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STATUS OF MODERN CONCEPTS OF HIGH POWER 14 MeV NEUTRON SOURCES.

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Different approaches to the problem of design and construction of high power 14 MeV neutron sources are described. It has been already well recognized that the problem of tests of existing structural materials so as problem of creation of new ones for future fusion power plants should be solved in the nearest years. It is shown that among plasma-based NSs the neutron sources on the basis of mirror machines are able to solve the problems of materials tests with lowest capital and operating cost. At present, the most advanced candidate both: from experimental and theoretical point of view is the Gas Dynamic Trap (GDT). Recent experiment with oblique injection of fast deuterium atoms in warm target hydrogen plasma has demonstrated a good agreement with results of calculations as from the viewpoint of spatial distribution of the neutrons of D-D reaction, so from the viewpoint of absolute value of the neutron flux density. It should be noted that the GDT-based NS is the object of interest even with existing, at present, plasma parameters (more exactly the electron temperature of the target plasma should be increased two times in comparison with the present level). The increase of the temperature from 130 eV up to 250 eV makes it possible to produce a moderate neutron flux density only several times less than that in the full-scale projects. An obvious advantage of this moderate version of the NS consists in the fact that the plasma physics database for such a source has already existed. Thus, the NS with neutron flux density of order of 200-400 kW/m^2 can be designed and constructed on the basis of the present day experience. As the next step of such approach significant increase of neutron flux density will be possible in result of increase of power of D-T neutral beam injection.

If to speak seriously about the next steps of future fusion program (ITER, DEMO, first commercial fusion power plant), one can see that this program can not be realized without high power 14 MeV neutron source for material tests of the main structural materials of future fusion reactor. In fact, testing of these materials should be finished before the end of the ITER program.

Typical neutron flux density of future fusion reactor incident upon the first wall is equal to $2 \div 3$ MW/m^2. The total time of influence of such a flux upon the reactor components is estimated as $10 \div 20$ years and corresponds to a fluence of $3 \div 4.5 \cdot 10^{22}$ neutron/cm^2 or $6 \div 9 \cdot 10^{22}$ neutron/cm^2 respectively.

Thus, a neutron source with neutron flux density of 2 MW/m^2 (10^{14} neutron/cm$^2 \cdot$s) should operate within $10 \div 15$ years (or even $20 \div 30$ years) to accumulate the fluence of $3 \div 4.5 \cdot 10^{22}$ neutrons/cm^2 (or $6 \div 9 \cdot 10^{22}$ neutron/cm^2). That is why the Fusion Program Evaluation Board headed by Prof. U.Colombo [1] has prepared special report for the Commission of the European Communities. In particular, the following statement was written in the report: «...the problem of the need for a powerful source for high energy neutrons for materials testing should be addressed with the utmost urgency. Such a source should be made an integral part of the ITER programme».

At present, only two main approaches exist: neutron source on the basis of accelerators and plasma-based neutron sources.

There exist four ways to obtain high energy neutrons with the did of accelerators. The first source is known as spallation source [2]. It uses bombardment of a heavy target (W, Pb, U) by protons (or deuterons) with energy of $1 \div 1.5$ GeV. About 30 neutrons can be produced per one proton. In this case, very wide spectrum of neutrons is obtained. Such a spectrum is hardly appropriate for tests of fusion structural materials. Similar accelerator can produce negative μ-mesons in result of interaction of accelerated protons, deuterons or tritons with target [3]. The physical cost of the formation of one μ-meson is about 20 GeV for proton beam case and 8 GeV in the case of deuteron beam [4]. In result of interaction of the mesons with a dense gas target from D_2 and T_2 molecules each meson produces for its lifetime over a hundred DT mesomolecules and these molecules will emit 14 MeV neutrons. In spite of very simple general idea of such a source it will be hardly constructed as one for fusion material tests. The walls of the vessel with D-T mixture should be thick enough because of high pressure (1000 atmospheres) and high temperature of the mixture (1000°C). Under these conditions 14 MeV neutrons passing through the thick wall of the vessel will lose their monochromaticity.

In this sense the projects on the basis of low energy accelerators look more realistic from technical point of view. In the range of energies 20-40 MeV two stripping reactions can be used:

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

$$\text{H} + \text{T}\ (21\ \text{MeV}) \Rightarrow {}^3\text{He} + \text{n}.$$

In the first case (D-Li reaction) the maximum neutron yield is obtained at energy of neutrons equal to 14 MeV. However, in this case, rather wide spectrum of neutrones (±7 MeV) generates [5].

Second reaction also has a wide neutron spectrum [6] but for definite conditions the spectrum is cut off sharply at neutron energies $E_n > 14$ MeV (14.6 MeV).

At present, experts of International Energy Agency (IEA) have selected the source on the basis of D-Li reaction as candidate number one among the accelerator-based schemes. The conceptual design of the International Fusion Materials Irradiation Facility (IFMIF) project is widely developed [7,8]. Final designed parameters of D-Li source are as follows: the deuteron beam energy is 35-40 MeV, the beam current is 2x125 mA, the testing volume with high (2 MW/m^2) neutron flux density is 0.5 liter. The most evident disadvantages of the project are as follows: too small irradiated volume and area. But, perhaps, even more significant disadvantage of such a source is the existence of high energy neutron tail (E_n > 14 MeV) which does not exist in the neutrons of fusion D-T plasma. As one can see in Fig. 1, a plasma-based neutron source GDT NS (see below) has the same spectrum of secondary neutrons as that in the ITER case. At the same time, the spectrum of D-Li source (the IFMIF project) differs significantly from that in the plasma-based neutron source case. A lot of neutrons are obtained with energies larger than 14 MeV. This circumstance can lead to errors during the material tests. Besides, the volume of testing zone in any accelerator-based source is too small. Thus, accelerator-based sources cannot solve many problems of materials tests. Therefore, a plasma-based neutron source is required by all means.

A special issue of the journal «Nuclear Instruments and Methods» devoted to different proposals of high power 14 MeV neutron sources has appeared in 1977 [10]. However, plasma parameters in those proposals were far enough from required ones. The first realistic projects of plasma-based NSs were proposed seven years later (see references of Ref. [11]). These projects were based on mirror machines. Among them the most promising were the NSs based on the Gas Dynamic Trap concept [12] and on the 2XIIB [13]. The tokamak-based NS projects have appeared only at the beginning of 90s. Most of these proposals dealt with large scale tokamaks. In this case, the level of plasma parameters is close enough to required ones. However, besides physical requirements there exist several economic limitations.

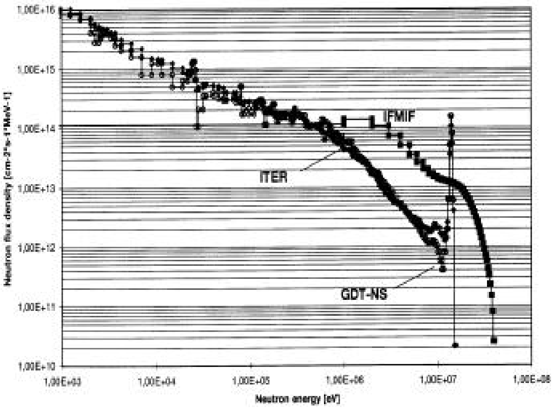

Figure 1. First wall neutron spectra in ITER, plasma-based neutron source (GDT type, see later) and IFMIF [9].

One of the significant factors which determine the operational cost is the power consumption. As it follows from data presented in Ref. [14], the capital cost of large tokamak-based NS can achieve 0.45÷0.48 of the ITER direct cost. Besides, the required power consumption is within 500÷1000 MW. For the typical energy cost (10 cents per kilowatt-hour) the annual energy expenses would amount to $M 438÷876.

The second component of the operational cost is determined by value of tritium consumption. Typical surface area of a vacuum chamber of large scale tokamak exceeds 100-200 m^2. Correspondingly, for desirable neutron flux density of 2 MW/m^2, the annual tritium consumption should be of the order of 14-28 kg (420-840 million USD). It is important to note that besides too high operational cost there exists very serious limitation of tokamak scale: the annual world production of tritium is of the order of 5 kg. Thus, as it follows from these comments, there exist two possibilities for the large scale tokamak-based NSs. At first, one can construct a neutron source with lithium blanket for a reproduction of tritium. Indeed, the projects of tokamak-based NS with a tritium production system using lithium containing blanket appeared [15]. Of course, such approach should significantly increase the capital cost of the NS. It is hardly possible to wait that such a source will be constructed. Really, in order to solve the problems of material tests, a neutron source is required to be operated very reliably over ten years. If one considers the concept of large scale tokamak with lithium blanket from this point of view, one should come to conclusion that such a source is similar to simplified fusion reactor. The neutron flux density (2 MW/m^2) will be practically the same as in the fusion reactor, but the lifetime of the first wall of the NS is unknown. If one adds the high capital and operating cost and the tritium problems, it becomes clear that there is no solution in this way. Really, in recent years the large scale tokamak-based projects of NS have disappeared.

However, one can try to decrease significantly the sizes of the tokamak-based NS and the area of the first wall. Indeed, appearance of compact spherical tokamaks with low aspect ratio initiated design works in this direction [16,17].

The decrease of the aspect ratio allows one to increase the parameter β (the ratio of plasma pressure to magnetic field pressure). Not long ago at START facility β=0.48 was achieved [18]. On the basis of this result two projects of compact volumetric NSs were proposed: Material Test Facility (MTF) in the United Kingdom [16] and ST VNS in the USA [17]. One should note, that very high electron and ion temperatures (T_e = T_i = 20 keV) are assumed in these projects, so as high plasma density (n_e = 10^{14}cm^{-3}). At present, real plasma parameters in the compact spherical tokamaks are very far from mentioned above. Besides, it should be mentioned that low aspect ratio can be obtained only for spherical tori (the internal torus diameter should be very small). This implies the impossibility of using a neutron shield and forced the authors of the projects to abandon not only from superconducting windings but even from warm multiturn windings of a toroidal magnetic field (the insulation does not withstand neutron irradiation).

Area of the vacuum chamber wall is planned to be 30 m^2. Thus, the annual tritium consumption should be a little more than 4 kg and even this compact system should have a lithium blanket.

As to the mirror-based NSs, at the moment, the most advanced concept is based on the so called Gas Dynamic Trap (GDT).

The GDT is one of the simplest systems for magnetic plasma confinement. As a matter of fact, it is an axisymmetric mirror machine of the Budker-Post type, but with a very high mirror ratio (R>10) and with a mirror to mirror length L exceeding an effective mean free path λ/R for the ion scattering into loss cone [19]. Thus, due to frequent collisions the plasma confined in the trap is very close to isotropic Maxwellian and therefore many instabilities can not excite and plasma behaviour is similar to classical one.

If the total number of particles in the trap is equal to LSn_o (here n_o is a plasma density and S is the plasma cross section at the central part of the trap) and if the number of particles leaving the trap through mirrors per second is $n_o V_{T_i} S_m$ (here V_{T_i} is ion thermal velocity and S_m is the plasma cross section in the end mirrors), then the confinement time can be determined as

$$\tau \approx LSn_o/S_m n_o V_{T_i} = RL/V_{T_i}\ .$$

Using an oblique injection of fast deuterium and tritium atoms into warm target plasma one can obtain a population of unisotropic fast D-T ions which oscillate back and forth between the turning points near the end mirrors. As calculations show, there should be an intensive radiation of 14 MeV neutrons in the vicinities of these turning points where the fast ions density has strong peaks. It is necessary to note that the GDT NS is the only one plasma-based source where the neutron flux density is strongly inhomogeneous. Due to that this source has the lowest tritium consumption (of the order of 100-200 gram per a year) among all the types of plasma-based NSs. At the same time the GDT NS can provide the required by material scientists neutron flux density of 2 MW/m^2 or even more within the testing zone area of the order of 1 m^2. Another advantage of the concept considered is the fact that the plasma diameter is substantially (by an order of magnitude) smaller than that of vacuum chamber. Thanks to that the neutron load at the chamber wall is substantially lower compared with other schemes. The inhomogeneity of sloshing ions distribution acts in the same direction. Thus, the main part of the vacuum chamber is irradiated to much weaker fluence compared with the test zones.

End mirror coils placed far enough from the turning points. Thus, there is no serious problem to shield these coils from the neutron irradiation. Besides, in the GDT case it is not necessary to heat all the plasma till high temperature. Most of 14 MeV neutrons creates in fast-fast collisions of D-T ions.

At present, the works under the problem of the GDT NS are doing in several directions. Among them one should point out the experimental studies on the acting model of the Gas Dynamic Trap. Besides there should be mentioned the works under mathematical model of plasma, under codes describing plasma and sloshing ions behavior in the GDT and GDT NS, the design studies of elements of future neutron source, etc.

Very important experiments have been already done on the Gas Dynamic Trap. In particular, it has been demonstrated that even in axisymmetric geometry large scale MHD instabilities can be suppressed [20].

At present, fast ions population with β=0.3 has already been obtained. However, up to now microinstabilities driven by the strongly anisotropic distribution function of hot ions in the velocity space have not been observed. Based on the results of previous studies of the microinstabilities in mirrors (see, for example, [21]) one could conclude that for the plasma conditions in the GDT NS, the most dangerous microinstabilities could be stabilized by the warm plasma background.

The issue of vital importance for the whole project is how to achieve the bulk electron temperature as high as 0.5 -1.2 keV whereas a maximum of 0.26 keV has been obtained as yet for relevant plasma density [22]. Generally, the longitudinal electron heat conduction to the end walls may be a critical issue for open-ended systems. In accordance with theoretical predictions [23] these heat losses can be strongly suppressed if the magnetic field on the end wall is less than $(m/M)^{1/2}$ compared to the end mirror field. Following to the increasing area of the magnetic flux tube, plasma density reduces that gives rise to ambipolar potential in the expander. This potential forces dragged back the central cell electrons. A depth of the potential well for the electrons increases when the magnetic field at the end wall reduces. The electrons emitted by the end wall are prevented from entering the central part of the trap by reflection back from the magnetic mirror. Therefore there is no an intense energy exchange between the different electron populations.

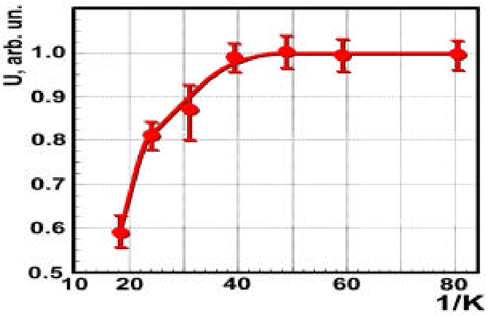

Figure 2. The potential in the central cell of the GDT for different positions of the emissive plasma absorber

Experimental data obtain in the GDT device generally well agree with the theory predications of Ref.[23]. Fig.2 presents the potential in the central cell of the GDT for different positions of the segment which can move in the expander from the end wall till the mirror. The position of the movable segment is marked by the expansion ratio $1/K=B_m/B_z$ on its surface. As it is seen in Fig.2, for large values of the expansion ratio (≥50), the central cell potential (that is T_e) is not sensitive to the position of the wall segment. When the expansion ratio decreases further (1/K<40-50), the potential drops down. Consequently, it was observed in this case that the electron temperature in the center cell decreases thus indicating an increase of longitudinal heat losses [24].

In the first versions of the GDT NS it was supposed to use combined mirror coils: superconducting and warm with total magnetic field strength up to 26 T [12, 25]. Two first basic versions have been analized. In the first one the two component case (GDT-2) was examined where 240 keV tritium beam should be injected into a warm deuterium plasma [12]. Later the conceptual design of three- component system with 80-100 keV D-T neutral beam injection was studied [25]. The weakest point of these two versions was low lifetime of mirror coils (of the order of two weeks [26]). Besides, one should add that 30 MW is required to obtain 26 T field in the mirror coils. Therefore an attempt was undertaken to avoid using the resistive coils in a subsequent design modifications. In Ref. [27] optimization of the SC mirror magnet with maximum on-axis magnetic field strength equaled to 13 T is presented. Corresponding version of neutron source with fully superconducting magnetic system was calculated by making use of a self-consistent numerical model [28]. Comparison of parameters of this source with ones of the GDT device is shown in the Table 1. It is important to note that quite a moderate energy of neutral beam injection is used in this version (65 keV). One can conclude that the neutron source with superconducting magnetic system has reasonable parameters and becomes more realistic.

TABLE 1

Design parameters	GDT	GDT NS
Injection energy, keV	15	65
Injection power, MW	4	60
Neutron flux density, MW/m^2	-	2
Injection angle, degree	45	30
Magnetic field strength in end mirrors, T	15	13
Magnetic field strength in the mid plane, T	0.2	1.3
Plasma density in the mid plane, cm^{-3}	10^{13}-10^{14}	$1.16\cdot10^{14}$
Plasma radius in the mid plane, cm	10	8
Electron temperature, keV	0.13	0.75

That's why it was interesting to revise the results of previous calculations, in particular, to extend ranges of the injection energies, electron temperatures, neutron flux density, etc.

Fig.3 demonstrates the dependence of neutron flux density on the injection energy of deuterium and tritium atoms into plasma. The electron temperature $T_e=10^{-2}E_{inj}$ is assumed in these calculations (it is well istablished that under this condition microinstabilities are not excited in a mirror plasma [21]). At present, there are no experimental data in the range $T_e>10^{-2}$ E_{inj} concerning microinstabilities excitation. The efficiency of the neutron source and neutron flux density strongly depends on the electron temperature of plasma. Fig.4 demonstrates the dependence of the neutron flux density on the electron temperature of target plasma. These calculations were made for the case E_{inj}=65 keV.

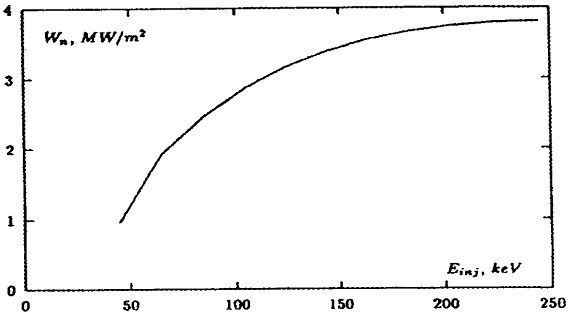

Figure 3. Neutron flux density in testing zone of GDT NS as a function of injection energy of deuterons and tritons (T_e is assumed to be 10^{-2} E_{inj}) [29].

Thus, most part of the curve corresponds to the case when $T_e \le 10^{-2}$ E_{inj}. One can see that even in this case the desired neutron flux density (≈2MW/m^2) can be obtained. If one supposes that microinstabilities do not excite at $T_e \cong 3\cdot10^{-2}$ E_{inj} then GDT NS will be able to produce up to 5 MW/m^2 neutron flux density at the same injection energy 65 keV (see Ref. [29]).

As to the results of calculations obtained with the aid of developed mathematical model of plasma [30], Fast Ion Transport code (FIT) based on the Monte Carlo method [31], and Fokker-Plank code FPM (Fast Particle Model) [32], one can note that the degree of reliability of the simulations is very high. Several figures illustrate this statement. The energy content of plasma in the GDT device as a function of time is shown in Fig.5. It is seen that the difference between experimental data and ones of calculations are insignificant. Besides, measured angular spread of fast ions corresponds well with results obtained by FIT code calculations and with analytic estimates [34].

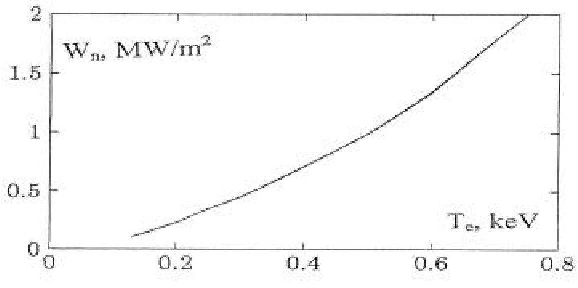

Figure 4. Neutron flux density vs electron temperature. Calculations were made at power of neutral beam injection W=60 MW and energy of D-T injection E_{inj}=65 keV.

Recently an experiment with injection of fast deuterium atoms was done [35]. In Fig.6 a longitudinal distribution of neutron flux density (D-D reaction) is presented in the vicinity of turning point. The solid line is the result of simulation, the discrete marks are the results of measuring. Again the agreement is rather

TABLE 2

Plasma radius in the mid plane, cm	8	8	8
Injection angle	30°	30°	30°
Magnetic field in the end mirrors, T	13	13	13
Mirror ratio	15	15	15
Injection energy, keV	65	65	65
Electron temperature, eV	200	250	300
Electron density in the mid plane, cm^{-3}	$1.2{\cdot}10^{14}$	$1.1{\cdot}10^{14}$	$1.1{\cdot}10^{14}$
Density of fast ions in the mid plane, cm^{-3}	$0.32{\cdot}10^{14}$	$0.37{\cdot}10^{14}$	$0.49{\cdot}10^{14}$
Electron density in the test zone, cm^{-3}	$2.5{\cdot}10^{14}$	$2.8{\cdot}10^{14}$	$3.0{\cdot}10^{14}$
Density of fast ions in the test zone, cm^{-3}	$1.87{\cdot}10^{14}$	$2.29{\cdot}10^{14}$	$2.53{\cdot}10^{14}$
Power consumption of injectors, MW	60	60	60
Neutron flux density in the test zone / in the mid plane, kW/m^2	230/7	350/10	450/20

Thus, it follows from the obtained data that the degree of confidence of the results of calculations for the GDT NS should be high enough. There is only one serious objection against this statement. The highest electron temperature in the GDT experiments, at present, is only 130 eV. In such situation the most reasonable strategy could look as follows. Taking into account that the experiments on suppression of electron heat conductivity have been done on the level of T_e=100-130 eV and that the electron temperature of 260 eV has been obtained in the mirror experiments, it is reasonable to estimate the parameters of the GDT-based neutron source at the range of low electron temperatures. The results of self-consistent simulations for moderate versions of the GDT NS are presented in the Table 2 [36].

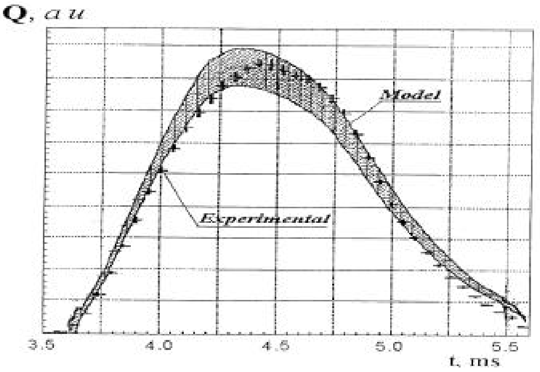

Figure 5. The energy content of target plasma and fast ions vs time [33].

As it is seen from the Table the neutron flux density of 350 kW/m^2 can be obtained for achieved in previous experiments with mirror machines electron temperature (250 eV) on the basis of present day plasma data base and technology. Even insignificant excess of T_e above this level till 300 eV leads to the value of this flux of 450 kW/m^2. At T_e=400 eV this value increase up to
710 kW/m^2.

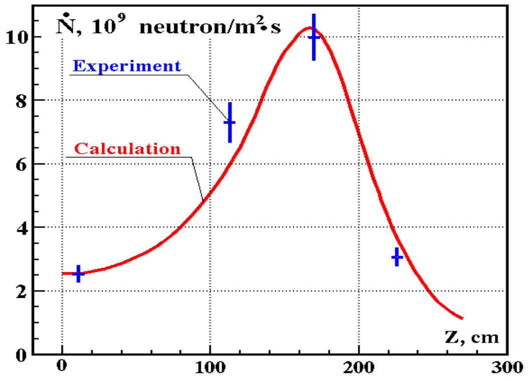

Figure 6. Distribution of the maximum neutron flux density (D-D reaction) along the GDT device length. Discrete marks are the experimental data, solid curve is the result of simulation.

Some of material scientists believe that even with moderate parameters of neutron flux they would be able to make important conclusions concerning the quality of main structural materials NS. Anyhow, the construction of powerful neutron source should begin from the moderate versions presented in the Table 2. It should be noted that the level of the neutron flux densities shown in the Table is minimum one. For 60 MW power consumption of injectors (roughly of 30 MW in the neutral beams) the electron temperature should be significantly higher than it is shown in the Table (the T_e values presented there is specially limited by adding of cold plasma). Thus, if the mechanism of electron heat conductivity will act on the level of $T_e \approx 1$ keV, in this case, neutron flux density will be significantly higher than one can see in the Table 2.

CONCLUSIONS

The urgency of design and construction of the dedicated neutron source, which is absolutely needed to perform material development for a future fusion power reactor, is obvious.

D-Li source can solve only a small part of the problems.

Among plasma-based sources only compact spherical tokamak and mirror machines can compete.

The axisymmetric GDT NS looks like the simplest and cheapest one. It requires minimum power and tritium consumption among plasma-based NSs but makes it possible a creation of testing zone area of the order of
1 m^2.

A moderate GDT-based neutron source with the neutron flux density not less than 350-450 kW/m^2 can be designed and constructed on the present day technology level as a first step of the program of material tests for fusion reactors.

Recent progress of superconducting technique (21 T was obtained in the coils of appropriate size [37]) allows one to revise the former GDT NS projects with high magnetic field in the end mirrors.

REFERENCES

1. Colombo U., Iaumotte A., Kennedy E., et al, *Report of the Fusion Programme Evaluation Board prepared for the Commission of the European Communities*, Bruxelles, (1990).
2. Carpenter J.H. *Nuclear Instruments and Methods*, v.**145**, p.91, (1977).
3. Petitjean C., Atchinson F., Heidenreich G., et al, *Fusion Technology*, v.**25**, p.437, (1994).
4. KuzminovV.V., Petrov Yu.V. and Shabelsky Y.M., *Hyperfine Interactions*, **82**, p.423, (1994).
5. Ikeda Y., Konno C., Oishi K., et al, *Activation Cross Section Measurements for Fusion Reactor Structural Materials at Neutron Energy from 13.3 to 15 MeV Using FNS Facility*, JAERI, 1312, Japan, March 1998.
6. Kondo T., Doran D.G., Ehrlich K., Wiffen F.W., *Journ. Nucl. Materials*, v.**191**, p.100, (1992).
7. Shannon T.E., Rennich M.J., Kondo T., et al, Proc. 16th Fusion Energy Conference IAEA (Montreal, Canada, Oct. 7-11, 1966). IAEA, Vienna, **3**, p.437, (1997).
8. *IFMIF CDA Final Report*. Edited by M.Martone, ENEA Frascati, Roma, 1997.
9. Fisher U., Möslang A., Ivanov A.A., *Fusion Technology Transactions*, v.**35**, ¹ 1T, p.160, (1999).
10. *Nuclear Instruments and Methods*, v.**145**, ¹ 1, p.p.1-128, (1977). Special issue of the journal devoted to the high power neutron sources.
11. Kruglyakov E.P., *Fusion Technology Transactions*, v.**35**, ¹ 1T, p.20, (1999).
12. Mirnov V.V., Nagornyi V.P. and Ryutov D.D., Preprint ¹ 40, Budker Institute of Nuclear Physics, Novosibirsk, (1984);
    Kotelnikov I.A., Mirnov V.V., Nagornyi V.P., Ryutov D.D., in: «Plasma Physics and Controlled Fusion Research», IAEA, Vienna, **2**, p.309, (1985).
13. Coensgen F.H., Casper T.A., Correl D.L., et al, *Journ. Fusion Energ.*, **8**, p.237, (1989).
14. Kruglyakov E.P., Intern. Conf. on Plasma Physics, ICPP 1994, Foz do Iguacu, Brazil, Oct.-Nov. 1994. AIP Conference Proceedings **345**, Woodbury, New York, p.247, (1995).
15. Tsuji-Jios, Tsutsui H., Kondoh J., et al, Proc. 16th Fusion Energy Conf. IAEA (Montreal, Canada, Oct. 7-11, 1996), IAEA, Vienna, **3**, p.685, (1997).
16. Buttery R., Counsell G., Cox M., et al, in: Plasma Phys. and Controlled Nucl. Fusion Research (Seville, Spain, Sept.26-Oct.1, 1994), IAEA, Vienna, **2**, p.633, (1995).
17. Cheng E.T., Intern. Workshop on ST VNS and Applications, Del Mar, California, USA, Oct. 13-15, (1997).
18. O'Brien M.R., Akers R., Bamford R.A., et al, Proc. 16th Fusion Energy Conf. IAEA (Montreal, Canada, Oct. 7-11, 1996), IAEA, Vienna, **2**, p.57, (1997).
19. Mirnov V.V., Ryutov D.D., *Sov. JTP Letters*, v.**5**, p.279, (1979).
20. Anikeev A.V., Bagryansky P.A., Ivanov A.A., et al, *Plasma Phys. and Contr. Fusion*, v.**34**, p.1185, (1992).
21. Post R.F. *Nuclear Fusion*, v.**27**, p.1579, (1987).
22. Simonen T.S. (Ed.), *«Summary of Results from Tandem Mirror Experiment»*, UCRL 53120, LLNL, (1981).
23. Konkashbaev I.K., Landman I.S., Ulinich F.R., *Sov. JETP*, v.**74**, ¹ 3, p.956, (1978).
24. Anikeev A.V., Bagryansky P.A., Deichuli P.P., et al, in: Proc. 23rd EPS Conference on Plasma Physics and Controlled Fusion, Kiev, **20C**, pt.2, p.688, (1996).
25. Ivanov A.A., Kotelnikov I.A., Kruglyakov E.P., et al, Proc. 17th Symp. on Fusion Techn. (SOFT), Rome, Italy, **2**, p.1394, (1992).
26. Klyavin P.P., Levashov A.D., Rozhdestvensky B.V., et al, *Pribory i Tekchnika Eksrepimenta* (in Russian), ¹ 5, p.232, (1976).
27. Ivanov A.A., Kruglyakov E.P., Tsidulko Yu.A., et al, Proc. of 16th Symp. on Fusion Engineering, Urbana, USA, Sept.30 - Oct.5, 1995 (SOFE'95). IEET/NPSS, v.**1**, p.66, (1995).
28. Ivanov A.A., Kruglyakov E.P., Tsidulko Yu.A., et al, Proc. of 16th Fusion Energy Conf. IAEA (Montreal, Oct. 7-11, 1996). IAEA, Vienna, **3**, p.667, (1997).
29. Ivanov A.A., Kruglyakov E.P., Tsidulko Yu.A., Proc. 17th Fusion Energy Conf. IAEA (Yokohama, Japan, Oct. 19-24, 1998), FTP/31.
30. Kotelnikov I.A., Ryutov D.D., Tsidulko Yu.A., et al, Preprint ¹ 105 of Budker INP, Novosibirsk, (1990).
31. Noack K., Otto G., Collatz, *Fusion Technology Transactions*, v.**35**, ¹ 1T, p.218, (1999).
32. Ivanov A.A., Karpushov A.N., Preprint 96-2, Budker INP, Novosibirsk, (1996).
33. Anikeev A.V., Bagryansky P.A., Bender E.D., et al, in: Proc 22nd EPS Conf. on Controlled Fusion and Plasma Physics, Bornemouth (UK), 3-7 July, 1995, v.**19C**, pt.IV, p.193, (1995).
34. Anikeev A.V., Bagryansky P.A., Ivanov A.A., et al, *Nuclear Fusion*, v.**40**, ¹ 4, p.753, (2000).
35. Anikeev A.V., Bagryansky P.A., Ivanov A.A., et al, in: Proc. 26th EPS Conf. on Controlled Fusion and Plasma Physics, Maastricht, v.**23J**, p.1781, (1999).
36. Ivanov A.A., Kruglyakov E.P., Tsidulko Yu.A., 27th EPS Conf. on Controlled Fusion and Plasma Physics, 12-16 June, 2000, Budapest.
37. Kiyoshi T., Kosuge M., Inone K., and Maeda N., *IEEE Trans. on Magnetics*, **32**, p.2478, (1996).