A Plasma Target for Neutralization of the Negative Ion Beam

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Abstract. The results of the experimental study of build-up and confinement of low-temperature plasma target for neutralization of high energy negative ion beam are presented in the paper. The cylindrical vacuum chamber of the plasma target is 1.2 m long and 0.2 m in diameter. The axisymmetric multicusp magnetic field is formed at the periphery of the target chamber by using an array of the permanent NdFeB magnets, which are placed closely on the thin chamber walls. The target chamber is ended by the two diaphragms with 0.1m diameter apertures for the negative ion beam passing through. For reduction of the plasma losses through the ends, the inverse magnetic field are formed in the apertures .The plasma is produced in the target by ionization of the working gas by electrons, which emitted by six plane LaB_6 cathodes, which are placed uniformly over azimuth at the center of the plasma target. The discharge duration is set to 1 s. In short pulses at 300 kW power, the hydrogen plasma with density $n_i \approx 2.5 \cdot 10^{13}\ cm^{-3}$ is produced. Spatial profiles of the plasma parameters in the target were measured.

INTRODUCTION

At the present time, the injection of energetic beams of hydrogen isotopes is one of the most important methods of plasma maintenance and heating in fusion devices with magnetic confinement. For example, in large tokamaks powerful neutral beams are used to sustain stationary toroidal plasma current. The required energy of beams is ~ 1 MeV, and power ~ 10-100 MW.

For obtaining neutral beams of atom with energies > 100 keV, it is necessary to neutralize the beams of accelerated negative ions in a special target. For that, a plasma neutralizer can be used. The neutral yield in the plasma target is higher than in a gas target [1]. The maximum neutralization efficiency can be obtained if one used the plasma of fully ionized hydrogen. The neutral yield in such a target is ~ 85 %. To maximize the atomic fraction, the line density of the target has to be $n_e \cdot l \approx 3{,}7 \cdot 10^{15}\ electron/cm^2$ at the beam energy 1 MeV. Give a reasonable length of a neutralizing target of several meters, plasma density in the target has to be $n_e \geq 10^{13} cm^{-3}$. The ionization degree of plasma in the target has to be as high as possible to provide the maximum neutral yield. However, this limitation is not too restrictive for hydrogen plasma target. For ionization degree of 70 %, the atomic fraction of the neutralized beam decreases only by 2 % [1,2].

A prototype of the plasma target for neutralization of high energy negative ion beams is developed in the Budker Institute of Nuclear Physics (BINP SB RAS). The paper reviewed the experimental results obtained in the studies of this prototype.

DESCRIPTION OF THE APPARATUS

Target plasma is produced in a confinement system with multipole magnetic walls. The cylindrical vacuum chamber of the target is 120 cm long and 20 cm diameter. At the end of the chamber there are 10 cm diameter apertures for passing of the neutralized beam through. The trap consists of two parts which are symmetric with respect to the central section. Plasma is generated by gas ionization by the electrons, which are emitted from cathodes. The cathodes are installed in the cathodic block, which is placed in the central section of the trap. In the cathodic block 6 cathodes are installed. The cathode is a heated laB_6 tablet 17 mm in diameter. They are located evenly on a circle at some distance from area of passing of the neutralized beam. The electrons emitted by LaB_6 tablets are injected in plasma. The general view of a trap is shown in fig. 1.

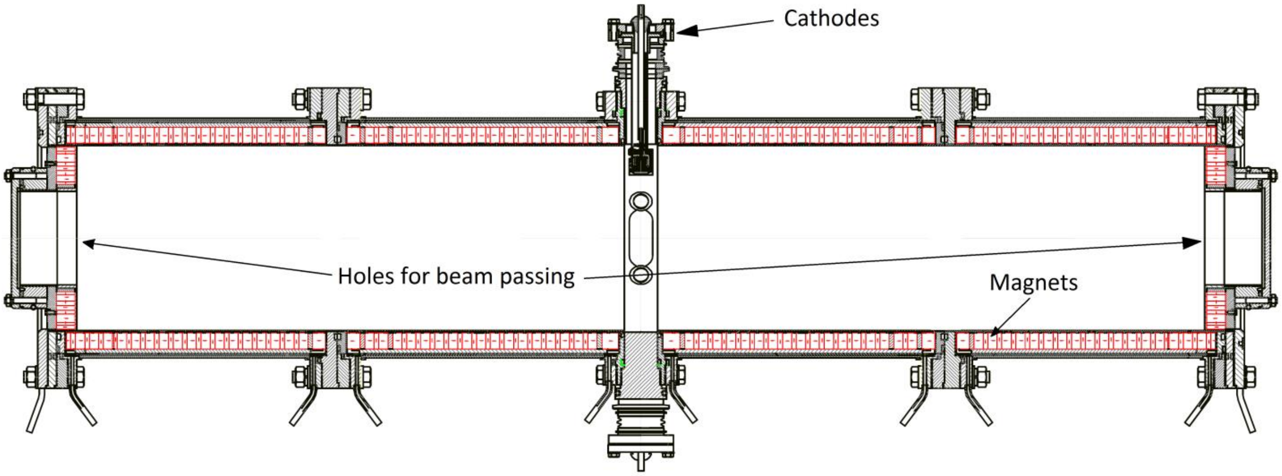


FIGURE 1. Scheme of the plasma trap.

The magnetic field in the trap is formed by permanent magnets with iron yokes. The magnets placed closely on a thin-walled vacuum chamber and surrounded by iron magnetic yokes. The magnets of one direction of magnetization are ring-shaped. The magnetic rings are set on a cylindrical vacuum chamber in such a way that the directions of magnetization sequentially alternate. There are rings with radial and axial directions of magnetizations. Thus, the strong multipolar axisymmetric magnetic field is formed near the wall of vacuum chamber. The distance between rings of the different directions of magnetization is 1,5 cm. This distance was selected in order that the strong magnetic field was only near the walls of a vacuum chamber and didn’t penetrate into the area of passing of the neutralized beam. The magnetic field on a wall of vacuum chamber has a value ~ 7 kGs. Such magnetic field geometry provides MHD stability of plasma in the trap.

In the central region of each halves of the trap the longitudinal magnetic field is ~ 100 Gs. The axial magnetic field is formed in the apertures in the end faces of a trap. This magnetic field is directed opposite in relation to a magnetic field in the central part of the corresponding half of the trap. This inverse magnetic field has to limit leakage of plasma particles in end apertures due to conservation of generalized angular momentum of particles in the axisymmetric magnetic field [3,4].

The plasma in the trap is produced due to hydrogen ionization by electrons which emitted from cathodes. There are two discharge power supply system. The first discharge power supply system is stationary. It allows to couple 60 kW power to the discharge permanently. The stable discharge lasting 1 sec has been received when using this power supply system. Plasma density was $n_i \approx 7 \cdot 10^{12} cm^{-3}$ at the power of 60 kW coupled into the plasma. The second power supply system was pulse. This power supply system allows the power of 300 kW to couple into the plasma in the 1 ms pulse mode. The bulk of experiments were done with a pulse power supply system at the power 100-300 kW coupled into the discharge.

Working gas (hydrogen) was filled in the center of the trap by the pulse valve lasting 1-10 ms (for short pulse). The voltage pulse put to the cathodes with some delay. The discharge supply was by rectangular pulses lasting 1 ms. The discharge had following parameters: current up to 500 A, discharge voltage up to 600 V, maximum power put in the discharge up to 300 kW.

A number of diagnostics for measurement of plasma parameters and gas density in the trap are on the device. Plasma density, electron temperatures and plasma density distribution in the trap are measured by probes. The movable single probe in one of the end holes to be entered into the trap along an axis. This probe measures plasma parameters in the trap and in area of inverse plug in the end opening. In the central part of the trap there is a transverse triple probe. It allows to measure radial distribution of plasma density and electron temperature in the main area of the trap, on removal from the cathodic block and end openings.

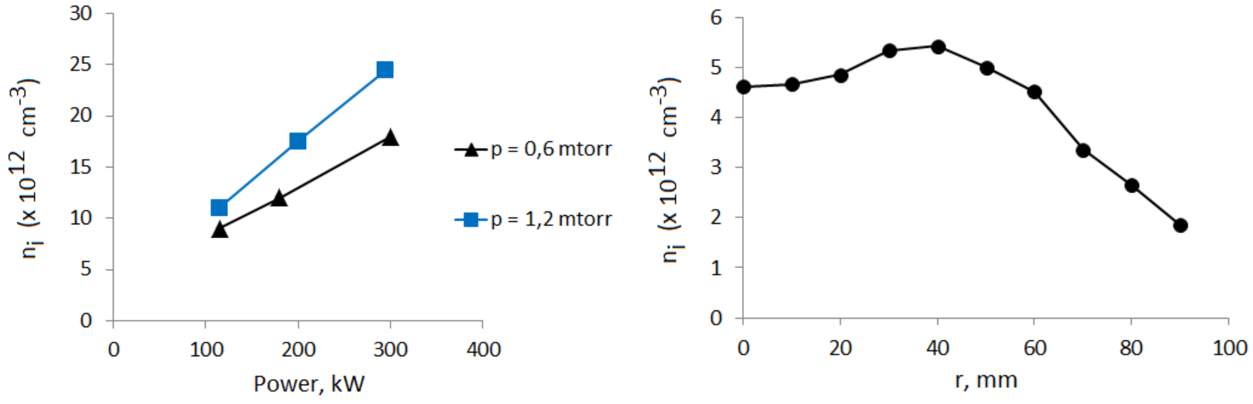
Plasma density and gas density (or ionization degree, depending on experiment statement) is defined by diagnostic beam from DINA-4 injector. We used atomic or proton beam. The initial beam passes through the plasma in the trap is partially recharged and gets to the magnetic analyzer. The beam is divided in the analyzer into three components: atomic component, protons and negative ions of hydrogen. The charged components of the beam are registered in the analyzer by Faraday‘s cups. The atomic component is registered in the analyzer by secondary emission detector.

Two scheme of experiment are provided. In the first scheme the plasma is probed by an atomic beam along the device. In this scheme of experiment the line-averaged density of plasma or ionization degree is measured along the axis. In the second experiment scheme the beam is injected across the axis. In this experiment scheme the radii-averaged linear density of plasma or gas is measured in the center of the trap.

EXPERIMENTAL RESULTS

The plasma density measured by the probe are given in fig. 2a. Results for several gas densities before the discharge are given. Plasma density linearly depends on the discharge power. The plasma density $n_i \approx 2{,}5 \cdot 10^{13} cm^{-3}$ is achieved in the trap at the discharge power 300 kW.

The electron temperature weakly depend on discharge power. The electron temperature decreases at increasing the gas density before the discharge. The electron temperature is $T_e \approx 3 \div 4\ eV$.



(a) (b)

FIGURE 2. (a) Plasma density at various values of discharge power and gas pressure; (b) radial distribution of plasma density

The plasma density dependence from radius is shown in fig.2b. This distribution is measured at the discharge power 80 kW. The plasma density has a small dip in the paraxial area, achieves a maximum on radius ~ 40 mm and falls down at a vacuum chamber wall protected by multipole magnetic field. In our trap the area of passing of the neutralized beam is defined by the diameter of end openings of the trap and is equal to radius of 50 mm. Thus, in the area of passing of the neutralized beam the plasma density is constant with an accuracy better, than 10 %.

Plasma density on an axis is measured on both part of a trap. Plasma density in different parts coincides with accuracy better, than 10 %. The density of plasma decreases in the area of an inverse magnetic field. It demonstrates the confinement of plasma from the outflow in the end openings by inverse magnetic field. Results show that plasma occupies all length of a trap limited by an inverse magnetic field in the end openings.

The lifetime of plasma in the trap is measured at fast shutdown of discharge voltage. The lifetime of plasma in the trap measured in such way is $45\,\mu s$. The reduction of plasma density is slowed down at plasma density is $\sim 3 \cdot 10^{12} cm^{-3}$. The lifetime of plasma in the trap increases to value of $170\,\mu s$.

The degree of ionization of plasma is measured at probing of plasma by a hydrogen atomic beam along a trap axis. The degree of ionization is ~ 20 % at plasma density on the axis is $n_i \approx 1 \cdot 10^{13} cm^{-3}$.

DISCUSSION

Efficiency of a trap can be estimated by definition plasma lifetime in a trap. In the presented geometry plasma can be lost from a trap on three channels: plasma leakage through a multipolar magnetic field on a camera wall, leakage on cathodes, plasma leakage through end openings. It is convenient to characterize the speed of loss plasma in each of channels the effective loss area. Plasma leaks through this effective area with an ion sound speed.

The plasma leakage through a multipolar magnetic field has been investigated [5]. Such losses occurs in the slit which formed by the converging lines of magnetic field. Width of such slits is equal to two hybrid Larmor radius $d_{sl} = 2 \cdot \sqrt{r_e \cdot r_i}$ [5]. We receive width of the slit $d_{sl} = 0{,}06\ mm$ substituting in this formula value of a magnetic field on a camera surface ($B_w = 7\ kGs$) and plasma parameters: $T_e = 4\ eV,\ T_i = 0{,}5\ eV$. The effective loss area through a multipolar magnetic field can be calculated

$$S_{loss\_1} = N \cdot 2 \cdot \pi \cdot r \cdot d_{sl} = 30\ cm^2 \tag{1}$$

Here N – number of the slits, r – radius of vacuum chamber.

Cathodes are in plasma, and plasma can directly be lost on them. In our trap the cathodes area is $S_{loss\_2} = 32\ cm^2$. This area is almost equal to the effective loss area on the camera through multipolar magnetic field. Thus the loss on the cathodes has an essential role in general plasma confinement in the described trap.

It is difficult to estimate the area of plasma losses at the end openings now. The area of two openings for neutralized beam passing is equal 160 cm^2. If the plasma flow in these openings is not effectively limited the plasma losses in the end openings exceed considerably the losses on the other channels. Measurement of the plasma flow in the end openings is one of tasks for further studying of such trap. There are results of preliminary experiments on model of the small size. It is shown that the inverse magnetic field applied in our trap in end openings effectively limits a plasma flow through such openings [4].

It is possible to estimate plasma lifetime in the trap

$$\tau \approx \frac{V \cdot n_i}{n_i \cdot v_s \cdot (S_{loss_1} + S_{loss_2})} = 170\ \mu s \tag{2}$$

Here V ($\approx 18 \cdot 10^3 cm^3$)– plasma volume, n_i – plasma density, v_s – ion sound speed.

The plasma lifetime measured in the experiment at the plasma density $n_i \leq 3 \cdot 10^{12} cm^{-3}$ well coincides with the calculated plasma lifetime. However at the plasma density $n_i > 3 \cdot 10^{12} cm^{-3}$ the lifetime of the plasma decreases to 45 μs. Perhaps the plasma lifetime is defined by some other mechanism under the circumstances.

CONCLUSION

We developed the prototype of the plasma target with parameters which are close to that necessary for neutralization of powerful beams of hydrogen negative ions. In the 120 cm long trap, the stable plasma column with volume ~ 20 l in the long pulse mode (1 s) is produced. The used LaB_6 cathodes allows to couple 300 kW power into plasma. The plasma density is $n_i = 2{,}5 \cdot 10^{13} cm^{-3}$. The degree of ionization is ~ 20 %.

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