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PROPOSAL FOR THE CONSTRUCTION OF THE NEW INTENSE RESONANCE NEUTRON SOURCE (IREN)

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CONTENTS

1. INTRODUCTION

1.1. Purposes of the Project

For three decades studies on:

- properties of the neutron as the fundamental particle;
- mechanism of nuclear reactions with neutrons;
- properties of high excited states with the most wide use of different channels of decay of compound nuclei

are being a speciality of the Laboratory of Neutron Physics, JINR. A number of them the Laboratory has pioneered and remained the neutron world acknowledged leader in. Widely known are the experiments conducted at this Laboratory on the study of hyperfine neutron-nucleus interactions, effects of parity violation in neutron resonances, rare (n, α) and (n, p) reactions in the resonance neutron region, the (n, 2γ) reaction as a new method for obtaining information about high excited states of nuclei and their nature, on a search for neutron polarizability, as well as on the first detection of ultracold neutrons (UCN) and investigations with them.

The high level of these investigations at LNP was achieved by means of the neutron time-of-flight spectrometers based on the original pulsed neutron sources till recently producing resonance neutrons of record intensity. First, it was the pulsed reactor IBR and, then, the original system which comprised the standard linear accelerator of electrons, LUE-40, and the neutron booster on the basis of the reactor IBR-30. The booster neutron multiplication coefficient of 200 allowed the integral yield of 5×10^{14} neutrons per second at a pulse duration of 4 μsec (at half maximum) to be obtained. With startup of the proton storage ring (PSR) of the Meson Facility at Los Alamos (LANSCE) the neutron physicists have obtained an integral neutron flux of 10^{16} n/sec at a pulse width of 0.13 μsec. This fact and the fact, that LUE-40 has

been operating for 20 years already and now needs reconstruction, made it our aim to design a new source of resonance neutrons for the time-of-flight spectrometry studies.

The proposed Dubna intense resonance neutron source (IREN) is optimized for investigations in the resonance neutron energy range and even outside this range it could give rather good opportunities for experiments with fast ($E_n \leq 5$ MeV) and thermal neutrons, including in the latter case high resolution measurements in the field of solid state physics. This dedication would complement the possibilities both of experiments on thermal neutron beams from continuous sources (Grenoble, Gatchina, etc.), as it has been the case with the study of parity violation in neutron interactions, and of experiments in nanosecond neutron range being carried out with pulsed neutron sources (GELINA, FAKEL, ORELA, LU-50) on the basis of linear electron accelerators, which provide optimum conditions for investigations of various averaged effects in the fast neutron range.

So the realization of the project IREN would pave the way for the wide collaboration in neutron nuclear physics investigations between the institutes of the JINR Member-States as well as of research institutions of Europe and Asia.

The suggestion to use as a neutron source the combination of an electron accelerator as injector and the reactor core as neutron multiplication booster is not only a tribute to tradition, but it also responds to our wish to have a number of advantages over the other time-of-flight high resolution neutron spectrometers, and particularly, over proton accelerator-based ones. This combination would allow:

- reduced requirements to electron accelerator parameters, that would permit us to have a safer in operation machine, though with no record parameters of the accelerator;
- reduced (by an order of magnitude and even more) construction cost;

- much cheaper in operation machine, both with respect to power consumption and number of staff;
- use of the whole infrastructure of the now existing spectrometer: buildings, flight paths, experimental pavilions, part of the experimental instruments and accelerator power supply system.

1.2. Physical Research Program

The project IREN as well as the research programme have many a times been the topic for discussion among the neutron community.

In June 1990 the project was reported and had won support at the session of the Physics Section of the Science and Technology Council of the Ministry of Atomic Energy and Industry of the USSR.

At the Dubna Workshop held on June 12-14, 1990 representatives of the leading institutes of the USSR active in design and manufacture of linear electron accelerators, including the Institute of Experimental Physics Instruments (NIIEFA); the Institute of Nuclear Physics of the Siberian Branch of the RF Academy of Sciences, the Kharkov Institute of Physics and Technology (KhFTI) have declared this project practicable and made their wish known to participate in its realization for 3-4 years.

The project IREN and the research programme were also discussed at the Workshop on Neutron-Nuclei Interactions (March 1991, Dubna), at the Nuclear Data Commission of the USSR (May 1991, Obninsk) and at the session of the Co-ordination Council on Nuclear Constants (February 1992, Arzamas-16). Everywhere they met support and encouragement from representatives of a wide circle of research centers of Russia and JINR Member-States.

The research programme for the IREN according to suggestions and discussions at meetings might cover a wide range of scientific interests. They are:

- the properties of the neutron as the fundamental particle, i.e. electric polarizability of the neutron and n-e interaction;
- symmetry fundamental properties violation in nuclear interactions, particularly the effects enhanced in neutron resonances;
- laws governing change of "order" and "chaos" at transition of excitations near the ground state to N.Bohr compound states (neutron resonances) and further to the new type of "order" - collective excitations of giant resonances, particularly, their study by using γ-spectrometry of radiative capture and $(n,2\gamma)$ reaction in search for nonstatistical mechanisms of excitation of compound nuclei;
- cluster phenomena preserving processes at high excitations of nuclei; search for α-cluster "shells" in compound nuclei;
- multidimensional studies of fission fragments characteristics and correlations between them in neutron induced fission from individual compound states, including those on aligned targets;
- photonuclear processes with superhigh resolution (10^{-6});
- excitation of electron shells in molecules, and of many other problems, and particularly, those that are at interface of atomic and nuclear interactions;
- interactions of neutrons with isomers and radioactive nuclei (data of importance for astrophysics, the nuclear synthesis process, as well as for learning the the possibility of "burning out" (transmutation) of radioactive, especially, long living isotopes in nuclear power stations wastes, which is vital for the future of nuclear energetics).

With the IREN we could successfully participate in the comprehensive research programme developed for the LANSCE facility (Los Alamos). Its realization will take a long time even with a wider front of investigations than available there now. C.Bowman gave outlines of this programme at the 1987 Lueven Symposium (Belgium).

Topics for eV Neutron Physics Research
at Spallation Sources

- Parity Violation
- T-violation in the weak and strong forces
- Unstable nuclei: (n,p) and (n,γ) reactions
- Neutron capture gamma-ray spectroscopy
- Ultrahigh resolution photonuclear research
- Neutron-pumped gamma-ray laser
- Neutron-induced electronic excitation
- Physics of neutron dosimetry
- Resonance neutron optics
- Resonance Neutron Radiography
- Lead slowing-down spectrometer
- Neutron-neutron scattering

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2. THE MAIN ASPECTS OF IREN PROJECT

2.1. The Pulsed Neutron Source

The new TOF spectrometer now under construction will mainly serve experiments with resonance neutrons, i.e. with slower neutrons than fission neutrons or photoneutrons. Therefore, the energy resolution of this spectrometer is determined not only by the duration of the primary neutron pulse but also by the neutron slowing-down time in the moderator enveloping the reactor core (see Table 1). This fact has to be accounted for when optimizing such parameters of the spectrometer as neutron pulse duration and resonance neutron flux. Our choice is the reduction of the neutron pulse duration to increase by an order of magnitude the resolution of the neutron spectrometer at high average neutron intensity. Because of the vast experience acquired by the Laboratory staff in design and construction of relatively cheap high flux pulsed neutron sources it was decided to stick to the old scheme: linear electron accelerator + neutron booster. Modern technology permits one to increase by an order of magnitude the intensity of photoneutron generation in the target of the electron accelerator, which followed by not so high multiplication (by a factor of 15 only) in the target surrounding fission material makes it possible to obtain neutron pulses of the order of 0.5 μsec duration (fig.1).

2.2. Neutron Spectrometer Surroundings

A special feature of this project is our decision not to construct any new building for the spectrometer. The new electron accelerator is planned to be installed vertically in place of the present LUE-40, and for the booster the building now occupied by the IBR-30 reactor will be utilized (fig.1). This will save money and time and allow the adaptation of a wide network of vacuum neutron guides, experimental pavilions and currently operating instruments for polarization of neutron beams and target nuclei, detection and spectrometry of neutrons, and as well as of a rich set of detectors and spectrometers of the products of interaction of resonance and slow neutrons with nuclei under investigation.

Figure 2 presents the schematical layout of the neutron beams with instruments on them. In fact we have a multipurpose neutron factory.

The present instrument suit:

- Beam No.1 (flight paths: 10, 20, 30, 85 m).
  Ionization chambers (sample working area up to 0.5 m^2), multilayer proportional chambers (rare reactions study).
- Beam No.1a (flight paths: 18, 30 m).
  Double-crystal Ge(Li) spectrometer of γ-cascades following neutron radiative capture.
- Beam No.2 (flight path: 20 m).
  High resolution diffractometer of slow neutrons.
- Beam No.3 (flight paths: 30, 60, 120 m).
  Large multisectional liquid detector of γ-rays following

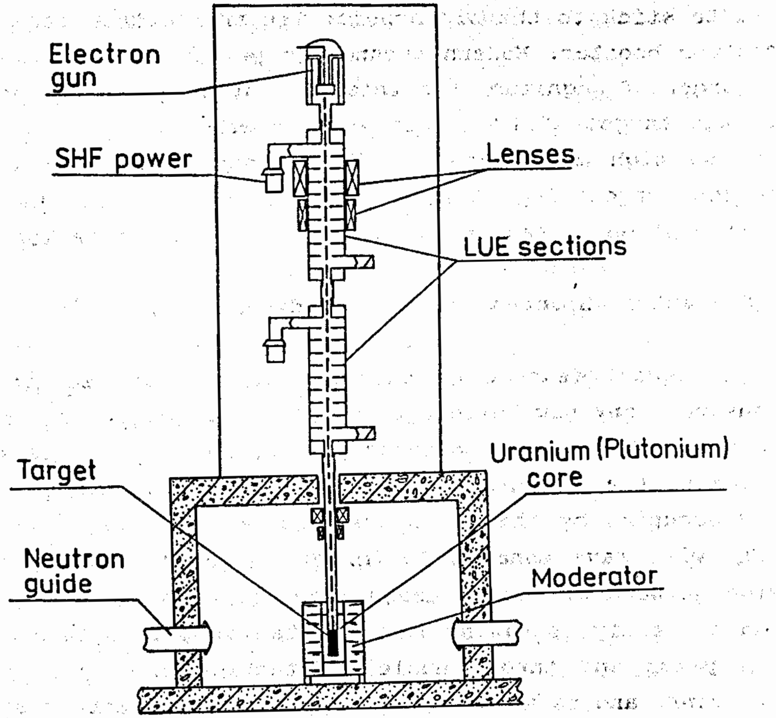

Fig. 1. Schematical lay-out of the IREN (the accelerator and the target facility) in bldg. 43.

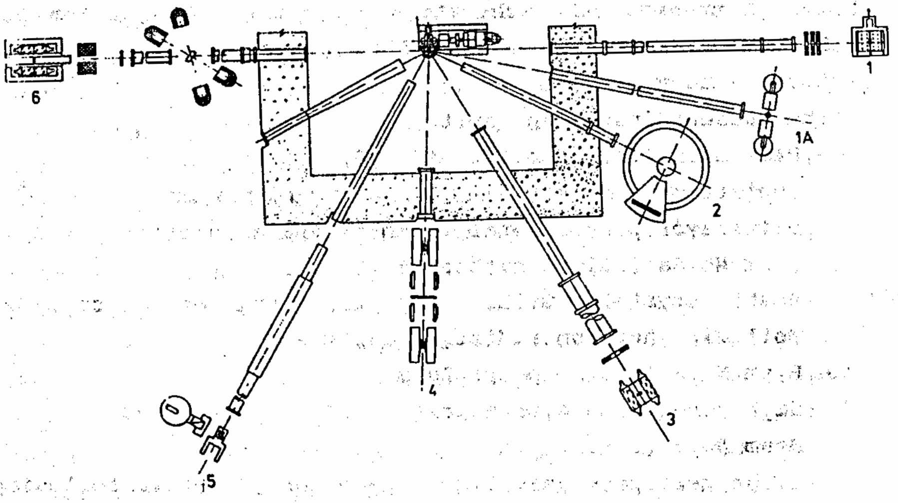

Fig. 2. Present-day infrastructure of neutron beams.

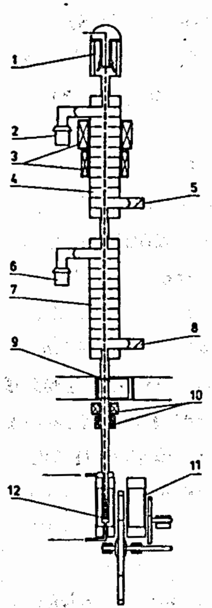

Fig. 3. The complex LUE-40+IBR-30.

radiation capture and fission, fission chamber.

- Beam No.4 (flight paths: 20, 50 m).
  Equipment for polarization of neutrons and target nuclei, neutron detector.
- Beam No.5 (flight paths: 20, 60 m).
  Fast fission chamber, detector of fission fragments for individual resonances.
- Beam No.6 (flight paths: 75, 250, 500, 750, 1000 m).
  Instrumentation for precise measurements of angular and energy dependences of scattering of neutrons with energies up to 0.5 MeV, 16-crystal NaJ(Tl) detector of γ-quanta multiplicity in resonances.

To add this instrument suit several new instruments have been designed to extend the range of physical research to become available with IREN.

2.3. Comparative Characteristics of the Currently Operating Time-of-Flight Resonance Neutron Spectrometers and the IREN

We take as the principal characteristics of resonance neutron spectrometers their integral neutron yield per second in units 10^{15} n/sec ($<I_n>$), the coefficient C, which characterizes the neutron flux (of energy E in eV at a distance of L meters from the moderator) incident on a sample area of 1 cm^2 according to the expression

$$\phi(E) = C/EL^2,$$

in units 10^7, the duration of the primary neutron pulse (τ), the real neutron pulse duration, e.g. at 100 eV (Δt), which is larger due to the neutron moderation process.

The data summarized in Table 1 show that in the resonance neutron range the IREN will become one of the world's best spectrometers with respect to the neutron flux incident on a sample at optimal energy resolution being inferior (by a factor of 4-5) only to the neutron spectrometer LANSCE on the proton storage ring of the Meson Facility at Los Alamos.

Table 1

Spectrometer, Laboratory	$<I_n>x10^{-15}$	$Cx10^{-7}$	τ nsec	Δt(100 eV) nsec
FAKEL (IAE, USSR)	0.003	0.03	50	200
ORELA (ORNL, USA)	0.13	1.5	30	180
LUE-40/IBR-30 (Dubna)	0.5	6	4000	4100
LANSCE (LANL, USA)*	10	40	150	300
IREN (Dubna, project)	0.9	9	400	430

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*The parameters of LANSCE are given for the current in the proton storage ring I_p = 100 μA.

3. TECHNOLOGICAL ASPECTS OF THE IREN PROJECT

As the IREN project is in fact the project for modernization of the existing pulsed neutron source it seems useful to dwell a little on the details of the now operating TOF spectrometer.

3.1. The Neutron Source Operating with the Electron Accelerator LUE-40 and the Pulsed Booster IBR-30

The schematical view of the facility is shown in Fig.3. Neutrons are produced in photoneutron reactions induced by beams of accelerated electrons directed at a heavy element target. The electrons are accelerated in the two-section travelling wave accelerator installed vertically so that its longitudinal axis goes through the center of the target in the core of the fast pulsed reactor IBR-30 (12 in Fig.3). This simplifies the transportation and focusing of the electron beam on the target, because there is no need in changing electrons travelling direction (otherwise it would necessarily lead to partial loss of intensity) and γ-radiation from the target is directed downwards producing no damage to measurement devices at experimental sites. Within this scheme the optimum positioning of neutron guides and experimental pavilions for TOF spectrometry is at an angle of 90° to the electron beam and primary γ-rays direction.

A beam of accelerated electrons is guided to the target which produces neutrons to feed the core of the IBR-30 (11 in Fig.3). The target is made from tungsten, and it is cooled with gaseous helium flow. The core (Fig.4) is the assembly of metallic plutonium rods (2) cooled with air. For crude reactivity modulation a regulator (1) made of U-235 is used, and for fine modulation a manual (16) and an automatic (17) regulator. Emergency reduction of reactivity is accomplished by removing from the core of two assemblies of plutonium rods (4 and 8). The most efficient in terms of reactivity central part of the core is made in the form of two U-235 inserts pressed diametrically opposite in a 1 m diameter disc (6). Rotation of the disc causes reactivity pulsation. This pulsation helps achieve high degree of multiplication of neutrons produced in the target (3) by electrons from the accelerator at the moment, when the moving part (5) of the core coincides with the fixed part, and have low neutron background between pulses. The neutrons having been multiplied in the IBR-30 are then slowed down in the water moderator (14) and guided via vacuum neutron guide-tubes to experimental sites on flight paths. There are eight flight paths with a maximum length of 1000 m (Fig.5).

The time-diagram of the reactor operation cycle is shown in Fig.6. The plot illustrates the dependence of the booster

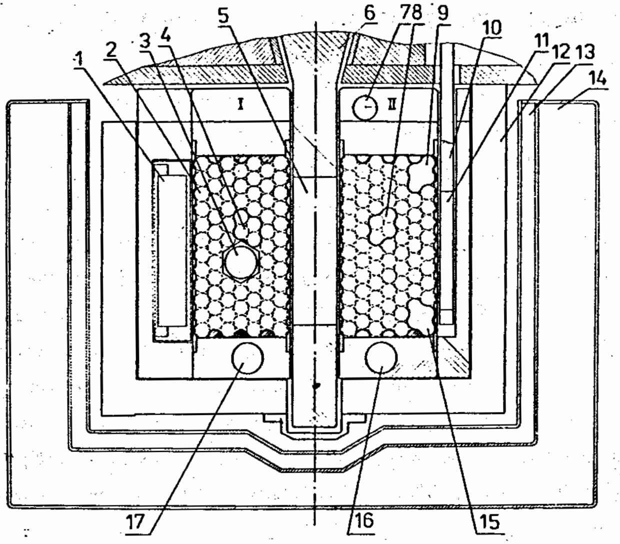


Fig. 4. The core of the booster-multiplicator IBR-30.

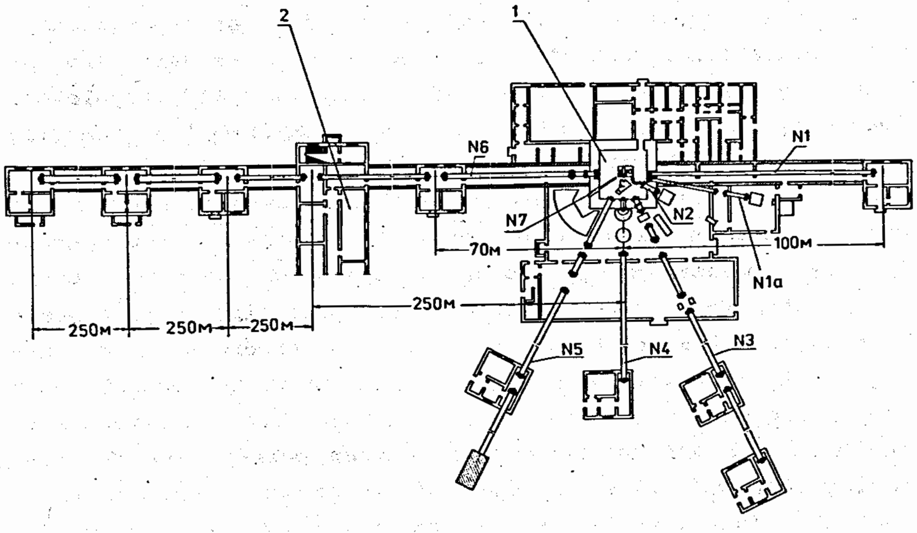


Fig. 5. Schematical view of existing measuring pavilions and flight paths for the IREN.

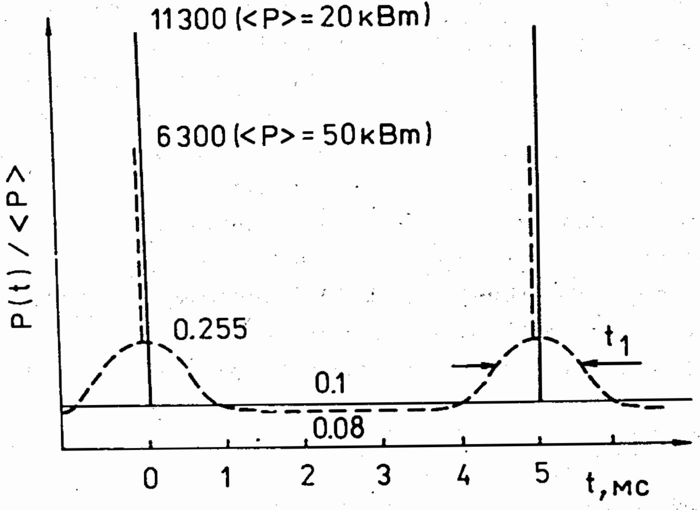


Fig. 6. Qualitative comparison of the pulsed (dotted curve) and the stationary mode of operation of the booster.

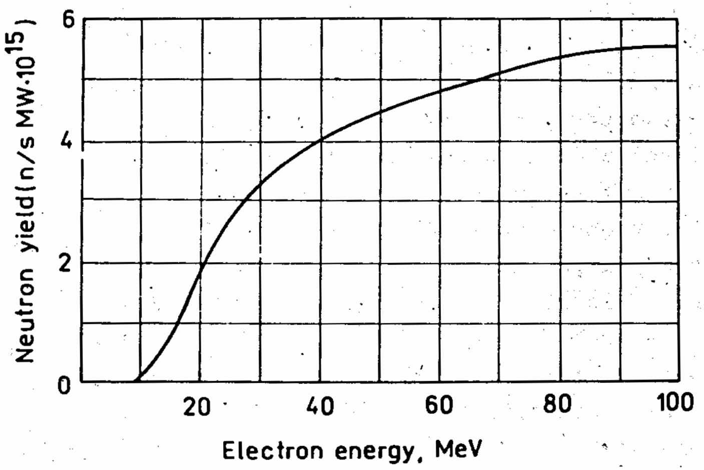


Fig. 7. The dependence of the photoneutron yield on the electron energy per unit power of the accelerator.

power on time. Power between pulses is determined by multiplication of delayed neutrons from the fixed part. The reactor is then $\varepsilon_{backgr.} \approx$ 6.0x10^{-2} subcritical and the multiplication coefficient is 16. As the moving part rotates towards coincidence with the fixed one, the reactor reactivity is growing as well as the multiplication coefficient. At the moment of the accelerator startup the power pulse develops. After reduction of reactivity, power falls to the background level. In the booster mode the IBR-30 is 5x10^{-3} subpromptcritical with the neutron multiplication coefficient of 200.

The parameters of the facility are summarized in Table 2.

Table 2

Electron energy, MeV	40
Current in pulse, A	0.4
Frequency, sec^{-1}	100
Electron pulse duration, μsec	1.6
Electron beam average power, kW	2.5
Neutron lifetime in booster IBR-30, nsec	16
Target material	tungsten
Neutron leakage average intensity (per 4π).sec^{-1}	0.5x10^{15}
Average booster power, kW	10
Background between pulses to average booster power ratio, %	4
Effective neutron pulse duration of booster, μsec	4.1
Booster multiplication level (coefficient)	200
Moving reactor core efficiency	5.5x10^{-2}
Disc rotation rate, rot./min	3000
IBR-30 core volume, liter	2.5
Core loading	20 kg U-~~239~~ 238 and 5 kg U-235
Average thermal neutron flux from moderator surface, cm^{-2}s^{-1}kW^{-1}	2.5x10^{9}
Resonance neutron flux (L in meters, E in eV, W in kW)sec^{-1}, cm^{-2}, ev^{-1}	$(270/E^{0.9})\times(W/L^2)$

3.2. Possibility of The LUE-40+IBR-30 Complex Reconstruction and Choice of Parameters for the New Resonance Neutron Source IREN

Though having rather high intensity, the LNP spectrometer cannot complete with a number of currently operating spectrometers in energy resolution, that depends on neutron pulse duration (see Table 1). The half width at half maximum of 4.5 μsec is less conditioned by the large duration of the electron pulse (1.6 μsec) from the LUE-40, than by neutron pulse delay in a phototarget after a 200 times multiplication in the booster IBR-30.

The real neutron pulse duration Δt depends both on the duration of a fast neutron pulse τ and on the time of fast neutrons moderation to the given energy Δt_3: $\Delta t = (\tau^2 + \Delta t_3)^{1/2}$. For the IREN version with a water moderator the electron pulse duration from the accelerator is chosen to be 200 nsec. Its further reduction is unfavourable as it would lead to a fall in integral neutron yield without essential benefit in real resolution at the neutron energies $E_n \sim 100$ eV (see Table 1).

In the IREN project to the chosen neutron pulse duration of 400 nsec there corresponds the electron pulse duration of 200 nsec and the neutron multiplication coefficient of 15. To preserve the high neutron intensity level of 10^{15} sec^{-1} it is necessary that simultaneously with duration reduction the average power of the electron beam be increased to about 10 kW. This is only possible with the replacement of the LUE-40 by a more powerful electron accelerator. Then the "quality" of the IREN as neutron spectrometer would be two orders of magnitude higher than that of the now operating facility. The most attractive feature of the IREN if compared with the existing complex LUE-40 + IBR-30 is that it suggests the change of plutonium for uranium-235 as fuel material and reduction of the reactor subcriticality down to K = 0.98. This would allow one to refuse from special control and safety facilities as well as from reactivity modulation. As the result the new source must be cheaper and safer in operation.

One cannot choose at random the neutron pulse frequency in the time-of-flight method. On one hand, by increasing the pulse frequency generated by the electron linear accelerator, its average current could be increased to be naturally followed by neutron intensity rise, while on the other hand, this would lead to the appearance (especially on long flight paths) of recycling neutrons, i.e. simultaneously with the registration of the "working" neutrons there becomes essential the role of the background due to slow neutrons from a preceeding pulse. As the result these contradictory requirements made us choose the maximum neutron pulse frequency of 200 Hz in the IREN project.

To summarize, the IREN design parameters are the following:

Energy of accelerated neutrons, not less than	60 MeV
Electron beam power at exit	10 kW
Electron pulse frequency	<200 Hz
Electron pulse width at half maximum height	≤0.3 μsec
Fast neutron pulse width at half maximum height	≤0.4 μsec
Length of accelerator	≤10 m

Specialists from the leading design institutes of St.Petersburg, Kharkov, Novosibirsk and Moscow in cooperation with JINR specialists have been conducting theoretical investigations to choose optimal parameters of the electron accelerator and multiplication target for the IRENin accordance with operational requirements.

Different versions of positioning the accelerator and the target in the buildings available have been considered in sketches and the cost of IREN construction estimated/1-7/. A short summary of the results of this work follows.

4. THE MAIN COMPONENTS OF THE IREN PROJECT

4.1. The Electron Accelerator for the IREN

We have decided in favour of the accelerator version designed at the Institute of Nuclear Physics of the Siberian Branch of the Academy of Sciences of Russia. This is the travelling wave accelerator. Accelerators of this type are widely used at world research centers. Their theoretical and technological aspects are well elaborated. Calculations have shown that optimal are the accelerator parameters summarized in Table 3.

Table 3

Electron energy (at start and end of current pulse), MeV	200-100
Current pulse duration, μsec	0.2
Current in pulse, A	2.2
Pulse frequency, Hz	150
Average electron power, kW	10
Number of sections and their length, m	2x3
Number of SHF generators and their power in pulse, MW	2x60

The minimum electron energy must be above 60 MeV as follows from the condition of effectiveness of neutron production in a phototarget. The neutron yield in dependence on the electron energy per unit beam power is shown in Fig.7. One may see that this dependence is strong up to the energy of 40 MeV, while above 60 MeV it is rather weak. From here it follows that for accelerator operation above 60 MeV practically no limits are imposed on energy spread in the electron beam. So the allowed energy spread is determined only by optimal conditions for electron guidance and focusing on the target. At high average power beam transportation losses are inadmissible. This requirement limits also beam emittance at the exit of the accelerator.

In the IREN project the accelerator length is restricted to 10 m to preserve the advantages of the vertical positioning of the accelerator and use the former LUE-40 building.

To shorten the starting date it is planned to utilize the systems and units that have been showing good performance with the former machine and require no expensive and cumbersome investigations.

As SHF-generators we chose klystrons 5045, the SLAC (Stanford, USA) products, that have build a reputation for themselves in a long-term operation for the linear collider. The parameters of the klystron are specified in Table 4 (together with those of other modern klystrons the products of some other laboratories and firms). The long, up to 40 th. hours, service life is characteristic of klystrons 5045. Moreover, these klystrons are supplied complete with a pulsed transformer, which fact could allow considerable reduction of the volume of work on design and manufacture of the high voltage modulator.

Effective acceleration is achievable with a rather short current pulse and we propose the use of the SLED scheme of SHF power compression. This scheme is worked through at the SLAC and is the optimal one for the given task.

The accelerator (Fig.1) comprises:

- the three-electrode gun with grid operation (initial current up to 10 A, voltage up to 200 kV);
- the buncher of beam with varying structure;
- two accelerating sections with focusing solenoids;
- the magnet-analyser;
- the vacuum electron guide to the target.

Table 5 gives the parameters of the most powerful of currently operating electron accelerators used for experiments in neutron physics.

It is proposed that the accelerator is manufactured at the INP of the Siberian Branch of the RF Academy of Sciences, where design work is now going on the linear electron accelerator-based foreinjector using klystrons 5045 in the framework of the B-factory project. It is thought to take approximately four years to manufacture the accelerator for the IREN at the cost of 14 mln roubles in prices of the 1991 year. After test on a rig the accelerator is to be transported to the working site. Then the interuption time in experimental work depends on the time necessary for the old machine dismantling, building reconstruction, the new accelerator assembly on site and adjustment, which would make about a year. The electric power supply system for the new machine has already been installed. The IREN will be operated by the former machine staff.

Table 4

	KIU-12	KIU-53	XK-5	5045	E 3712	TH 2132
Output power, MW	18	18	36	67	100	45
Frequency SHF, mHz	2797	2797	2856	2856	2856	2998.5
Anode voltage, kV	270	260	265	350	450	314
Klystron current, A	220	230	286	414	604	350
Duration SHF, μsec	2.5	3.3	2.5	3.5	1.0	4.5
Pulse frequency,Hz	50	300	360	180	50	100
State-manufacturer	Russia		USA	USA	Japan	France
Firm	Saratov		Varian		Toshiba	Thomson

Table 5

Accelerator	Current pulse duration, nsec	Average power, kW	Output energy, MeV	Pulsed current, A	Frequency, Hz
GELINA Belgium	0.67-2000	4.6-12	87-120	0.22-100	250-900
LU-50 Arzamas	10	13,2	55	10	2400
ORELA USA	3-10001	6-43	100-140	0.5-15	710-1000
FAKEL Moscow	50	1.5	60	0.5	900
LUE-40 Dubna	1600	2.5	40	0.4	100
IREN accelerator Dubna	200	10	150	2.2	150

4.2. The Multiplication Target for the IREN

Ten versions of the multiplication target for the IREN/4/ have been considered and the choice made for the platish uranium core cooled by air with the uranium-mercury converter having an autonomous system of cooling due to natural convection of mercury. The second version was a compact target with two rotating blocks of highly enriched uranium. In the first case just the possibility of reactivity modulation is foreseen, which if it is necessary, can be easily realized on the facility now used as the stationary booster. In the second case it is vice versa. Here reactivity modulation forms the essence of the project: the reduction of delayed neutrons background down to 2% at the smallest possible neutron lifetime (of about 10 nsec). Preference was given to the first one as being cheaper and simpler in realization.

The third version - a Np-237 core for the IREN booster is now in the stage of preliminary estimates and, therefore, will not be the subject of detail discussion here. The advantage of the use of Np-237 as fission material is in comparatively short lifetime of prompt neutrons (6 nsec) being virtually independent of the presence of neutron slow-down admixtures in the core, at comparatively low critical mass (not more than 130 kg). Availability of practically any amounts of neptunium allows hope that in future this material will appear the most suitable for the production of multiplication targets of high resolution.

The important feature of all the versions is the limited multiplication coefficient (subcriticality is not more than 0.98). This permits one to avoid construction of a complicated and expensive emergency protection system.

The multiplication target will be positioned at the center of a hall 7 m high and $10x10^2$ in area. The center of the core is at 2.2 m above the concrete floor level. Eight horizontal neutron vacuum guides with flight paths ranging from 12 to 1000 m penetrate the 2 m thick concrete walls of the hall.

The target-converter is a hexahedral assembly with a "Turn-Key" dimension of 60 mm filled with uranium-molybdenum (OM9 alloy) fuel elements and mercury as a cooling and, partially, conversion medium. The lower end of the converter

is closed. Mercury flows are in countercurrent: downwards along the side and upwards along the central part of the converter volume. The mercury flows are separated with a hexahedral partition plate with the "Turn-Key" dimension of 31.4 mm. Confined within the partition are, in the lower part, 7 shortened fuel elements (15 cm long) in tantalum claddings and, above the central cross section of the core, a vacuum electron guide. The upper ends of these shortened elements are 11 mm thick pellets of natural uranium. The conversion medium is then a 6 mm thick mercury layer (18% conversion and 40% heat release in the beam), an 11 mm thick layer of natural uranium (50% conversion and 40% heat release) and a 14 cm thick layer of OM9 alloy (32% conversion at 20% heat release).

Another converter version is possible with shortened fuel elements just natural uranium rods. In this case the number of elements could be reduced to one. The volume between the partition and the outer hexahedral shell is filled with 12 fuel elements, identical to those in the core, placed in the downwards mercury flow.

At a distance of 1,000 mm from the vacuum electron guide bottom the converter has a pocket with water inlet and outlet tubes. This is to remove heat from mercury. By cooling the outer layer of mercury convection is stimulated in the converter.

The core (Fig.8) is composed of 12 uranium-molybdenum fuel element subassemblies (FES) with "Turn-Key" dimensions of 60 mm each cooled with forced air flow. The thirteenth FES of the same outer dimension is the accelerator target - the electron-neutron converter. It is installed in the center of the core and has its own independent mercury cooling system.

This platish shape of the core is chosen with the aim to increase efficiency of the moving reflector of neutrons and neutron leakage in the direction of the beam. The length and width of an equiarea to core rectangle is 261.7 mm and 156.9 mm, respectively. The height of the core is 28 cm. The total

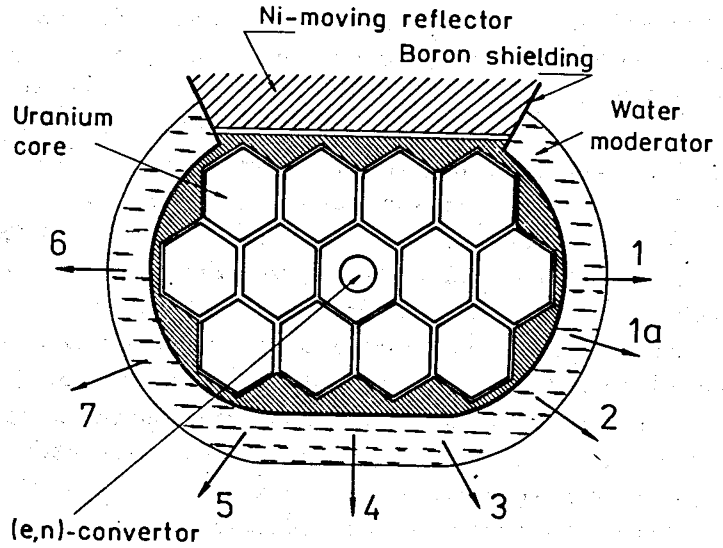


Fig. 8. The IREN multiplication target and the scheme of neutron beams arrangement.

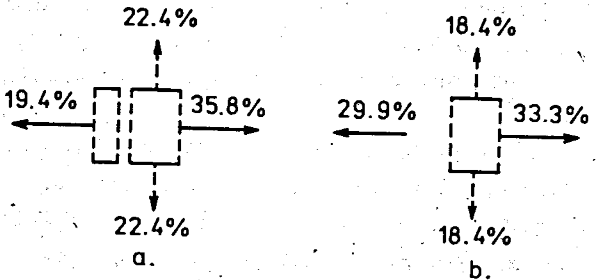


Fig. 9. Fast neutron leakage distribution in four directions with (a) and without (b) nickel reflector.

volume occupied by thirteen FES including interassembly space is 11.5 liters. The material of the core jacket and of fillers separating it from FES is steel EI-847. The thickness of the steel jacket is 18.7 mm and it is equivalent to the volume of materials in the core: fuel - 60.31%; steel - 17.42%.

The moderator has three independent sections (a front section and two side ones) in aluminium (the AM-3 type alloy) containers separated from the core with a 1 cm thick layer of tungsten boride enriched to 75% with ^{10}B. The absorbing layer is in a 0.75 mm thick aluminium envelope. The moderator shape follows in general the shape of the jacket (Fig.8 illustrates the case when the sections have the same thickness).

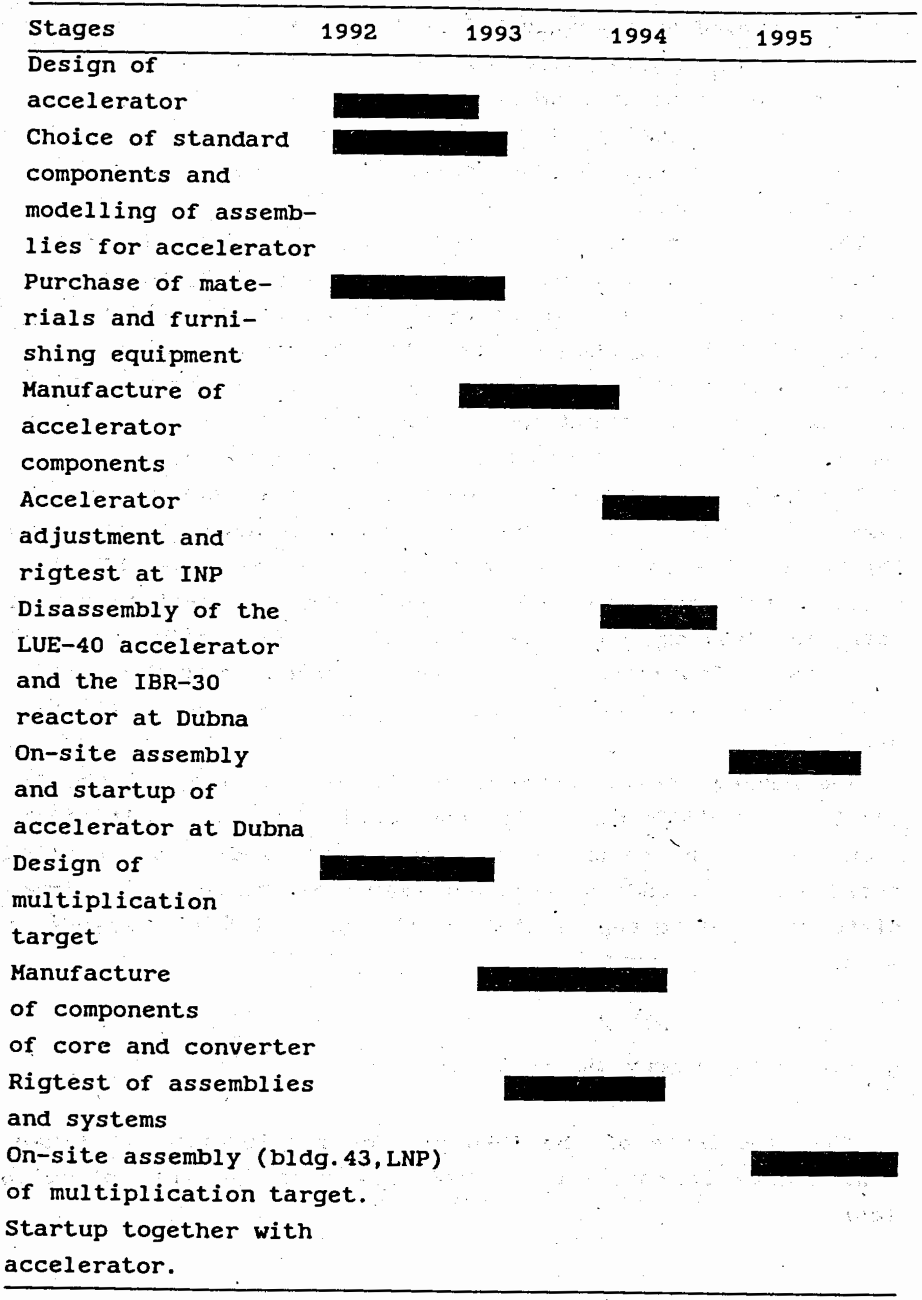
The height of the water layer in all the sections is the same and equal to 38 cm. When the sections have all the same thickness of 3 cm and they are at the nearest possible distance to the core, the moderator surface area "seen" by beam 4 measures 38x39 cm^2 and by beams 1 and 2 - 38x25 cm^2.

The water moderators jacket is suspended on moving bars that allow moderators' displacement in the vertical direction.

The moving reflector made of the nickel alloy of the EI-437 type and dedicated to fit the required neutron multiplication coefficient in the stationary booster mode is installed between the two ends of the hoof-shaped moderator in the immediate vicinity to the active core shell with a clearance of 2 mm.

5. PROJECT SCHEDULE AND COST ESTIMATE

The time-table of the IREN project realization, if financing starts in March-April 1992, are given in the following Table.



This schedule can vary in dependence on supply dates of materials and equipment.

The cost of the Project IREN is estimated in follars USA in view of rouble inflation. The rate of exchange is taken 55 roubles per 1 dollar USA.

The cost of the electron accelerator is the purchase cost of 3 klystrons 5045, which is about \$ 0.600 mln added by the manufacture cost and the cost of materials of 94×10^3 norm.hr to be equal to ≈ \$ 0.4 mln at a salary of \$ 300 and to ≈ 4.7 mln at the norm.hr of \$ 50 in USA.

The cost of the multiplication target is \$ 4×10^4 (or 2.2×10^6 roubles). It can be manufactured at LNP with only FES purchased.

Construction cost. Maximum estimate is \$ 2×10^4 (or 1×10^6 roubles), including the cost of the control unit removal to the building where the accelerator and the target will be installed.

Operation cost. The main part of it is power, heat and water supply expenditures. For 2500 hr operation time per year they will amount to \$ 2×10^4 (or 1×10^6roubles) taking into account the price rise of 1 April 1992.

APPENDIX 1

1. CALCULATED PARAMETERS
OF NEUTRON FLUXES FROM THE IREN

The neutron-physical characteristics of the IREN were calculated by the Monte-Carlo method using the MCU program/8/ in real geometry. Estimates of K were made with a reserve of 2% in view of changes in converter's design as well as of calculation and technological errors.

We use Fig.8 to illustrate the calculated characteristics of the multiplication target for the IREN. Calculated are: the multiplication coefficient, the average lifetime of prompt neutrons generation, the scalar and vector fluxes of neutron leakage, the fission density distribution, the FES effectiveness and some other characteristics.

The multiplication coefficient, the average lifetime of prompt neutron generation and leakage probability.

Number of neutron generations: $N = 853800$

Multiplication coefficient: $K = 1.0055 \pm 0.0012$

Average lifetime of prompt neutrons "from fission to fission":

$$\tau = 20.61 \div 0.04 \text{ nsec}$$

Probability of neutron leakage through interface with vacuum:

$$\eta = 0.441.$$

In Table 7 there are given group fluxes of leakage neutrons from the thicker side of the moderator. The

Table 7

Leakage from the front surface of the 3 cm thick moderator (Beam 4). The working area is 38x38.5 cm

Group number	Neutron energy, eV	Scalar flux in group	Vector (cos(x)=1) flux	Number of neutrons in group
1	1.05E+07	1.034E-03	3.06024E-04	641.
2	6.50E+06	4.808E-03	1.36330E-03	2894.
3	4.00E+06	9.726E-03	2.93906E-03	5832.
4	2.50E+06	1.797E-02	5.00074E-03	10715.
5	1.40E+06	1.820E-02	4.73992E-03	10405.
6	8.00E+05	2.106E-02	5.28483E-03	11773.
7	4.00E+05	1.572E-02	3.59052E-03	8273.
8	2.00E+05	1.084E-02	2.42421E-03	5682.
9	1.00E+05	8.881E-03	1.85158E-03	4491.
10	4.65E+04	7.012E-03	1.39231E-03	3449.
11	2.15E+04	5.418E-03	1.13984E-03	2745.
12	1.00E+04	4.929E-03	9.59726E-04	2349.
13	4.65E+03	4.470E-03	8.92964E-04	2212.
14	2.15E+03	3.820E-03	7.89953E-04	1929.
15	1.00E+03	3.576E-03	6.95664E-04	1752.
16	4.65E+02	3.502E-03	6.68507E-04	1681.
17	2.15E+02	2.911E-03	5.72429E-04	1428.
18	1.00E+02	2.775E-03	5.39590E-04	1356.
19	4.65E+01	2.556E-03	4.77178E-04	1211.
20	2.15E+01	2.339E-03	4.08162E-04	1056.
21	1.00E+01	2.069E-03	4.20106E-04	1028.
22	4.65E+00	1.864E-03	3.71174E-04	924.
23	2.15E+00	1.742E-03	3.11504E-04	814.
24	1.00E+00	1.592E-03	2.99200E-04	765.
25	4.65E-01	1.211E-03	2.57587E-04	627.
26	2.15E-01	1.078E-02	2.07539E-03	5222.
Total neutron leakage				91254.

direction cos(x) = 1 corresponds to the direction to "the target" of beam 4. The neutron energy is indicated only for the upper limit of the group interval. The vector fluxes are calculated in the P_2 approximation.

The group fluxes of leakage neutrons are given in units:

- scalar flux: (n/sec)/(fission n/sec);
- vector flux (n/sec st.)/(fission n/sec).

Leakage neutrons redistribution at the introduction of a nickel reflector

To find out how much the neutron leakage in the beam direction will increase with the introduction of a nickel reflector calculations were made of the leakage along four horizontal directions with the nickel reflector in and out in the absence of the water moderator and boron shield. The results are illustrated in Fig.9. The comparison of Fig.9a and Fig.9b shows that the introduction of the nickel reflector causes increase in neutron leakage from the thinner sides of the core (in the direction of beams 1 and 6). Its influence on the leakage from the thicker side of the moderator (in the direction of beam 4) is negligible.

Vector fluxes of leakage neutrons calculated per lethargy unit interval are approximated by the following dependences:

$$\Phi_4(M = 1,u) = 2.24\times10^{-3}\nu P \cdot e^{-u/8}, \qquad (1a)$$

$$\Phi_6(M = 1,u) = 1.59\times10^{-3}\nu P \cdot e^{-u/7}, \qquad (2a)$$

where Φ_4 is the vector flux (n/sec.st.unit lethargy) from the front surface of the 3 cm thick water moderator (in the direction of beam 4), Φ_6 is, correspondingly, the vector flux of leakage neutrons from the side surface of the moderator (in the direction of beams 6 and 1); P is the power (fission/sec), ν is the number of secondary fission neutrons, u = *ln* (1.4 MeV/E) is the lethargy.

Formulas (1a-2a) hold at 0.5 eV<E<25 keV. The number of fission neutrons born in a second is

$$\nu \cdot P = f_{en} \cdot P_e \cdot RVP \cdot \frac{\langle K\rangle}{\langle K-1\rangle}, \qquad (3a)$$

where f_{en} is the conversion coefficient (equal to 0.9 n/GeV for the natural uranium electron target), P_e = 10 kW is the power of electron beam, RVP = 1.75 is the relative value of photoneutron,

$$(\langle K\rangle/\langle 1-K\rangle) = ((1/\varepsilon)/(1-B)) \qquad (4a)$$

is the total multiplication of neutrons from the source, with $1/\varepsilon$ being the multiplication of prompt neutrons and B the background due to delayed neutrons.

In the reactivity modulation mode <K> and B are the averaged over pulse duration values, ε the prompt neutron subcriticality at k-values achieved in the moment of neutron pulse.

Difference in values of the absorption coefficients (1/8 and 1/7) in formulas (1a) and (2a) seems to be due to inexactness of the P_2 approximation.

As it follows from exps. (1a) and (2a) the moderated neutrons leakage from the side surfaces of the moderator is about a factor of 1.5 weaker than from the front surface of the moderator. To calculate the neutron flux density on the sample one must divide flux by square length of the corresponding flight path (L).

Table 8 gives the values of fluxes (1a) and (2a) (in the energy representation) and the corresponding to them values of flux density on sample for the two values of the neutron multiplication $1/\varepsilon$: 36.5 (reactivity modulation mode, background = 11.8%) and 14.3 (stationary booster mode, background = 10%). Electron energy E is in eV (0.5 eV < E < < 25 keV). The thickness of the water moderator is 3 cm.

Table 8

The integral vector flux of neutron leakage from the moderator and the sample flux density for beams 1,4,6 at 36.5 multiplication (reactivity modulation mode) and at 14.3 multiplication (stationary booster mode) for the energies 0.5 eV < E < 25000 eV

Beam No.	T (m)	Vector flux Φ(E,1) (10^{12}n/sec st.eV)		Sample flux density Φ/L^2 (neutr/cm^{2}s eV)	
		$1/\varepsilon=36.5$	$1/\varepsilon=14.3$	$1/\varepsilon=36.5$	$1/\varepsilon=14.3$
1	100	$0.86\ E^{-6/7}$	$0.33\ E^{-6/7}$	$8600\ E^{-6/7}$	$3300\ E^{-6/7}$
4	50	$1.56\ E^{-7/8}$	$0.60\ E^{-7/8}$	$62000\ E^{-7/8}$	$24000\ E^{-7/8}$
6	1000	$0.86\ E^{-6/7}$	$0.33\ E^{-6/7}$	$86\ E^{-6/7}$	$33\ E^{-6/7}$

The vector fluxes in the direction of the other beams have intermediate between Φ_6 and Φ_4 values.

The scalar density of thermal neutron flux (E<0.215 eV) on the front surface of the moderator is estimated to have the average value of 6×10^8 n/cm^2·sec per 1 kW neutron power (i.e. it is equal to 3×10^{10} n/cm^2·sec at the power of 50 kW). The maximum flux density is about 10^9 n/cm^2·sec·kW). The maximum and average thermal neutron flux density on the side surface of the moderator are, respectively, 2.9×10^8 and 2.2×10^8n/cm^2·sec·kW. The estimates are given for the moderator with the thickness of 3 cm.

THE CONVERTER.
THERMAL AND HYDRAULIC CHARACTERISTICS

The thermohydraulic characteristics of the uranium-mercury converter are estimated by the formula for the total hydraulic resistance of a loop with natural circulation of the cooler:

$$\Delta p = \beta\rho \cdot \oint T(l)\vec{q}\, d\vec{l} = \beta\rho\ q \cdot \Delta h \cdot \Delta T, \qquad (5a)$$

where $\beta = (-1/\rho)\cdot(d\rho/dT)$ is the coefficient of volumetric expansion: $q = 9.81$ m/sec^2; $T(l)$ is the temperature distribution along the loop length; ρ the density, Δh the height difference between the converter and the outer heat exchanger (the effective value).

The cooler in the converter is heated by

$$\Delta T = P_1/c_pG. \qquad (6a)$$

where P_1 is the power release in the converter, G the consumption mass of the cooler, c_p its specific heat.

At the total fission of 50 kW and the electron flux power of 10 kW the converter power P_1 = 14.5 kW.

The dependence of the total resistence on the consumption in the form:

$$\Delta P = A(n)\cdot G^{2-n} \qquad (7a)$$

closes this system of equations.

The cooler consumption at established circulation is

$$G = [\rho q \cdot \Delta h \frac{\beta P_1}{c_p \cdot A(n)}]^{1/(3-n)} \qquad (8a)$$

The heating of the cooler and the loop resistance are found directly by formulas (6a) and (7a). The coefficient A in (7a) is

$$A(1/4) = 987\ (\text{kg/sec})^{-0.75}/(\text{M}\cdot\text{C}).$$

The total height of the mercury column in the converter is 1600 mm. The water-mercury heat exchanger 300 mm high is positioned in the upper part of the converter and so the height difference between it and the converter is 1.3 m.

On the basis of these estimates the characteristics of the converter exploiting the principle of counterlow were accepted to be:

Mercury consumption rate	5500 kg/hr
Mercury heating	70°C
Circulation loop resistance	0.02 atm
Mercury volume	3.0 *l*

For the beam power of 10 kW and the electron energy of 150 MeV the average values of calculated from the data of refs./11-14/ power release from:

Vacuum bottom (1.5 mm thickness aluminium layer)	23 W
6 mm mercury layer	3710 W
1 mm natural uranium layer	4080 W
140 mm OM9 alloy layer	2180 W

For the electron spot radius of 1 cm and the mercury circulation rate of 30 cm/sec the maximum value for the temperature of:

Vacuum bottom	108°C
Mercury	100°C
Natural uranium	800°C

Temperature differential over thickness of the aliminium bottom is 0.2°C. The maximum temperature in the natural uranium layer is achieved at 4.3 mm from the top of the pellet. The temperature at the top of the pellet is 230°C. The inlet mercury temperature is 30°C in the converter and 52°C in the conversion zone. It is assumed that the whole upward mercury flow (5500 kg/hr consumption rate) gets focused in the region of the electron spot.

The OM9 alloy temperature is maximum at the top end of the shortened rod and does not exceed the value of 240°C.

According to estimates/4/ the conversion coefficient of the three-layer uranium-mercury target (the third layer is the OM9 alloy) is about 0.8 n/GeV at the electron energy of 150 MeV.

If OM9 alloy is substituted by natural uranium, the conversion coefficient drops to 0.7 n/GeV. With mercury the only conversion medium this coefficient equals 0.34 n/GeV. For the converter with seven shortened FES's the first two values will appear overestimated, if the beam radius is larger than the radius of FES. Then the change of the set of seven thin FES with OM9 alloy for one thick natural uranium one may appear advantageous both from the point of view of a simpler design and better conversion.

Thermal shock in the conversion zone and in the core is negligibly small: 2 kg sec/cm^2 in the bottom layer and 70 kg sec/cm^2 in the uranium pellet at the frequency of 200 Hz (allowed stress is by about 3 and, respectively, 2 orders of magnitude higher).

The minimum allowed velocity for mercury in the conversion zone, below which local boiling starts (followed by condensation as the result of liquid stirring; stirring average heating is assumed not to lead to boiling), is 17 cm/sec for the electron spot area of 1 cm^2. To increase the mercury velocity in the conversion zone it is thought sensible to use a tantalum diaphragm to focuse the upward liquid flow on the area of maximum heat release.

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Аксенов В.Л. и др. E3-92-110
Предложения по созданию нового
интенсивного источника резонансных нейтронов (ИРЕН)

Дано физическое обоснование и техническое описание проекта нового источника резонансных нейтронов (ИРЕН), сооружение которого предполагается в ЛНФ ОИЯИ. Представлена программа физических исследований на установке ИРЕН, проанализирована ее конкурентоспособность и показано, что она может быть привлекательной для пользователей из стран-участниц и неучастниц ОИЯИ.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1992

Aksenov V.L. et al. E3-92-110
Proposal for the Construction
of the New Intense Resonance Neutron Source (IREN)

This is the technical proposal, including the physical foundation and provisional parameters, for the new intense resonance neutron source (IREN) planned to be constructed at LNP, JINR. The research programme on the IREN is discussed. The comparative analysis of the parameters of the IREN and the best now operating pulsed neutron sources shows that the IREN could appear attractive to the wide users community of Europe and Asia.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1992