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A first step in the development of a powerful 14 MeV neutron source

A.A. Ivanov *, E.P. Kruglyakov, Yu.A. Tsidulko

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

Abstract

This paper reviews the latest results of the numerical optimization of the powerful 14 MeV neutron source based on gas dynamic trap (GDT). 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 here.

1. Introduction

Serious consideration of the next steps in the international fusion program (DEMO, fusion power plant) immediately reveals that this program cannot be realized without construction of a high-power 14 MeV neutron source for fusion reactor materials testing. Notwithstanding that this has been discussed for more than 10 years, none has been built in the world so far. The reasons for this for many of the proposed neutron sources include high construction and operational costs and unacceptably large tritium consumption [1]. One of the most promising approaches, especially in terms of lower costs and low tritium consumption, is based on the gas dynamic trap (GDT) [2].

2. The GDT neutron source

At present, a conceptual design of the GDT-based neutron source (GDT NS) is reasonably developed for a version that is intended to produce ~2 MW of 14 MeV neutrons on an area about 1 m^2 [3]. GDT is one of the simplest systems for magnetic plasma confinement. It is an axially symmetric 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 the effective mean free path $\sim\lambda_{ii} \ln R/R$ for ion scattering into the loss cone. Thus, due to frequent collisions, the plasma confined in the trap is very close to isotropic Maxwellian, many instabilities cannot be excited, and the plasma behavior is similar to a classical one. Besides, for neutron source applications, it is not necessary to create a high temperature plasma. Using an oblique injection of fast deuterium and tritium atoms into a warm plasma one can obtain a population of anisotropic fast D^+ and T^+ ions which oscillate back and forth between the turning points near the end mirrors. For a moderate energy of fast ions ($E < 100$ keV), the collisions of fast D^+–T^+ ions will be mainly responsible for the generation of 14 MeV neutrons. Thus, a strongly inhomogeneous neutron flux will be obtained with maxima in the vicinity of the turning points. An example of a calculated profile for one of the versions of the GDT NS is presented in Fig. 1.

An asymmetry of the profile relative to the midplane is provided by special corrections to the magnetic field (B). Namely, by decreasing the derivative $|dB/dz|$ in the vicinity of the turning point, one can increase the longitudinal size of the testing zone (see Fig. 1) with a high neutron flux. As estimations have shown, one can obtain an effective testing zone area of the order of 1 m^2 for a neutron flux density of 2 MW/m^2. In this case the annual tritium consumption will be of the order of 150 g. In addition, for the GDT NS the electric power

* Corresponding author. Tel.: +7-3832 394128; fax: +7-3832 342163.

E-mail address: ivanov@inp.nsk.su (A.A. Ivanov).

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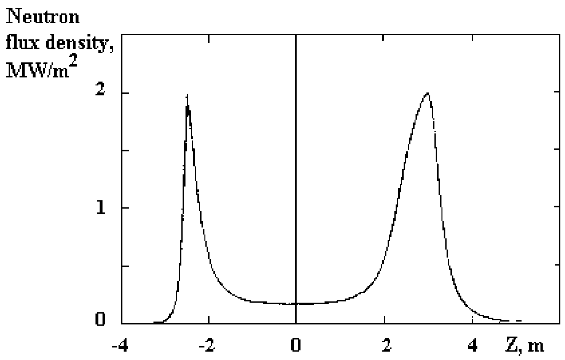

Fig. 1. Longitudinal profile of 14 MeV neutron flux density.

consumption will be rather modest in comparison with other plasma-based NSs [1]. Therefore, a comparative analysis of different type 14 MeV neutron sources suggests that a relatively inexpensive neutron source can be built on the basis of GDT.

By now the mathematical model of the GDT plasma has been developed [4], the fast ion transport (FIT) code based on the Monte Carlo method has been developed for numerical simulations [5]. Additionally, the one-dimensional Fokker–Planck code FPM (fast particle model) has been applied to 'on-line' calculations of the global fast ion parameters [6].

To date, quite reasonable agreement has been obtained between experimental data on the GDT device and results of numerical simulations. Fig. 2 demonstrates an example of such agreement for the case of an experiment with injection of fast ($E \sim 15$ keV) deuterium atoms into target plasma of the GDT device [7]. As one can see in the figure, the experimentally observed profile of the neutron flux corresponds well to the results of simulations.

At present, however, plasma parameters required for the high power GDT NS have not been obtained on the existing GDT device. In particular (see, for example, Ref. [3]), to achieve the required level of neutron flux, higher electron temperatures are required. It is believed that high heat losses due to direct plasma contact to the end wall would not allow the achievement of such high electron temperatures in classic mirror machines. For instance, in the experiments on TMX [8] the record electron temperature was only 260 eV in spite of very high ion temperature. However, for the gas-dynamic trap, it has been shown both theoretically [9] and experimentally (for the electron temperature ~100 eV [10]) that the heat losses to the end walls can be significantly suppressed. As shown in [7], the neutron flux density in the GDT NS depends strongly on the electron temperature. In particular, these calculations show that for the electron temperatures $T_e \geq 1$ keV a neutron flux density higher than 4 MW/m^2 can be obtained.

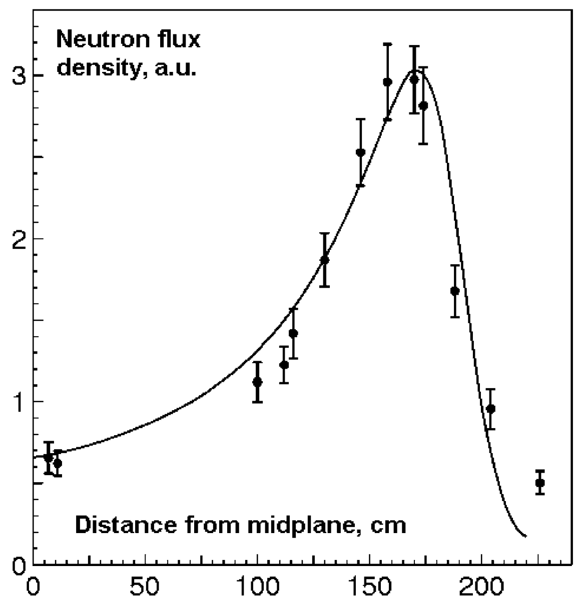

Fig. 2. Experimental profile of the D–D neutron yield along the axis of the GDT device. Results of numerical simulations by the Monte Carlo method presented by solid line.

Moreover, the applicability of the codes to direct simulation of the GDT NS plasma needs to be experimentally proven for plasma parameters that are similar to those required for a NS. Thus, first of all, it needs to be demonstrated that the required electron temperature, exceeding that already achieved in classic mirror machines, can be obtained. The developed codes should be benchmarked at these higher temperatures. This will improve the degree of confidence in the results of computer simulations of a GDT NS for the most significant plasma parameters, especially the electron temperature, which should be increased not more than two or three times. 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 Table 1. The maximum magnetic strength in the end mirror is taken to be 13 T. This implies that a fully superconducting magnetic system, without warm solenoids, must be used.

It is necessary to add several comments to the data presented in Table 1.

1. For 30° injection, the turning points correspond to mirror ratio $R = 4$. Thus, the distance between the turning points will be about 5 m and the mirror-to-mirror distance is about 11 m (see Fig. 1). Thus, in this case, there should be no problem in shielding the end mirror against neutron irradiation.

Table 1
GDT parameters

Plasma radius in the central part (cm)	8	8	8
Injection angle (°)	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 (cm^{-3})	1.2×10^{14}	1.1×10^{14}	1.2×10^{14}
Density of fast ions in the central part (cm^{-3})	0.32×10^{14}	0.37×10^{14}	0.42×10^{14}
Electron density in the test zone (cm^{-3})	2.5×10^{14}	2.8×10^{14}	3.0×10^{14}
Density of fast ions in the test zone (cm^{-3})	1.87×10^{14}	2.29×10^{14}	2.43×10^{14}
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

2. The efficiency of injection is estimated to be 50% (28–29 MW of the 60 MW is trapped in the target plasma).
3. A strong mechanism for electron cooling is assumed to persist. Due to this mechanism electrons cannot be heated higher than 200–300 eV.

But even in this pessimistic case, which is not probable, the level of neutron flux could be interesting for materials testing purposes.

3. Proposed upgrades to the GDT NS

The above calculations were made assuming a fixed power consumption of neutral beam (NB) injectors, a fixed magnetic field strength in the mirror coils (13 T), and a fixed mirror ratio (15). At present, there is little doubt that $T_e = 250$–300 eV can be obtained, and this is planned as the major objective of the GDT-Upgrade. To achieve this objective, three important changes should be made to the GDT device: an increase in the magnetic field at the midplane from 0.2 up to 0.35 T, 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 3 ms. According to calculations, these measures will lead to an increase in the electron temperature up to more than 260 eV. If this can be obtained, a neutron source with a moderate neutron flux density of order 350–430 kW/m^2 can be constructed. Of course, this is the most pessimistic estimation of the achievable flux. In reality, one may expect a substantially higher neutron flux, for reasons discussed above. In fact, due to very strong magnetic field reduction beyond the end mirror towards the end wall, the longitudinal electron heat conduction is suppressed. According to theory [9], this reduction takes place if the ratio of magnetic fields at the mirror and at the end wall exceeds $\sqrt{M/m}$, where M and m are the ion and electron mass, respectively. Experiments [10] have shown reasonable agreement with this estimate. Thus, one can assume that in the GDT case, the problem of electron temperature limitation due to electron heat conduction to the end walls can be solved. Special calculations have been made under this assumption. In this case, as is seen in Fig. 3, the efficiency of the neutron source becomes significantly higher. In particular, in order to obtain 2 MW/m^2 neutron flux density, a total power of less than 35 MW is required.

Considering the GDT experiment, we should note that, at present, the maximum electron temperature (130 eV) exactly corresponds to that predicted by the numerical codes for given experimental conditions. After the proposed upgrade of the GDT device, the electron temperature is to be increased up to 260–300 eV. From our calculations, this will demonstrate the feasibility of a

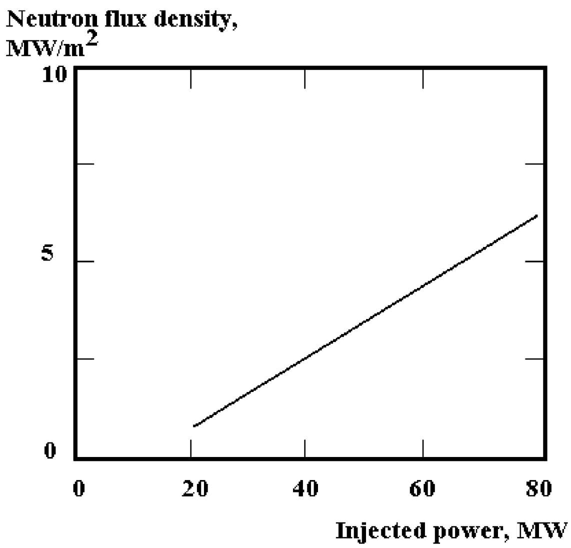

Fig. 3. Maximal neutron flux density as a function of the injection power (no limitation on electron temperature is assumed).

GDT NS first stage with the 14 MeV neutron flux density of 0.35–0.42 MW/m^2.

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