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SUSTAINMENT OF HIGH-BETA MIRROR PLASMA BY NEUTRAL BEAMS

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Abstract. The report presents two experiments carried out in Budker Institute for obtaining the maximum plasma beta (ratio of the plasma pressure to magnetic field pressure) in axially symmetric magnetic field. The experiments are based on injection of powerful focused neutral beams with high neutral power density in the plasma. The produced fast ion population significantly increases the plasma pressure. It the axially symmetric GDT experiment (Gas Dynamic Trap) the plasma beta exceeded 0.6 at the fast ion turning points. The CAT experiment (Compact Axisymmetric Toroid) is being prepared for obtaining a plasmoid with extremely high diamagnetism in axially symmetric magnetic field. Reversal of magnetic field in the plasmoid is possible in this experiment.

Keywords: axisymmetric mirror, neutral beam injection.

1. Introduction

Axisymmetric mirror configurations for plasma confinement have several advantages compared to traditional tandem mirrors with “minimum-B” quadrupole stabilizing anchors and to “closed” devices like tokamaks. The axisymmetric mirrors have simpler magnetic coils, high plasma pressure, reduced transverse transport, no need for electric currents in the plasma, natural exhaust power handling [1]. Axisymmetric magnetic field allows stable equilibrium of a high-pressure plasma. The initial cold plasma in mirror machines is usually produced by plasma guns, then high pressure is achieved by building up a population of energetic particles either by neutral beam injection (NBI) or by absorption of radio-frequency waves by plasma ions and electrons. Budker INP has been developing mainly the direction of neutral beam heating of axisymmetric mirror-confined plasma.

2. Heating of axisymmetric plasma by neutral beams

2.1. Gas Dynamic Trap

In the axially symmetric GDT device shown in Fig.1, a high-β plasma build-up and sustainment is provided by injection of 25 keV neutral beams with the total power of 5 MW at the center of the device at 45 °C during 5 ms [2–4]. The initial cold plasma for trapping of the beams is produced either by a plasma gun installed at an end wall or alternatively by gas ionization with gyrotrons inside the confinement region between the end magnetic mirrors. Sheared plasma rotation is produced by applying voltages to a system of nested circular electrodes placed at the end walls and by radial limiters inside the central cell. The sheared plasma rotation suppresses the radial plasma transport caused by flute instability. The neutral beam injection results in accumulation of fast ions and heating of bulk electrons. The plasma pressure profile, which determined by fast ions with mean energy 10–12 keV, is strongly inhomogeneous with strong peaks near the fast ion turning points near the end magnetic mirrors, where the magnetic field is about 0.6 T. Following the achievements of $\beta \sim 1$ in quadrupole magnetic mirror experiment [5], it has been demonstrated that in the axially symmetric GDT experiment the plasma beta exceeded 0.6 [4, 6] at the fast ion turning points.

At the same time, the electron temperature reached 0.25 keV with the 5 MW neutral beam injection only, and ~ 1 keV with auxiliary 0.7 MW electron cyclotron resonance heating (ECRH). The plasma parameters in the experiment are relevant to those in a neutron source (NS) for material testing, which is based on the gas-dynamic trap (GDTNS [7, 8]). Neutron production depends mainly on the electron temperature. With the achieved GDT electron temperature of 0.9 keV, the expected neutron flux would be 2 MW/m^2. The test area is 1 m^2 and the spatial uniformity is well within the requirements of material scientists. The conceptual design shows that up to 8000 small material samples could be irradiated with a temperature controlled environment. Alternatively, one of the ends could be employed to test a few larger sub-components and blanket modules. In this way tritium breeding studies could be carried out.

2.2. Compact Axisymmetric Toroid experiment

To study production and maintenance of high-β plasmas in more detail, now the CAT (Compact Axisymmetric Toroid) experimental device is under con-

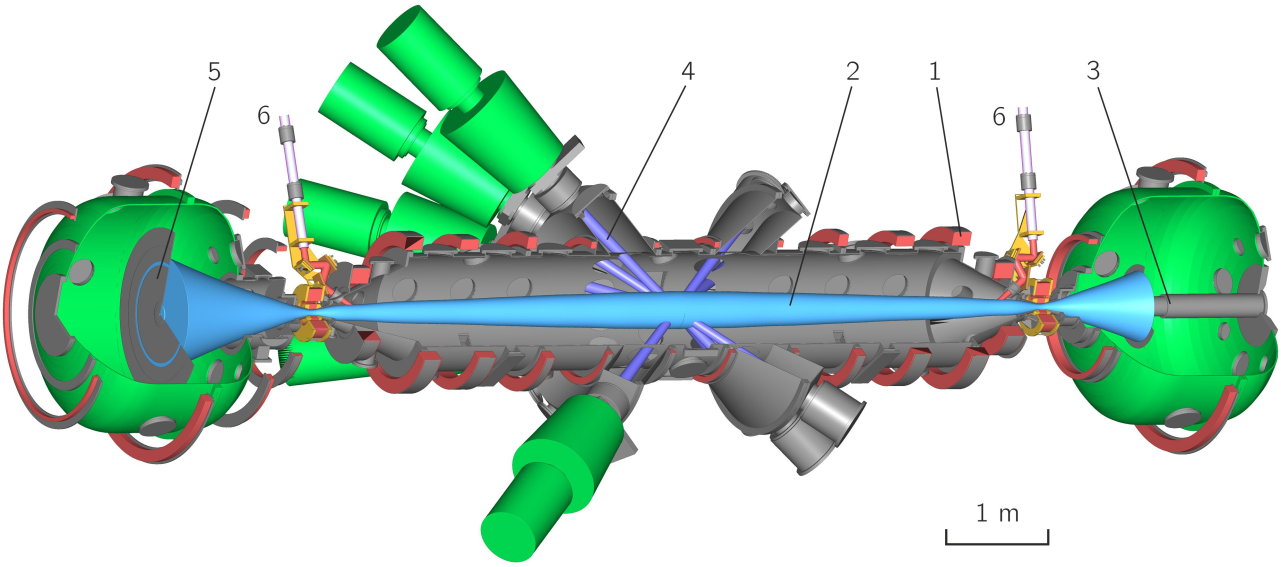

Figure 1. Layout of Gas Dynamic Trap. Magnetic coils (1), plasma column (2), plasma gun (3), 8 neutral beams (4), biased end plates (5), ECRH waveguides (6).

struction at the Budker Institute, in which fast ions are produced by injection of 3.5 MW, 15 keV, 5 ms neutral beams into a compact axisymmetric mirror trap [9]. The neutral power density exceeds the previous records [5] attained in the mirror machines by a factor of 2–3. Simulations show that accumulation of fast ions would provide the initial 0.3 T field reversal within the first 0.3–0.5 ms of injection. An increase of plasma pressure with higher neutral beam injection power may significantly improve the plasma confinement by increasing the effective mirror ratio or even form a reversed field configuration with transition to plasma confinement at the closed field lines, as in [10]. The experimental layout is shown in Fig.2. The vacuum chamber consists of a cylindrical central cell 3.5 m long and 1 m in diameter and an expander tank attached to the central cell at the end. A set of coils mounted inside and on the vacuum chamber produce an axisymmetric magnetic field with a mirror ratio of 1.5, when the central magnetic field is set to 0.3 T. The initial plasma is produced by a washer stack hydrogen-fed plasma gun. The gun is located in one of the end tanks beyond the mirror throat. The two neutral beams are injected perpendicularly to the plasma axis. Neutral beam currents in excess of 250 equivalent atomic amperes will be injected with an accelerating voltage of 15 keV [11]. Partial line-tying to the gun would provide stability of the plasma column during accumulation of the fast ions. Between the plasma gun muzzle and the entrance mirror coil, the magnetic field has a special profile with local minimum near the mirror coil, which produces the effect of a thermal barrier [12]. This effect was previously observed in the Ambal-M experiment [13] and was attributed to development of Kelvin-Helmholtz instability, which made the ion velocity distribution function strongly anisotropic in

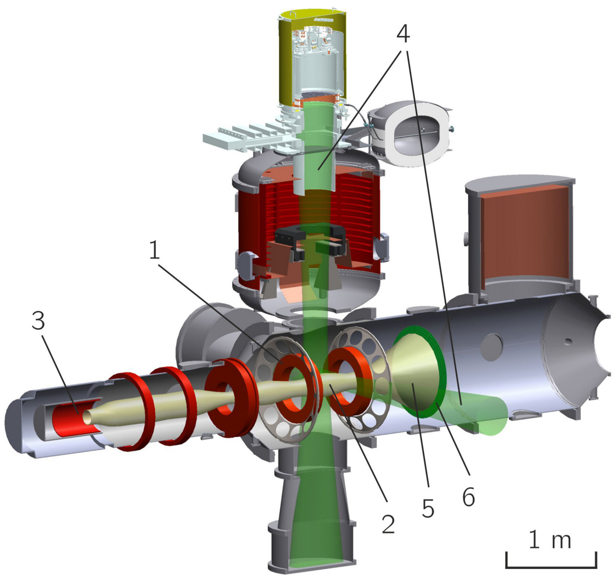

Figure 2. Compact Axisymmetric Toroid device. Magnetic coils (1), plasma column (2), plasma gun (3), two neutral beams (4), expander (5), biased end plates (6).

the region right at the entrance mirror coil. In the opposite end tank the magnetic field gradually decreases beyond the exit mirror thereby forming a potential barrier to prevent most of electrons from arriving to the end wall, thus providing the hot plasma thermal insulation from the end wall. As demonstrated in the GDT experiments, the electron heat flux to the end walls was substantially suppressed in the magnetic expanders [3]. This effect should provide the conditions for self-consistent increase of the electron temperature during the neutral beam injection. So, it is expected that the electron temperature of the gun-produced plasma should considerably increase from the initial value of 3–10 eV.

The numerical simulations show that the field reversal would become possible at an early stage of the beam injection. However, there are several open questions. The first one is the behavior of the electrons during the field reversal, which cannot be the fully modeled by the existing code. To control the electron collisionality, which would be playing the critical role during the reversal, the electron gun would be installed on-axis in the tank opposite to the plasma gun. Another problem would be the growth of the plasma instabilities during the reversal, which would deteriorate plasma confinement. To stabilize the unstable tilts, it is foreseen to vary the plasma axial extent by slightly changing the injection angle or by changing the axial positions of the internal mirrors coils. The plasma gun produces the inward radial electric field localized mostly at the edge of the plasma column, and provides also line-tying of the plasma in the main chamber to the gun electrodes which suppresses the flute instability [13]. This radial electric field caused sheared rotation and stabilized the $n = 2$ rotational mode in the field-reversed configuration experiments at the C-2 device [10]. Better plasma centering was also obtained in C-2, presumably from the line-tying to the gun. To ensure all these advantages, a sufficiently high-density plasma has to be maintained between the central cell and the gun.

3. Conclusions

Neutral beam injection into the GDT axisymmetric mirror plasma allowed stable accumulation of fast ions, which increased the plasma β up to 0.6. High current-density NBI will be used in the CAT device to produce high plasma pressure up to magnetic field reversal. Gas Dynamic Multimirror Trap (GDMT) [14] will combine the experience on axisymmetric mirrors.

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