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To the memory of A.M.Budker

Neutron facilities of Moscow meson and kaon factories.

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The questions of new generation of intensive pulse neutron sources for elementary interaction physics, neutron nuclear physics, solid state and radiation physics, on the base of Moscow meson and projected kaon factories are discussed.

The neutron studies allow to obtain a unique information on fundamental questions of elementary interaction physics, on the properties and the mechanism of nuclear reactions, on the structure and the properties of the condensed matter.

The studies in neutron low energy range (cold, thermal and resonance neutrons) are of special interest.

The neutron studies development is strongly related to new neutron sources, which can allow to increase the neutron experiments luminosity.

Up till now the main volume of neutron studies were carried out on high-flux research reactors. Due to some reasons (limitation of the fuel heat release density, overloads, safety problems) the possibility for increasing neutron flux in such reactors is limited. The flux density $2\text{-}3\cdot10^{15}$ $n/s\cdot cm^2$ on the moderator surface, "radiating" into the neutron channel of a high-flux research reactor of ~ 100 MW power (for example, ILL-reactor, Grenoble, or "PIK" reactor, being constructed at LNPI, Gatchina) is close to its top limit.

Because of these circumstances, in the 60's, the suggestion was made at Canada, Chalk River, to use the spallation process with 1 GeV protons to obtain slow neutrons fluxes. The "Canadian design" is well known - a neutron source on the base of 65 mA, 1 GeV separated-orbits cyclotrons with the liquid-metal target (Pb-Bi eutectics) and the heavy-water moderator /1/.

The calculated neutron flux density value was about 10^{16} $n/s\cdot cm^2$ in this system. The calculated neutron flux density value for the system with a circular tungsten water-cooled target and the beryllium moderator (Obninsk, 1970, /2/) reached the value of about $1.5\cdot10^{17}$ $n/s\cdot cm^2$, the current of 1 Gev protons being 100 mA. However, the development of medium-energy proton accelerators for the currents about hundreds of milliampers, encounters great difficulties (energetics, exploitation, capital investments);

therefore the only neutron source SINQ /3/, based on this scheme is currently constructed in Paul Sherer Institute (PSI, Schwitzerland) with 1.5 mA current of 600 MeV protons and, accordingly, with thermal neutron flux density of $1.5\text{-}2\cdot10^{14}$ n/cm^2·s.

The wide application of time-of-flight technique in neutron experiments opened the way for the development of intensive pulse neutron sources on the base of electron accelerators and pulse fast reactors /4/. However, the average neutron intensity from electron accelerators is relatively low. The development of pulse reactors didn't allow the sufficient increase in neutron experiments luminosity - the powerful pulse reactor "IBR-2" is close to high-flux research reactor (ILL-"PIK" /6/) by its experimental abilities.

New possibilities for neutron studies development are opened while using medium- and high-energy proton accelerators for pulse neutron sources creation. The use of charge-exchange injection in proton sinchrotrons and storage rings proposed firstly by L.Alvarez /7/ and implemented by A.M.Budker with co-workers /8/ is of principal importance in this case.

In the beginning of 60's in the Institute of Nuclear Physics, Novosibirsk and Physical-Energical Institute, Obninsk the pulse neutron source on the base of 0.5 GeV fast-cycling proton synchrotron with single-turn ejection onto the natural uranium target was worked out /9/. Currently, a number of facilities are operating on this scheme basis. These are: IPNS, Argonne laboratory; KENS, Institute of High-energy physics, Tsucuba, Japan; ISIS, Rutherford laboratory. In another scheme the proton storage ring with the single-turn ejection is used to compress linear accelerators macropulsis to short proton bursts on the neutron target /10/. This scheme is used in the following facilities: LANSCE, Los-Alamos; MMF-0,6, INR USSR Ac. of Sc. (in construction); SNQ, Julich (project); KENS-II, KEK, Tsucuba (project). High-energy protons from high-current synchrotrons of tens GeV - kaon factories being projected in a number of laboratories (Los Alamos, KEK, TRIUMF, INR Ac. of Sc. USSR), are of special interest. Some time ago R.R.Vilson suggested to use the spallation process based on high-energy protons for electro-nuclear breeding - the nuclear fuel production on the accelerators /12/. However, the energy losses, associated with the electron-photon showers in the target matter, initiated by π^0-mesons, cause 1.5-2 times decrease in nuclear fuel yield for proton energy unit, compared with 1.5 GeV protons. Therefore the high-energy protons use for electrobreeding looks rather doubtful. This circumstance is not so important for creating intensive pulse neutron sources /13/.

The neutron source facility of INR meson factory (Figs. 1, 2) /14/ involves the pulse neutron source for the beam time-of-flight experiments, time-moderation lead spectrometer, the quasi-stationary source of thermal and cold neutrons for the studies with time selection of fast neutrons background, the proton beam dump with channels, which allow one to carry out radiation studies and to produce radionuclides in proton and neutron fluxes.

The pulse neutron source includes the array of uranium rods, covered with stainless steel and cooled by water (Fig.3). For full proton current (500 μA), the heat release in the target reaches about 1 MW. During the first research stage it is planned to use metal tungsten, formed as an array of plates. The target is adjoined by water and liquid-hydrogen moderators, "radiating" into the biological shield channels. The possibility to use the multiplicating target made of U-235 with the limited multiplication (up to about 20) for thermal and cold neutron studies is under investigation /15/. The channels of 200 mm diameter allow one to set collimators, providing the required experiment geometry. The channels come through the vertical wells on the distance of about 4.5 m from the target; wells are intended for the experimental equipment. The channels are equipped by the guillotine-type gates. The external neutron channels going through the neutron experimental hall, provide the flight path up to 500 m long.

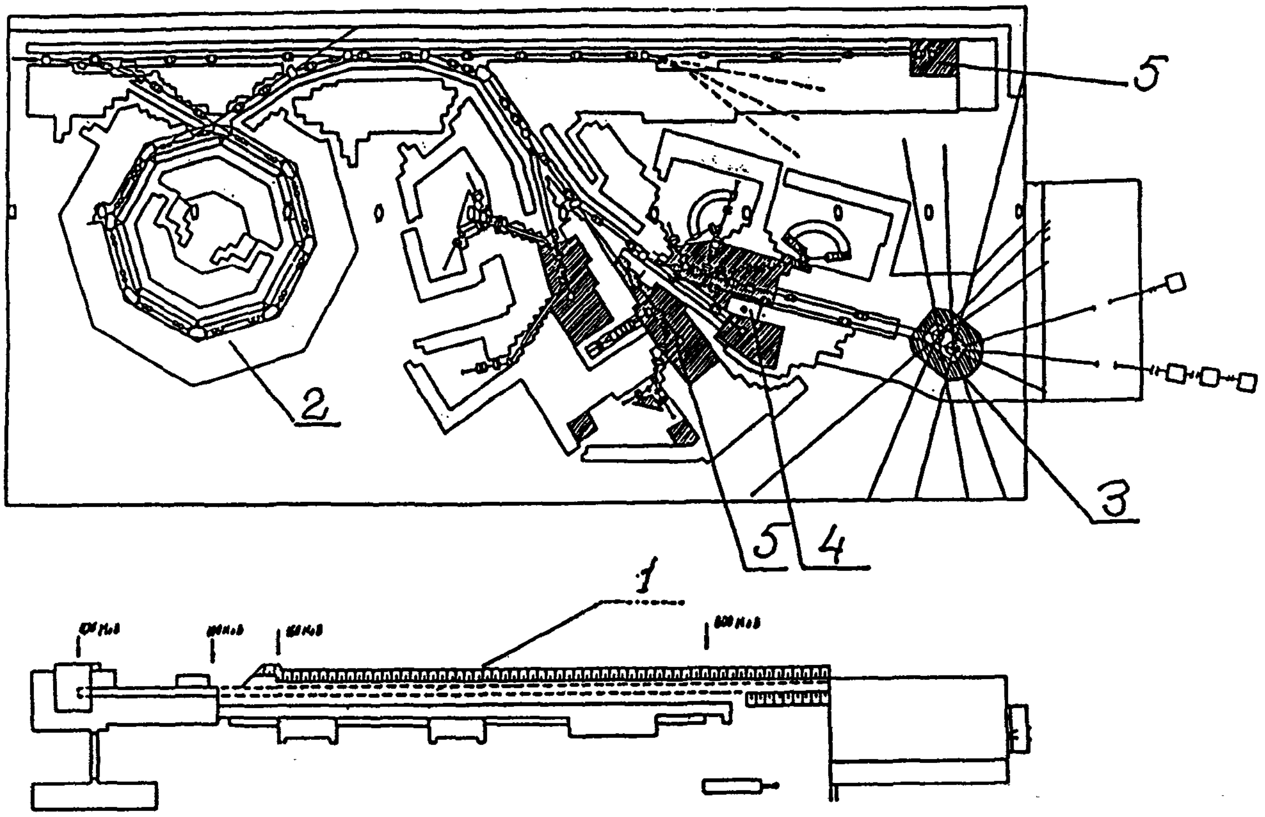

Fig. 1. Linear proton accelerator and experimental area of the Moscow meson factory. 1. Linear proton accelerator. 2. Proton storage ring. 3. Pulse and quasistationary neutron sources. 4. Time-moderation neutron lead spectrometer. 5. Proton beam dumps.

The proton current time structure in the accelerator is a sequence of 100 μs pulses following with the repetition rate 100 pps. To decrease the neutron pulse width up to 0.5-30 μs the beam interruption system after the ion source is used (with the corresponding intensity loss), or the proton storage ring with the charge-exchange injection of H^- ions and the single-turn proton ejection onto the pulse neutron source target /16/. The storage ring allows one to form proton and, correspondingly, neutron pulses about 300 ns long almost without any intensity losses, and more short pulses with the according intensity loss.

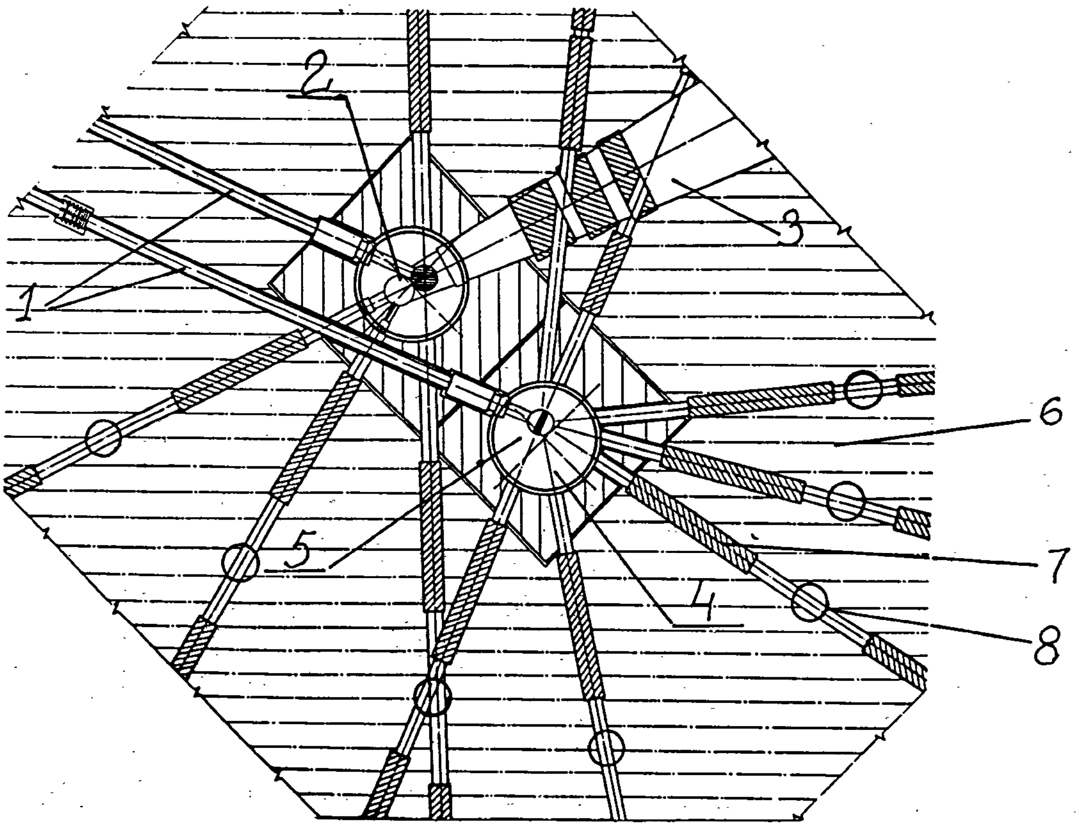

Fig. 2. Central part of the neutron facility.
1. Proton beams. 2. Heavy-water moderator with liquid-deuterium vessel. 3. Channel of n – $\tilde{n}$ experiment. 4. Vacuum vessel of the pulse neutron source. 5. Heat shield. 6. Biological shield. 7. Horizontal channels with gates. 8. Vertical wells.

The pulse neutron source allows one to develop a wide range of studies on nuclear reactions properties /11/. Particularly, the studies on the space parity violation problem in neutron reactions in the separated resonances with the help of wide-aperture neutron polarizer are planned. The high neutron source intensity will allow one to study the partial processes in the separated resonances and to obtain such phenomena detalization, which has been possible up to now only in thermal neutron experiments or in total cross-section measurement (gamma-ray spectra of neutron capture, the fission process studies, including the oriented nuclei targets and polarized neutrons, the studies on n,p- and n,α- reactions in the separated resonances of known nature etc.).

The interesting possibilities are opened by using time-moderating lead spectrometer /17/, based on grouped proton beam, which allow one to study some "low-background" processes (fission, n,p- and n,α-reactions, for example) at high intensity. For example, heavy nuclei fission cross-section measurements could be carried out on 10^{-11} to 10^{-12} gram samples.

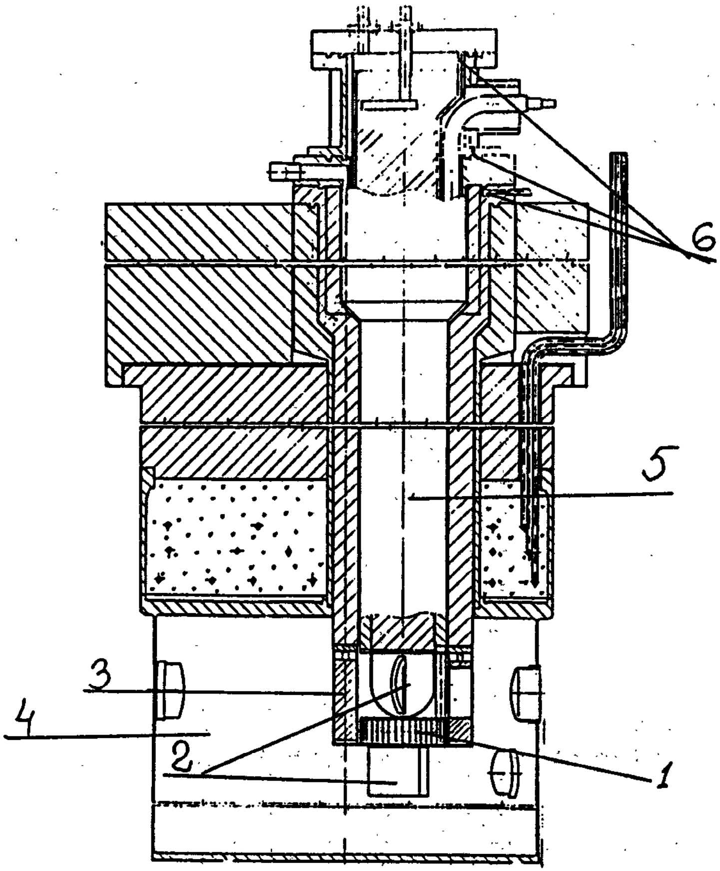

Fig. 3. Pulse neutron source.
1.Neutron target. 2. Moderators. 3. Moderator's reflector. 4. Vacuum vessel. 5. Shielding plug. 6. Vacuum seal.

The pulse neutron source will allow one to expand sufficiently a potential of experimental studies on solid state physics. The high pulse and average densities of thermal and cold neutrons allow one to perform experiments with luminosity considerably exceeding that of stationary and pulse reactors. The measurements of dispersion relationships for elastic coherent thermal neutron scattering with the help of time-of-flight spectrometer with the inverse geometry were considered as an example. The calculations showed /18/ the total luminosity to be several tens times higher, than that for three-crystal spectrometer on high-flux research reactor ILL (Grenoble).

Short neutron pulses in the electron-volt region will open unique possibilities for the high-energy phonon and electron excitation spectroscopy.

The quasi-stationary source of thermal and cold neutrons includes the water-cooled target in the form of assembly of natural-uranium or lead rods, covered with stainless steel surrounded by heavy water moderator of about 1.6 m diameter. The liquid deuterium moderator allows one to obtain a cold neutron flux of 10^{16} n/s in the wide-apperture channel. If the liquid-deuterium moderator is removed the through channel is formed in the heavy-water. Small intensity between pulses from delayed neutrons (about 2% for uranium target and 0.2% for the tungsten one), the time selection of events, caused by epithermal neutrons, opens way for such fundamental experiments as the search for neutron - antineutron oscillations, predicted in some versions of the Grand Unification theory /19/, and with the through channel application - the experiment on direct measurement of neutron - neutron scattering length /20/, which is of fundamental interest of examination of isotopic invariancy of the nucleon-nucleon interaction.

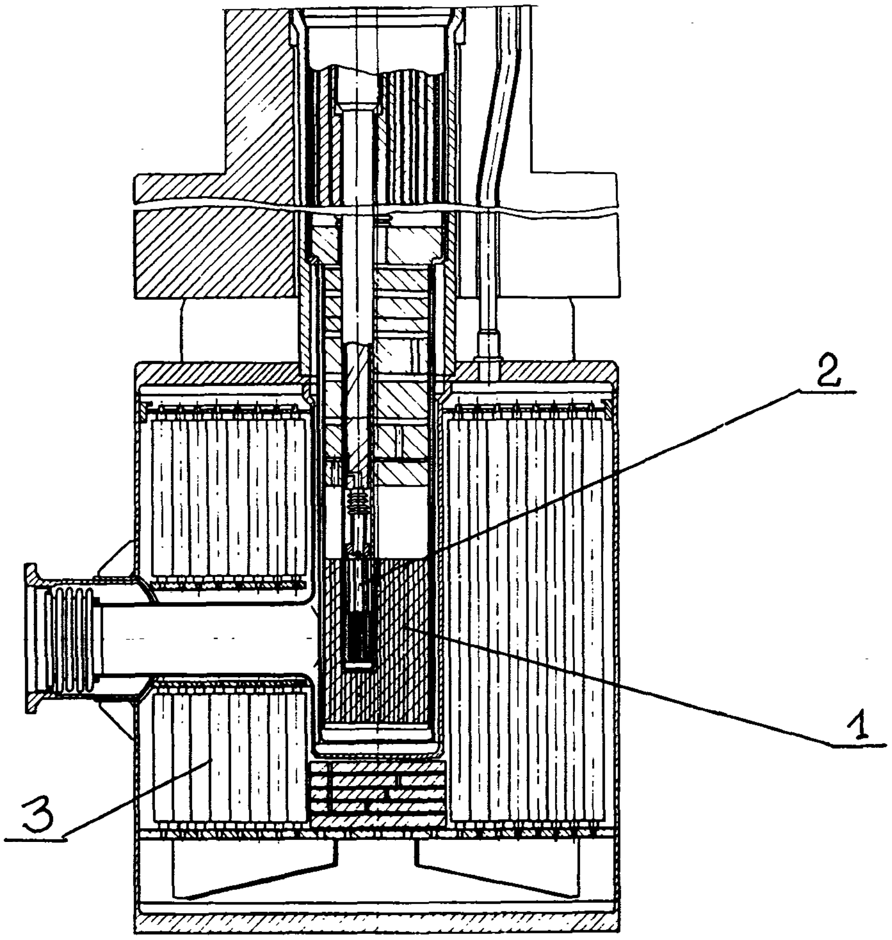

Fig. 4. Proton beam dump. 1. Tungsten plate assembly. 2. Vertical channel. 3. Iron-water heat shield.

Proton beam-dumps are positioned in proton beams, which go through the meson targets, cooled by water, and have a vertical channel, allowing samples for radiation physics studies to be inserted. The high fluxes of fast neutrons and protons, being inside the beam dump, open a unique possibility for studies of the behavior of construction materials of atomic reactors and thermo-nuclear fusion devices. The calculations showed that the density of fast neutrons flux inside the tungsten beam-dump is about $4 \cdot 10^{14}$ $n/s \cdot cm^2$ per 1 mA current /21/. Ratio of atomic displacements number to (n,α) reactions number is approximately the same as for neutron spectrum on the 1st wall of thermonuclear fusion facilities (Figs. 5, 6, 7).

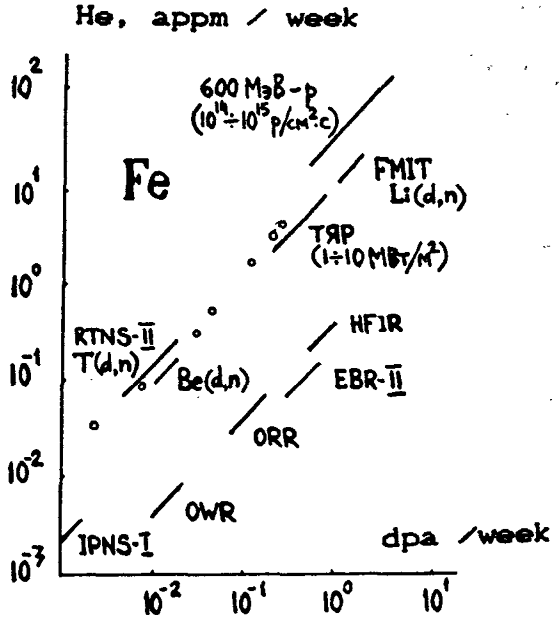

Fig. 5.

The kaon factory on the base of high-current 45 GeV - proton synchrotron with 7.5 GeV booster that is under design in INR AS USSR /22/, /23/ will use the proton linac of the Moscow meson factory as an injector. As the evaluation shows the one-turn ejection of protons from the synchrotron onto the neutron target gives the possibility to create the pulse neutron source with the average neutron intensity nearly the same as for the 15 MW reactor and with the peak thermal neutrons flux density about of 10^{18} $n/cm^2 \cdot s$. Spallation neutrons pulse duration depends on the revolution time of protons in the synchrotron and will be 1.3 μs for the beam extraction from the booster and 4.4 μs - from the main ring. Thus the pulse neutron source based on the kaon factory is of great interest for research with cold, thermal and epithermal neutrons (up to several eV, mostly for solid state physics). This neutron source, if constructed, will be used for the solid state physics research, while the neutron source with short pulses based on the Moscow meson factory (MMF-0,6) will be used mostly for research in nuclear physics.

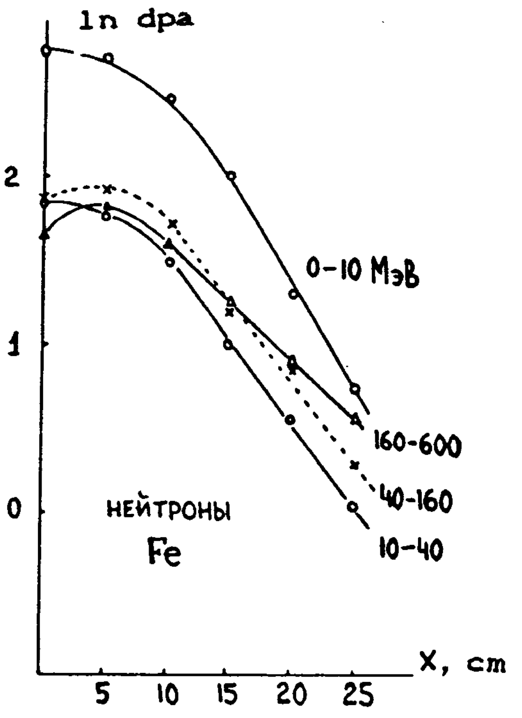

Fig. 6. Relative contribution of various energy groups neutrons to the iron damage.

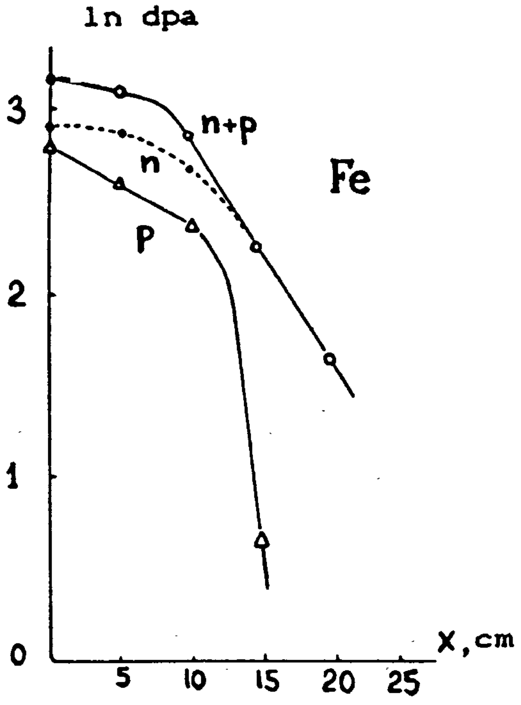

Fig. 7. Relative contribution of neutrons and protons to the iron damage.

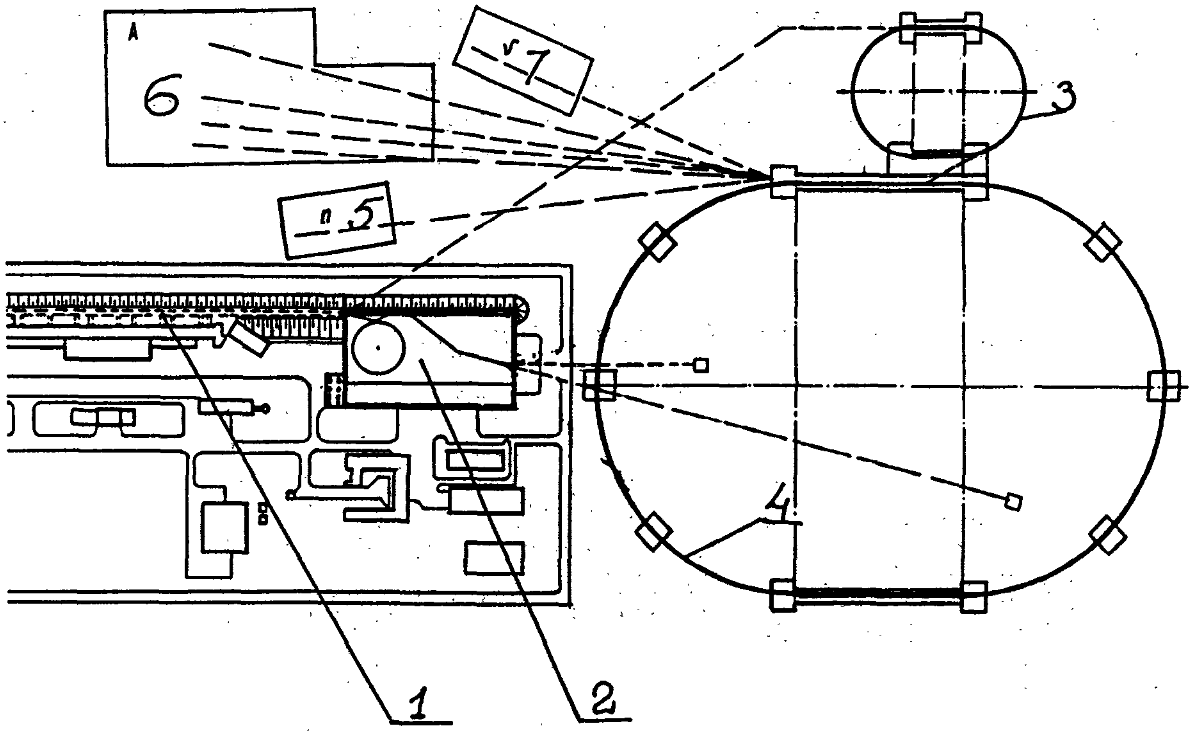

Fig.8. Scheme of the Kaon factory INR USSR Academy of Sciences.
1. Linear proton accelerator. 2. Meson factory experimental area. 3. 7.5 GeV booster. 4. 45 GeV main ring. 5. Neutron source experimental area. 6. Hadron experimental area. 7. Neutrino experimental area.

Since there were no experimental data on the neutron yield in heavy targets for proton energy greater than 7 GeV, the data on the energy balance in ionization calorimeters obtained in cosmic rays experiments /13,24/ were used for primary evaluation of spallation neutrons yield. Hadron cascade computations carried out by Monte-Carlo program SHIELD /25/ later gave similar results.

The results, obtained in the recent experiment carried out on the 70 GeV proton beam of the accelerator in IPHE (Serpuchow) /27/, are in good agreement with previous computational evaluations.

The scheme of the experimental hall of the pulse neutron source is presented in Fig. 9. The neutron source /26/ is surrounded by radiation shield consisting of iron and heavy concrete. The shield thickness in lateral direction is determined by cascade neutrons and in forward direction - by muons. The neutron target represents the compact assembly of tungsten rods cooled by water and has dimensions 40*40*16 cm^3. The target is placed inside the vertical ampoule and adjoined by liquid hydrogen and water moderators. The beam dump provided with the inner vertical and outer through horizontal channels used for experiments in inner thermal neutron fluxes (Fig. 10) is located behind the target, in the analogous ampoule. The target and beam dump are surrounded by the reflector (made of iron-nickel alloy or beryllium). If the 45 GeV proton beam with the current 125 μA and dispersion 6.7*1.3 cm^2 (90% of protons hits the target) is directed onto the target, average heat release in the target will be 2.5 MW, average temperature in the center of tungsten rod ≈ 150°C, maximum heating up of tungsten ≈ 60°C per pulse at 8.3 pps.

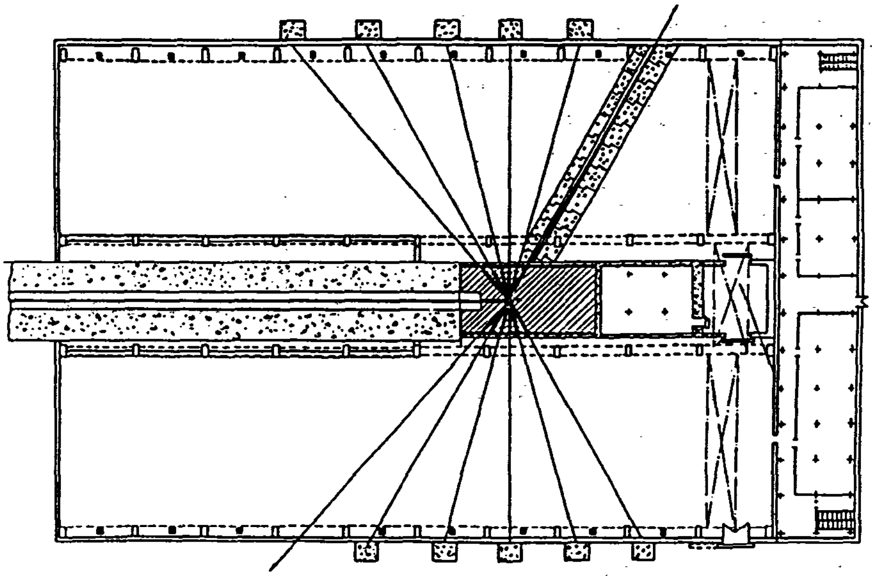

Fig. 9. Experimental area of SIN - 45.

The results of computations of hadron cascade in the target and reflector carried out by the Monte-Carlo program SHIELD for 25 GeV protons were linearly extrapolated to 45 GeV taking experimental data /27/ into account. Neutron transport calculation for energies below 10.5 MeV was carried out using the neutron data system BNAB - 64 /28/. At 8.3 pps the peak neutron flux density is about $7 \cdot 10^{17}$ $n/cm^2 \cdot s$ and time average one - $2 \cdot 10^{14}$ $n/cm^2 \cdot s$.

Operability of the neutron source depends essentially on radiation damage rate of it's main components. The comparative data on radiation damage of the first wall of neutron sources SIN-45, MMF-0.6 and thermonuclear reactor (thermal load on the first wall 1 MW/m^2) are presented in Table 1. Radiation damage computations were carried out using efficient crossections of defect production /21/.

The value of K_{dpa} 9 dpa/year corresponds to fast neutron fluence 10^{22} n/cm^2. Material properties changes are expected to be small enough at that dose.

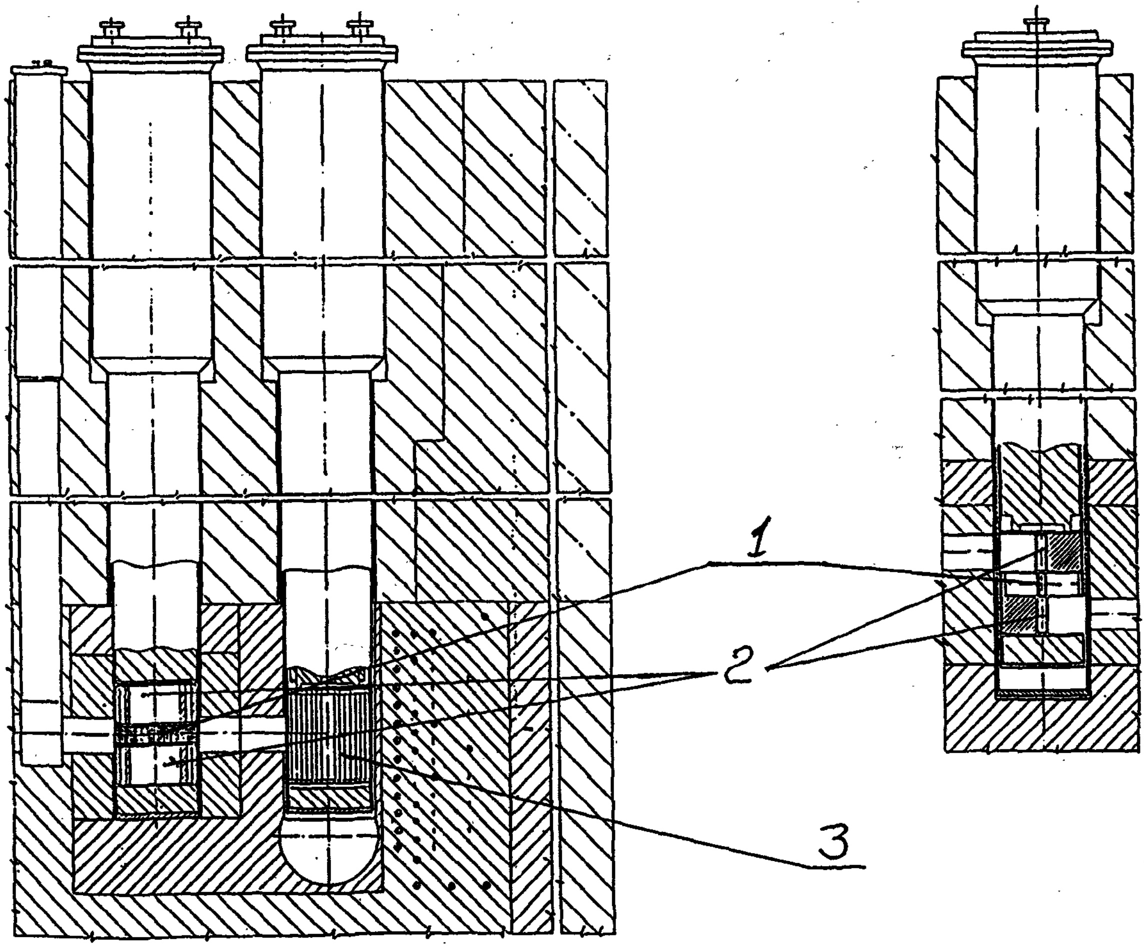

Fig. 10. Target-beam-dump device of SIN-45. 1. Tungsten target. 2. Moderators (H_2 and H_2O). 3. Beam dump.

Table 1.

system	material	damage rate dpa/year	helium prod.rate appm $\cdot 10^{-6}$/year	He/dpa $\cdot 10^{-6}$
SIN-45	Al	27	370	14
	Fe	9	430	48
	W	6	750	130
MMP-0.6	Fe	13	220	17
Fusion	Fe	14	150	11

The main parameters of pulse neutron sources MMF-0.6 and

SIN-45 in comparison with other pulse neutron sources are presented in Table 2. To compare the sources MMF-0.6 target - moderator geometry and figure-of-merit criterion $K=\bar{\Phi}_T/\theta_T^2$ were used, where $\bar{\Phi}_T$ -average thermal neutron flux density on the moderator surface, θ_T - thermal neutron pulse duration.

Table 2.

system	proton energy, GeV	θ_p, μs	f, pps	$\bar{\Phi}_T$, n/cm^2·s	$\hat{\Phi}_T$, n/cm^2·s	$\frac{\bar{\Phi}_T}{\theta_T^2}$, r.u.	note
INI	0.5	0.01	10	$1.6\cdot10^{10}$	$3\cdot10^{13}$	0.01	project 1964
KENS	0.5	0.01	15	$4.4\cdot10^{10}$	$5\cdot10^{14}$	0.24	oper.
KENS-II	1.0	0.2	50	$2.0\cdot10^{13}$	$7\cdot10^{15}$	11	project
IPNS	0.5	0.01	30	$5.6\cdot10^{11}$	$3\cdot10^{14}$	0.3	oper.
LANSCE	0.8	0.1	12	$8.0\cdot10^{12}$	$1.1\cdot10^{16}$	4.2	oper.
IBR-2	f, 4 MW	100	5	$2.2\cdot10^{13}$	$3.5\cdot10^{16}$	1	oper.
ASPUN	1.6	0.5	60	$2.8\cdot10^{14}$	$8\cdot10^{16}$	250	project
MMP-0.6	0.6 (20)	0.3 (1)	100 (30)	$2.8\cdot10^{13}$	$5\cdot10^{15}$	15 (45)	constr.
ISIS	0.8	0.2	50	$1.4\cdot10^{13}$	$5\cdot10^{15}$	7.5	oper.
SIN-45	45 7.5	4.4 1.3	8.3 50	$2.0\cdot10^{14}$ $7.0\cdot10^{13}$	$7\cdot10^{17}$ $4.3\cdot10^{16}$	110 38	project

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