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Pulsed neutron sources at Dubna: their past, present and future status

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ABSTRACT

In 1960 the first world repetitively pulsed reactor IBR was put into operation. It was the beginning of the story how fission based pulsed neutron sources at Dubna have survived. The engineers involved have experienced many successes and failures in the course of new sources upgrading to finally come to possess the world's brightest neutron source - IBR-2. The details are being reviewed through the paper.

The fission based pulsed neutron sources did not reach their final state as yet- the conceptual views of IBR prospects are being discussed with the goal to double the thermal neutron peak flux (up to $2 \cdot 10^{16}$) and to enhance the cold neutron flux by 10 times (with the present one being as high as that of the ISIS cold moderator).

I. FEW COMMENTS ON THE PPR HISTORY AT DUBNA

Dubna is the only place where fission chain reaction based facilities are used as pulsed neutron sources. Their advantages are evident - big neutron flux and low cost of construction. But disadvantages are common famous so - more risk for pollution and too long neutron pulse duration.

The history of pulsed reactors had yet begun not in Dubna but during the Manhathen project in 1945 when special superpromptcritical experiments named "Dragon" were performed. The paper on the Dragon programme had included the part concerning the "repetitive Dragon"; the idea invented by D.Judd was to fasten a moving slug of uranium to the rotor getting so periodic pulses of fission power. The secure project was not realized and the paper was declassified only in 1960-th after the official report on the start-up of the Sovjet periodically pulsed reactor (abbrevation PPR) IBR was issued.

The IBR reactor was the first PPR in the world and it was the "bride present" to JINR from dr. Blokhintsev who arrived at Dubna from Obninsk where he and his colleagues invented (independently of Americans) the concept of a PPR. The young physicists dr. I.I.Bondarenko and Yu.Ya.Stavissky had created the exact PPR theory including the most important part concerning with power fluctuation /1/. The principle of IBR design was to divide a small fast reactor core into two parts - one of them moveable, imbedded in the fast rotating steel disk (see fig.1). The power pulse duration had appeared to be 40 μsec - more than expected 10 μsec but yet short enough for time of fligt (TOF) experiments. The time averaged power was 1 kW initially and was increased temporarily up to 6 kW for the next 3 years / 2 /.

The IBR was reconstructed in 1969; its new version, desighnated as IBR-30, had 30 kW mean power. It was achieved partly by placing two uranium inserts into the disk that consequently passed the unmoving core. The reactor could operate over the wide range of pulse repetition rates - from 100 pps to single pulses with a fission yield up to 10^{16}. The half width of fast neutron pulses was 55-60 μsec.

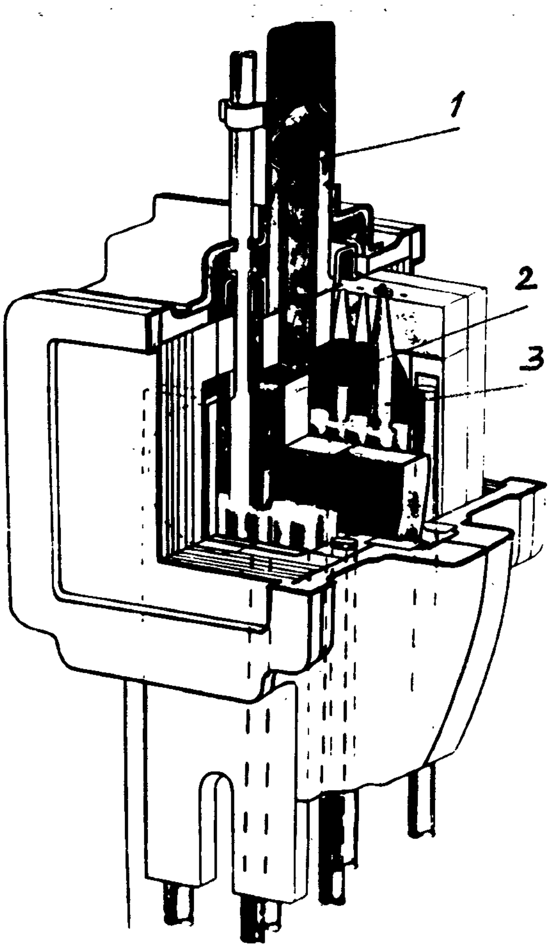

Fig.1 The IBR sketch
1-rotating steel disk
2-uranium insert
3-fuel rod of the unmoving core

To get the pulse duration in IBR shorter, it was decided in the early of 60-th to make it operating as a multiplicator of neutrons from accelarator target - "booster" mode of operation. This idea was realized earlier at Harwell but IBR was the more convenient device as the large reactivity modulation enabled a high multiplication of prompt neutrons during a pulse. The injectors (electron accelerators) for IBR and IBR-30 were the microtron (cyclic one) then LUE-40 (linear, of resonant type) that is used up to now. The pulse duration was (and is) 4 μsec at time averaged fission power from 1.2 to 13 kW depending on accelerator performances / 3 /.
The Dubna's booster scope is nuclear physics experiments by TOF method. It was the brightest neutron source in this occupation for 15-20 years until SNS appeared (the neutron luminousity of IBR booster is equal to that of 10-15 μA proton accelerator target).

It is worthy to tell about the most dramatic mode of IBR-30 operation - so called "rare pulses" one, the essence of which is in what a big reactor pulse is generated periodically but seldom - once per some seconds / 3 /. The special device was constructed to modulate reactivity with such frequency; it was the tungsten rod (reflector) swinging up and down near the core and being synchronized to the moving part of the core (uranium insert). The special emergency response facilities were established to avoid asynchronization.

The mode of rare pulses was experienced for about 2 years with energy yield in a pulse up to 100 kJ till it had finished dramatically... The mechanical part of the rod driver was not reliable enough as it became known afterwards. Once a day in the June 1972 (it was the last day before stopping for annual examination) some of the emergency systems failed, casually and simultaneously. But the maintenance stoff was ordered not to stop reactor operation. At the night the driving mechanism of swinging rod got broken, the rod started to move away the synchonized oscillation period. The reactor power started to decay according to a removal of reactivity. The emergency responce systems that might shut the reactor down were switched off and could not control situation. The power was being equal near to zero for about 15 sec Naturally, the huge amount of concealed reactivity was accumulated due to core temperature decaying. At one unpleasant moment the slowing rod found occasionally itself in the position near to maximum reactivity simultaneously with the uranium insert so the concealed reactivity was summarized to the reactivity of the rod , and the very big power burst with about 2 MJ yield was aroused. The consequence was plutonium fuel melting. Fortunately, the fuel rod claddings successfully resisted inner pressure, and no radionuclides released outside. Otherwise the accident might be severe one with bad radioactive contamination. Since that time the rare pulses mode of operation is forbidden to maintain. Moreover, after the Chernobyl catastrophe any pulsed supercritical mode of IBR-30 operation (its fuel is metallic plutonium) is prohibited; it is used as a booster only.

In the middle of 60-th the scientific people involved in intense neutron source desighning were rather stimulated by a successful operation of IBR to be approved that PPR construction is the right way to go on. That's why so many projects of more powerful PPR's had been proposed that times - SORA in Europe, PFR in BNL(USA), KPFR in India and the others. But only one of them was realized, again in Dubna - IBR-2 (not taking into account the small PPR in Japan - JAJOI). The reason why the others designs were given up was that SNS projects won the rivals due to more broad applications and shorter pulse duration.

The principal idea and construction of IBR-2 were discussed in many papers /4 - 6 / and need not to be repeated. Let us be restricted by displaying two figures (2 and 3) and the list of IBR-2 performances (table 1).

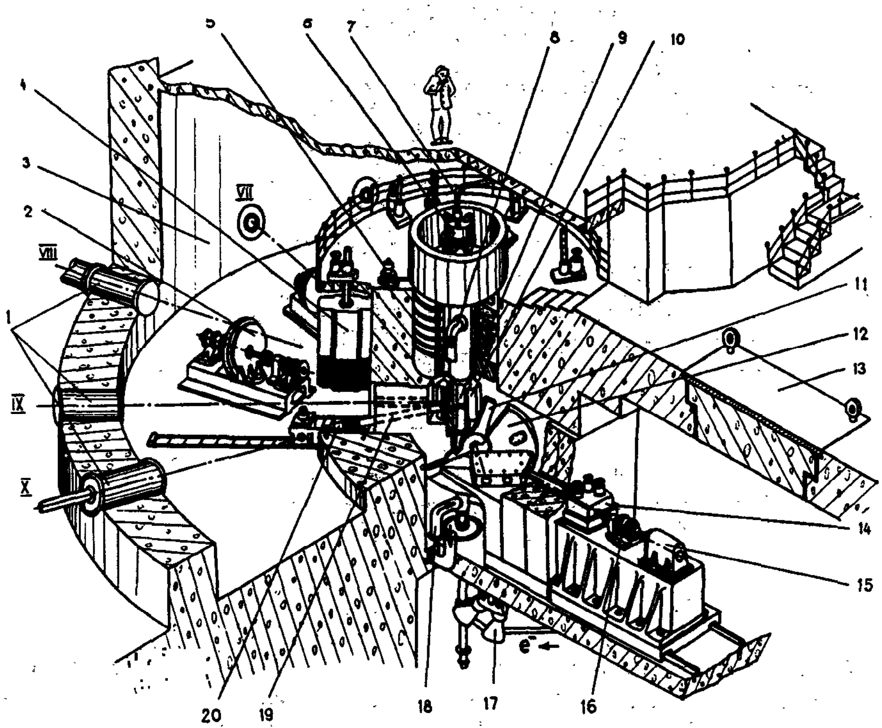

Fig.2 The general drawing of IBR-2: 1-neutron beam tubes; 2-choppers; 3-outer ring of biological shield; 4-neutron beam shutters; 5-control rod drive; 6-reactor vessel; 7-irradiation tube; 8-sodium outlet; 9-the core; 10-unmoving reflector; 11-moving reflector,MR; 12-its jacket; 13-manhole for MR withdrawing; 14,15,16-the parts of MR driver; 17-magnets for electron beam (not installed);18-sodium inlet; 19,20-safety block driving mechanism.

Table 1

The IBR-2 reactor performances.

	Today	In future
Mean power, MW	2	4
Peak power, MW	1500	10000
Pulse duration, μsec	215	70
Background power, MW	0.1	<0.15
Thermal neutron flux (n/cm^2/s):		
1) time averaged	10^{13}	10^{13}
2) Peak	$0.7\ 10^{16}$	$2\ 10^{16}$

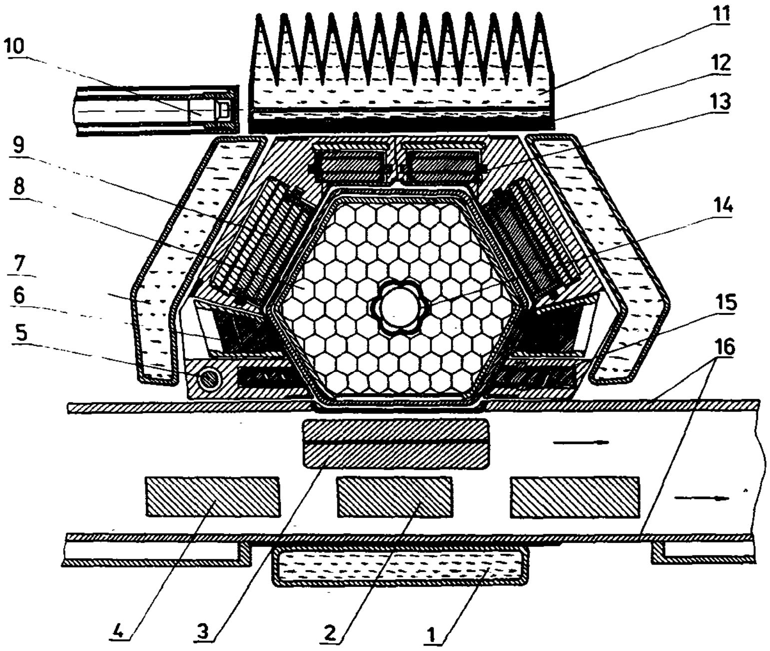

Fig.3 The IBR-2 reactor cross-section. 1,7-flat light water moderators; 2,4-auxillary moving reflector (AMR); 3-main moving rerflector (MR); 5,9,15-control blocks; 6-fast safety block; 8-fuel rods subassembly; 10-irradiation tube; 11-grooved water moderator; 12-boron filter; 13-slow safety blocks; 14 irradiation hole; 16-MR jacket.

The only thing is worthy to discuss about - the exciting scenario played by the reactor physicists to overcome difficulties with the long pulse duration. The initial value of it appeared to be more than 300 μsec - absolutely unsuitable to condensed matter reseaches. The reason for such a bad situation was so called "shadow effect" on neutron reflection, that spoiled pulse shape at the first version of IBR-2 moving reflector MR-1 in 1978. The pulse duration is defined (it was derived by Stavissky in 1956 yet) as

$$\Theta = \sqrt{2\pi\tau / \gamma}$$

where τ is the prompt neutron life time, and γ is the rate of reactivity changing at the moment of a peak power. The figure 4a shows clearly that the totally shaded auxillary reflector (AMR, used for slow reactivity modulation) is partly got open when MMR (main reflector,that is nearer to the core) is shifted in right-hand direction, and therefore some positive reactivity is released which was initially shaded by MMR. This positive reactivity decreases γ rate value in comparison with that for a single MMR. After some trials it was found that AMR of "folk type" (fig.4b) gives no shadow effects.

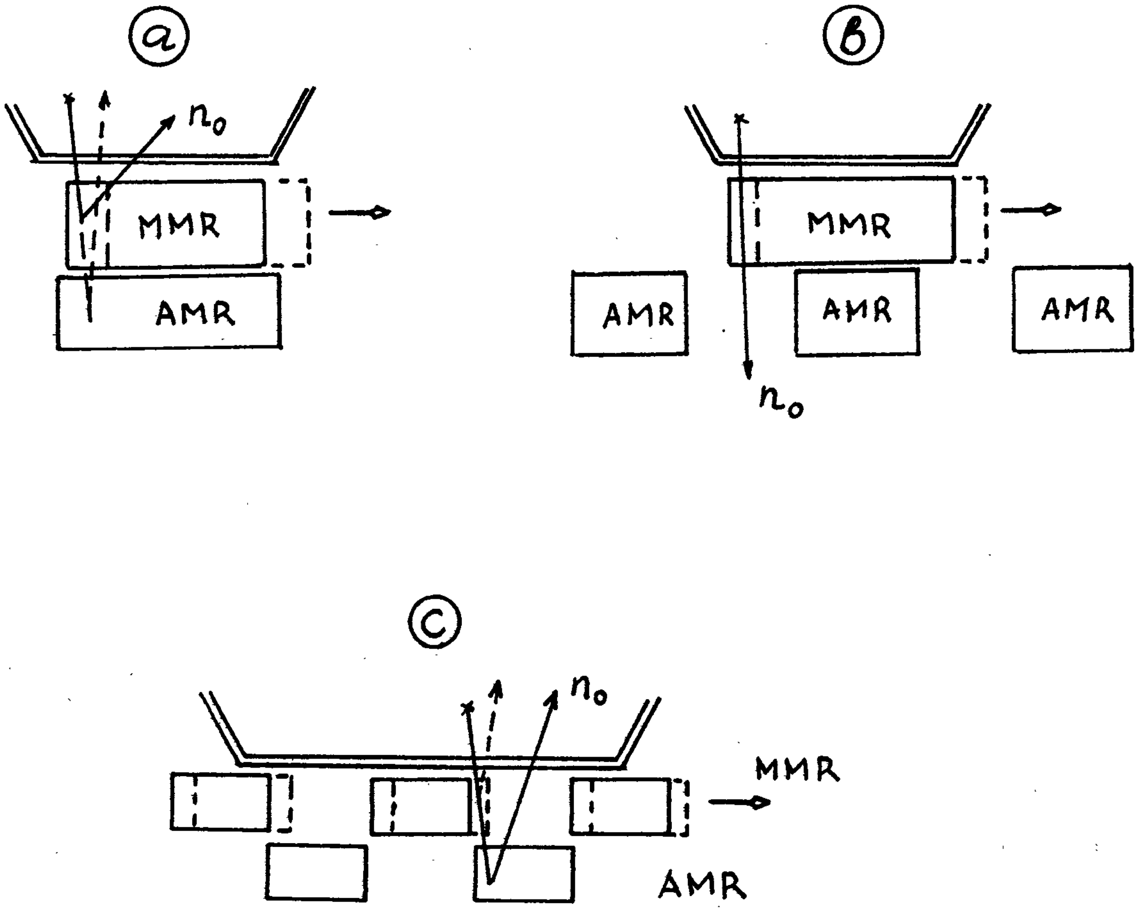

Fig.4 The diagrams of moving reflectors geometry to explain the "shadow" effect of neutron reflection. a-the first version of MR; b- MR-2; c-MR-3.

The new IBR-2 modulator MR-2 having such construction was installed in 1981 and ensured 215 μsec fast neutron pulse (fig.5).Some later (in 1983) it was proved by experimentally that the "shadow" effect could be forced to play useful role if two reflectors are shaped in special way (say, as that grid type reflectors displayed at the diagram of fig. 4c. For a such geometry of reflectors the shadow effect causes additional reactivity removing that leads to shortening a pulse duration significantly. The experiments of 1987 enabled to optimize modulator shape and material. The result is that the new project of MR-3 modulator for IBR-2 ensures 110-115 μsec pulse duration. Moreover, this modulator will be safer It is planned to be installed in 1992-1993.

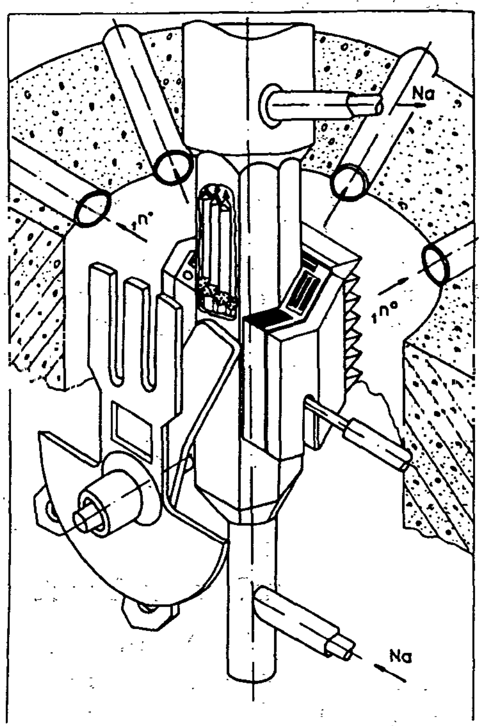

Fig.5. The IBR-2 sketch with MR-2 moving reflector rotors.

The IBR-2 started to be used for science in April 1982 mainly for condensed matter reseach by TOF method on extracted beams (but the very first experiment was concerned with searching of axion, a gypothetical particle, and not needed neutron beam).

The IBR-2 is well suit for condensed matter reseaches, especially with cold neutrons. It is resolved by 3 factors:

1. The power pulse duration is near to a cold neutrons life time in moderators.
2. The reactor core size and shape are optimized for thermal neutron intensity in outer beams.
3. The heat deposition in outer moderators per one cold neutron production is much less in comparison to that of SNS facilities or thermal reseach reactors (due to that γ-ray flux and fast neutron energy are both profoundly low).

So, yet today the cold neutron flux from the IBR-2 room temperature light water moderator equals to that of ISIS cryogenic moderator (see table 2).

Table 2. Cold neutron fluxes ($\lambda > 4Å$) of IBR-2 and the others sources.

	From whole moderator surface, time averaged 10^{13} n/sec/sr	Peak density flux at $\lambda = 9Å$ 10^{15} n/cm^2/s/sr/eV
IBR-2 light water grooved moderator	1.2	1.3
IBR-2 solid methane	5-10	30-60
ISIS liqiud hydrogen (200 μkA)	0.8	2
ILL (Grenoble), 1 cm^2	1.5	5

As soon as the solid methane moderator would be installed at IBR-2 (see the description below) no device with the same fission density in the core could reach the cold neutron performances of IBR-2 in principle.

The IBR-2 is operated 100 days per year; the initial fuel charge ensures more than 10 years of operation with no fuel reloading.

During the IBR-2 desighning it was decided to construct a powerful electron accelerator as an injector for IBR-2 to get a short duration of neutron pulse. The induction principle was chosen to accelerate electrons as the most suitable for high current. Its essence is in that the electron beam is used as a secondary coil of a transformer with a primary one reeled on the permalloy toroidal cores. The construction of LIU-30 accelerator lasted 20 years but nothing came of it as the electron beam occured to be unstable in radial motion. All attempts to stabilize it appeared to be unsuccessful; construction was given up in the last year. We know no other electron accelerator being adequate to IBR-2 performances, i.e. so powerful as to generate more than $2\ 10^{14}$ n/sec in the target (if not proton accelerator with >2 μkA current). So, the IBR-2 operates only as a pulsed reactor contrary to the IBR-30 operating as a booster exclusively.

It is interesting to say that many uncommon effects were observed during the Dubna's pulsed facilities exploitation. Each of them worthy to tell in a proper paper / 7,8 /; here we give the headings of some of them only:

-the selfcompensating a fuel burn-up reactivity effect in IBR-2 reactor;
-the possibility of an instability of a new, "pulsed" type in PPR and transient to a chaotic behavior at a great power;
-mirror reflection of relativistic electrons of the front panel of a target.

II. THE PROSPECTS FOR PULSED NEUTRON SOURCES AT DUBNA.

We intend to install the two new devices at IBR-2 in the nearest future (1992-1993) : moving reflector MR-3 to reach 110 μsec pulse duration (yet described in the part I) and the cold moderator. The latter will be solid methane one of a grooved type at 20-25 K combined with the light water premoderator. The methane container box (fig.6) is fabricated of Al alloy and is tightly surrounded by another container to hold gaseous helium that removes heat off methane and alumium walls. Many small channels for helium flow are cut inside the front wall of methane box to enlarge the cooling surface. The heat will be transferred through low-conducting methane by the same way the Japaneses use at KENS - aluminium wires forced into the front wall, some of them twisted.

To control the methane temperature three kinds of gages will be used: gaseous thermometers,thermocouples and neutron thermometer. The latter will measure the instant cold neutron spectrum by TOF on-line method enabling to scram the reactor down just as soon as chemical energy stored at methane due to irradiation starts casually to be released.

The other pecularity of the cold moderator construction is that the back (outletting) wall of helium container is supplied with special ribs to restrain helium pressure against vacuum outside ; to avoid cold neutron absorption the ribs are placed just opposite to methane ledges at grooved side of the box. Such ribs are arranged at the vacuum container too (it is not shown in the picture).

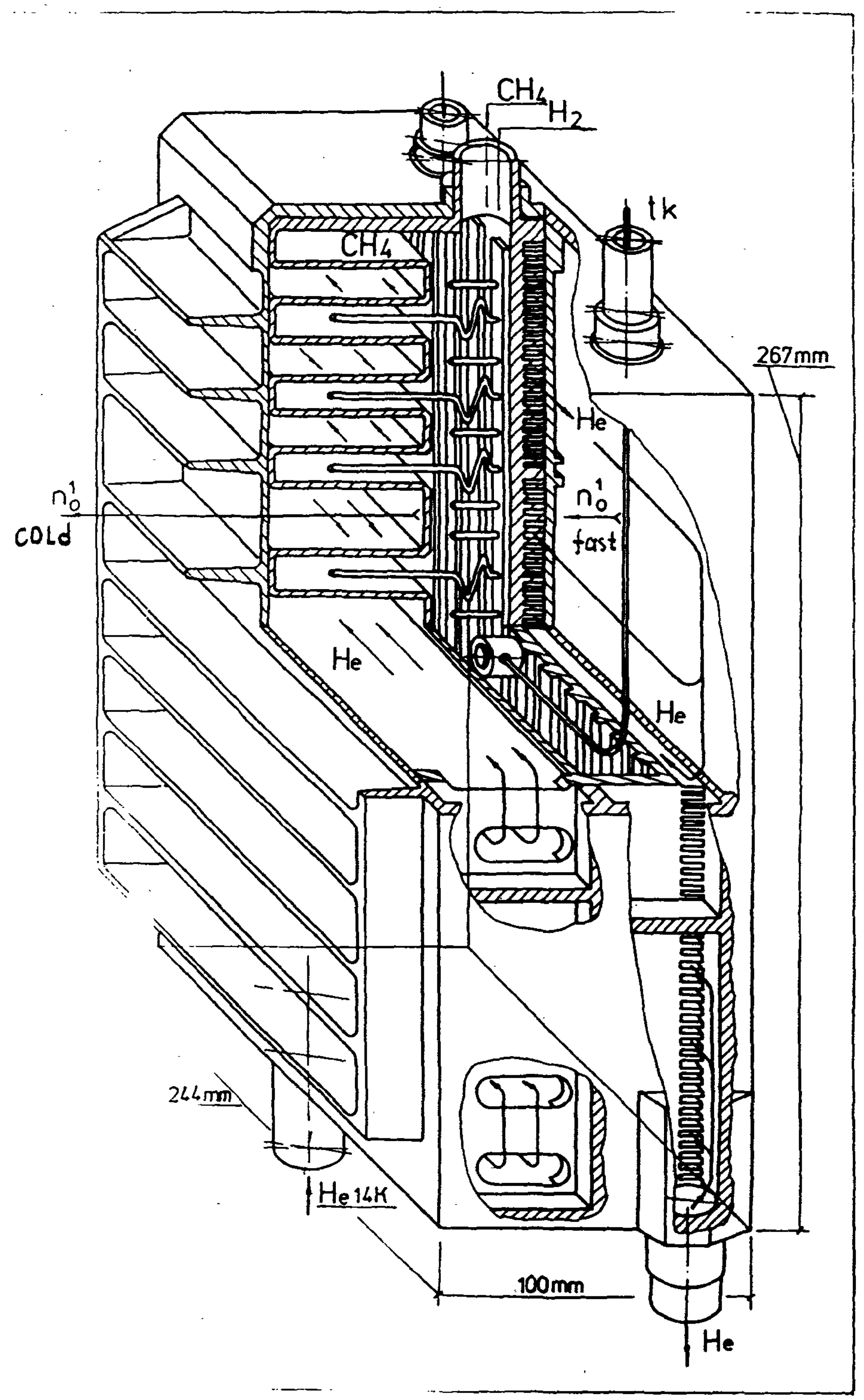

Fig.6. The solid methane moderator of IBR-2, the cross-section drawing of the methane and helium cameras.

The power generated in methane due to neutrons slowing-down and γ-capture amounts to 110 W, in aluminium - 470 W. The maximum of heat production per unit volume will be near to that of solid methane at KENS or IPNS - about 0.1 W/g (the volume of the box is 2 ltrs). Therefore the rate of radiolysis is expected to be at appropriate grade to enable us not to replace methane by the fresh one during one run of IBR-2 operation - two weeks. If not, there is possibility to decrease heat generation in methane by adjusting the thickness of the water premoderator.

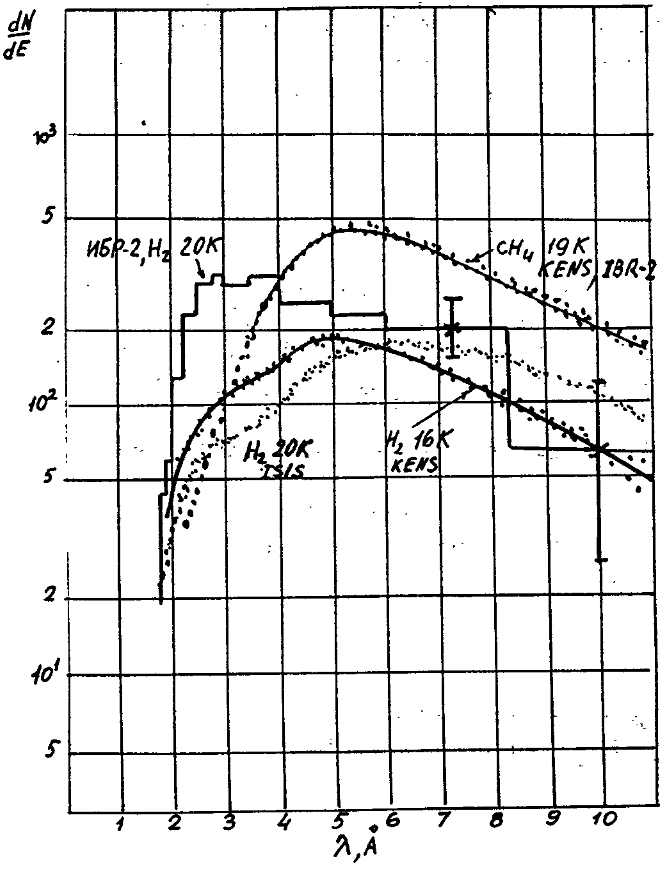

Fig.7. The relative neutron spectra for the various moderators.

It is worthy to explain that at the same heat production rate as SNS have the IBR-2 moderator supplies physicists with more cold neutrons (table 2) due to both the fast neutron mean energy kicked methane is much less than that of SNS and the moderator surface is about one order larger.

The cold moderator construction enables to optimize neutron spectrum. It is possible not to fill up the camera with methane or to fill it up partly. The goal is to get "warmer" neutrons. The most good opportunity to get very broad neutron spectrum is to fill up the camera with liquid hydrogen instead methane(see fig.7). We were aspired by this idea after learning IPNS's experience with replacing solid methane by liquid hydrogen with no changing in the technology system. But we suffer of the strong formal limitations concerning nuclear safety to intrude liquid hydrogen at the reactor.

Besides these two up-grading of IBR-2 (MR-3 and methane moderator) we are planning more radical modifications of it. The main trend is replacing plutonium fuel by uranium one; it is desireable because of a big potencial danger of plutonium as a α-particles source. It is not easy to make such replacing not aggravating reactor performances. One possible concept of a new reactor version (let us name it as IBR-3) is to replace the reactor core of traditional type by a moving long bar placed inside the reactor vessel and cooled by sodium. This uranium slug (or few slugs) will be moved up and down so power pulses will be flashed at different parts of the slug consequently. The fissions will be diverged through all the slug enabling deminishing delayed neutrons intensities to get low background power between pulses (about 3%). Besides the duration of pulses would be reduced due to more delicate sizes of the core. No modifications are needed with nowdays cooling system, shielding, scientific instrumentation; MR-3 and the cold moderator could operate perfectly at IBR-3 too. The reactor vessel and the control blocks must be changed at some degree. Which is the most important the melting of the core is principally unprobable due to small residual power density.

The main expected performances of IBR-3 are displayed in Table 1, the second column.

And finally, a very brief comments on the future of nuclear physics by neutron experiments at JINR. After the creation of LIU-30 was finished unsuccessfully, it was decided to improve the IBR-30 booster performances to get higher time resolution. Now the desighning of a new electron injector and the new booster are under the progress. The goal is to generate short pulses <0.5 μsec at mean power of the booster 20-30 kW. The booster is proposed to be with no reactivity modulator. Thus the history revolves backwards to the first booster at Harwell but with more modern accelerator.

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Q(G.S.Bauer): What is the value of K_{eff} during the pulse in IBR-30 and IBR-2?
A(E.P.Shabalin): At the moment of maximum reactivity K_{eff} equals to ~0.995 for IBR-30 and ~1.001 for IBR-2.