ADVANCED NEUTRON SOURCE FOR PHYSICAL RESEARCH

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The possibility to create the super-intensive pulsed neutron source for solid state neutron research based on fast-cycling proton synchrotron, liquid-metal Pb-Bi, PuO_2-Na multiplying targets is discussed. The thermal neutron peak flux as high as ~ 10^{18} n/cm^{2}s is expected to be achieved using this scheme.

Slow neutrons (resonant, thermal and cold) are quite effective means for investigation of fundamental properties of matter. The unique features of neutrons (strong interactions with nuclear matter, absence of electric charge and corresponding limitations, connected with ionization losses in matter as well as Coulomb barriers in nuclei) reveals themselves most completely at low neutron energies. These features of neutron, high intensities, accessible in nuclear reactors (flux densities up to (2-3) 10^{15} neut/cm^{2}s) give wide possibilities for development of neutron research in regions of particle physics, nuclear physics and, in particular, condensed matter research (up to 85% program of research on nuclear reactors). The future of these investigations depend on the possibility to increase intensity of neutron sources. However, neutron flux in research nuclear reactors is limited by heat release density in fuel and safety problems. Respectively, already in the middle of sixties the possibility to obtain the thermal neutron flux up to 10^{16} neut/cm^{2}sec by spallation process at energy 1 GeV was considered. However, having the gain in flux about 5, the facility was overcomplicated and too expensive (ING, "Canadian project").

At present, in our opinion, the only way to increase significantly (tens and hundreds times) the effiency of neutron experiments is using a pulsed neutron spallation source. The pulsed slow neutron source allows to develop practically the same research program as the steady-state one if their thermal neutron flux densities (but pulsed) are comparable.

Now, we see a number facilities, being in operation or under construction or development, that are based on proton synchrotrons or storage rings with charge-exchange injection from linear proton accelerators and one-turn extraction of proton bursts onto neutron targets. Those in operation are KENS (KEK), IPNS (Argonne Lab), LANSCE (LANL), ISIS (Rutherford Lab); the construction of the Moscow meson factory's pulse neutron source IN-06 /2/ is at the final stage. All this facilities are driven with proton beams with energy of 0,5-1 GeV and average proton currents up to 200 mA.

The next generation of spallation pulsed neutron sources with tens times higher intensity is being developed - 1 MW Spallation Source in USA, European Spallation Sources (ESS).

The first priority for this sources, intended for wide physical research program (tens of simultaneously running experiments), is their reliability. As a consequence, in our opinion, we should use elaborated accelerator and nuclear facility technologies and look for optimal complex ways to create such a facility.

1. The radiation damages of the first wall of the target due to primary protons are of special importance for reliability. Among other factors the energy of primary protons plays, maybe, the decisive role. The optimal proton energy for neutron production in extent targets lies in the region of 1.5 to 2 GeV. This value is determined by competition between nuclear interaction and ionization losses. At low proton energies (below 1 GeV) the direct proton ionization losses prevail, while at energies above 1 GeV the ionization of electron-photon showers, initiated by π^o-meson decay, becomes more important. The results of computations, that were carried out by V. Miroshnichenko, N. Sobolevsky, A. Kuzin and S. Lebedev which are consistent with the experiments on neutron yield measurements in region up to 70 Gev, (/4/, /5/), are presented on Figs. 1 and 2. While the proton energy increases above 1.5 -2 GeV, the specific neutron yield (per unit of thermal neutron flux density on surface of water moderator and unit of proton energy) decreases slowly (Fig. 1), but the specific first wall radiation damage rate decreases significantly (Fig. 2).

2. The second significant factor is the limitations due to the space charge and collective effects in proton beams. These effects are approximately inversely proportional to the proton energy for a constant neutron yield.

3. After all, the high energy of protons and, as a consequence, relatively small proton current provide more possibilities to create the radiation pure accelerator system localising radioactive wastes within the easy-serviceable target system. Therefore, apparently, the most realistic scheme of an advanced pulsed neutron source (ANS) may be based on a fast-cycling proton synchrotron for about 10 GeV, 50 pps, with average current 500 mA or more, with injection from 1 GeV linac and one-turn extraction onto the neutron target system. To enlarge the experimental possibilities of the source it is expedient to use two independent neutron targets with vertical (from bottom up) beam injection.

The first target - liquid-metal Pb-Bi /6/ or water cooled tungsten /2/ with thick beryllium reflector and water moderators inside is intended for high pulse repetition rate (40 pps), moderate average pulsed neutron flux densities and small neutron background between pulses (below 10^{-5}).

For experiments with high pulsed neutron fluxes of thermal and cold neutrons it is expedient to use a multiplying target with moderate gain factor (~ 15) /7/. So, the fast breeder prototype, based on plutonium or uranium oxide core with sodium cooling, inner tungsten proton-to-neutron converter, thick Ni reflector with air cooling, water and liquid hydrogen moderators inside the reflector may be considered as the most suitable concept. There is many-years experience of successful operation (since the end of fifties) of plutonium-oxide fast reactors with compact core, sodium cooling - BR-5, BR-10 (Physical - Energetical Institute, Russia, /8/), pulsed reactor IBR-2 (JINR, Dubna) /9/, experimental fast reactors EBR-2 (USA), Phoenix (France).

The peak thermal neutron flux density at repetition rate 10 pps and pulse width ~30 ms will be about ~10^{18} neut/cm^{2}sec. This value by approximately two orders of magnitude exceeds the flux density in the most powerful research pulsed or steady-state reactors. The background power between pulses will be 4-5% in system without movable mechanical reflector elements.

Since the main requirements for high intensity proton accelerator complex are the reliability and the radioactive purity, which are the same as for Meson and Kaon factories, many technical and scientific decisions are given from Moscow Kaon project ("The proposal of the accelerator complex of the Moscow Kaon Factory", Yu. Senichev et al., San Francisco, IEEE, PAC /10/).

The accelerator complex consists of proton linac and fast cycling synchrotron (FCS) with average beam intensity 500 mA and energy 10 GeV.

The injector includes 100 KeV H-source and RFQ with final energy 2 MeV and resonant frequency 198.2 MHz.

The Linac consists of two parts DTL and DW structures with transition at 100 MeV. The Linac accelerates the beam with a pulse length 1 ms and amplitude 10 mA up to 1 GeV with repetition frequency 50 Hz.

Then each pulse is transferred in FCS and is injected during 1 ms on flat-bottom magnetic field. During 16 ms particles are accelerated and then magnetic field fall up to initial magnitude. Resonant frequency is changed from 33 MHz up to 37.6 MHz. For optimization of RF cavity number the magnet waveform is complicated and consists of three parts - harmonic, linear and harmonic.

Since FCS is of high-intensity synchrotron with large transverse beam size, deep beam loading and significant collective instability, we have focussed on the following features of structure :

- the transition energy has to be high enough to satisfy conditions of collective instability
- the dynamic aperture in presence of chromaticity-correcting sextupoles has to be more than three emittance of beam which satisfy to not crossing of integer and half-integer resonances with space charge
- long dispersion-free straight sections are required for RF cavity, extraction and injection system
- eddy current problem has to be solved in RF tuner and vacuum chamber of dipole.

From the general consideration the lattice with both modulation of quadrupoles strength and distribution of bend magnets is most suitable for FCS /10/. The synchrotron has a racetrack shape with two 180 degree arc and two dispersion-free straight sections. The arcs have 8 superperiods. Each superperiod contains 4 FODO cells, two central half-cells do not have dipoles ("missing magnet"). The horizontal tune of are equals to 3, that gives zero dispersion in 5-cells FODO straight sections. The phase advance of the straight section in vertical plane equals to 2.66/2 and in horizontal plane is 1.66/2. Each arc is a second order achromt. A high energy transition energy is reached by "missing" scheme and equals to 17 GeV. In order to reduce the tune spread, 32 sextupoles are placed in arcs for chromaticity correction.

In FCS RF cavity has to be very fast retuned so the usual variant with ferrite tuner looks not very reliable due to ferrite heating. Idea to use reactive properties of electron cloud in magnetron type diode for tuning of accelerating cavity in fast cycling synchrotrons was proposed under development Moscow Kaon project. In 1990 first tests of "varactor" in scheme of capacitor divider have shown possibility to change capacity in range 100-160 pf with applied voltage 20 kV /11/.

The very important question in FCS is the ceramic vacuum chamber. The first stage of our investigations in this field was successfully completed in 1991. We have now a technology for producing a ceramic segments with lengths 250-500 mm and wall thickness 4 mm.

The basic parameters of accelerators and targets complex ANS is given in Table 1.

TABLE 1

1 GeV - Linac	
av. current	0.5 ma (50 pps, 1 msec)
RFQ	2 MeV
DTL - (Alvarez) structure	100 MeV
DW - (Andreev) structure	1 GeV
10 GeV - FCS	
total circumference	573 m
revolution time	2 msec
max horizontal size	75 mm
max vertical size	60 mm
Pb -Bi target system	
power	2 MW
Dimensions	
target	15 cm
Be-reflector	75 cm
H_2O-moderator	15 x 5 cm^2
av. proton current	.4 mA
pulse repetition rate	40 pps
av. density of thermal neutron flux	3:1-12:10^{13}neutr/cm^2sec
peak density of thermal neutron flux (30 mcs)	2.6-10.10^{16}neutr/cm^2sec
first wall radiation damage rate	14 dpa/year
PuO_2- Na target system	
power	15 MW
background power	4.5 %
core	23 x 30 cm
W-convertor	5 x 30 cm
Ni-reflector	83 cm
H_2O-moderator	12 x 5 cm
av.proton current	100 mA
multiplication factor	15
life-time of prompt neutron	130 nsec
pulse repetition rate	10 pps
av.demsity of thermal neutrons	$2.2\cdot10^{14}$neutr/cm^2sec
peak density of thermal neutrons (27 mcs)	$8.4\cdot10^{17}$neutr/cm^2sec
first wall radiation damage rate	60 dpa/year

Comparative parameters of intensive neutron sources for research in solid state physics region placed in TABLE 2.

TABLE 2

Facility	Type	av.current on target	T neut/cm^2	T sec	K =	dpa/year
IBR-2 (~ILL)	pulsed reactor,4MWt	PuO$_2$+Na	10^{13} (120	10^{16} mcs)	1*	12
ISIS	PS,70 MeV- -0.8 GeV	0.2mA U238	2.1·10^{12}	1.4·10^{15}	3.3*	6.3
MMF IN-06	stor.ring 0.6 GeV	0.5 mA U238	4·10^{12}	1.3·10^{15}	6.4**	14
		0.15 mA U233	1.8·10^{13}	2.·10^{16}	30**	14.5
ESS	stor.ring 1 GeV	6.3 ma Pb-Bi	6.3·10^{13}	4.2·10^{16}	100**	125
ANS	PS, 1 GeV- 10 GeV	0.4 mA Pb-Bi	3.1·10^{13}	2.6·10^{16}	50**	14
		0.1 mA PuO$_2$-Na	2.2·10^{14}	8.4·10^{17}	350***	60

* - design parameters (now K~1.6)
** - real geometry of 1 stage IN-06 (thin Be-reflector)
*** - thick reflector

The experimental possibilities of the high-power pulsed reactor IBR-2 with design parameters (pulse width 100 ms, average power ~4 MW) are close to those of a high-flux steady-state research reactor (ILL, Grenoble). These parameters are still not achieved - (170 ms, 2 MW power now). The comparison of pulse systems are made using the figure-of-merit factor Φ_T / θ_T^2 . Here Φ_T - average thermal neutron flux density on the water moderator surface, θ_T - thermal neutron pulse width.

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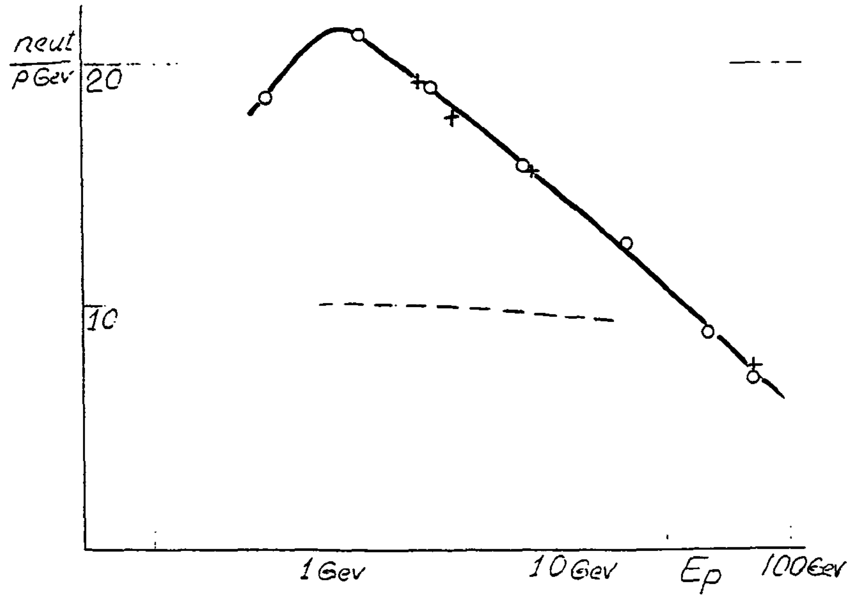

Fig.1.
Specific yield of spallation neutrons (per 1 GeV proton energy, Pb);
- - - - - - thermal neutron flux density on surface water moderator per one source neutron (arbitrary units); O - calculation, + experiment

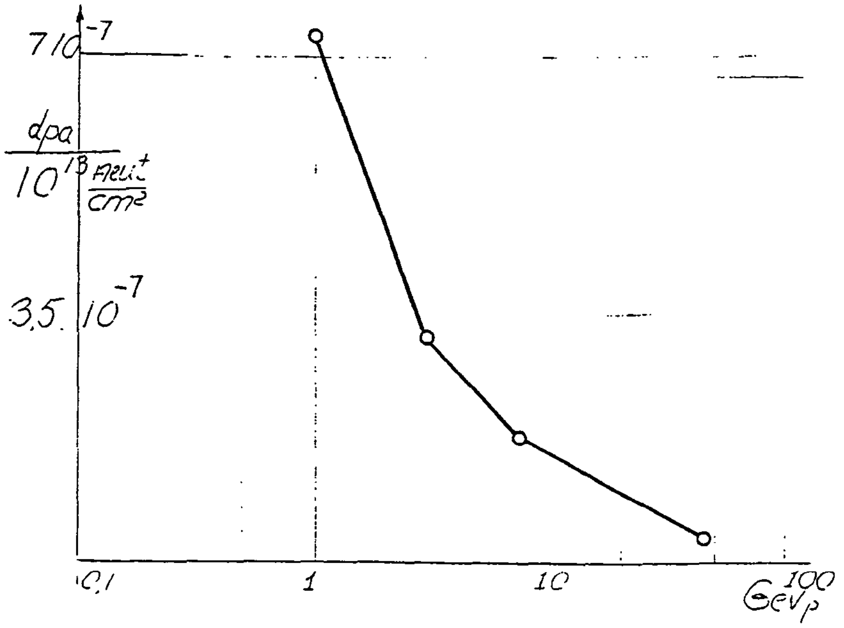

Fig.2.
Radiation damage first wall (iron) for 10^{13} neutrons/cm^2 on water moderator surface for protons (beam cross-section $20cm^2$)