and second stage of linac. During the measurements the linac worked at nominal parameters at the repetition rate of 50 Hz. After the installation of the second accelerating section and the second klystron, the neutron yield increased by 3 times compared to the work with 1 accelerating section and one klystron.

The graphs (Fig.12) show the parameters that characterize the timing, and energy resolution of the facility, and demonstrate the advantage of using a short flash.

The left figure shows the time characteristics of the neutron flux on the surface of the moderator in this configuration for different groups of neutrons.

The right figure shows that for neutrons above 20 eV, the energy resolution that provides IREN (pulse duration 100 ns) at the flight base of 10 m is better than the resolution of the IBR-30 (pulse duration of 4.5 μs) at 100 m. So, if the IBR-30 for any measurements one has to stand on the basis of 100 m, now it can be carried out at 10 m.   At the same time the increase in the neutron flux will be 100 times.

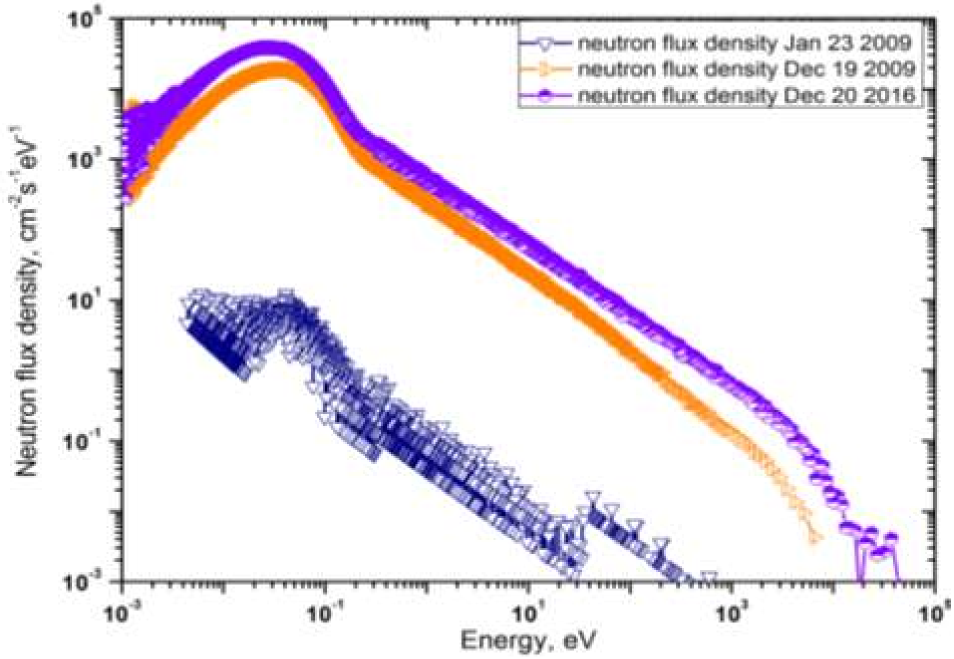


Fig.11. Spectra of neutron flux density from IREN obtained during development of the facility.

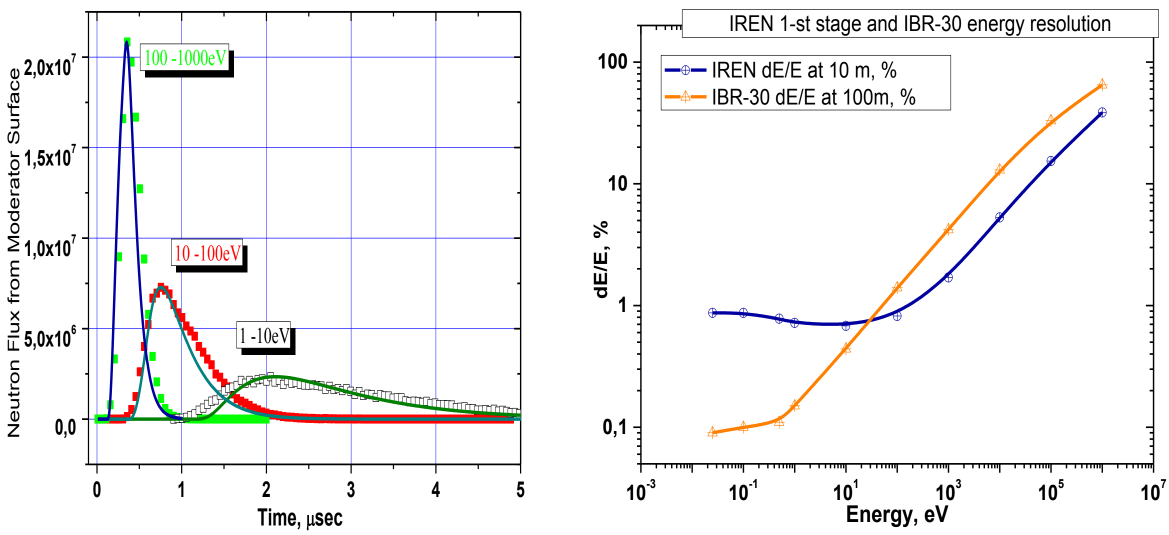


Fig.12. IREN vs IBR-30.

Fig.13 shows an experimental comparison of the energy resolutions of IREN and IBR-30. Measurements were made on the flight base 60 m with Ta(n,γ) sample. It is seen that the width of the resonances in the region up to 20 eV are approximately equal, but higher energy it is much better for IREN facility.

But this is one of the first measurements. Now the neutron flux at IREN is about 5 times more.

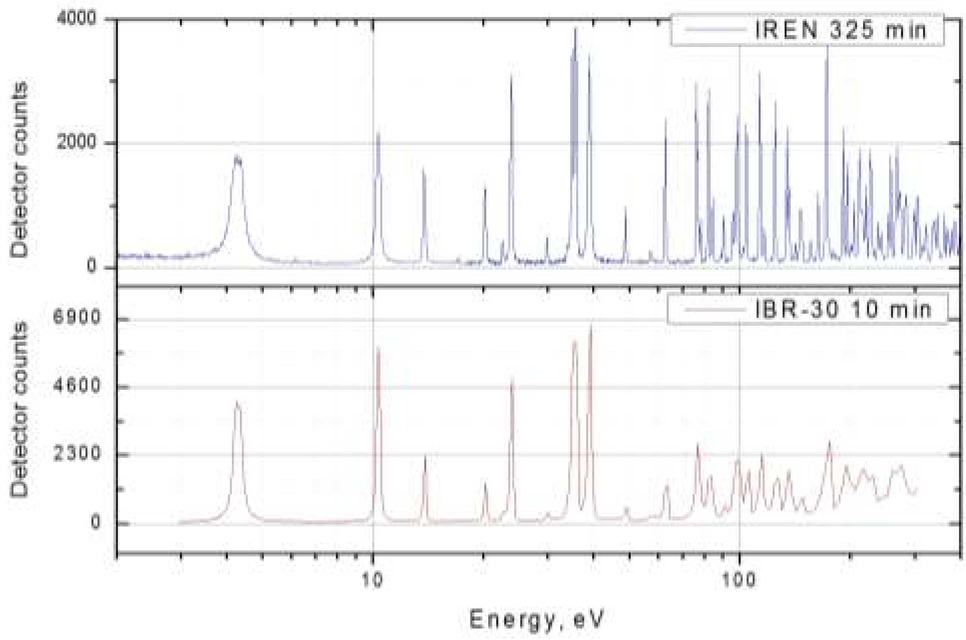


Fig.13. Energy resolution IREN vs IBR-30.

The scientific program at the IREN facility includes research:

- symmetries violation in neutron induced reactions;
- neutron induced fission;
- neutron fundamental properties;
- nuclear structure;
- nuclear data;
- resonance capture and transmission analysis.

Due to the fact that IREN facility has not yet reached the design parameters, now we conduct preliminary experiments, tests of new equipment and perform some applied research.

Preliminary experiments to assess the possibility of studying the fission physics in neutron resonances are carried out (Fig.14).

The measurements were carried out on the flight base 10 m. As the detector an ionization fission chamber was used. The target was the uranium-235.

The ionization chamber was organized so, that it was possible to register both binary fission (signals from the cathode in the interval A1-A2) and ternary fission – 2 fission fragments + alpha particle (alpha particles with high energy passed through the thin foil of the electrode A2 and were registered by the anode A3).

Also new detector system on neutron beams is being tested.

«Romashka" is a mobile, easily tunable, multi-detector system with the scintillator detectors. The system allows to register both time of flight and energy spectra, to analyze pileaps, multiplicity of coincidences, dead time and other parameters which are necessary for the correct determination of neutron cross sections and neutron resonance parameters. The graph (Fig.15) shows the dependence of the output of (n, γ)-reaction from tantalum sample on neutron energy, obtained by measurements on the flight base of 30 m.

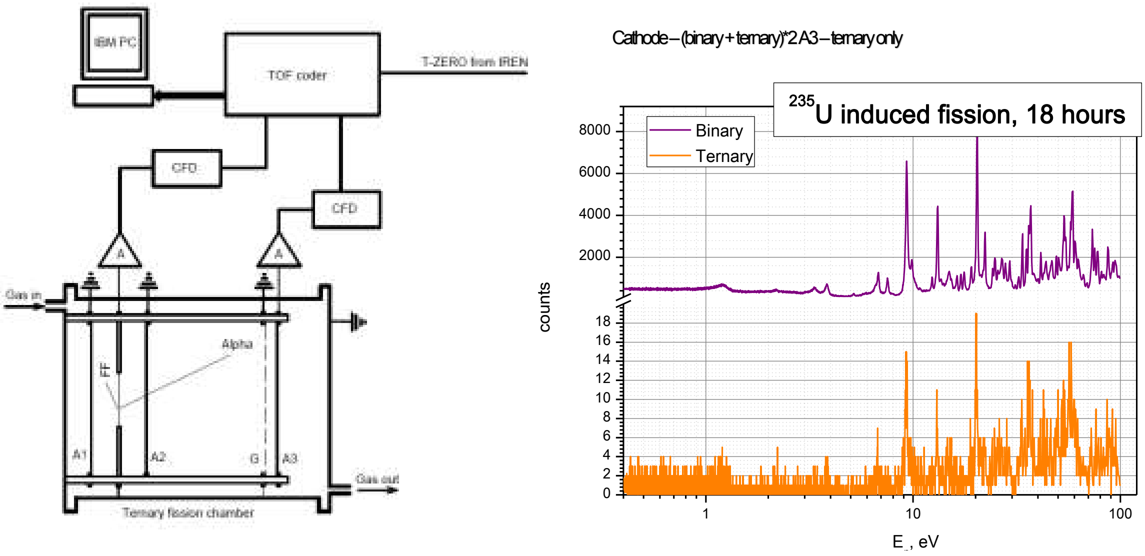


Fig.14. Investigation of fission in neutron resonances.

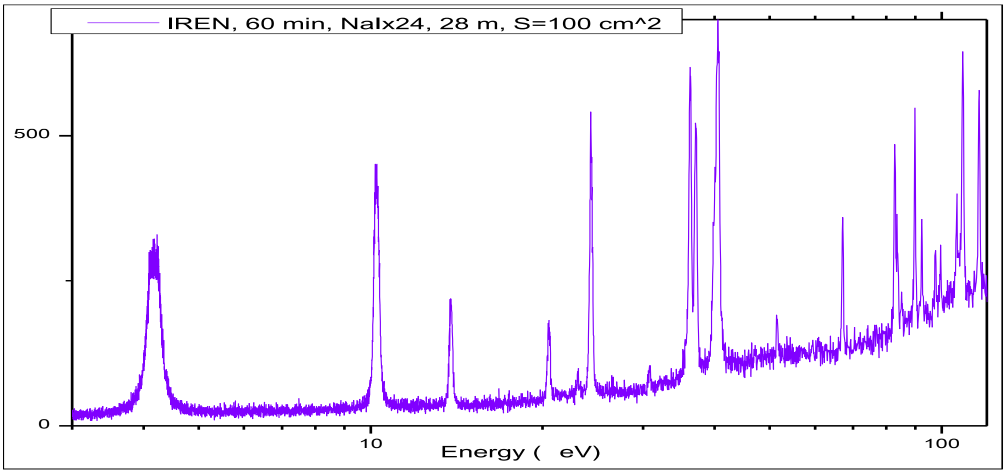


Fig. 15. Tests of new detector systems on neutron beams. The multi-detector system “Romashka-IREN”.

At the IREN facility the effects of neutrons and gamma rays on plastic scintillators used in the CMS experiment at CERN was studied.

The experience of three years of operation of the hadron calorimeter showed an unexpectedly large decrease in the light output of plastic detectors. It was concluded that not all the factors of radioactive radiation influence on scintillators were taken into account. To address this issue, four types of plastic scintillators were studied. The maximum irradiation time is 30 days. The value of light output of samples of different shapes after irradiation was compared with the value of light output before irradiation. The results obtained showed no substantial effect of rate of irradiation on the light output.

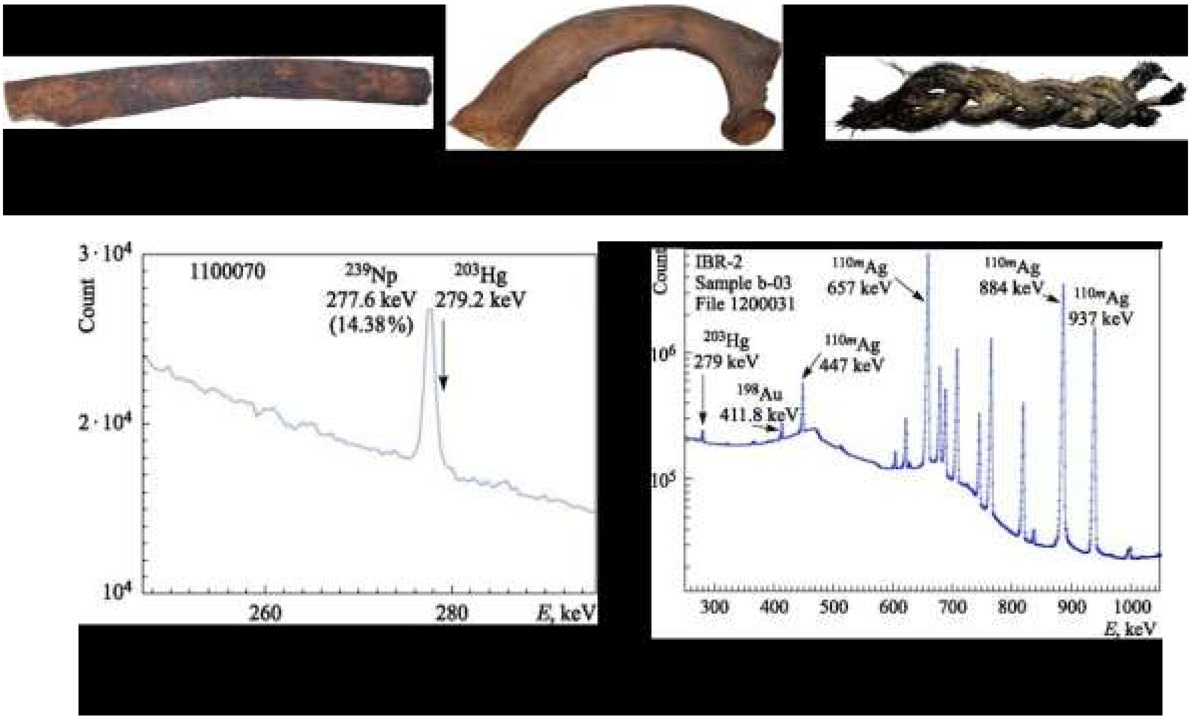
In the CMS experiment, there is a large amount of bronze between scintillators. Therefore, the effect of the additional induced radioactivity emitted by the radioisotopes resulting from the neutron irradiation of bronze was studied. To do this, two identical SCSN-81 scintillators were irradiated at the same distance from the IREN target. But behind one of them there was a disk made of bronze. Measurements of light output showed that there is a substantial contribution from induced activity. The results of the measurements confirmed the results of the calculation using the program FLUKA. Thus, the reason for reducing the light output of the hadron calorimeter scintillators was found out.

Another example of applied work is the use of neutron resonance analysis for non-destructive determination of the elemental composition of various samples.

Last year, at IREN facility experiments to determine the elemental composition of a number of archaeological artifacts were conducted. Neutron resonance capture analysis - NRCA was used in the studies. A large liquid scintillator detector was used as a γ-quantum detector.

In Frank Laboratory neutron activation analysis three samples of human remains from necropolis of the Moscow Kremlin (Fig.16) was conducted. The samples were the rib and hair of Queen Anastasia, who was the first wife of king Ivan 4, as well as the rib of Knyaz Dmitry, who was the son of Tsar Ivan 4.

The samples were irradiated at two facilities – IREN and IBR-2 reactor. The induced activity spectra of the irradiated samples were measured using a germanium detector. The mass fractions of arsenic, mercury and some other elements were determined by relative and absolute methods. The obtained values confirmed the fact of mercury poisoning of Queen Anastasia. Increased mercury content was found in the bone remains of Knyaz Dmitry.



Sample №	Arsenic (As)		Mercury (Hg)	
	Mass fraction, mg/kg	Relative error, %	Mass fraction, mg/kg	Relative error, %
1	0.19	30	0.36	19.1
2	0.23	30	0.2	29.5
3	1.18	18.3	46.6	2.5

Fig.16. Analysis of arsenic and mercury in human remains of the 16th – 17th centuries at IBR-2 reactor and IREN facility.

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