Options for Future Development of Mirror Type 14 MeV Neutron Source

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Abstract: It has been already recognized that a powerful 14 MeV neutron source (NS), which is capable of solving a problem of material tests for future fusion program, is required urgently. At present, a lot of different proposals of NSs have been emerged. One of the most attractive schemes is developed in Novosibirsk. This scheme is based on using a mirror machine with collisional "warm" plasma confined in the trap with a high mirror ratio (so called Gas Dynamic Trap, GDT). If fast D and T neutral beams are obliquely injected into this plasma, it results in accumulation of fast anisotropic D-T ions. The density of the ions has strong peaks near the vicinity of their turning points. As it follows from calculations, the 14 MeV neutron flux density more than 2 MW/m^2 (or 10^{18} netrons/m^2s) on the area of about 1 m^2 can be achieved in such a source. From the viewpoint of material scientists these parameters are enough for testing of candidate materials for fusion reactors. Preliminary experiments with injections of 15 – 17 keV deuterium beams have shown that longitudinal profile and absolute value of D-D neutron flux reasonably agree with the results of calculations. The experiments planned for near future on the upgraded experimental device with more powerful neutral bean injection, according to our simulations, will provide the electron temperature of the "warm" plasma of about 300 eV. In this case, the neutron flux density of the order of 0.5 MW/m^2 can be obtained with a higher energy D-T injection. Such an intermediate result will be a good basis for design and construction of full-scale device. Further experiments on the existing GDT device in Novosibirsk, which are planned to prove the key physical issues of the plasma confinement in the neutron source, are also discussed in the paper.

It is of common knowledge that next steps of fusion program (DEMO, fusion power plant) cannot be realized without construction of a high-power 14 MeV neutron source for fusion reactor materials testing. At present, there are many projects of neutron sources (NSs) based on use of accelerators and magnetic confinement systems with high temperature D-T plasma [1]. Among them the system based on a gas dynamic trap (GDT) [2] looks as one of the most promising. The GDT is one of the simplest systems for magnetic plasma confinement. It is essentially an axially symmetric mirror machine of the Budker-Post type, but with a very large mirror ratio (R>10) and with a mirror-to-mirror length L exceeding the effective mean free path $\lambda \sim \lambda_{ii} * \ln R / R$ for the ion scattering into loss cone. Thus, due to frequent collisions many instabilities can not be excited, and plasma behavior is similar to a classical one. If to speak about the GDT NS, in this case it is not necessary to create high temperature plasma. During an oblique injection of fast deuterium and tritium atoms into a warm plasma these atoms are trapped as a result of charge exchange and ionization by plasma particles. As a result, " sloshing" high energy ions are formed in the plasma, which oscillate back and forth between the turning points near the end mirrors. For the chosen energy of the injected fast atoms (within several tens – one hundred keV) the collisions between the fast D^+-T^+ ions will be mainly responsible for a generation of 14 MeV neutrons. Thus, a strongly inhomogeneous along the system axis neutron flux will be obtained with maxima in the vicinity of the turning points (see Fig.1). As estimations showed, in the case of GDT NS one can obtain an effective testing zone area of the order of 1 m^2 for the required neutron flux density of 2MW/m^2.

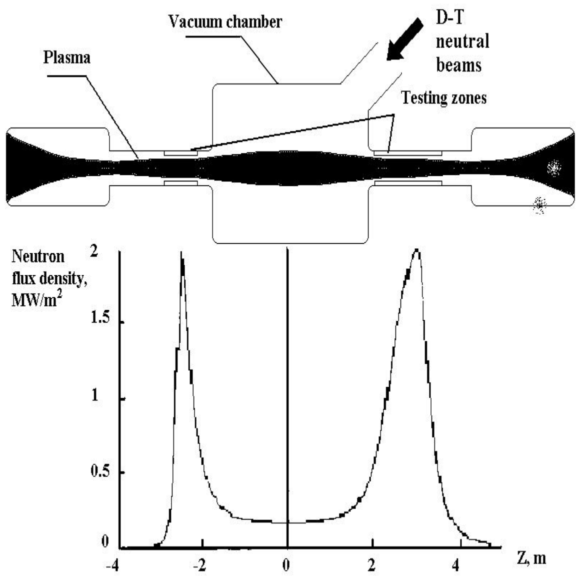

FIG. 1. Schematic of neutron source and axial profile of neutron flux density.

The reason why the area of the testing zone of the GDT NS is quite small can be understood if one takes into account that the diameter of the plasma in the vicinity of testing zone is not more than 12 cm (and only two times more in the mid-plane). An 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 vacuum chamber in the central part (see Fig. 1). Therefore, the neutron load at the chamber walls is substantially lower compared to that typical for the other schemes. Besides, the density of the "sloshing" ions also appears to be relatively much smaller with the exception of the vicinity of the turning points. As a consequence, the main part of the vacuum chamber is irradiated to much weaker fluence compared with the test zone. Thus, only small part of the chamber housing the testing zones should be replaced from time to time.

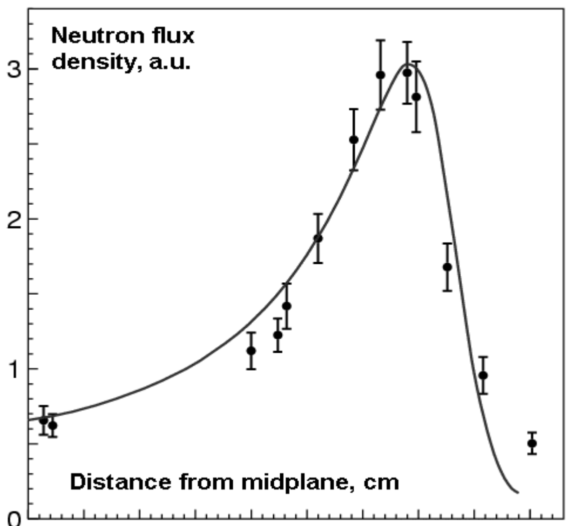

FIG. 2. Profile of the D-D neutron yield along the axis of the GDT device. Results of numerical simulations by the Monte Carlo method presented by solid line.

To produce 1 MW neutron flux during a year one should spend about 70 gram of tritium per a year. Minimum size of an area of the first wall in the case of tokamak-based NS cannot be less than 10 – 20 m^2 . Thus, for required 2 MW/m^2 neutron flux density the annual tritium consumption should be of the order of 1.5 – 3 kg. At the same time, in the case of the GDT NS the annual tritium consumption will be only of the order of 150 gram/yr. Besides, in the former case the electric power consumption will be rather modest in comparison with the other plasma-based NSs [1]. A comparative analysis of different types of 14 MeV neutron sources shows that the cheapest and simplest neutron source can be built on the basis of the GDT. At the moment, there is quite reasonable agreement between experimental data on the GDT device and results of numerical simulations. As an example, Fig. 2 demonstrates such an agreement for the case of the experiment with injection of 15 – 17 keV deuterium neutral beams into target plasma of the GDT device [3]. It is seen that the experimentally observed profile of the neutron flux

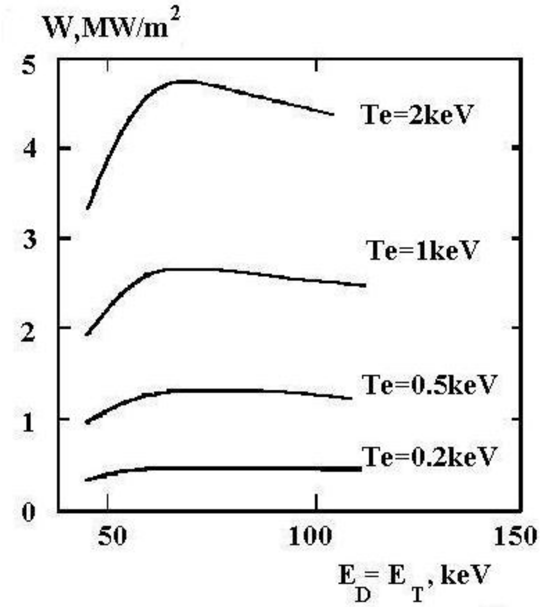

FIG. 3. Neutron flux density as a function of energy of injected beams at different T_e

corresponds well to the results of simulations. However, at present, the plasma parameters required for the high power GDT NS are far enough from those obtained on the existing GDT device. In particular, to achieve the required level of the neutron flux density, one should obtain significantly higher electron temperature [4]. The reason of this requirement is rather obvious: the higher electron temperature, the smaller energy loss rate of the fast ions and the larger time of life of these ions will be obtained. Really, as one can see in Fig.3, the neutron flux density (and neutron flux power) strongly increases with a growth of T_e. The injection power dependence of W is not so significant. Nevertheless, it is seen that at the fixed injection power an optimal injection energy is rather low and amounts to 65 keV. This circumstance strongly simplifies the development of the neutral beam injectors for the GDT NS.

There exists an opinion that tremendous heat losses due to direct plasma contact to the end wall do not allow to obtain a high temperature of electrons in mirror machines. The difficulties with longitudinal heat losses really persist for classic mirror machines. However, for the gas-dynamic trap, it was shown both theoretically [5] and experimentally [6] that the heat losses to the end walls can be significantly suppressed because of formation of high ambipolar potential and reflection most of the electrons leaving the central solenoid back into the trap.

The calculations indicate that for the electron temperature $T_e \geq 1$keV neutron flux density exceeding 4 MW/m^2 can be provided [4]. At the same time, the applicability of the codes to direct simulation of the GDT NS plasma is rather questionable and those codes should be experimentally proven at the plasma parameters that differ not so significantly from the required ones. In this respect, the GDT NS versions with moderate electron temperature are of particular interest. The results of calculations for these versions are presented in the Table I. The maximum magnetic field strength in the end mirror is taken to be 13 T. It means that fully superconducting magnetic system, without warm solenoids, can be used.

It is necessary to add several comments to the data presented in the Table I:

1. For 30° injection, the turning points correspond to mirror ratio R=4. Thus, the distance between the turning points will be about 5 meters when mirror-to-mirror distance is about 11m. Thus, in this case, there is no problem to shield the end mirrors against neutron irradiation.
2. The efficiency of injection is estimated as 50%. (28-29 MW from 60 MW is trapped in the target plasma).
3. Strong mechanism of electron cooling is supposed to persist. Due to this mechanism the electron temperature is limited maximally to 300 eV. Of course, actually, situation will be not so pessimistic as it is shown in the calculation presented in the Table I. But even in this the most

pessimistic case, which is hardly possible in reality, the level of neutron flux density will already be interesting for the material tests.

Table I

Plasma radius in the central part, m	0.08	0.08	0.08
Injection angle, deg.	30	30	30
Magnetic field strength 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 central part, m^{-3}	$1.2\ 10^{203}$	$1.1\ 10^{20}$	$1.2\ 10^{20}$
Density of fast ions in the central part, m^{-3}	$0.32\ 10^{20}$	$0.37\ 10^{20}$	$0.42\ 10^{20}$
Electron density in the test zone, m^{-3}	$2.5\ 10^{20}$	$2.8\ 10^{20}$	$3.0\ 10^{20}$
Density of fast ions in the test zone, m^{-3}	$1.87\ 10^{20}$	$2.29\ 10^{20}$	$2.43\ 10^{20}$
Power consumption of injectors, MW	60	60	60
Neutron flux density: in the test zone / in the central part, kW/m^2	230/7	350/10	420/16

The simulation results presented in the Table I were obtained with the fixed power consumption of NB injectors, fixed magnetic field strength in the mirror coils (13T) and with the fixed mirror ratio (15). There are no doubts today that T_e = 300 eV can be obtained with significantly less power of the NB injection and this is planned as the major objective of the planned upgrade of the GDT. To achieve this objective, three important changes should be done on the GDT device.

These changes are as follows: an increase in the magnetic field at the mid-plane from 0.2 up to 0.35T, an increase in the NB injection power from 4 up to 10 MW, and an increase in the beam duration from 1 ms up to 4-5 ms (from the physical viewpoint steady state regime begins at the duration of injection of t~5 ms). Calculations show that these measures will lead to the increase in the electron temperature up to 260-320eV. If this is obtained, the neutron source with a moderate neutron flux density of order 350-450 kW/m^2 can be constructed. Returning back to the Table I, it is necessary to note that the weaker longitudinal heat conduction, the higher electron temperature. According to the theory [5], a reduction of electron thermal conductivity takes place if the ratio of magnetic fields at the mirror and at the end wall exceeds $\sqrt{M/m}$, where M, m are ion and electron masses, correspondingly. As the experiments have shown, in the GDT case an influence of the end wall really disappeared when $(\mathbf{M/m})^{1/2}$ was larger than 45 (see Ref. [6]).
Special calculations were made under the assumption that the electron heat conduction is suppressed. In this case, as is seen in Fig.3, the neutron source efficiency substantially increases. In particular, to obtain 2 MW/m^2 neutron flux density, the total power of the order of 35 MW is then required.

Conclusions

The numerical simulations of the plasma parameters in the GDT-based neutron source were done under assumption of limiting the attainable electron temperature to 300 eV. Even in this pessimistic case, rather high neutron flux density can be provided, which is already of interest for a number of applications.

After the proposed upgrade of the GDT device, the electron temperature is to be increased up to 260-320 eV. As it follows from our calculations, this will demonstrate a feasibility of the GDT NS first stage with the 14 MeV neutron flux density of 0.35-0.45 MW/m^2. More well-founded estimations for full scale NS will be available.

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