Status of a Mirror Type 14 MeV Neutron Source Project in Novosibirsk

E.P.Kruglyakov, A.A.Ivanov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

e-mail contact of main author: E.P.Kruglyakov@inp.nsk.su

Abstract. A gas-dynamic trap is a Budker-type mirror machine with axially symmetric magnetic field and a high mirror ratio, operated with relatively cold and dense plasma. Oblique injection of high energy deuterium and tritium neutral beams into the warm target plasma results in build up of population of fast anisotropic ions. Their density is strongly peaked near the turning points, in which neutron flux as high as 2 MW/m^2 (or even more) can be generated within ~1-2 m^2 testing zone. The paper discusses status of experiments at a scalable model of the gas dynamic trap and current upgrade of the device. Major goal to be achieved in the nearest time is an increase of the electron temperature up to $T_e \cong 300$ eV that will immediately prove a practicability of moderate power neutron source with a flux of 0.45÷0.5 MW/m^2.

1. Introduction

It is now widely recognized that further progress towards a commercial fusion reactor critically depends on the availability of low activated structural materials. These materials, which are not now available in the market, should withstand for tens of years fusion neutron irradiation in reactor environment without degradation of their electrical and mechanical properties. Therefore, development of a powerful 14 MeV neutron source (NS) capable of solving the problem of constructive material tests for future fusion program is required urgently. One of the most promising approaches to this problem is based on the gas dynamic trap (GDT) concept [1]. GDT is essentially a modification of the Budker type mirror machine with axially symmetric magnetic field and a high mirror ratio (R>10), operated with relatively cold and dense plasma. Oblique injection of high energy deuterium and tritium neutral beams into the warm target plasma results in build up of population of fast anisotropic ions. Their density is strongly peaked near the turning points where axial ion velocities are small. As a result of collisions of fast D-T ions 14 MeV neutrons are produced. Compared to other proposals, this approach differs by low tritium consumption and relatively low construction and operational costs [2, 3]. The plasma parameters in the proposed GDT-based neutron source were optimized by numerical simulations to generate 2 MW/m^2 (or even more) flux density of uncollided 14 MeV neutrons within ~1-2 m^2 testing zone. For that the electron temperature of 0.75 keV should be provided. Such temperatures have not been yet achieved in mirror machines. Further experiments to demonstrate possibility of an increase of the electron temperature in GDT are planned. In order to achieve the electron temperature as high as ~300eV, which is already high enough to produce ~ 0.45MW/m^2 neutron flux if tritium and deuterium beams are injected, substantial increase of neutral beam injection power is required. The existing six neutral beams of GDT device provide up to 4 MW of power incident on plasma at midplane. After upgrade of the injector system, beam power will be increased from 4 MW up to 10MW with simultaneous extension of the beam pulse from 1 to 5ms. Note that extension of the pulse duration up to 5ms provides steady state regime of confinement from physical viewpoint, which is important for correct simulation of the conditions in GDT-based neutron source.

2. Experimental setup and diagnostics

The experiments on study of the effects of gas dynamic plasma confinement are carried out on GDT device. Vacuum chamber and magnetic coils are shown in Fig.1. The vacuum chamber of the GDT consists of a cylindrical central cell 7 m long and 1 m in diameter and two expander tanks attached at both ends. The device has an axisymmetric magnetic field configuration. Mirror to mirror distance is 7 m, plasma radius at the midplane is within 8-15 cm, plasma density is $3\text{-}20\cdot10^{19}$ m^{-3}, electron temperature after neutral beam injection is up to 130 eV, magnetic field value in the mirrors is up to 15 T, in the midplane is .22 T. The plasma is heated by injection of neutral beams at the center of the device. The beams energy E_b = 15-17 keV, total injection power P_b = 4.1 MW, pulse duration τ_b = 1.1 ms. The injection angle is 45^0.

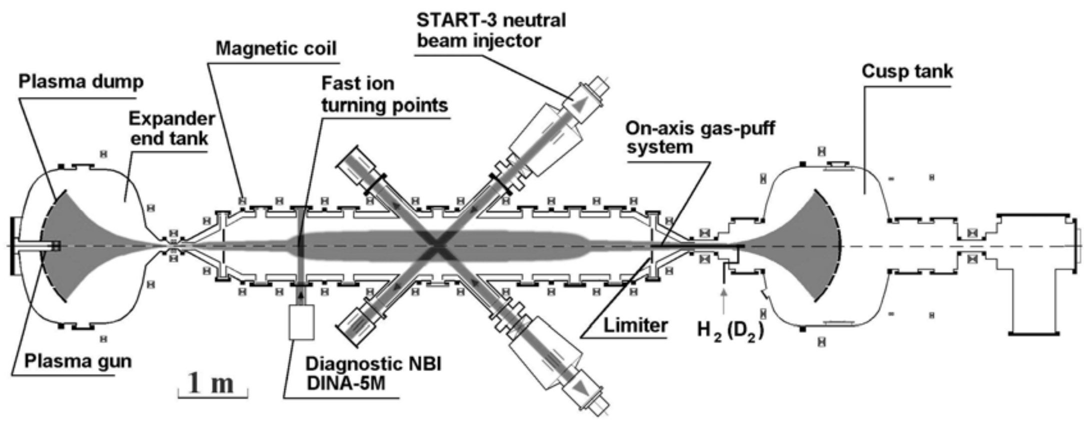

FIG. 1. Experimental model of gas-dynamic trap.

The initial plasma is produced by a ~3 ms pulse from a washer stack hydrogen-fed plasma gun. The gun is located in one of the end tanks beyond the mirror. Under standard conditions, within ~3 ms, the plasma density reached desired density, after that the gun current was terminated and the plasma begun to decay. The electron temperature of the gun-produced plasma reached about 3-10 eV and was nearly constant across the radius. Initially, the radial density profile was well fitted by a Gaussian with characteristic scale length of 7-8 cm.

The plasma rotation caused by radial electric field in the plasma was controlled by a set of electrically biased limiters and plasma dumps. This enabled to avoid significant broadening of the radial density profile and target plasma losses during initial stage of the plasma heating and accumulation of the fast ions. When the radial potential drop was minimized, radial extent of the plasma with energetic ions increased during the neutral beam injection from initial 7-8 cm to about 14 cm. No gross instability that could preclude the production of high-β, multi-component plasma in a gas-dynamic trap configuration has been observed.

The plasma parameters at the solenoid were measured with a number of diagnostics. The density profile was derived from the measured attenuation of neutral beams and from Thomson scattering data near the mid-plane. The Thomson scattering system also measured electron temperature in the plasma core. These data were combined with the data from the probes installed in a radial limiter shadow to provide the electron temperature profile. Under typical experimental conditions, the measured profile was almost flat in the core, with approximately linear decrease out of the limiter edge. Temporal variation of the ion temperature of the target plasma was measured by Rutherford scattering of a diagnostic neutral beam. At the end of beam injection pulse, the ion temperature was close to that of electrons. The parameters of the fast ions were measured by using an artificial target method, neutral particle analysers, and an array of diamagnetic loops installed at different axial positions inside the solenoid. We estimated the average energy of the beam-produced deuterons to be about 10 keV. The measured angular width of fast ion distribution and their energy distribution well correspond to the results of numerical simulations[7]. We also found that the losses of the heated target plasma are dominated by the axial ones through the mirrors, as predicted.

Both axial and radial profiles of plasma beta have been measured by making use of Motional Stark Effect (MSE) diagnostic, which was recently installed at GDT device [4]. The measured reduction of the magnetic field provided a maximum on-axis beta value in the turning point as high as 0.4. A flux of the DD fusion products was measured with an organic scintillator detector. The detector was operated in a single-particle counting mode. The major parameters of the GDT device are shown below in Table I.

TABLE I: The parameters of GDT device

Parameter	Value
Mirror to mirror distance	7 m
Magnetic field at midplane	0.26 T
in mirrors	11 T
Target plasma density (typical)	$6{\times}10^{19} m^{-3}$
radius at the midplane	0.14 m
electron temperature	90-130eV
Neutral beams injection energy	15-17 keV
pulse duration	1.1 ms
injection power	3.9–4.1 MW
Injection angle	45^o
Fast ion density	up to 1-2 $10^{19} m^{-3}$
Mean energy of fast ions	10 keV
Maximal local plasma ß	0.4

3. Major findings from the experiments

In the previous experiments it has been successfully demonstrated that the MHD plasma stability can be achieved in GDT for axially symmetric magnetic field. Flute modes were stabilized by field line curvature in using external anchor cells in which the curvature was favorable for stability. The stability was achieved if the contribution of the anchor cells to pressure-weighted curvature overcame negative contribution of the central cell. Remote anchor cells of two different types were experimentally tested. The first one was an expander end cell in which the plasma from the mirror throat expanded along gradually decreasing magnetic field to the end walls. The magnetic field inside the expander end cells was formed by a combination the above mentioned decreasing magnetic field of the central cell and the field of additional large radius expander coils mounted at the end tanks. A current in these coils was opposite to that of the central cell coils providing the required concave form of the field lines. An additional coil installed in one of the end tank enabled to form here a cusp end cell. Effects of stabilization by the cusp end cell were also studied. These experiments have

shown that the problem of MHD stabilization of the plasma in the axisymmetric magnetic configuration can be successfully solved.
Theoretical studies of ballooning modes stability in GDT predicts that the central cell β must be less than 0.7-0.8 for stability. In order to obtain such a high β limit, magnetic field profile in the central cell has to be properly optimized. For the GDT device, magnetic field in the central cell differs from this optimized field and, therefore, the β limit amounts to 0.36 in this case. Recently, on-axis β exceeding 0.4 was obtained and measured in GDT near turning point of the fast ions by Motional Stark Effect diagnostics [4].
One of the most critical issues related to plasma confinement in mirrors is the danger of too high electron heat losses due to direct plasma contact to the end wall. However, for sufficiently high expansion of the field lines from the mirror to the end wall the theory predicts strong reduction of the longitudinal electron heat losses. As experiments have demonstrated, in the case of large expansion of the magnetic field lines the movable end wall does not exert influence on plasma potential in the central cell [6].
Correspondingly, the electron temperature remains constant. However, when the expansion ratio decreases down to the level $B_m/B(z) < \sqrt{M/m}$, (here B(z) is the field strength at the movable end wall), the potential fell down and the electron temperature in the center cell decreased thus indicating an increase in longitudinal losses.
Formation of peaked axial profiles of the fusion product flux has been demonstrated in the GDT device. In the experiments, fast ions were produced by injection of 4 MW, 15-17 keV deuterium neutral beams. Axial dependence of the flux, as well as its absolute values were compared with simulation results. Reasonable agreement was found.
The distinctive feature of the radial profiles of chord-averaged DD fusion yield is their quite small radial width, about 7 cm at 1/e-level mapped onto the GDT midplane. This is only slightly larger than the fast deuteron gyro-radius of $\rho_i \approx 5.6$ cm as calculated for the magnetic field of 0.26 T and 10 keV energy that is close to the fast ion mean energy. The same feature exhibits the radial profile of plasma beta, which has been previously measured with MSE diagnostic [4]. Possible relevant mechanisms that could be responsible for the formation of these narrow profiles are now under consideration.
In recent experiments at GDT device with injection of near 4 MW deuterium neutral beams, no indications of either enhanced radial plasma losses, which might be caused by MHD instabilities or significant anomalies in fast ion scattering and slowing down have been found. This fact has also been concluded from the earlier measurements with smaller injected power, in which the fast ion relaxation in the GDT has been studied [7].

2. Neutral beam system upgrade

Upgrade of the GDT injection system assumes substitution of six existing ion sources by the new ones with increased current, extracting voltage and pulse duration. The parameters of new ion source, which could operate with hydrogen or deuterium, were specified to be 25 keV energy and 70 A extracted ion current. Total injection power in access of 10 MW incident on plasma could be then provided. The pulse duration will be extended from 1 to 5 ms after the upgrade enabling to reach steady state conditions for electron heating in the device. A prototype of the ion source has been developed (see Fig.2).

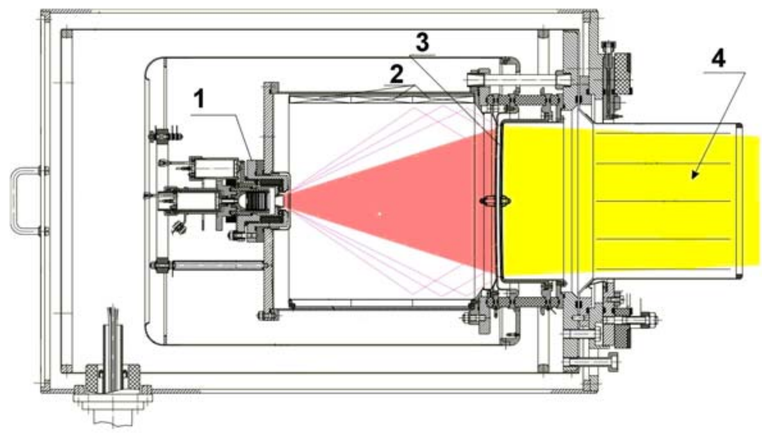

FIG.2. General view of the ion source prototype.

Plasma, from which ion beam is extracted, is generated by an arc-discharge plasma source (1). Fully ionized plasma jet diverging from the anode opening enters a volume (2) with multipole magnetic field at periphery. The field is produced by an array of permanent magnets installed on outer wall of the volume. After reflection of a part of plasma from this magnetic field, homogeneous plasma emitter is formed at the plane of the first plasma grid. The ions are extracted by four electrode ion optical system (3) with 2.5 mm in diameter apertures arranged into hexagonal array. The edges of the apertures and gaps between the electrodes were optimized to obtain angular divergence as small as 10^{-2} radian. After formation of the ion beam it is neutralized in a cell (4) with pulsed gas puff. The neutralizing cell is divided into several sub-cells by internal axial plates directed along the beam. This substantially decreases axial gas conduction in the neutralizer and the gas puffing on to the plasma. To increase the beam current density within the plasma, it is focused onto desired region inside the plasma column. The focusing is provided by spherical shape of the grids, so that all beamlets are directed at the desired focal point. Adopted design has several advantages compared to the existed injectors, in which three plane electrodes are used, providing less divergent focused beam. The prototype of the ion source has been successfully tested and fabrication of a set of injectors for GDT upgrade has been started. The new injectors will be installed on the GDT device at the beginning of the next year.

The parameters of the developed prototype of the ion source for GDT –upgrade are shown in Table II, in which the target parameters are marked by asterisks.

TABLE II: PAMETERS OF ION SOURCE FOR GDT UPGRADE.

Parameter	Value
Beam energy	25 keV
Extracted ion current	60(80*)A
Proton fraction	>90% by current
Equivalent neutral beam current	50(65*)A
Beam duration	3(5*)ms
Focal distance of beam	3m
Initial beam diameter	0.2m

Experiments with injection of fast (15-17keV) atoms have already been made [4,5]. These experiments have shown that the neutron flux density and its longitudinal profile well correspond to the simulation results. Note, that an increase of the electron temperature to the desired values corresponding to 2 MW/m^2 neutron flux seems to be feasible. At least, up to now there is no indication that a mechanism limiting the electron temperature does exist in the gas dynamic trap, i.e. the experimentally measured electron temperature well corresponds to that predicted by the codes for given experimental conditions. It should be noted that a mechanism of suppression of longitudinal electron heat conduction was observed experimentally on GDT device [6]. For the temperatures already achieved in the mirror experiments or not considerably higher, the level of neutron flux density, which can be generated in the GDT-based neutron source, is already appropriate for some material tests. Table III shows an increase in the neutron flux density with the electron temperature increase. It is seen that the options with lower electron temperatures, which closer to that experimentally achieved in mirror machines, still are capable of generating the neutron flux of the order of 0.5-1 MW/m^2.

TABLE III: PARAMETERS OF THE GDT–BASED NEUTRON SOURCE.

T_e, eV	200	250	300	400	500
W_n,MW/m^2	0.23	0.35	0.45	0.715	1.00

The calculations were made with the fixed power consumption of neutral beam (NB) injectors (60MW), fixed magnetic field strength in the mirror coils (13 T) and with the fixed mirror ratio (R=15).

After increase of the injected power in the GDT device, extension of the beam pulse and increase of the magnetic field strength at the mid plane from 0.2 up to 0.35 T electron temperature as high as ~300eV will be achieved. If it is obtained, the neutron source with a moderate neutron flux density of order of 0.35-0.45 MW/m^2 will immediately become feasible.

One should note that that extension of the pulse duration up to 5ms provides steady state regime of confinement from physical viewpoint, which is important for correct simulation of the conditions in GDT-based neutron source.

Summarizing, at present it is not found any physical problems prevented from construction of high power 14 MeV neutron source for fusion material tests. At present, the new injector prototypes have been successfully tested and a series of injectors with total power of 10 MW are under construction. After a year, the electron temperature Te ≅ 300eV will be obtained and a practicability of moderate power neutron source with a flux of 0.45÷0.5 MW/m^2 will be thus demonstrated.

References.

[1] I.A.KOTELNIKOV, I.A., MIRNOV, V.V., NAGORNY, V.P., RYUTOV, D.D., Plasma Physics and Controlled Fusion Research, 2, IAEA, Vienna, p.309, (1985).

[2] BAGRYANSKY, P.A., IVANOV, A.A., KRUGLYAKOV, E.P., et. al., Fusion Eng. and Design, 70, p.13(2004).

[3] KRUGLYAKOV, E.P., Transactions of Fusion Technology, v.35, № IT, Fuste 8(1), p.20, (1999).
[4] IVANOV, A.A., ANIKEEV, A.V., BAGRYANSKY, P.A., et al, Phys. Rev. Lett, v. 90, #10, p.p.105002-1 – 10500-4 (2003).
[5] MAXIMOV, V.V., et. al., Nuclear Fusion, v.44(4), p.542 (2004).
[6] ANIKEV, A.V., BAGRYANSKY, P.A., DEICHULI, P.P., et al., in: Proc. 23rd EPS Conf. on Plasma Physics and Controlled Fusion, Kiev, 20C, pt.2, p.p. 688-691 (1996).
[7] ANIKEEV, A.V., *et al*, Nuclear Fusion, **40**, v.4, 753 (2000)