Journal of Applied Mechanics and Technical Physics, Vol. 38, No. 4, 1997

HIGH-POWER NEUTRON SOURCES

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UDC 539.125.5;539.164

Introduction. The most advanced countries of the world — the USA, Japan, the countries of the European Union, and Russia — have approached the solution of the controlled fusion (CF) problem and continue to develop the International Experimental Reactor (ITER). Although the science is familiar with many fusion reactions that are perfect from the ecological viewpoint, i.e., without neutron emission ($p + \mathrm{B}$, $^3\mathrm{He} + {}^3\mathrm{He}$, and $^3\mathrm{He} + \mathrm{D}$; in the latter case, neutrons are created only in the side channel of the low-intensity reaction D+D), in the forthcoming decades the level of engineering will allow one to use only the D–T reaction: $\mathrm{D} + \mathrm{T} = {}^4\mathrm{He}(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV})$, in which most of the energy is released with neutrons. The development of fusion energetics in the near future is associated precisely with this reaction because it proceeds at the lowest temperatures (100–200 million degrees) [1].

Since the density of the neutron flux which acts on the wall of a thermonuclear DT reactor should be of the order of a few MW/m^2, one of the key problems of fusion energetics is the creation of new radiation-stable structural materials and low activated materials. This complicated physicotechnical problem can be solved by the joint efforts of materials science researchers in many countries. It is impossible to go ahead in this field of research without the creation of a high-power source of thermonuclear neutrons. The Fusion Programme Evaluation Board headed by H. Colombo concluded that such a source should be created within the framework of the ITER program for the shortest period [2].

At present, reliable data on the behavior of structural materials exposed to long-term high-energy neutron irradiation are absent, because low-energy neutron tests in nuclear reactors cannot answer most of the questions. Thus, there is uncertainty the in evaluation of the radiation stability and durability of the basic structural materials. The ITER itself will not solve the problems encountered, since the total fluence for the period of its operation will amount to as little as 1 MW·yr/m^2 ($1.5 \cdot 10^{21}$ neutrons/cm^2) [3], and this fluence will be accumulated only at the end of the reactor run, so that the data obtained will not offer the possibility of making a correct choice of structural materials for an experimental thermonuclear power plant. Despite the fairly moderate density of the thermonuclear power released per unit volume in the case of a tokamak reactor (~3 MW/m^3) [1], the neutron load at the first wall of a thermonuclear reactor should be 2–3 MW/m^2 (or $\sim 10^{14}$–$1.5 \cdot 10^{14}$ neutrons/cm^2 · sec). The time of action of the neutron flux at the wall should be equal to 10–20 yr. Thus, the total fluence experienced by the first wall for the period of the campaign is estimated to be $3 \cdot 10^{22}$–$9 \cdot 10^{22}$ neutrons/cm^2.

Clearly, however successful the operation of the ITER, an experimental fusion power plant cannot be created if a large program of fusion materials development (durability, decrease in the conductivity upon irradiation damage, variations in the mechanical properties of materials, soldered joints, and welds, etc. because of hydrogen and helium accumulation in them) is not realized long before the beginning of its construction. To implement such a program, it is necessary to create a dedicated source of D–T neutrons with a rather large volume of the test zone. Apart from the solution of the materials science problems mentioned above, such a source could be very useful in the creation of low activated materials.

At present, a large number of approaches to the solution of the problem of the creation of a high-flux neutron source are known. Several workshops concerning this problem were held under the aegis of the International Energy Agency (IEA) [4–7]. At the first of them, the basic requirements for a high-power

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Budker Institute of Nuclear Physics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 38, No. 4, pp. 77–89, July–August, 1997. Original article submitted February 24, 1997.

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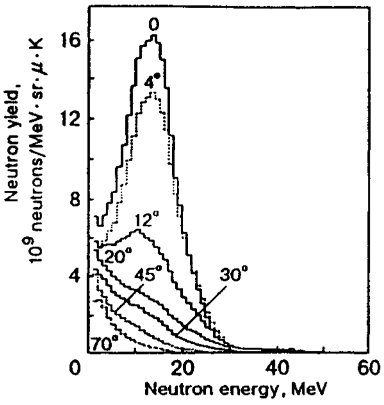

Fig. 1

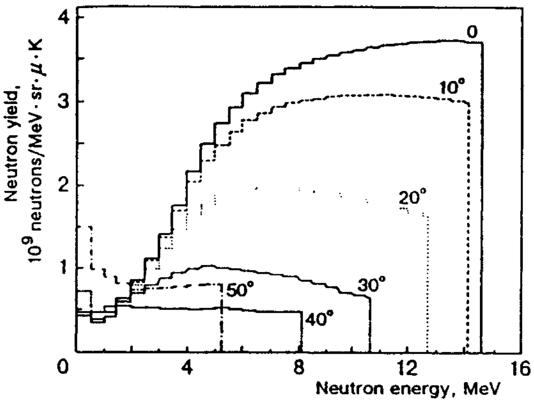

Fig. 2

neutron source for the purposes of materials science were formulated: the neutron fluence should be not less than 2 MW/m^2, the volume of the test zone should be not less than 10 liters, and the flux gradient should be not less than 10% per centimeter. It was later proposed to test not only materials, but also the components of a future thermonuclear reactor [8]. In this case, the test-zone area was estimated to be equal to 10–20 m^2.

At workshops, the opinion that the cost of a neutron source should not exceed 5–10% of the cost of the ITER project was voiced repeatedly. This is also true for the operating cost [9], which mainly covers the energy and tritium cost. Nonsatisfaction of these conditions can lead to revision of the entire project.

At the modern level of electricity prices, the consumption of a megawatt will cost 860 thousand USD annually. To generate a 14-MeV neutron flux at a power of 1 MW, it is necessary to expend approximately 70 g of tritium per annum; at a price of 30 thousand USD per gram, this will cost 2 million USD. In most of the source projects considered above, the energy consumption amounts to hundreds of megawatts, and the tritium consumption amounts to several (sometimes over ten) kilograms. The world production of tritium is estimated to be 5 kg annually. Despite the diversity of the proposed designs of neutron sources, one can group them into two groups: accelerator-based neutron sources and plasma-based ones.

1. Accelerator-Based Neutron Sources. Four types of neutron sources based on the use of charged-particle accelerators are known.

Spallation Sources [10]. In bombarding heavy targets (Bi, Pb, and U) by a proton beam with an energy of approximately 1 GeV, a wide spectrum of neutrons (0–1 GeV) whose intensity rapidly decreases with increasing neutron energy is formed. Within the interval 10–15 MeV, only a few percent of the total amount of neutrons are emitted, and the efficiency for this spectral range is as small as fractions of a percent.

A Source Based on the D–Li Reaction. The D–Li reaction, which is sometimes called the stripping reaction, allows one to produce neutrons with an energy close to that of thermonuclear neutrons as a result of the accelerated deuteron–lithium target interaction:

$$^7\text{Li} + \text{D}(35\text{–}40\ \text{MeV}) \Rightarrow {}^8\text{Be} + n.$$

Figure 1 shows neutron spectra of this reaction which are observed at various angles to the normal [11, 12]. Similar spectra are observed upon bombardment of a beryllium target by deuterons. There are several projects of a D–Li-based source (see the references cited in the review [12]). The FMIT project (USA) (35 MeV and 100 mA) makes it possible to produce a 2 MW/m^2 neutron flux on a 5 × 5 cm surface. The parameters in the ESNIT project (Japan) are more moderate: 10–40 MeV and 50 mA. Finally, the conceptual IFMIF project (40 MeV and 250 mA) [13] is being developed on a three-sided basis: the USA, European Union, and Russia.

Neutron Source on the Basis of the T–H$_2$O Reaction. In the bombardment of water by accelerated tritium atoms, the reaction occurs with neutron emission: $^1\text{H} + \text{T}(21\ \text{MeV}) \Rightarrow {}^3\text{He} + n$. The maximum neutron energy in this reaction is 14.6 MeV (at the triton energy equal to 21 MeV). Figure 2 shows the neutron yield of

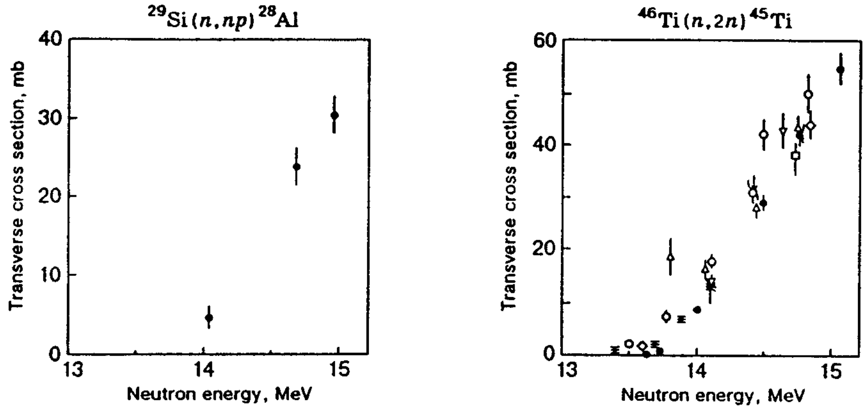

Fig. 3

the H-T reaction for various angles of neutron emission. The calculation was performed for 21-MeV tritons incident on a thick water target. In the triton-oxygen collision, the maximum neutron energy corresponds to the initial triton energy (21 MeV), but the yield of this reaction is an order of magnitude smaller compared with the first case. The source considered yields to the D-Li source in terms of efficiency by approximately a factor of 2. In addition, the feasibility of a water target at the power level in a 5-MW tritium beam still remains open.

As for the D-Li reaction, the IFMIF project is the best from the engineering viewpoint. The neutron source is assumed to consist of two linacs, each with energy 40 MeV and current 125 mA. In the opinion of the International Energy Agency's experts, precisely this source deserves to be built and could be ready in 2006 [13]. This source would allow one to obtain many results important for fusion materials science but would not be able to solve all the problems of structure materials tests. Apart from a very small testing zone (0.5 liter at a neutron-flux density of 2 MW/m^2), the source has another drawback: unlike a thermonuclear reactor, it cannot produce 14-MeV monochromatic neutrons. As is seen in Fig. 3, the activation cross sections depend strongly on the neutron energy [14]. This means that in analysis of materials exposed to an irradiation cycle by a nonmonochromatic neutron flux, substantial errors are possible, especially in cases where there are "tails" of the neutron spectra in the range of energies higher than 14 MeV.

Summarizing the consideration of accelerator systems, one should mention that all of them have a low energy effectiveness (high cost of a neutron), a small volume of the test zone, and an inadequate neutron spectrum.

μ-Catalysis-Based Source. Among the designs of neutron sources based on the use of accelerators, there is a single design allowing the production of a flux of 14-MeV monochromatic neutrons. During bombardment of a target by a beam of protons, deuterons, or tritons with energy 1-1.5 GeV, negative μ-mesons are produced in one of the reaction channels. The interaction of these mesons with a dense gas target consisting of D_2 and T_2 molecules results in the production of DT molecules in which one of the electrons is replaced by a negative μ-meson.

As a result of nuclear fusion whose probability in mesomolecules is very high, a target containing a low-temperature mixture of deuterium and tritium emits 14-MeV monochromatic neutrons. As experiments show, one meson for its lifetime produces over a hundred mesomolecules and initiates the production of the same amount of neutrons [15]. In [16], Petitjean et al. described the design of a hybrid reactor in which a dense DT target placed in a magnetic field of mirror geometry is used to produce a primary-neutron flux. The concept of the source is based on the use of an accelerator of protons or deuterons with energy 1.5 GeV and current 12 mA. The idea of monochromatic neutron generation is clearly demonstrated in Fig. 4. The beam of accelerated particles is directed to a rotating graphite target 1 located in a strong mirror-geometry magnetic field. Negative π-mesons are produced under the action of the beam particles. During further motion of pions in a vacuum chamber 2 along the magnetic-field lines, μ^--mesons are generated as a result of π^--meson decay.

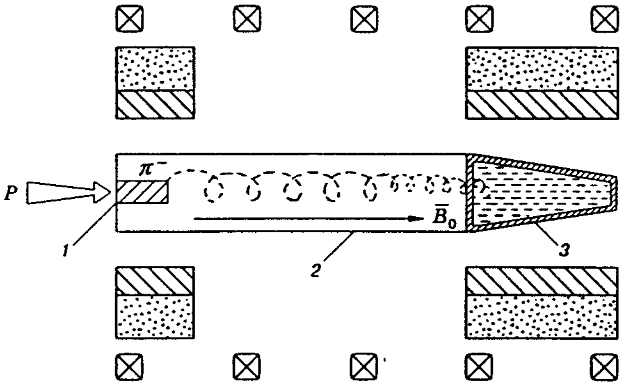

Fig. 4

The μ^--mesons produced penetrate into a DT target 3 of length 50 cm at a mixture pressure of 1000 atm. The physical cost of the formation of one μ^--meson upon irradiation of the input target by a deuteron beam is approximately 8 GeV (for the proton beam, the cost is even higher and is approximately 20 GeV) [17].

Thus, under the above-indicated parameters of the accelerator with a deuteron beam, the source will produce approximately 200 kW neutrons with energy 14 MeV. Despite the seeming attractiveness of this approach, it is very far from practical realization. It is worth mentioning only one difficulty: as noted, to utilize each meson effectively, the pressure of a DT mixture should be 1000 atm. The target temperature should rise over 1000°C because the energy of alpha particles is released in the target (3.5 MeV per fusion act).

2. Plasma-Based Neutron Sources. The necessity of creating high-power sources of 14 MeV neutrons was recognized as early as the 1970s when low-power neutron sources with 10^{11}–10^{12} neutrons/sec (0.2-2 W) fluxes were built and when the first projects of plasma neutron sources, which were very far from reality, were developed. A special issue of the journal "Nuclear Instruments and Methods" including 17 papers [18] was published in early 1977. This issue was devoted to a description of sources which were built at that time on the basis of an acceleration technique and also to a discussion of various concepts of plasma-based neutron sources. The plasma parameters in those projects were too far from those required. This problem was addressed again in 1983–1984. In the papers published in the 1980s, the possibilities of using modern types of open magnetic traps were mainly analyzed [19–27]. The first projects of tokamak-based neutron sources have appeared quite recently, at the beginning of the 1990s [28–32]. It is well known that among the existing concepts of plasma confinement and heating, tokamaks have a leading place. In 1992–1994, the high-power neutron radiation of the thermonuclear DT reaction was already observed for several seconds at the biggest tokamaks in the world (JET, TFTR, and JT-60). Note that at TFTR (USA), the power of the neutron flux reached 10.6 MW. The level of understanding of the physical processes occurring in the high-temperature plasma of tokamaks is rather high and, hence, even the very first neutron-source projects based on tokamaks did not require too considerable extrapolations of the parameters relative to the existing tokamaks (in any case, this assertion is true for big tokamaks), i.e., these projects looked quite realistic. The proposed projects, however, had some shortcomings. In most of the first projects, the power consumption ranged from 500 to 1000 MW. For the European energy price (10 cents per kilowatt-hour), the energy expenses alone would amount to 430 and 860 million USD annually. The characteristic surface area of a vacuum chamber in a big tokamak exceeds a hundred square meters. With a neutron-flux density of 2 MW/m^2, 14 kg of tritium per annum would be required (420 million USD), whereas the annual production of tritium throughout the world amounts to approximately 5 kg. This enables one to conclude that even if the financial problems could be overcome, the creation of tokamak-based neutron sources is questionable.

Subsequent efforts were devoted to the projects of neutron sources with a tritium-production system using a lithium-containing blanket. In [33], Ogawa et al. noted that, for a Li–Pb mixture, the tritium reproduction coefficient is 1.4. Tsuji-Iios et al. [34] also analyzed the problem of tritium reproduction in the blanket. In addition to material tests, the authors proposed to use neutron fluxes for transmutation of the radioactive waste of atomic power plants.

We shall return to the original formulation of the problem. The status of research in high-temperature plasma physics makes it possible to set up the problem of construction of an experimental thermonuclear power plant DEMO in the near decades. A high-temperature plasma with required parameters ($n \simeq 10^{14}$ cm^{-3} and $T_e \simeq T_i > 10$ keV) has already been reached. After the ITER is created, the ignition of the self-sustaining controlled nuclear fusion reaction will be demonstrated. In this regime, a DT plasma will liberate through alpha-particles and neutrons a giant heat power, which can be utilized. What is still needed? Only the properties of structural materials and their resistance to neutron fluxes are unknown. To test materials under conditions close to operating ones, a high-power neutron source that must work continuously for a decade is needed. If one considers the projects of neutron sources based on the concept of big tokamaks from this point of view, one can notice that they are similar to the simplified designs of thermonuclear reactors. The neutron-flux density in these projects is the same as in the reactor (2 MW/m^2), but the lifetime of the first wall of the neutron source is unknown. If one adds the cost of the source construction, operating expenditures, and tritium problems, it becomes clear that there is no solution along this line of research.

However, there is one more approach associated with compact tokamaks. In recent years, the interest of researchers has turned to tokamaks with small aspect ratio $R/a < 1.6$ (R and a are the long and short radii of the torus). In conventional tokamaks, this quantity exceeds 3. The decrease in the aspect ratio allows one to increase considerably the parameter $\beta = P/(H^2/8\pi)$, where $P = 2nT$ is the plasma pressure. This gives the possibility of producing a plasma with thermonuclear parameters in tokamaks of small dimensions. Correspondingly, the tritium and power consumption decreases. The realizability of a tokamak with small aspect ratio was demonstrated on the START facility in Culham [35] in 1992. Not long ago, at this tokamak the quantity β reached 0.48, which is one order of magnitude greater than in conventional tokamaks, with conservation of the magnetohydrodynamic (MHD) stability [36]. In 1993, the first project of a neutron source based on a compact tokamak with tight aspect ratio was proposed by Hender [32]. A year later, the Material Test Facility (MTF) project was considerably improved [37]. In this project, a compact steady-state spherical tokamak with low aspect ratio ($R/a < 1.6$) is considered. To form a toroidal magnetic field, a low-voltage source with current 0.5 MA is needed. Plasma heating and current sustainment in a plasma is accomplished by means of the injection of neutral atoms (injector power is 28 MW). For $T_e = T_i = 20$ keV and a plasma density of 10^{14} cm^{-3}, the density of the neutron flux will reach 1.4 MW/m^2, and the total power of this flux is 14 MW. It is important that the low aspect ratio can be obtained only for spherical tori (the internal toroid diameter should be very small). This implies the impossibility of using a neutron shield and forced the authors of the project to abandon the multicoil winding of a toroidal magnetic field (intercoil insulation does not withstand neutron irradiation). Therefore, they suggested inserting a massive copper column through an opening in the toroid and connecting the coils of the toroidal winding to one of its ends. On the opposite side, a low-voltage current generator should be located between the column face and the extremities of the winding coils. The current density in the column reaches 12 MA/m^2. In water cooling under pressure, the working temperature of the copper column is 127°C. Owing to transmutations, the conductivity of copper will decrease with time, which will have a negative effect on power consumption. The authors of the project note that the ohmic losses alone in the column will amount to 30 MW in the initial state. The column is expected to be replaced every 2–3 yr. Since hydrogen and helium accumulation in copper owing to nuclear reactions leads to the loss of its mechanical uniformity, it is not ruled out that the conductivity will decrease much more rapidly than the authors assume. Despite the attractiveness of the possibility of creating a neutron source based on a compact tokamak with low aspect ratio, a large amount of work needs to be done to accumulate a physical data base and to improve the parameters of such facilities. Unlike big tokamaks, where the parameters are close to those desired, they are far from the required parameters in compact tori. Despite the fact that after modernization of the START tokamak and application of a neutral-beam injection system, the ion and electron temperatures rose, respectively, from several tens to 300 [36] and 600 eV [38] with plasma density required for the source ($n = 10^{14}$ cm^{-3}), the needed parameters ($T_e = T_i = 20$ keV) are still far from being reached. After one more compact torus, GLOBUS-M, is put into operation, which is planned in early 1998,

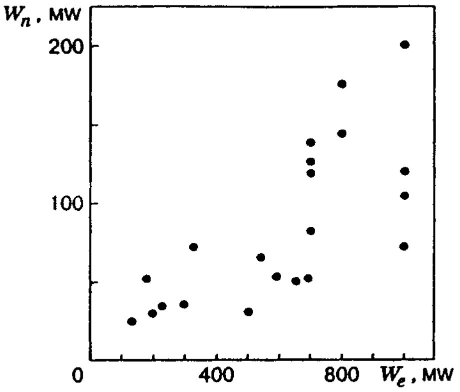

Fig. 5

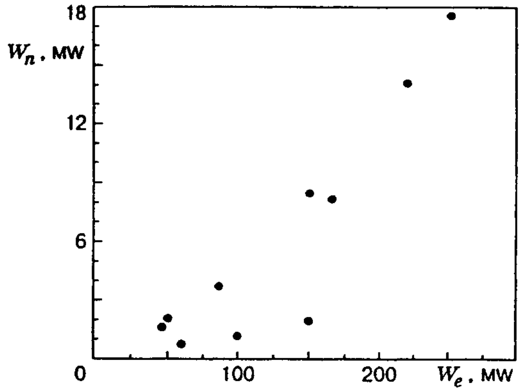

Fig. 6

the accumulation of a plasma-physical data base for compact tokamaks with tight aspect ratio will occur much more intensively. Possibly, in a few years the project of a neutron source based on a compact tokamak will be regarded as one of the most promising.

The total number of tokamak-based neutron-source projects is rather large. Along with the above-mentioned concepts of large and small tokamaks are the concepts of intermediate facilities. Each point in Fig. 5 refers to a separate project: points on the right indicate large-scale tokamaks and points on the left indicate compact torus-based sources; W_n is the total neutron-flux power and W_e is the power consumption. The diagram does not show some projects with high amplification factor and high thermonuclear power [34, 40].

We have not touched upon the problem of the use of superconducting windings for tokamak-based neutron sources. Superconductors are very sensitive to neutron irradiation. Clearly, they offer no promise for compact facilities. The shield thickness is estimated to be equal to 0.8–1.2 m. It follows that superconductors can be employed only in tokamaks with radius 4–5 m. Hence, a similar system appears to be noncompetitive from economic considerations: its cost will be comparable with that of the ITER. In addition, the problem of tritium consumption is also unavoidable.

As noted, the problem of the creation of high-power neutron sources began to be discussed in the 1980s. The first projects of such sources were based on open magnetic traps [19–27]. Such sources have a number of important advantages. The power Q_n emitted from a plasma in the form of neutrons is determined by the following quantities:

$$Q_n \backsim n_{\mathrm{D}} n_{\mathrm{T}} \backsim p^2 = (\beta H^2/8\pi)^2 \backsim \beta^2 H^4.$$

It is seen from the above relation that the specific power increases considerably with increasing β. For tokamaks, the value of $\beta < 0.1$, whereas in the case of open traps (and this is shown experimentally by Coensgen et al. [41]), this quantity is significantly greater: $\beta \simeq 1$. As a consequence, sources based on open systems are more compact compared with tokamaks. They can be built on a step-by-step basis, beginning with devices with a relatively small neutron flux. Lengthening gradually the traps and increasing the power of neutral injection, one can increase the neutron flux and the test-zone area. Each point in Fig. 6 indicates a separate project with total neutron power W_n and power consumption W_e.

It is evident that such sources allow one to generate neutron fluxes whose power is one order of magnitude smaller (1–18 MW) than that of tokamaks, and whose power consumption is a factor of 4–5 lower. Their cost is also incomparably lower compared with tokamak-based projects. A steady-state mode of operation is typical of open traps. Disruptions, which are dangerous for the vacuum chamber walls of tokamaks, are not inherent in open traps. However, despite the undoubted advantages of open traps, we have to say that most of the projects based on them require plasma parameters considerably exceeding those that can be reached at present. Table 1 lists the basic parameters of source projects based on ambipolar-confinement traps.

Unfortunately, the plasma parameters required for implementation of these projects give no grounds

TABLE 1

Design parameters of source	TASKA-M [19]	FEF-II [22]	TDF [23]	MIT-87 [24]	K-88 [27]
Power consumption, MW	166	40	250	150	220
Maximum density of neutron flux, MW/m^2	1.3	2	1.4	1.8	2.5
Tritium consumption, kg/yr	0.55	0.37	1.2	0.57	1
Neutral-beam injection power, MW	50.4	5.5	76	100	98
Test-zone radius, m	0.25	0.16	0.25	0.25	0.3
Plasma density, cm^{-3}	$3.2 \cdot 10^{14}$	$4.1 \cdot 10^{14}$	$6.0 \cdot 10^{14}$	$6.7 \cdot 10^{14}$	$2.4 \cdot 10^{14}$
Electron temperature, keV	14	4.4	2.1	2	—

TABLE 2

Design parameters of neutron injectors	2XIIB	GDT-2	GDT-3	GDT-3M
Power consumption, MW	100	50	60	47
Maximum density of neutron flux, MW/m^2	10.0	3.9	2.0	1.8
Test-zone radius, m	0.06	0.06	0.07	0.07
Test-zone length, m	0.35	1.2	2.5	3
Tritium consumption, kg/yr	0.1	0.12	0.15	0.16
Plasma density, cm^{-3}	$1.3 \cdot 10^{15}$	$3.7 \cdot 10^{14}$	$2 \cdot 10^{14}$	$1.7 \cdot 10^{14}$
Electron temperature, keV	0.19	0.52	1.1	0.65
Injection energy, keV	200(D)	240(T)	80(D) 94(T)	65(D) 65(T)
Neutral-beam injection power, MW	47	20	15	22
Magnetic field in mirrors/in the midplane, T	12/4	25/1.25	26/1.8	13/1.3

to hope to realize them in the near future. The maximum experimental plasma density is only $2 \cdot 10^{12}$ cm^{-3} [42], and the electron temperature is 0.26 keV [41]. However, there are two concepts in which a considerable increase in plasma parameters compared with those already reached is not needed. The first is based on the use of the 2XIIB-type open trap [25, 41] (Livermore, USA). The basis for this project is a very moderate extrapolation of experimental data. The attractive feature of the project lies in dropping attempts to reach thermonuclear plasma temperatures. A two-component plasma ("cold" tritons and fast deutrons) is assumed to be used. High-energy deutrons (200 keV) are formed using external sources of neutral atoms. Neutrons are produced from the collisions of fast deutrons with plasma tritons. The longitudinal plasma thermoinsulation in the trap is accomplished using long end sections with collisional heat conductivity. To suppress MHD instabilities, quadrupole windings of a magnetic field are employed. Application of superconductors to the formation of a quadrupole configuration of the magnetic field leads to increasing winding dimensions, because the superconductors should be reliably shielded (shielding thickness is over a meter). A limitation of the project is the fact that deuterium injectors "look" directly at the plasma volume emitting neutrons. This decreases the lifetime of high-voltage insulators. However, all tokamak-based neutron sources have the same drawback. Unfortunately, the project was not continued and, in practice, is not developed for the time being.

The second concept based on the use of an axisymmetric gas-dynamic trap (GDT) and formulated as early as 1984 [20] is being developed. Several versions of a GDT-based neutron source have been considered: a two-component version of GDT-2 where high-energy tritons are injected into a "warm" deuterium plasma [20] and a three-component version GDT-3, where beams of deuterium and tritium atoms are injected into a "warm" target plasma [43]. Recently, the source parameters have been optimized based on the accumulated

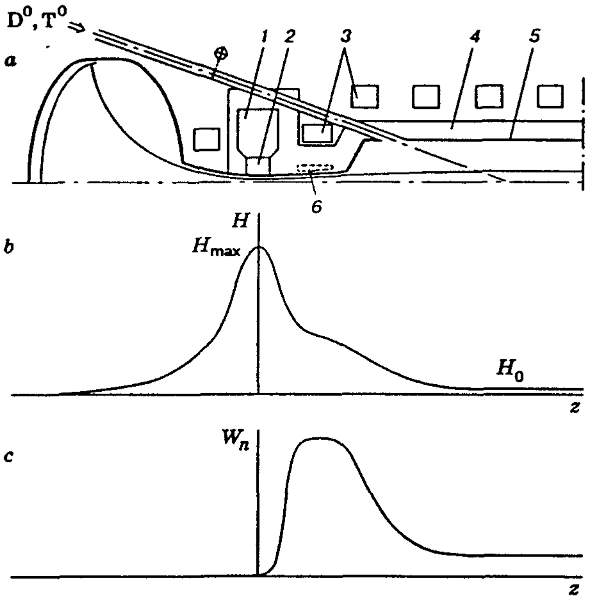

Fig. 7

experimental data and computations, thus allowing a substantial simplification of its design, with a very insignificant decrease in the neutron-flux total power [44].

Table 2 shows the parameters of the neutron sources based on the 2XIIB and GDT concepts.

The principle of operation of the GDT-based neutron source is very simple (Fig. 7a). During oblique injection of neutral atoms into a "warm" plasma in an axisymmetric trap with large mirror ratio ($K > 10$), fast atoms are captured as a result of the charge exchange on slow plasma ions. Fast atoms are transformed into fast ions, while slow ions are transformed into slow atoms and leave the plasma after such collisions. As a result, a population of "sloshing" high-energy ions is formed in the plasma. The density of these ions is strongly inhomogeneous along the system's axis.

As the computations performed by Ivanov et al. [44] showed, in the last versions (GDT-3 and GDT-3M), the main contribution to the output neutron power is given by fast–fast DT collisions. The contribution of these ions to neutron yield because of collisions with "warm" plasma ions is negligible. It is noteworthy that the realization of this scheme of the source requires very moderate plasma parameters. The electron temperature (0.65 keV) is only a factor of 2.5 greater than that reached in open-trap experiments. At the large mirror ratios peculiar to gas-dynamic traps (the magnetic-field profile is shown in Fig. 7b), the maximum neutral-flux zone is rather far from the mirrors (see Fig. 7c). This makes it possible to reliably shield 4 mirror coils 1 and 2 (see Fig. 7a). Another important advantage of the concept considered is the fact that the plasma diameter is considerably (by an order of magnitude) smaller than the diameter of a vacuum chamber 5. Thanks to this, the neutron load at the chamber walls is substantially lower compared with the load typical of other schemes. The second factor acting in the same direction lies in the fact that the density of "sloshing" ions appears to be much smaller over most of the trap length rather than in the vicinities of the reflection points. As a consequence, the basic part of the vacuum chamber is exposed to much weaker irradiation compared with test zone 6. This enables one to employ superconducting windings 3 for creation of a longitudinal magnetic field. Owing to the above-mentioned factors, unlike any other designs of neutron sources, high-voltage insulators of neutral-beam injectors operate under more favorable conditions. Finally, among the merits of the scheme considered, one should mention the possibility of creating an MHD-stable plasma configuration in an axisymmetric magnetic system [45] and also a simple and reliable physics of longitudinal confinement.

The major technical difficulties encountered in the creation of a GDT-based source are reduced to the problem of the formation of a strong magnetic field in mirrors, the problem of the first wall of a test zone, and the problem of magnetic field generation based on superconductors, or more precisely, the problem of

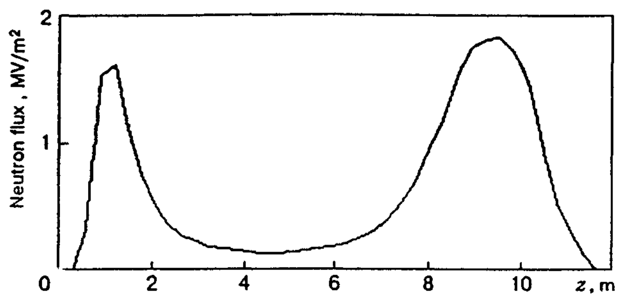

Fig. 8

shielding superconducting windings against neutrons. As for a high magnetic field (26 T), despite the fact that no reliable solutions that would allow one to obtain a similar field for a year are available, this value does not seem, nevertheless, fantastic. A magnetic system with a 25-T field strength and with a resource of approximately 300 h is described by Klyavin et al. [46]. The problem of periodic removal of the first wall from the test zone by means of robotics was discussed by Astapkovich et al. [47] in connection with the development of the GDT-based neutron source project. Finally, the possibility of shielding superconducting windings against neutrons was shown by Robouch et al. [48]. It is noteworthy that the level of development of a GDT-based neutron source is fairly high from both the physical and engineering viewpoints [44, 49–51]. Accumulation of the plasmaphysical data base using the operating GDT facility is being continued. In addition, joint studies of this problem are being performed by the Budker Institute of Nuclear Physics, Siberian Division of the Russian Academy of Sciences, Institute of Technical Physics (Snezhinsk, Chelyabinsk Region), Nuclear Physical Center in Rossendorf (Germany), and Laboratory of Ionized Gases in Frascati (Italy).

From the engineering point of view, the GDT-3M looks most promising, because, owing to the increase in DT injection power and to an insignificant decrease in neutron flux power, the required electron temperature was decreased by approximately a factor of 2 and the magnetic-field strength in the mirrors was decreased by exactly a factor of 2, thus allowing one to use superconducting windings. Figure 8 shows the longitudinal density distribution of the neutron flux for GDT-3M. The asymmetry in the distribution arises owing to a special magnetic-field profile [51].

Although the GDT-based neutron-flux source seems the simplest and not so expensive as the sources considered above, its cost is, nevertheless, rather high (250–300 million USD). In this connection, the Budker INP has begun to construct a full-scale pulsed (stationary from the physical viewpoint) model of a neutron source without the tritium cycle (the so-called hydrogen prototype) [52].

Finally, we consider the only known project of a pulse-periodic neutron source based on a laser-compressed target [53]. In this paper, Basov et al. proposed using a 200-kJ laser (wavelength 1–0.3 mm) to obtain $Q \simeq 1$ in an optimized target with a DT mixture, i.e., 200 kJ in thermonuclear neutrons. With a repetition rate of 10 Hz, such a source will produce 2 MW in neutrons. The efficiency of the system is assumed to be 2%. The Livermore laser system NOVA emits approximately 100 kJ with efficiency ~1%. At present, the repetition rate reaches $\sim 10^{-4}$ Hz, and the maximum number of neutrons per pulse equals 10^{14} (10^{17} need to be obtained). The real resource of pumping lamps is very far from that required as well. The situation can change owing to the appearance of diode semiconductor lasers by means of which the problems of pumping efficiency, repetition rate, and, possibly, of the resource of the entire laser system can be solved. However, long hurdles need to be overcome along this line of research, because, at present, the energy of lasers with semiconductor pumping reaches 1 J. In addition, at the current cost of semiconductor lasers, each joule of laser power is estimated to be 200 USD. The semiconductor pumping in the project will be realizable only if the cost of the laser energy is considerably reduced.

Conclusion. The creation of thermonuclear energetics is impossible without high-power neutron sources. Apparently, the D–Li reaction-based accelerator source will be the first to be constructed (IFMIF project). Since this source cannot solve all the problems of thermonuclear materials science, a source of 14-MeV monochromatic neutrons is needed. Despite a comprehensive understanding of the processes in large tokamaks, it is unlikely that even a single source based on a large tokamak will be constructed.

Among small-scale plasma sources (with test-zone area 1-2 m^2), a source based on a gas-dynamic trap is best developed. If testing the components of the fusion reactor requires a 10–20-m^2 test-zone area, such a source can be constructed using compact tokamaks with low aspect ratio. However, it will be necessary to spend several years acumulating a plasmaphysical data base to substantiate well a similar design.

Apart from the solution of purely thermonuclear problems, a high-power neutron source can find other applications. It can be useful for solving of the problems of the creation of safe deeply subcritical atomic electric-power plants and of "burn-up" of radioactive wastes, as well as in performing fundamental research in the field of solid-state physics, radiochemistry, and radiobiology.

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