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Giant pulses of thermal neutrons in large accelerator beam dumps. Possibilities for experiments

Yu Ya Stavissky

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Contents

Abstract. **A short review is presented of the development in Russia of intense pulsed neutron sources for physical research — the pulsating fast reactors IBR-1, IBR-30, IBR-2 (Joint Institute for Nuclear Research, Dubna), and the neutron-radiation complex of the Moscow meson factory — the 'Troitsk Trinity' (RAS Institute for Nuclear Research, Troitsk, Moscow region). The possibility of generating giant neutron pulses in beam dumps of superhigh energy accelerators is discussed. In particular, the possibility of producing giant pulsed thermal neutron fluxes in modified beam dumps of the large hadron collider (LHC) under construction at CERN is considered. It is shown that in the case of one-turn extraction of 7-TeV protons accumulated in the LHC main rings on heavy targets with water or zirconium-hydride moderators placed in the front part of the LHC graphite beam-dump blocks, every 10 hours relatively short (from ~ 100 μs) thermal neutron pulses with a peak flux density of up to $\sim 10^{20}$ neutrons cm^{-2} s^{-1} may be produced. The possibility of applying such neutron pulses in physical research is discussed.**

1. Introduction

In the old Obninsk times (the 1950s), I I Bondarenko attracted the attention of his friends and colleagues to the possibilities that had opened up for experiments in low- and intermediate-energy nuclear physics with the use of proton accelerators with strong focusing. In September of 1963, during a visit to the Institute of Nuclear Physics of the Siberian Branch of the USSR Academy of Sciences (Novosibirsk), I became interested in the rapid-cycle 500-MeV proton synchrotron developed by A A Sokolov and others under the guidance of G I Budker.

Yu Ya Stavissky Joint Institute for Nuclear Research,
141980 Dubna, Moscow region, Russian Federation
Tel. +49 (0) 961 6-34-15-05
Fax +49 (961) 6-28-56
E-mail: stavss@freenet.de

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At the end of the 1950s, a group from FEI (at present, the A I Leipunskii Institute of Physics and Power Engineering) together with TsNII-58 (the former Design Bureau headed by V G Grabin, which during the Great Patriotic war provided the Soviet Army with artillery of small and average caliber — up to 100 mm) and with the participation of the P I Baranov Central Institute of Aviation Motors (TsIAM), the A A Bochvar All-Russia Research Institute of Inorganic Materials (VNIINM) and of other scientific research and designing groups completed the development and construction of the equipment for the first pulsating reactor IBR-1, the theory of which had been developed at FEI by Bondarenko and myself at the beginning of 1956 [1] on the proposal of the Director of the Institute Dmitrii I Blokhintsev. Later on, Lennard Pal (Hungary) contributed significantly to that part of the theory which dealt with the stochastic spread of pulse amplitudes.

It all began in the autumn of 1955 at the general seminar led by A I Leipunskii at FEI. During his talk Blokhintsev proposed creating an intensive pulsed source of neutrons for physical research in the form of a periodic pulsed (pulsating) fast reactor, part of the active core of which would be fastened on the periphery of a rapidly rotating disk. The mobile part of the reactor core crossing the stationary part was due to initiate the development of an above-critical chain reaction and to give rise to a pulse of energy and, consequently, of neutrons.

During those years discussions took place concerning the prospects for developing intensive neutron sources for physical research. Indeed, neutrons represent a unique instrument for studying nuclear structure and the mechanism of nuclear reactions, and at the same time a powerful means for investigating the structure and dynamics of condensed matter, which significantly complements methods of studies based on X-ray scattering and optical methods. Also discussed were the prospects of stationary sources built around high-flux research reactors and of intensive pulsed neutron sources. We were inclined to favor pulsed sources, which was apparently due to scientific activity having been exhibited at FEI on Leipunskii's initiative at the beginning of the 1950s and aimed at the measurement of neutron reaction cross sections and spectra for nuclear power engineering, as well as relevant investigations in neutron nuclear physics. The most promising approach here involved the neutron time-of-flight technique with the application of pulsed neutron sources, based at the time on direct-action proton accelerators (cascade generators and Van de Graaff accelerators with pulsed ion sources) and p, n-reactions on tritium and lithium targets (work performed by the group led by V N Kononov; see, for example, Ref. [2]). The doubtless influence of works [3] published by the Los Alamos group led by B Diven at the end of the 1940s and the beginning of the 1950s must also be noted.

In these conditions, the proposal made by Blokhintsev happened to come just at the right time. It would be difficult to overestimate the importance of Blokhintsev's activity in realizing pulsed (pulsating) reactors. No doubt that without his interest and influence such systems would certainly have never been created. For many years we thought the idea of such a reactor also belonged to him. However, 3 or 4 years ago a report by David Lockhart Judd from the Los Alamos National Laboratory, dated back to the end of the 1940s or the beginning of the 1950s (it is difficult to give the correct reference), was found at the Joint Institute for Nuclear Research (JINR) (Dubna), but shortly after inexplicably disappeared. The report dealt with a similar scheme of a periodic pulsed reactor with a part of the active core fastened at the periphery of a rotating disk. However, inadequate assumptions were made in the reactor theory, which apparently explains why the work was not published and why no attempts were made to realize the device, although, in my opinion, the main reason consisted in there being no practical interest in constructing it, while its safety also gave rise to concerns. Only after the IBR-1 reactor at JINR (Dubna) had successfully been in operation for several years, the work was done for the development and design of powerful pulsating reactors for Euroatom ('Sora' of an average power equal to $\sim$ 1 MW with mercury cooling) and for Brookhaven National Laboratory (USA) with 22-MW average power using sodium cooling. But they were not realized.

On the initiative of Blokhintsev, who was charged with creating the international nuclear research scientific center at Dubna, JINR [4], in which he was quite successful, the Laboratory of Neutron Physics (LNF) was organized at the Institute. The pulsating reactor IBR-1 was presumed to be used as the base LNF installation. I M Frank was appointed Director of the laboratory. My group was entrusted to implement scientific leadership in the creation and putting in operation the IBR-1 reactor in the LNF of JINR.

After a wide range of experimental studies with test benches and IBR prototypes had been carried out, since no analogs of such a reactor existed, and by the way hitherto nothing has changed, IBR-1 was put in operation on June 23, 1960, and the average power of 1 kW was achieved [5]. I shall now briefly dwell upon its further destiny. In the course of development of the JINR experimental facilities, the actual LNF scientific leader Fedor L'vovich Shapiro took the initiative in carrying out work for enhancing the power of the device and, correspondingly, enhancing the intensity of neutron beams, while keeping the actual construction scheme of the device intact. Only the second balancing insert made from natural uranium in the main rotating disk was replaced by a second active one of a uranium-235 alloy, and the plutonium rods of the stationary reactor core were replaced by thinner ones, which permitted achieving a more than 20-fold increase in the average power, while the air cooling was retained, with the result that IBR-30 came out, which was, regretfully, disassembled prematurely during Russian science difficult times.

As the next step in developing the LNF experimental base, Blokhintsev proposed creating a pulsating reactor of one-megawatt average power using as a prototype the 5-MW Obninsk fast research reactor BR-5 with its plutonium oxide fuel and sodium coolant. This proposal was not put forward by chance: creation of the BR-5 reactor at FEI (Obninsk) happened to be the consequence of a particularly successful proposal made by DI (as we used to call Blokhintsev among ourselves) after the BR-2 reactor with a mercury coolant broke down owing to radiation-stimulated corrosion of the stainless steel covers of the plutonium fuel elements. I think that Blokhintsev's initiative in creating BR-5 was an outstanding achievement in his life, of which he was aware. Hence, his proposal to use BR-5 as a prototype for the new generation of pulsating reactors, although there did exist other less expensive options...

The physical 'dry' (without coolant) commissioning of BR-5 and its being put into operation with sodium coolant were carried out in Obninsk by my group in the summer of 1958. (Note that this was done in the actual place of the BR-2 reactor dismantled in the spring of 1956. The equipment was designed and constructed by the same TsNII-58. From the standpoint of present-day time schedules, the time period was fantastic!) One cannot overestimate the role of the chief engineer D S Pinkhasik in assembling BR-5. "Cities are surrendered by soldiers, but captured by generals" (after Soviet poet Alexander Tvardovsky). For more than ten years the fast research reactor BR-5 served as the best installation of such a type in the world. Its application contributed essentially to the development of nuclear power engineering based on fast reactors in Russia.

Transformation of the stationary prototype into the pulsating reactor IBR-2 with an average power of $\sim$ 2 MW was practically done without our participation — the main contributions to the development of the physical – technical details of the construction of the device (the reactivity modulator — the mobile reflector, the electromagnetic pumps for sodium circulation) were made by E P Shabalin and the LNF chief engineer V N Anan'ev. At present, IBR-2 is the main experimental facility of the JINR Laboratory of Neutron Physics.

Enhanced interest in the aforementioned 500-MeV Novosibirsk proton synchrotron was due to the following. While IBR-1 was in the course of being put in operation and investigated, the neutron pulses were revealed for certain reasons not to be $\sim$ 13 μs long, as we had estimated them to be in Ref. [1], but significantly longer, over 36 μs. For work to be carried out in neutron nuclear physics, for which IBR-1 was initially destined, the length of the primary neutron pulse is very critical: the 'quality of the installation', as formulated by Bondarenko, is proportional to I/Θ^2, where I is the average neutron intensity, and Θ is the neutron pulse duration. Subsequently, on Shapiro's initiative, IBRs were extensively used in developing work in the physics of condensed matter, for which the pulse duration is not so critical, but at the beginning of the 1960s we were mostly interested in work in neutron nuclear physics. On the other hand, in the case of one-turn extraction of protons guided

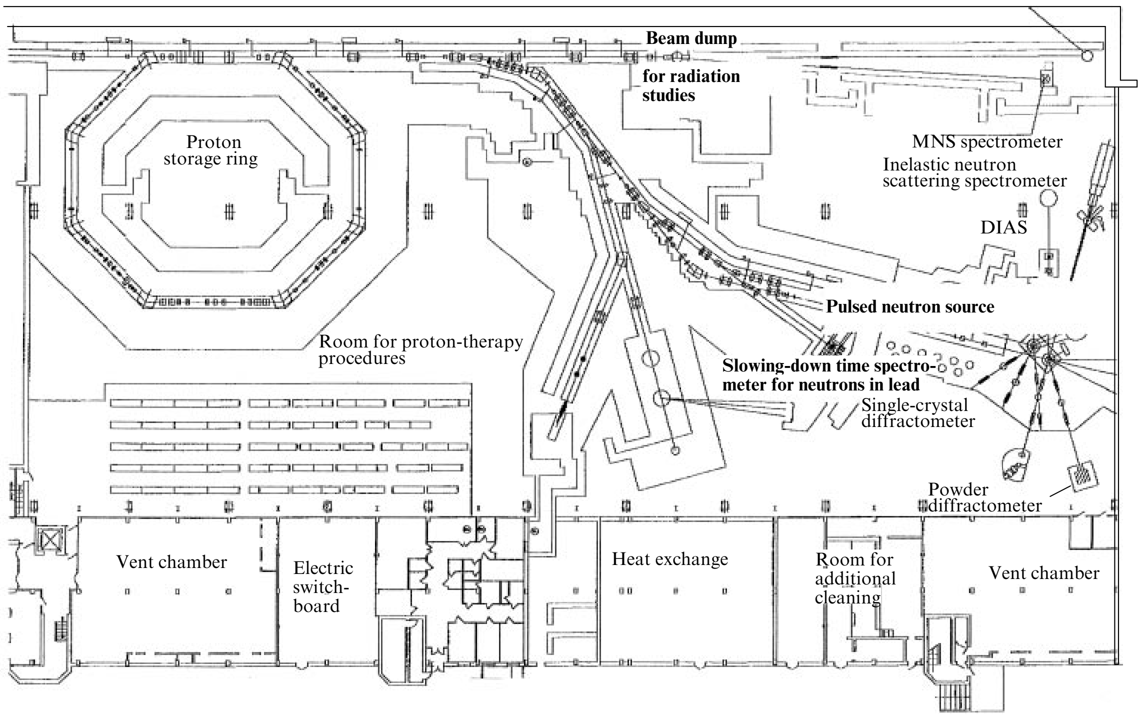


Figure 1. Neutron-radiation complex of the meson factory.

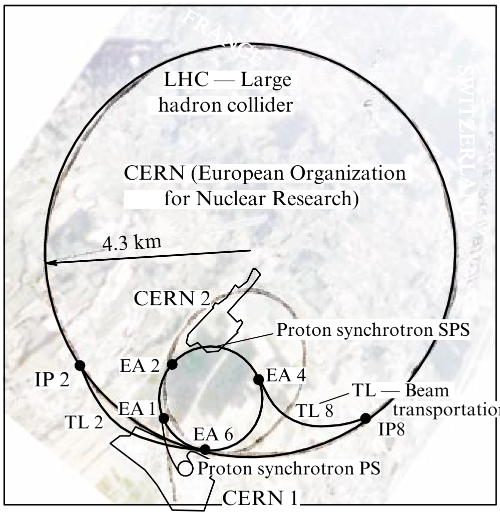
toward a uranium target, a fast-cycle proton synchrotron could provide a pulse length of ~ 10 ns and a ~ 10 Hz repetition rate, which was very attractive for a wide range of neutron-nuclear studies.

With the support of G I Budker and A I Leipunskii, work was initiated at FEI (Obninsk) to create the pulsed neutron source INI-500 based on a proton synchrotron. Regretfully, financial and subjective reasons led to the situation that this work only resulted in the development in 1964 of a detailed technical – economical substantiation at the level of a technical project and a first-cycle construction survey. Subsequently, a similar plan was applied in creating pulsed neutron sources on the base of rapid-cycle proton synchrotrons in the Argonne National Laboratory (USA) — the IPNS series, in the KEK Laboratory (Japan) — KENS, and in the Rutherford Laboratory (England) — ISIS. However, the beginning was set in Russia by the INI-500 project.

The long-lived discussion of the prospects of stationary and pulsed neutron sources was ultimately summed up and brought to an end by practice. At present, the best stationary research reactor for physical studies is the high-flux reactor at the Laue – Langevin Institute (ILL, Grenoble, France). Its key peculiarity consists in the fact that the channels forming the neutron beams extracted beyond the radiation shielding do not 'look' at the active core, but at the 'burst' of thermal neutron flux density in the reflector weakly absorbing neutrons (the 'adjacent' channels). Thus, the contamination of fast neutrons and γ-rays in the neutron beams is reduced by a factor of dozens, which essentially improves the experimental conditions. A similar reactor, but of lower power, has started to operate at München Technical University (Garching, near München, Germany) and a more powerful reactor, of ~ 100 MW design power, is under construction in the Petersburg Nuclear Physics Institute (Gatchina). It must be said that the burst effect of a thermal neutron flux density, occurring inside the extended weakly absorbing reflector of the reactor core with a hard neutron spectrum, was first encountered at the beginning of the 1950s in Russia at FEI (Obninsk). At the time, no calculation methods were available that could permit predicting this effect, and it was tragically revealed during the putting in operation of the reactor-prototype for a submarine power system. The 'uncontrollable start-up phase' of the reactor with an intermediate neutron spectrum and thick graphite reflector, caused by the unexpected high influence of the extreme fuel rods on the reactivity, resulted in the destruction of the core and the death of A V Malyshev, who was loading the fuel [5].

Today, the most effective pulsed neutron source is the ISIS installation of the Rutherford Laboratory (England) based on the rapid-cycle (50 Hz) 800-MeV proton synchrotron. But not for long... .

The pulsed neutron sources presently considered to be the most promising ones are based on strong-current accelerators of protons and of H^- ions with GeV energies. In the Oak-Ridge National Laboratory (ORNL, USA), construction is under way of the intense pulsed neutron source SNS [6] based on a linear ~ 1-GeV accelerator of H^- ions and a storage ring for reduction of the pulse duration. It must be noted that this device is being created in accordance with the US patent [7] obtained in 1975 by our group. Regretfully, not even a single Oak-Ridge reference to this patent and to our relevant publications of the 1970s could be found. In accordance with this patent, the pulsed neutron source was also created at the Institute for Nuclear Research (INR RAS) in Troitsk near Moscow on the base of the 0.6-GeV linear accelerator of protons and H^- ions of the 'meson factory' and the storage ring, which serves as a constituent part of the 'Troitsk Trinity' which also includes a superluminous slowing-down time spectrometer for the neutrons in lead and a radiation complex based on the proton beam dump [8, 9] (Fig. 1). Regretfully, creation of the neutron-radiation complex in the INR RAS has been



Total energy	$E = 7.0$ TeV
Field in dipoles	$B = 8.4$ T
Luminosity of bunches	$L = 10^{35}$ cm^2 s^{-1}
Injection energy	$E_i = 450$ GeV
Circulating (Beam) current	$I_{beam} = 0.53$ A
Number of bunches	$k_b = 2835$
Number of particles per bunch	$N_b = 1.05 \times 10^{11}$
Energy accumulated in beam	334 MJ
Beam lifetime	22 h
Luminosity lifetime	10 h

Figure 2. Layout of Large hadron collider (LHC CERN).

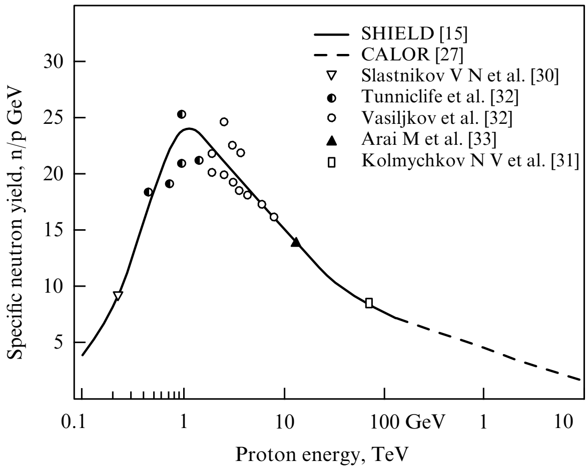


Figure 3.

'held up' at the intermediate stage owing to an ill-considered technical policy... The most powerful pulsed neutron source and, I think, the most promising one from the point of view of its future application is being created as a combination of a $\sim$ 1-GeV linear accelerator of H^- ions (the injector) and a $\sim$ 3-GeV proton synchrotron [the High-Energy Accelerator Research Organization (KEK, Tsukuba, Japan) in collaboration with the Japan Atomic Energy Research Institute (JAERI, Tokai-mura, Japan)] [10].

In this work, another extreme case is considered concerning the application of proton synchrotrons for neutron physics: of superhigh-energy synchrotrons serving as the base of superintense low-frequency pulsed neutron sources (on the order of one pulse in 10 hours). This area of activity was also first framed in Russia at the end of the 1970s [11]. An international workshop dealing with issues of the creation of such a source and its possible applications in various branches of physics was held at JINR (Dubna) in April 2005. Part of the reports presented are to be found in the proceedings of the workshop, published by JINR [12].

Creation of the Large Hadron Collider complex at CERN (LHC CERN, see Fig. 2 [13]) opens up unexpected possibilities for physical research in pulsed superdense fluxes of slow neutrons (thermal, cold, and ultracold). Here, research involving thermal neutrons is considered. Possible experiments with cold and ultracold neutrons are at the discussion and estimation stage.

One of the 'wonders' of nature turned out to lie in the comparability of the proton revolution time in large circular accelerators providing TeV energies ($\sim 70-80$ μs) and the lifetime of thermal neutrons in moderators of limited volume containing hydrogen (water, zirconium hydride) — ~ 100 μs. Precisely this serves as the basis for generating relatively short pulses of thermal neutrons of giant peak flux densities, up to $\sim 10^{20}$ neutrons cm^{-2} s^{-1} [11].

In his time, R R Wilson [14] proposed using high-energy (hundreds of GeV) proton accelerators for so-called 'electronuclear breeding' (ENB signifies obtaining energy and fissionable materials with the aid of accelerated protons or nuclei). This proposal turned out to be erroneous, since the most effective proton energy range for producing neutrons in heavy targets via the cascade-evaporation (spallation) process lies in the vicinity of 1.2 GeV [15]. As the energy E of protons increases, their direct ionization losses in matter drop (approximately as $1/E$), and an increasing fraction of their energy is spent on nuclear excitation which ultimately results in the evaporation of neutrons — the main process in such breeding. However, intensive production of π^0-mesons starts in the 400 – 500-MeV energy range, the decays of which give rise to electron – photon showers. They lead to 'secondary' ionization energy losses of the protons. Competition of the primary and secondary ionization losses results in a broad maximum in the *specific* yield of neutrons from extended heavy targets irradiated by protons (the specific yield is the number of neutrons produced per proton and per unit proton energy) [15, 16] (Fig. 3).

The specific yield of neutrons at this maximum in the case of heavy extended targets (lead, tungsten) amounts to $\sim$ 24 neutrons/proton GeV and in approaching the energy $\sim$ 7 TeV it falls down to $\sim$ 2.5 neutrons/proton GeV. Nevertheless, the large number of protons accumulated in the rings of the accelerator complex [the design value for LHC (CERN) amounts to $\sim 3 \times 10^{14}$ protons] and their high energy provides for the generation of giant neutron pulses in the case of one-turn extraction of the accumulated protons onto a heavy target [11]. The total yield for an extended tungsten target is expected to be $\sim 2 \times 10^4$ neutrons/proton. The main restriction is due to heating of the target during the pulse.

2. Giant pulses of neutrons in LHC beam dumps

The accelerator complex of the Large Hadron Collider comprises two storage rings $\sim$ 27 km long each, in which colliding circulating beams of protons or of other charged particles (nuclei) are created, and a system of accelerators-injectors. The rings have intersections providing for the possibility of performing experiments with colliding proton

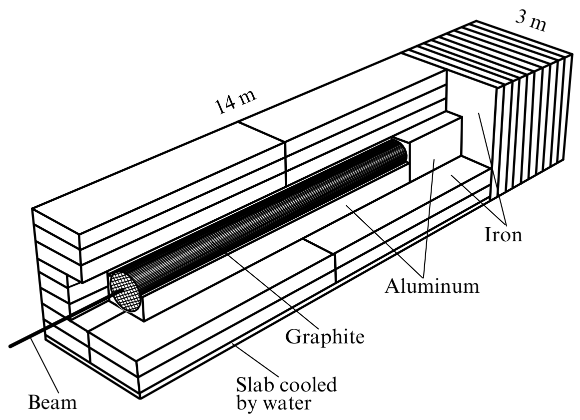


Figure 4. Beam dump.

beams of an energy up to 7 TeV. The initial diameter of the proton beam at the intersection points amounts to approximately 15 μm. With time, the scattering of protons by protons and the accumulation of errors in the bending magnets and focusing lenses lead to a 'swelling' of the beam and to a loss of luminosity which is inversely proportional to the fourth power of the beam diameter. The luminosity lifetime ranges up to about 10 hours. Therefore, every ten hours all the accumulated proton intensity will presumably be dumped via one-turn extraction toward the beam dumps, and the process of proton acceleration and accumulation will be started all over again. The beam dump represents a graphite cylinder ~ 1 m in diameter and about 15 m long, surrounded by radiation shielding (Fig. 4). If a heavy target of thickness amounting to 2–3 nuclear path ranges of protons (about 60 cm in the case of tungsten) is placed at the initial part of the graphite beam dump (at a distance of 10–20 cm away from its frontal surface), then most of the protons will undergo nuclear interactions that will ultimately result in the evaporation of neutrons from the excited nuclei. As already noted, there also exists a competing process — the production of π^0-mesons generates electron–photon showers, the interaction of which with matter produces about two orders of magnitude fewer neutrons than the interaction of hadrons with nuclei. It is precisely the transfer of proton energy to showers that reduces the specific yield of neutrons.

Thus, a heavy target inside a graphite beam dump will represent an intensive pulsed neutron source exhibiting a cascade-evaporation energy spectrum. About 90% of the neutrons will have an average energy of 2–3 MeV and an angular distribution close to isotropic. The remaining cascade neutrons will exhibit an angular distribution strongly stretched out in the forward direction and acquire energies right up to the primary proton energy (7 TeV). The neutron pulse duration will amount to approximately 70 μs — the proton revolution time in the ring.

Such a neutron source will have significant advantages as compared to burst pulsed reactors with self-quenching temperature, having a similar total neutron yield but a longer pulse, a significant yield of delayed neutrons, and essential restrictions in carrying out experiments, especially when it is necessary to 'enter' the reactor core. The neutron source considered will permit making use of practically all the intensity of the superaccelerator for neutron experiments without having to trouble other programs, i.e., it will essentially expand the experimental possibilities of the accelerator complex. It can be readily seen that the complex should have two independent beam dumps, which will provide for at least a twofold enhancement of the experimental possibilities.

To determine the neutron yield when heavy extended targets are irradiated by protons of ultrahigh energies, our group (INR, RAS [15, 16]) and, independently, the group of V F Kolesov (VNIIEF, Sarov [17]) have performed a series of Monte Carlo calculations.

At present, a number of computer programs are being employed in computing the interactions of high-energy protons with matter.

The following are widespread: the modern version of HETC (High Energy Transport Code [18]); LAHET of the Los Alamos National Laboratory (USA); HERMES of the Juelich Research Center, Germany; NMTC — JAERI, Japan, and some others. These programs make use of the H Bertini internuclear cascade model [19] describing in detail all the stages of nuclear reactions in an extended target within the exclusive approach. They are applicable for proton energies up to 10–20 GeV.

The Russian analog of HETC is called SHIELD. The modern version of SHIELD [20–22] permits simulating the production and transportation of nucleons, pions, kaons, antinucleons, muons, and nuclei with arbitrary (A, Z) in extended complex targets for proton energies up to ~ 100 GeV.

The next independent hadron transportation code is termed FLUKA (the first version [23] dates back to 1974). The inclusive approach is applied in simulating nuclear interactions. Its modern version [24, 25] makes use of the two-parton model at high energies (DPMJET, J Ranft), while an original version of the cascade-evaporation model is applied at energies in the vicinity of 1 GeV. The program permits us to simulate hadron cascades in matter at energies up to 20 TeV.

Combinations of computer programs permitting resolving a wide range of problems are also being applied. Such, for instance, is the program CALOR [26, 27] that takes advantage of HETC, MORSE, EGS4, and the multifragmentation model of hadron–nucleus interactions [28]. This program also permits performing calculations for proton energies amounting up to ~ 20 TeV.

Application of the inclusive transportation program MARS [29], the first version of which was developed by N V Mokhov (1975, IHEP, Protvino), has also become widespread.

By now, quite a lot of experiments have been performed for determining the neutron yield from extended heavy targets in the proton energy range from 0.25 up to 70 GeV. Both extreme points were obtained by our experimental groups (INR, RAS) — for 0.25 GeV [30] at the medical channel of the IHEP proton synchrotron, and for 70 GeV [31] at the Serpukhov accelerator. The results of early experiments in the vicinity of ~ 1 GeV are best presented in Ref. [32]. In recent years, data have been obtained at a proton energy of 12 GeV [33].

All these results are in reasonable agreement with our calculations of neutron yields for proton energies in the 0.2–10 TeV range. This opens up the possibility of choosing the most effective proton energy for concrete tasks. Thus, the optimum proton energy for electronuclear breeding equals ~ 1.2 GeV. However, from the standpoint of the accelerator's

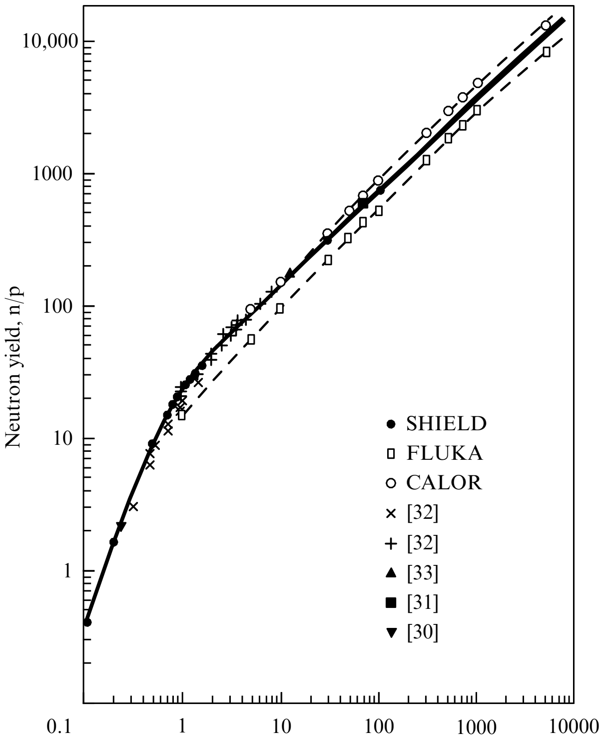


Figure 5.

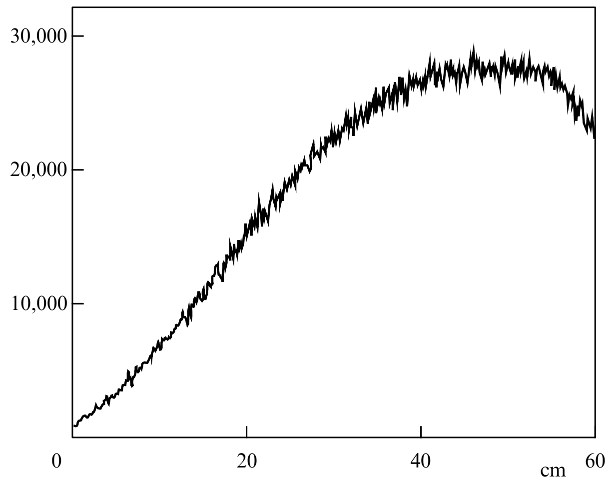


Figure 6. Distribution of neutron sources along the length of the tungsten target.

operation capacity, the compromise energy of about 10 GeV may turn out to be more efficient, providing for a longer lifetime of the ion source with relatively small currents and for less radiation damage, reduced to one neutron produced, to the first wall of the target [34].

Calculations were performed by the Dementyevs et al. [16] for a lead target exhibiting a natural isotopic composition and the shape of a cylinder 20 cm in diameter and 60 cm long. A thin proton beam impinged upon the center of the target along its axis. The FLUKA and CALOR programs were applied in the TeV range, while in the low-energy range the original LOENT program was used with the 26-group set of neutron data obtained by Bondarenko et al. [35]. Electron – photon showers were simulated using the program EGS4 connected to SHIELD by a special interface. Figure 5 shows the yield of neutrons with energies below 10.5 MeV versus the proton energy in the 0.1 – 10 TeV range. Figure 6 presents the distribution of neutron sources along the length of the tungsten target.

A significant discrepancy (with a factor of about 1.6 at 6 TeV) can be observed between the results of calculations performed using FLUKA and CALOR programs. The best agreement with our experimental results at 70 GeV [31] is reached for calculations using the CALOR program, but the energy 70 GeV is too far from the region we are interested in. Therefore, it would be very interesting to obtain at least a single value for TeV energies. This could be done at an energy of 0.9 TeV at the tevatron of the E Fermi National Accelerator Laboratory (FNAL, USA).

In accordance with available information [13], the LHC circulating beams will be dumped horizontally into septum magnets which will bend them vertically and direct toward the beam dumps situated in a distant zone ($\sim$ 750 m).

According to Ref. [13], in order to reduce the thermal load the beam will be 'smeared' over the frontal surface of the graphite by two orthogonal magnets with sinusoidal voltage supplies (14 kHz, 15 kV).

It can be readily seen that synchronization of both magnets would permit us to obtain inside the graphite a circular beam 'blown up' owing to multiple scattering. If a ring-shaped tungsten target with an internal hydrogen-containing moderator is introduced into this beam, it becomes possible to obtain a circular source of cascade-evaporation neutrons with a pulsed flux of thermal neutrons in the cavity of the moderator having a density of $\sim 2 \times 10^{19}$ neutrons cm^{-2} s^{-1} and a pulse length of $\sim$ 100 μs. When a flattened target with a lateral moderator is applied, thermal neutron pulses with a density of $\sim 3 \times 10^{19}$ neutrons cm^{-2} s^{-1} and duration of about 100 μs are obtained for experiments outside the target [37]. This corresponds to a maximum heating of the tungsten (taking into account the inhomogeneity of the energy release) up to about 1500 K per pulse, if $\sim$ 30% of the proton beam intensity is utilized. An analysis performed by Lomidze [38] reveals that this is admissible from the point of view of the target-dump thermomechanics. A possible layout of the rod version of a tungsten target with an internal moderator made from zirconium hydride is presented in Fig. 7.

Within Kolesov's (VNIIEF, Sarov) conception, a target is considered that consists of monolithic tungsten elements distanced with the aid of titanium inserts (Fig. 8). Calculations of neutron fluxes and thermal mechanic stresses have been performed independently of ours making use of the programs GEANT-3 (CERN) and C-95 (VNIIEF). Such a target permits the utilization of the entire intensity dumped from the storage ring, and the peak density of the thermal neutron flux in the cavity of the zirconium hydride moderator will amount up to $\sim 6 \times 10^{19}$ neutrons cm^{-2} s^{-1}, while on the surface illuminating the neutron channel it is approximately 10^{20} neutrons cm^{-2} s^{-1}.

As can be seen from the examples presented, the main operation modes and devices envisaged by the conceptual LHC design provide the possibility of generating powerful pulses of thermal neutrons. Additionally, a target must be created with a system of moderators and experimental channels. In this way, the experimental possibilities of the LHC complex could be significantly expanded.

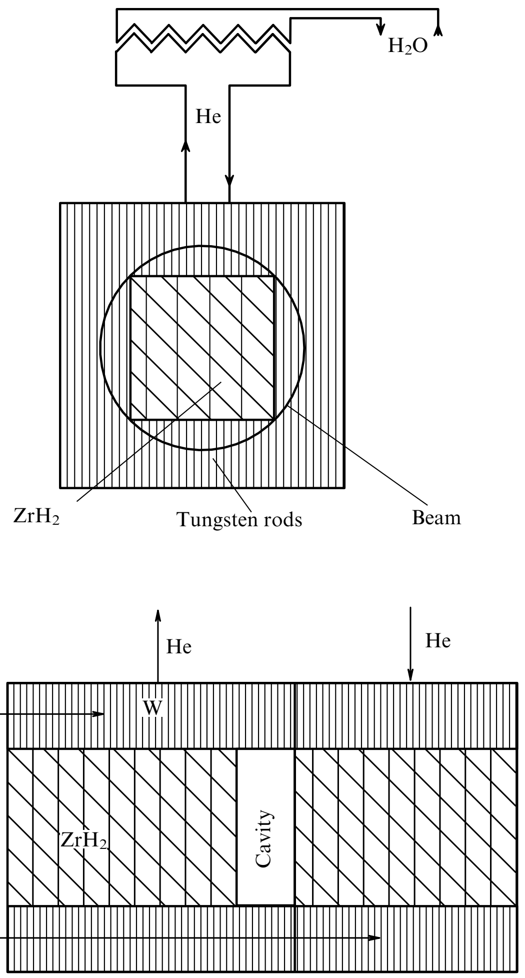


Figure 7. Possible layout of a 'ring-shaped' target of tungsten rods with an internal moderator made from zirconium hydride. Helium cooling is used.

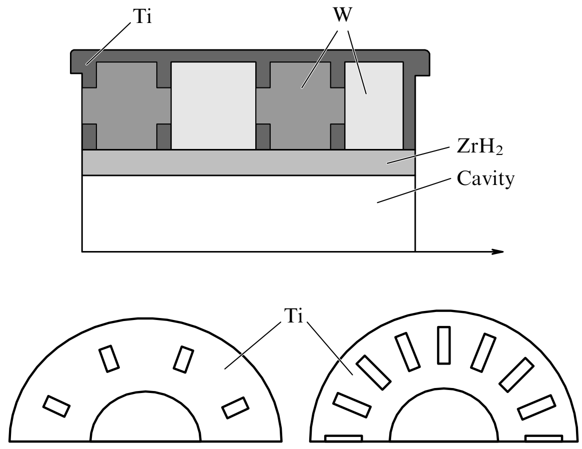


Figure 8. Possible layout of a target consisting of monolithic tungsten elements distanced with the aid of titanium inserts.

3. Possible applications of LHC beam dumps in neutron studies

A pulsed neutron source based on the LHC beam dumps opens up interesting possibilities for studies relevant to neutron nuclear physics, neutron physics of condensed media, and neutrino physics. In parallel with experiments performed in the classical manner, it would be useful to take advantage of giant thermal neutron pulses for studying processes in superdense laser light fields, in superstrong pulsed magnetic fields, and under other extreme states of matter and energy, available only in the 'infrequent-pulses' form, as well as for studying rare processes such as direct scattering of laser light by the magnetic moment of a free neutron or by its polarization, or experimental investigation of light scattering from neutrons bound in a crystal and of the enhancement of this effect in the vicinity of phonon resonances, predicted in Ref. [36].

It makes sense to consider two targets which could be 'coupled' to two dumps — one for the generation of dense pulsed neutron fluxes inside the moderator ('neutron gas'), and the second for generating fluxes of thermal neutrons illuminating the external neutron channel. As already mentioned, computational estimations [17] have revealed that the half-width of the pulse of thermal neutrons inside the cavity of a hydrogen-containing moderator and on its surface, which 'illuminates' the neutron channel, amounts to about 100 μs for a peak thermal neutron flux density of approximately 6×10^{19} and 10^{20} neutrons cm^{-2} s^{-1}, respectively (in the latter case, when a beryllium reflector is utilized).

At present, sufficiently detailed computations have only been performed for one experiment that is of fundamental significance — for the direct measurement of the neutron–neutron scattering length in a vacuum (in the 'neutron gas') [39]. The sole possibility of performing such an experiment with the required accuracy will apparently open up with the LHC beam dump. The other aforementioned possible avenues of research are better treated as information for meditation...

3.1 Experiments in 'neutron gas'

3.1.1 Direct measurement of the neutron–neutron scattering length. Here, the possibility arises (apparently, for the first time) of the direct measurement of the scattering cross section of a neutron by a neutron. In accordance with the hypothesis for charge independence of nuclear forces, the interaction of two nucleons in the same quantum state should not depend on their charge. Thus, for example, the n–p scattering length at low energies should be equal to the n–n scattering length (isospin $T = 1$, spin $S = 0$). The experimental accuracy achieved in the measurements of the n–p scattering length is equal to $\sim 0.5\%$.

There exist over 50 estimates for n–n scattering, which are based on the studies of the influence of the interaction of two free neutrons on the energy spectrum of C-particles in the reaction $A + B = C + 2\text{n}$. These estimates show that the scattering lengths lie within the range of $-11.2 > a_{\text{nn}} > -25$ fm. The average scattering length from these data equals $a_{\text{nn}} = -16.70 \pm 0.38$ fm [40], as compared with $a_{\text{np}} = -23.56 \pm 0.56$ fm. The discrepancy is quite large, not to mention that an essential role is played by assumptions concerning the reaction mechanism, when the estimation is performed. Therefore, although modern theories of elementary interactions have achieved significant success, it is difficult to overestimate the importance of direct experimental determination of the n–n scattering length...

Direct experiments aimed at measuring the n–n scattering length have been proposed many times. The proposal of Ref. [41] was to take advantage of a nuclear explosion. Bondarenko et al. [42] proposed using a burst pulsed reactor

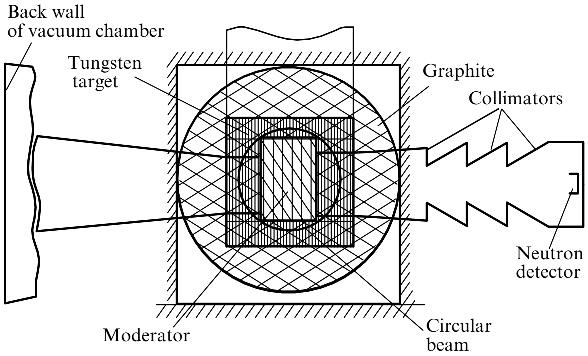


Figure 9. Possible layout of an experiment for the measurement of the n – n scattering length in the beam dump of the Large Hadron Collider (LHC).

operating in outer space. Utilization has been proposed of the powerful pulsating reactor IBR-2 [43] and of burst pulsed reactors [8]. Detailed analysis, however, has revealed it to be impossible to resolve the problem of backgrounds from prompt and delayed neutrons and, moreover, the expected effects are small...

Calculations performed by S A Novoselov with colleagues [39], using the computational program NeuMC developed by V N Miroshnichenko for the LHC beam dump made of tungsten and equipped with an internal zirconium hydride moderator with a cavity, showed that the neutron current across a detector of diameter 2.2 cm will amount to $\sim 10^5$ neutrons per giant pulse due to neutron – neutron scattering in the vacuum cavity of the moderator, while for the Kolesov conception of the target even to $\sim 1.6 \times 10^6$. This would permit obtaining a high statistical accuracy already during a single pulse. Another 5 – 10 pulses would enable introducing the necessary corrections (neutron scattering by nuclei knocked out of the walls of the vacuum chamber, by the residual gas, taking into account the neutron flux density distribution in the cavity, measuring the neutron spectrum applying the time-of-flight technique, etc.). Precisely large effects and relatively small backgrounds give rise to hopes of achieving a high experimental precision on the order of 1%. A possible layout of the experiment (see Fig. 9) includes a ring-shaped target with an internal zirconium hydride moderator. The vacuum chamber is situated in the cavity of the moderator, its back wall is offset by ~ 25 m from the target, while the detector is at a distance of ~ 12 m. The system is equipped with collimators and diaphragms, so the detector does not 'see' the moderator or the walls of the vacuum chamber.

It is proposed to employ three iron-water collimators at distances of 2, 4, and 6 m from the target with average thicknesses of 100, 150, and 180 cm, respectively, with the layers of B_4C and covered with cadmium.

After the onset of the neutron pulse, the detector is supposed to be closed for ~ 3 ms. In this case, no neutrons of energy > 0.84 eV from the moderator or neutrons of energy > 2.2 eV from the back wall of the vacuum chamber will be detected. About 70% of the neutrons scattered in the neutron gas will be registered. The background of thermal neutrons scattered from the sides of the collimators and from the walls of the vacuum chamber will amount to $\sim 1\%$ of the effect, and the background from scattering by the residual gas at a pressure of $\sim 10^{-7}$ Torr will be about 6%. The background of delayed neutrons is negligible. The background of cosmic neutrons is significantly lower than one percent.

3.1.2 Multineutron nuclear reactions. The high pulsed density of thermal neutrons and the large cross sections of their radiation capture, which are not rare in the thermal energy range, paves the way for studies of multineutron reactions, when at least two neutrons are captured by the nucleus before it undergoes β-decay. Hitherto, such reactions have only been observed in nuclear explosions, and even then in the region of above-thermal neutrons or averaged cross sections. In particular, there arises the possibility of synthesizing neutron-enriched transuranium nuclei in the case of multineutron capture in heavy targets (Cm, Cf, Md, and so on). Since the lifetime of a nucleus increases with the number of neutrons in it, isotopes overloaded with neutrons may turn out to be relatively long-lived. This will open possibilities for detailed studies of their properties.

3.1.3 Studies of the interaction between neutrons and radioactive nuclei. The possibility opens up for studying the interaction of neutrons with radioactive nuclei and isomers, in particular, with the nuclei produced in the neutron captures during the pulse.

3.2 Beam experiments

The giant pulses of thermal neutrons at the surface of a flat hydrogen-containing moderator 'looking at' the neutron channel permit studying the properties of condensed media in extreme conditions which can only be realized in the pulsed operation mode — in superstrong magnetic fields, under superhigh pressures, when powerful fluxes of laser radiation are made to interact with matter, and so on.

As an example, one can compare the available fluxes and luminosities in experimental neutron studies of the magnetic properties of matter, carried out with different pulsed neutron sources — the powerful pulsating reactor IBR-2 at LNF of JINR (with a pulse repetition rate of 5 s^{-1}), the single-pulse reactor BIGR (VNIIEF, Sarov, Russia), and the beam dump of LHC (CERN) [44]. In performing the comparison, the layout was used of the neutron spectrometer with a pulsed magnetic field, SNIM-2, for the pulsating reactor IBR-2 of the JINR Laboratory of Neutron Physics. The high repetition rate of the neutron pulses (5 pulses s^{-1}) excludes the applicability of pulsed magnetic fields of high strength (only up to ~ 250 kOe) in the case of magnets produced by the National High Magnetic Field Laboratory (NHMFL, Tallahassee, USA). In the case of infrequent-pulses sources (BIGR, the LHC beam dump), pulsed magnets can be used with a peak field of 600 – 1000 kOe, in the latter case involving destruction of the magnet (see Table 1).

Table 1.

	SNIM-2 (IBR-2)	BIGR	LHC
Peak flux density, neutrons cm^{-2} s^{-1}	7×10^{15}	2.5×10^{17}	10^{20}
Pulse duration, μs	300	2000	100
Repetition rate	5 pulses s^{-1}	day^{-1}	1/10 h
$P1\Delta\lambda_m(3$ Å), neutrons cm^{-2} per pulse	1.25×10^3	4.5×10^4	1.5×10^6

Here, $P1\Delta\lambda_m$ is the number of neutrons scattered during one magnetic field pulse, if the reflectivity of the sample-crystal is considered equal to unity.

3.3 Neutrino studies

3.3.1 Studies in neutrino fluxes from the target. It is of interest to compare nuclear reactions in fluxes of reactor antineutrinos, the source of which are actually neutron-excess fission fragments, with nuclear reactions in neutrino fluxes from decays of neutron-deficient products of the cascade-evaporation process in heavy target-dumps (the problem of Majorana forces).

3.3.2 Studies in hard neutrino fluxes. It is interesting to apply giant thermal neutron pulses for generating hard neutrino fluxes making use, for example, of a lithium convertor (see, e.g., Ref. [45]).

4. Conclusion

The creation, in the frontal part of the LHC graphite beam dump, of a heavy target with a hydrogen-containing moderator opens up new possibilities for neutron studies in particle physics, nuclear physics, and the physics of condensed media, with the use of the total intensity of the complex and without any competition with other programs considered for LHC (CERN).

I must once again recall (see the first lines of the Introduction) that back at the end of the 1950s Igor' Il'ich Bondarenko (FEI, Obninsk) drew our attention to the experimental possibilities for the nuclear physics of low and intermediate energies, which open up with the creation of high-energy accelerators with strong focusing. Essentially, this is what gave rise to the proposal presented in this article.

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