# Neutral Beam Injection System for the CAT Experiment*)

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In the Budker Institute, the CAT (Compact Axisymmtric Toroid) experiment is being prepared for obtaining a plasmoid with high diamagnetism in axially symmetric magnetic field. Reverse of magnetic field in the plasmoid is also possible in this experiment. The experiment is based on injection of powerful focused neutral beams with extremely large neutral power density in the plasma. Two neutral beam injectors with the energy of hydrogen atoms of 15 keV will be used in the experiment. The neutral beam power of each injector is 2 MW, pulse duration is 5 ms. In the ion source of the injector, plasma emitter is produced by plasma jets from four arc plasma generators. Proton beam with current up to 170 A is formed by multi-slit three-electrode ion-optical system with ballistic focusing. Measured angular divergence of the formed beam along the slits is 10 mrad, divergence in the direction across the slits is 35 mrad. The injector is equipped with a neutralizer, bending magnet, residual ion dump, calorimeter, high speed pumping system with titanium arc evaporation.



Keywords: neutral beam injector, ion source, axisymmetric magnetic trap

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## 1. Introduction

Within the last twenty years more than thirty diagnostic and heating neutral beam injectors with ballistic beam focusing have been developed and produced in the Budker Institute [1]. The ballistic beam focusing is provided by spherically shaped multi-aperture electrodes of ion optical system. The injectors are successfully used in different plasma physics experiments. In the Budker Institute the developed injectors are used for heating and diagnostic of axisymmetric mirror-confined plasma.

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 [2]. Axisymmetric magnetic field allows stable equilibrium of a high pressure plasma. In the paper the neutral beam injection system for axisymmetric experiment with high pressure plasma is presented.

## 2. The CAT Experiment

To study production and sustainment of high pressure plasmas in more detail, now the CAT (Compact Axisymmetric Toroid) experimental device is under construction 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 [3]. The neutral power density exceeds the previous records [4] 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 [5].

The experimental layout is shown in Fig. 1. 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 [6]. The gun is located in one of the end tanks beyond the mirror throat. 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 [7].

The two neutral beams are injected perpendicularly to the plasma axis. Axes of atomic beams are shifted by a 10 cm with respect to the device axis. Under these conditions, ions tend to be trapped on orbits encircling the

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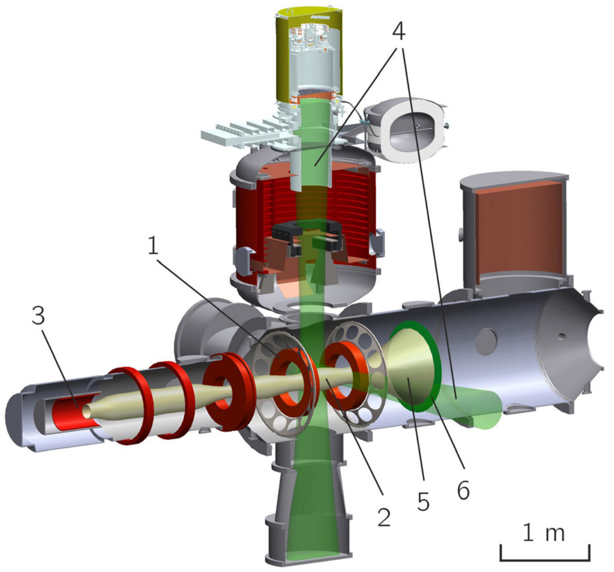


Fig. 1 Compact Axisymmetric Toroid device. 1 - magnetic coils, 2 - plasma column, 3 - plasma gun, 4 - two neutral beams, 5 - expander, 6 - biased end plates.

magnetic axis. Trapped neutral beam power of 2.5 MW is predicted.

## 3. Neutral Beam Injector

The neutral beam injection system consists of two 2 MW, 15 keV hydrogen neutral beam modules with a geometrical beam focusing. The planned time of neutral beam operation is 5 ms. Specialized injector was developed that produces a high power neutral beam at relatively low energy. The injector beamline is shown in Fig. 2. It includes a neutralizer, calorimeter, ion deflection magnet, residual ion dump, cryopump, and other major components which are housed inside or at a cylindrical vacuum tank. A beamline neutralization duct serves to convert the primary ion beam into the atomic one. Gas is partly supplied into the duct by puff from the discharge chamber, the rest amount is puffed into the duct through a manifold by making use of a pulse gas valve. During a beam injection, the typical hydrogen pressure in the neutralizer is ~ 2 mTorr. Bending magnet and residual ion dumps are placed inside the vacuum vessel. The beam main vessel has inner copper liner which has thermal insulation from the wall and can be cooled down to the liquid nitrogen temperature. The inner ribbed surface of the liner is coated by fresh titanium film and works as a getter pump. Four identical titanium arc evaporators are inserted through the ports on the tank front side. Measured pumping speed is about $4 \cdot 10^5$ l/s [8].

A retractable calorimeter for beam profile and position measurements is available at the exit of the injector tank.

Shown in Fig. 3 ion source [9] of the injector forms a proton beam with the particle energy of 15 keV, current of up to 175 A, and pulse duration of 8 ms. The plasma

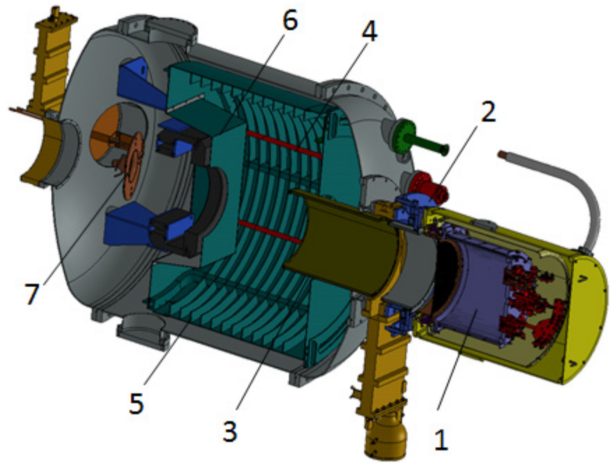


Fig. 2 Neutral beam injector. 1 - ion source, 2 - aiming unit, 3 - neutralizer, 4 - Ti arc evaporator, 5 - liner, 6 - bending magnet, 7 - movable calorimeter.

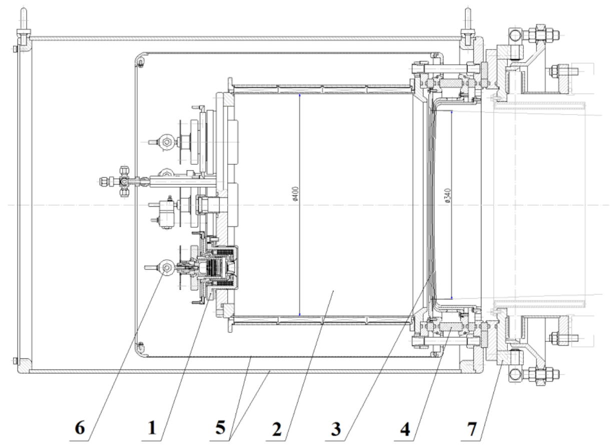


Fig. 3 Ion source of the high power injector : 1 - arc discharge plasma generator, 2 - expander chamber, 3 - grids, 4 - insulator, 5 - shields, 6 - gas valve, 7 - aiming unit.

emitter of the ion source is produced by superimposing highly ionized plasma jets from four arc-discharge plasma generators. Part of the collisionless expanded jets is reflected from a multipole magnetic field produced with permanent NdFeB magnets at the periphery of the plasma box. The reflection provides increased efficiency and improved uniformity of the plasma emitter. The ion emission current density at the exit of the plasma emitter is quite high and has a value of 600 mA/cm$^2$. Such a value of the ion emission current density exceeds the usually used current density in the ion sources of the injectors and is needed to form a beam with a high current. The proton beam is formed by three electrode multi-slit ion optical system with 48% transparency, 34 cm initial beam diameter is and 3.5 m focal length. Photo of the assembled ion optical system is presented in Fig. 4. Spherically shaped multi-slit grids of the ion optical system are produced from CuCrZr

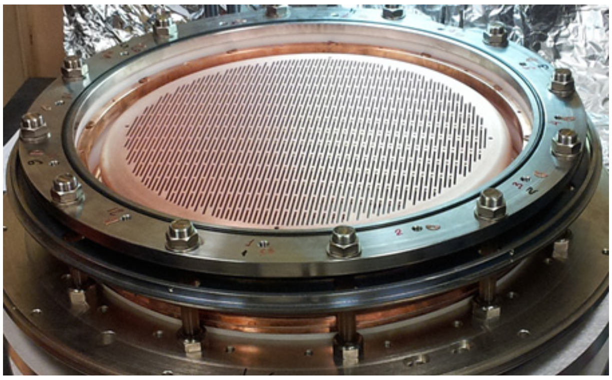

Fig. 4 Assembled ion optical system.

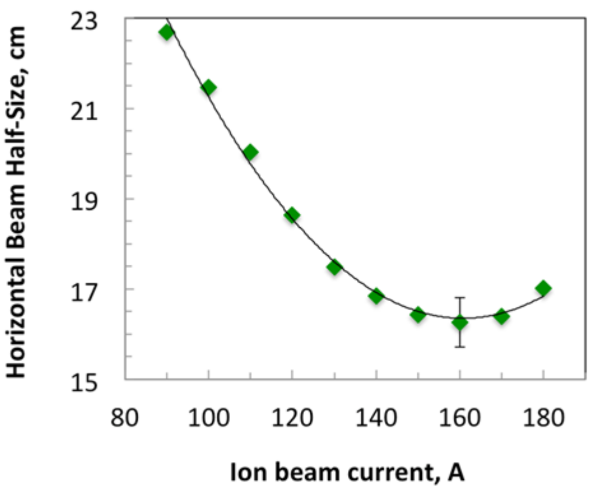


Fig. 5 Horizontal beam half-width (at the e-folding level) measured at 4 m from the grids.

alloy. The geometry and potentials of the slit elementary cell [10, 11] of the ion optical system were optimized numerically and experimentally to ensure accurate beam formation. The measured angular divergences of the elementary beam are 10 mrad parallel to the slits and 30 mrad in the transverse direction.

Tests of the injector were carried out at the specialized test bed. Beam radial profiles are measured at several axial locations along the beamline with secondary electron emission detectors and with a retractable calorimeter. The scan of the beam width versus the beam current at 4 meters from the source is shown in Fig. 5. It displays the typical V-shape dependence with a minimum beam size corresponding to the optimal perveance at the ion current of ~160 A. The beam profile measurements at two distances from the source (3.5 m and 4 m) allow to estimate the focal length, which is found to be ~350 cm at the grid curvature of 350 cm, in good agreement with the calculated focus length. Also inferred from the profile measurements are the beam divergence half-angles across and along the slits, 0.035 and 0.01 radians, respectively.

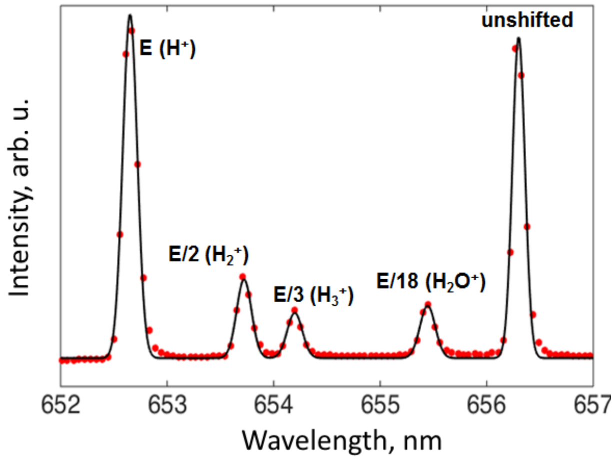


Fig. 6 Doppler shifted $H_\alpha$ peaks for 15 kV neutral beam.

The measured Doppler-shifted spectrum of the beam radiation is shown in Fig. 6. The energy fraction analysis indicates that $H^+$, $H_2^+$, and $H_3^+$ percentages in the extracted ion beam (at 160 A) are 85%, 10%, and 4%, respectively. The water is initially low, ~ 1%, and gradually conditions away. Similar results for the beam composition were obtained with magnetic mass-spectrometer measurements.

## 4. Conclusions

Experimental tests of the injector shown good ion source reliability of operation with projected parameters. The distinguishing feature of the injector is the capability of strong beam focusing. After initial experiments at the CAT device the neutral beam energy can be changed to optimize behavior of fast ion in plasma. To change the beam energy the accelerating gap in ion optical system should be varied for optimal beam formation. To achieve higher neutral beam current density in the plasma the integral angular divergence across the slits can be decreased by change of ion optical system elementary cell geometry. Reduction of beam focal distance by shortening the injector beamline also can increase the neutral beam current density in the plasma.

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[1] V.I. Davydenko, A.A. Ivanov, P.P. Deichuli *et al.*, Fusion Sci. Technol. **59,** No1T, 128 (2011).
[2] D.D. Ryutov, H.L. Berk, B.I. Cohen *et al.*, Phys. Plasmas **18**(**9**), 092301 (2011).
[3] P.A. Bagryansky, T.D. Akhmetov *et al.*, AIP Conf. Proc. **1771**, 030015 (2016).
[4] F.H. Coensgen, C.A. Anderson, T.A. Casper *et al.*, Phys. Rev. Lett. **44**, 1132 (1980).
[5] M. Tuszewski, A. Smirnov, M.C. Thompson *et al.*, Phys. Plasmas **19**, 056108 (2012).

[6] G.I. Dimov, A.A. Ivanov and G.V. Roslyakov, Sov. J. Plasma Phys. **8**, 546 (1982).
[7] T.D. Akhmetov, V.S. Belkin, E.D. Bender *et al.*, Plasma Phys. Rep. **23**, 911 (1997).
[8] A. Sorokin, A. Ivanov, P. Deichuli *et al*. AIP Conf. Proc. **1771**, 030026 (2016).
[9] P. Deichuli, V. Davydenko, A. Ivanov *et al*., Rev. Sci. Instrum. **86**, 113509 (2015).
[10] V. Davydenko, V. Amirov, A. Gorbovsky *et al*., Rev. Sci. Instrum. **87**, 02B303 (2016).
[11] A.V. Sorokin, V.I. Davydenko, P.P. Deichuli and A.A. Ivanov, Tech. Phys. **61**, 1004 (2016).