Status of the Experiment on Magnetic Field Reversal at BINP

P.A.Bagryansky[1,2,a)], T.D.Akhmetov[1,2], I.S.Chernoshtanov[1,2], P.P.Deichuli[1], A.A.Ivanov[1,2], A.A.Lizunov[1], V.V.Maximov[1,2], V.V.Mishagin[1], S.V.Murakhtin[1,2], E.I.Pinzhenin[1] , V.V.Pikhodko[1,2], A.V.Sorokin[1], V.V.Oreshonok[1,2].

[1]*Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences, Novosibirsk, Russia*.
[2]*Novosibirsk State University, Novosibirsk, Russia.*

[a)] e-mail: P.A.Bagryansky@inp.nsk.su

Abstract. The paper describes experiment devoted to the field reversal in a mirror trap with neutral beam injection, which is planned for realization now in Budker Institute. The technical details of experimental device and expected plasma parameters are discussed. In accordance with theoretical predictions, parameters of experimental facility (neutral beam current - 240 atom A, energy of neutrals - 15 keV, magnetic field - 0.2 T, electron temperature 50 eV and target plasma density ~10^{13}–10^{14} cm^{-3}) are expected to be sufficient to field reversal in the case, if anomalous ion losses are not essential.

INTRODUCTION

The unique result obtained in the seventies of the last century on 2XIIB (LLNL, USA) device [1] gives reason to expect for the possibility of realization of reversed magnetic field configuration in a mirror trap with powerful neutral beams. Ratio between diamagnetic field perturbation and vacuum magnetic field $\Delta B/B$=0.9 was achieved with 7 MW of full power of neutral beams and current density of neutrals 0.7 atomic A/cm^2 at the plasma axis in special series of 2XIIB experiment. Progress in the development of neutral beam injection allows now to realize the neutral current density approximately 3-4 times higher than in 2XIIB experiment at lower total power ($\approx$ 3 MW).
Circumstances mentioned above have motivated development the project CAT (Compact Axisymmetric Toroid) directed on field-reversal experiments in axisymmetric magnetic mirror trap equipped with two geometrically focused high equivalent current density neutral beams. Estimated maximal current density of neutral beams is 3 atom A/cm^2. Target plasma with characteristic radius a=10 cm, density of 10^{13}–10^{14} cm^{-3} and electron temperature about 50 eV will be generated by special plasma source, developed at the former time for AMBAL experiment. Based on computer simulations under certain assumptions these parameters of neutral beam system and plasma source allow us to obtain the field-reversed configuration (FRC) [3]. During the experiment the processes accompanying fast ions accumulation, which are able to prevent field reversal (such as the MHD and kinetic instabilities) and methods of overcoming of these phenomena will be studied. Another possible direction of planned CAT experiment is realization and studies of a “magnet bubble” configuration [2]. Paper describes physical and technical details of the CAT project, which scheduled for realization at the Budker Institute.

EXPERIMENTAL DEVICE

The CAT (see Fig.1) is an axisymmetric mirror trap for confinement of population of fast axis-encircled ions (1) produced by off-axis neutral beams (NB) injection in the collisional warm (target) plasma. The accumulation of fast ions give rise of azimuthal current and results in decreasing and reversing magnet field. The device consists of central-cell (3), plasma gun cell (5) and plasma dump cell (6) with target plate (11) for absorption of plasma flowing from the mirror trap.

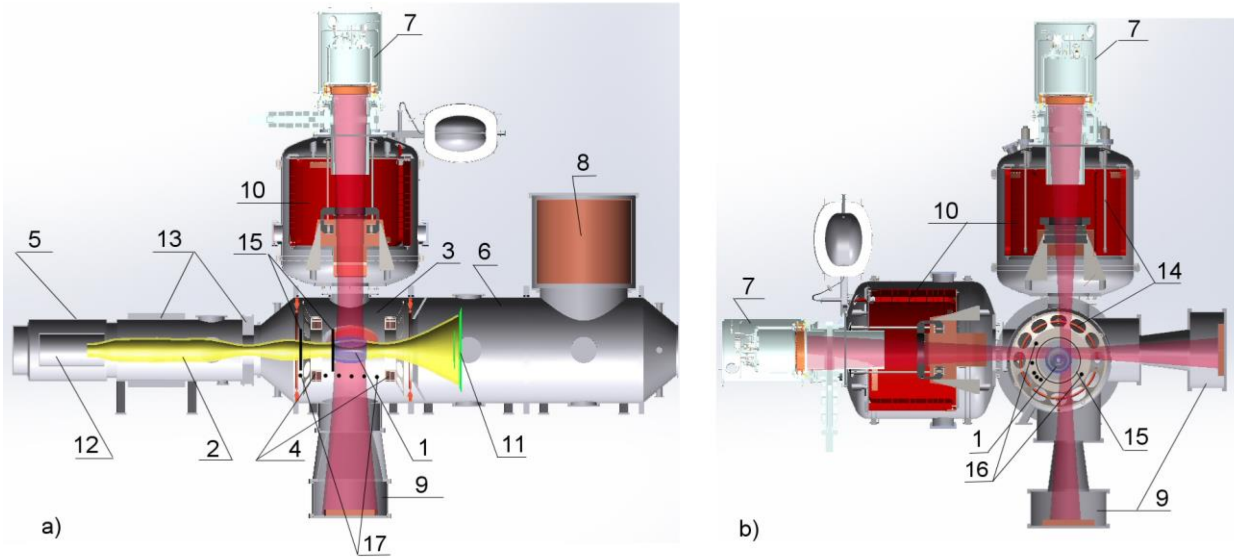

FIGURE 1. The CAT layout: a) Longitudinal section of the experimental setup, b) the cross-section in the meddle plane.

1 – Hot ion plasmoid in the central-cell, 2 – target plasma in the region of transportation; 3 – cental-cell vacuum chamber; 4 - mirror coils; 5 – plasma gun chamber; 6 – plasma dump chamber; 7 – neutral beam injectors; 8 – liquid-helium pump, 9 - neutral beam dump; 10 – NB vacuum tank; 11 – end plates; 12 – plasma gun; 13 – magnetic coils to form region of transportation and thermal barrier, 14 – Ti-getter pumps, 15 – diamagnetic loops, 16 – diamagnetic probes (azimuthal set), 17 – diamagnetic probes (longitudinal set).

The expected times dependences of ratio between diamagnetic field perturbation and vacuum magnetic field at different values of target plasma density and electron temperature are shown in Fig. 2. The dependences are given from Particle-in-Cell simulations [3] in assumptions of absence of non-axially symmetrical perturbation. The higher target plasma density, the faster accumulation of ions and the stronger field decreases. If electron temperature is too small than ion losses caused by electron drag is too strong and one can conclude that field reversal can be obtained at planned experimental parameters if anomalous losses of fast ions will be suppressed.

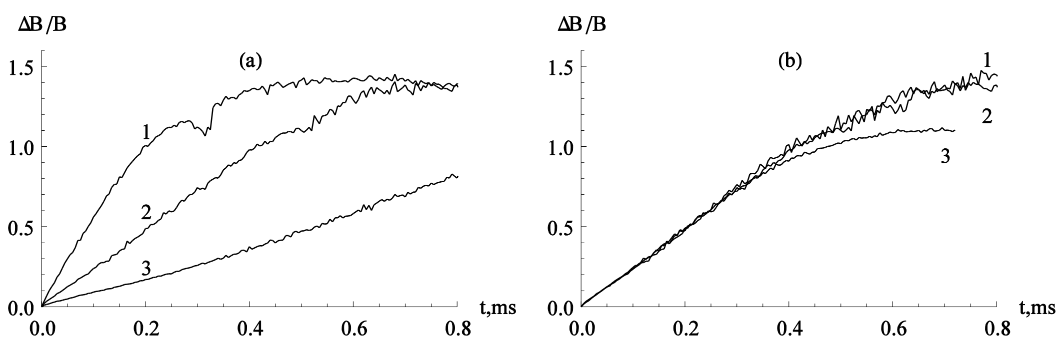

FIGURE 2. Time dependence of ratio between diamagnetic field perturbation and vacuum magnetic field at different target plasma densities (a) and electron temperatures (b) determined from PiC simulations [3]. Injection energy 15 keV, neutral beam current 240 A. Target plasma density: 1 – n_e=10^{14}cm^{-3}, 2 - n_e=$3\cdot10^{13}$ cm^{-3}, 3 – n_e=10^{13} cm^{-3}. Electron temperature: 1 – T_e=100 eV, 2 – T_e=50 eV, 3 – T_e=30 eV.

Neutral Beam System and Plasma Gun System

The NB system consists of two 2 MW, 15 keV hydrogen neutral beam modules with a geometrical beam focusing [4]. A pitch angle of NB injection is 90°. The divergence of the beams is 30 mrad along the devise axis and

11 mrad in the transverse direction. The planned time of NB operation is 5 ms. The geometrically focusing ion-optical system allows obtain current up to 2 atom A/cm^2 per one NB module, that few times exceeds current density achieved in 2XIIB experiment. Axes of atomic beams are shifted by a 10 cm with respect to the device axis (see Fig 1b). Under these conditions, ions tend to be trapped on orbits encircling the magnetic axis. Trapped NB power of 2.5 MW is predicted.

By means a plasma gun (12) positioned in the gun vessel [5], the CAT will be filled with warm plasma. Time of plasma gun (PG) operation is 5 ms. We plan to use the plasma gun with a coaxial configuration of the discharge channel [5]. The radial electric field that is generated in the discharge channel has a value sufficient to generate the Kelvin-Helmholtz instability. This instability caused by the differential rotation of the plasma in the region projected on the discharge channel. In the process of the plasma flow through the area of transport (13) instability leads to heating of the ions to energies of several hundred eV. In the magnetic mirror under the coil located between the transportation region and the central part of the device, the ion density decreases. This leads to the formation of negative potential peak. This peak is a thermal barrier, limiting electronic thermal conductivity between the main mirror cell and discharge channel of the plasma gun. In the central mirror cell, the electrons are heated by relaxation of ions heated in the transportation region (13). In this way, a thermally insulated plasma with electron temperature of several tens of eV was produced in the experiments on AMBAL facility [5].

Magnetic System and Diagnostics

Facility magnet system consists of a central solenoid and plasma gun solenoid (13). The magnetic field of the central-cell is produced by two mirror units (4) installed in the vacuum chamber. The coils of the central-cell and coils of the plasma gun are supplied from an individual capacitor bank. The oscillation half-period of this system is ≈200 ms, and the maximum attainable field on the axis in the middle plane is B_0=2 kG. Magnetic field in the mirror coils region is B_m=4 kG. The main parameters are subscribed in Table 1.

TABLE 1. The CAT parameters.

Parameter	Value
Total device length	**7 m**
Mirror to mirror distance	**58 cm**
Magnetic fields at midplane	**2 kG**
In mirror	**4 kG**
Pulse duration of PG	**5 ms**
Target plasma radius	**10 cm**
Target plasma density	**10^{13}–10^{14}cm^{-3}**
Injection energy of NB	**15 keV**
Total injection power of NB	**4.5 MW**
Pulse duration of NB	**5 ms**
Injection angle of NB	**90°**

In a deemed experiment, accumulation of fast ions in a volume encompassing neutral beam injection target would make a significant diamagnetic reduction of magnetic field with a characteristic radial gradient scale of an order of the fast ion gyroradius. In an extreme case, an initial magnetic field would be reduced down to zero and then reversed. To provide localized measurements of both the magnetic field magnitude and direction, we propose application of a combined diagnostic of motional Stark effect [6] with a laser-induced fluorescence [7]. The optical system design gives eight points of measurement inside the plasma with the spatial resolution of a few millimeters. Distributed along a plasma radius of approximately 20 cm, these eight lines of sight deliver good resolution of a disturbed magnetic field structure. The control and data acquisition system of the MSE-LIF diagnostic is to provide recording signals continuously within a plasma shot with a time resolution in the range of 0.02÷1 ms. Plasma diamagnetism will be measured by two diamagnetic loops. The diamagnetic loop at the midplane measures diamagnetism of the both bulk plasma and FRC (15). An additional diamagnetic loop located outside the turning point of hot ions sees only the signal from the bulk plasma.

The particle scattering caused by ion-cyclotron fluctuations was one of the reason restricted ion pressure in 2XIIB experiment. The Particle-in-Cell simulations show the possibility of kinetic instability arising also [3]. Magnetic field fluctuations will be measured by longitudinal and azimuthal sets of high-frequency magnetic probes (16, 17). The following methods can be used in CAT experiment for suppressing kinetic instabilities: varying of injection angle, generation of axial current causing magnet shear, potential controlling by sectioned plasma end plates.

CAT Vacuum System

The CAT vacuum vessel consists of the three main chambers: a central cell confining the main plasma (3), plasma gun cell (5) and plasma dump chamber (6). The central-cell volume is 1 m^3, The volume of the plasma bump cell is 2 m^3. All the joints that require periodic connections and disconnections are made with the viton sealing. The central-cell are pumped out by 700 l/s turbo molecular pump Shimadzu TMP1103. Additionally it equipped with pulsed Ti-evaporator (14). The plasma bump cell are additionally installed 1000 m^3/s liquid helium pump (8). We hope that the measures make it possible to obtain a vacuum better than 10^{-5} Pa.

Both injectors and the main vacuum chamber have similar pumping systems. Each system includes a dry vacuum pump (Edwards XDS35 or Kashiyama MU100), a turbo molecular pump Shimadzu TMP1103 and a set of electrically controlled gas valves to connect to the vacuum tank and prevent the alarm situations with vacuum conditions and pumps operation. All pumps are controlled remotely via ADAM-4055 digital I/O modules with RS-485 interface. The same modules are used to control valves and get its status signals. For the vacuum monitoring an ADAM-4117 analog input module is used. It monitors the signals from vacuum gauges installed in vacuum tanks and pumping lines as well.

To maintain the vacuum system operation an in-house designed controller based on the ARM Cortex-M4 MCU is used. It has four independent serial (UART) fiber optic channels to communicate with I/O modules installed locally near each pumping system. Three channels are used to control injectors and the main chamber vacuum equipment while another one is intended to acquire vacuum measurements. The vacuum system current status and settings can be controlled locally from the controller front panel or remotely via the web interface.

CONCLUSION

Experimental device for investigation of possibility of field reversal by neutral beam injection in an axisymmetric mirror trap is under construction in the Budker INP now. In comparison with the 2XIIB experiment, the neutral current density increased few times and flexible design of NB system is developed. It allows us to expect the accumulation of fast ions enough for field reversal. Target time of physical start of CAT device is close of 2018 year.

ACKNOWLEDGMENTS

This work supported by Russian Science Foundation (project 14-50-00080).

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