# Computer Simulation Of Cylindrical Plasma Target Trap With Inverse Magnetic Mirrors

E. A. Berendeev[1,a)], G. I. Dudnikova[1,2,b)], A. A. Efimova[1,c)], A. V. Ivanov[3,d)] and V. A. Vshivkov[1,e)]

[1]*Institute of Computational Mathematics and Mathematical Geophysics SB RAS, prospect Akademika Lavrentjeva, 6, Novosibirsk, 630090, Russia*

[2]*Institute of Computational Technologies SB RAS, prospect Akademika Lavrentjeva, 6, Novosibirsk, 630090, Russia*

[3]*Budker Institute of Nuclear Physics SB RAS, prospect Akademika Lavrentjeva, 11, Novosibirsk, 630090, Russia*

[a)]Corresponding author: evgeny.berendeev@gmail.com
[b)]dudn@ict.nsc.ru
[c)]anna.an.efimova@gmail.com
[d)]avi_nsk@mail.ru
[e)]vsh@ssd.sscc.ru

**Abstract.** Computer simulation of dynamic of plasma target for highly efficient neutralization of powerful negative ion beams is considered. The plasma is confined within a magnetic trap with multipole magnetic walls. Mathematical model is based on the Boltzmann equation for the distribution functions for ions and electrons and system of the Maxwell's equations for the self-consistent electromagnetic fields. The combination of the modified PIC-method in the cylindrical R-Z coordinates and the Monte-Carlo methods is used to solve these equations. The complex nature of the processes studied, and also the need of calculation of trajectories of billions of particles required the use scalable parallel algorithm. The use of modern supercomputers has allowed to calculate plasma dynamics, to determine plasma streams both on the walls of the trap and through end holes.

## INTRODUCTION

It is known that the injection of powerful beams of neutral atoms is one of the methods of accumulation and heating of a high-temperature plasma confined in a magnetic field. So the problem of development of efficient sources of such beams is one of the important problems of the fusion. For creating neutral atomic beam with energy exceeding 0.1 MeV/nucleon, accelerated up to a specified energy negative ion beam is passed through a neutralizing target. This is especially important for reactions with small energy yield. Various types of neutralizing targets (gas, plasma, photon) are developed in a number of laboratories at present [1], [2], [3]. The concept of the high-energy negative ion beam neutralization by the low-temperature plasma target has been proposed and developed at BINP [4].The yield of neutral atoms has reached 85% in a plasma target, and high rates of plasma confinement were obtained. At present an axisymmetric magnetic trap with a weak longitudinal magnetic field and inverse mirrors in the holes has been proposed [5]. The trap is a cylindrical vacuum chamber of diameter 199 mm and the length of the trap is 1355 mm. The trap consists of a central cathode block and two mirror-symmetric cylindrical sections and end holes. Additional separation of each of the cylindrical sections into two halves is due to mechanical resistance. Figure 1 shows the configuration of the magnetic field at the walls of the trap.

The complex configuration of the magnetic field and the non-linear nature of the plasma processes in the trap imposes significant constraints on theoretical estimates of the required parameters of plasma and neutralized beam. Accurate assessment and minimization of plasma losses in the passages at the ends as well as through the multipole magnetic walls of the trap can be obtained by numerical modeling that takes into account the basic laws of physical processes.

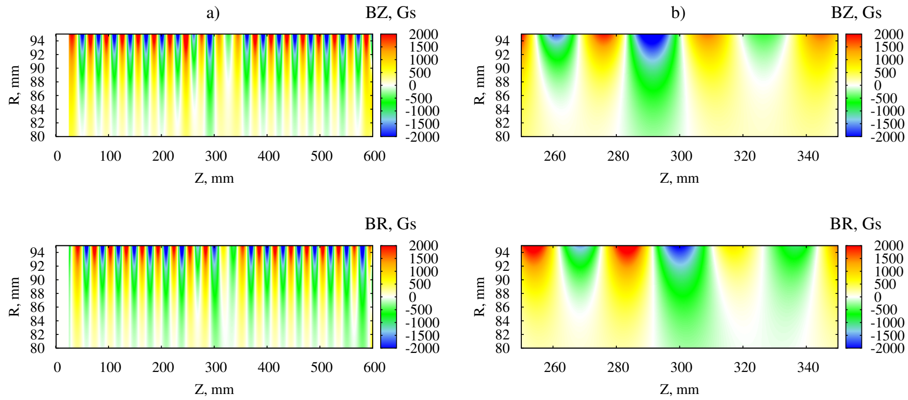


**FIGURE 1.** Configuration of the magnetic field of the trap of a) along all wall, b) in the central section of a wall. Z corresponds to the position of the cathodic block.

## THE MATHEMATICAL MODEL

It is important to take into account the phase distribution of the particles, the area of losses and the area of plasma confinement in the calculation because of locking of electrons in the considered trap. Plasma dynamics is described by the Boltzmann equation for ion and electron distribution functions $f_\alpha(t, \vec{r}, \vec{p})$ (Eq. 1) and the Maxwell's equations with self-consistent electromagnetic field.

$$\frac{\partial f_\alpha}{\partial t} + \vec{v}\frac{\partial f_\alpha}{\partial \vec{r}} + q_\alpha\left(\vec{E} + \frac{1}{c}[\vec{v}, \vec{B}]\right)\frac{\partial f_\alpha}{\partial \vec{p}} = St\{f_\alpha\}, \quad (1)$$

Function $St\{f_\alpha\}$ is the function describing the following physical processes:

1. ionization of the hydrogen atoms of the cathode electrons $H + e^- \to H^+ + 2e^-$;
2. ionization of the hydrogen molecules of the cathode electrons $H_2 + e^- \to H_2^+ + 2e^-$;
3. ionization of the ions $H^+$ hydrogen atoms $H_2 + H^+ \to H_3^+ + H$.

In the case of collisionless plasma approximation $St\{f_\alpha\} = 0$, and the Boltzmann equation (1) turns into the Vlasov equation. Based on the splitting method, the solution of the Boltzmann equation is reduced to the solution of the Vlasov equation with the corresponding corrections of the particle trajectories with allowance for physical processes using the Monte-Carlo method. The kinetic description of plasma with using the PIC-method [6], [7] and the Monte-Carlo method [8] for accounting of the charged particle collisions with gas is the most appropriate way of modeling plasma in considered trap. Since the target has a shape of a cylinder, we consider two-dimensional problem in cylindrical coordinates R-Z. It is 2D3V statement, so all three components of fields and speeds of particles are considered.

Standard FDTD scheme is used to solve the Maxwell's equations. The current density is calculated according to [9]. The probability of the charged particle collision with neutral atoms is used to simulate the process of ionization. If collision has occurred, particles with required parameters are added in the computational domain [8]. There are significant limitations on the required spatial grid step $h \leq 0.1$ *mm* due to the large gradient of the magnetic field in the trap. Thus, if the area size is equal 1355 mm $\times$ 99.6 mm, then we have to use 13550$\times$996 grid nodes for computations. We use $5 \cdot 10^9$ model particles for statistically correct computation of the ionization process. Calculations are performed on the supercomputers NKS-30T (the Siberian Supercomputing Center) and the Lomonosov (the Supercomputing Center of Lomonosov Moscow State University).

## SIMULATION RESULTS

The total current on the walls and the end of the trap and distribution of the plasma density in the area of the inverted magnetic plugs were computed in works [10], [11] for the following parameters: $I = 150$ $A$ is the cathode current,

$T = 5\ eV$ is the plasma temperature, $n_0 = 10^{13}\ cm^{-3}$ is the plasma density. Values of the ion current which is stabilized over time and the plasma flow in the walls of the trap were found as a result of the numerical simulation. In the paper we consider the dynamics of the plasma density on the boundaries of the trap and the current distribution along the walls for the same parameters. To determine the current distribution on the wall of the trap the following approach is used. The all area of the trap having the cylinder shape is divided into a set of rings by width $L = 50\ mm$. The current flowing through the surface of these rings is considered.

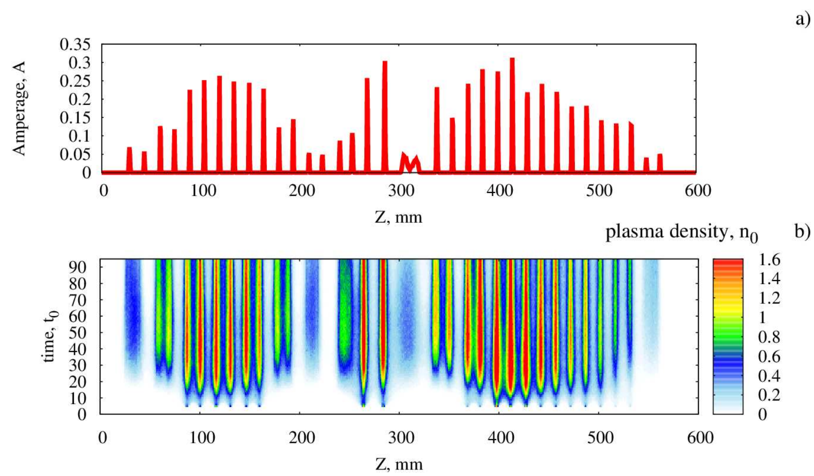


**FIGURE 2.** a) The current distribution on the walls of the trap, b) Changes of the plasma density over time in the border area. Here $t_0 = 10^{-6}\ s$.

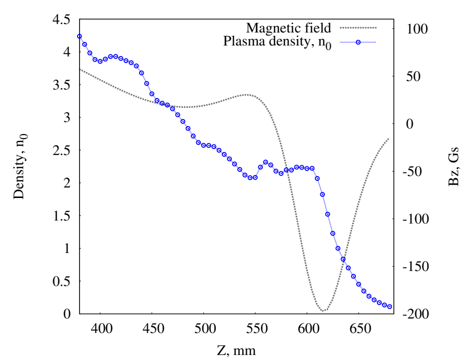


**FIGURE 3.** The density and distribution of the Z-component of magnetic field of the trap axis.

Figure 2 shows the distribution of current along the wall of the trap. One can see from the figure that the main plasma stream is defined by the magnetic field of the trap. The current distribution in the areas with the same magnetic field is uneven. The maximum value of the current is $Im = 0.3\ A$. In addition, there is the correlation between the values of the plasma density at the border and the current on the wall. Note that cooled copper wall of the chamber is quite able to cope with such power (there will be no local overheating or high heat chamber generally) when the temperature of the plasma is $T \approx 5\ eV$. The calculation results of the plasma density on the axis in the magnetic plug ($550 < Z < 680$) are shown in Figure 3. There is a stepwise decrease of the density of all ion plasma components in the inverse magnetic mirror along the axis. The inverse mirror consisted of a set of coil producing various reverse magnetic field. The stepwise decrease of the density caused by summation of magnetic field of the inverse mirror with the total magnetic field. A similar step drop of plasma density along the axis in each inverted tube was found in experiment [12]. Figure 4 shows the change of the plasma density at the end of the trap ($Z = 650$) over time. For the considered region the main plasma stream is concentrated in the central part near the axis, as it has been found in [12]. The plasma flow through the end holes of the trap is substantially less than on the wall. The total rated current of ions on the end holes is $It \approx 0.5\ A$.

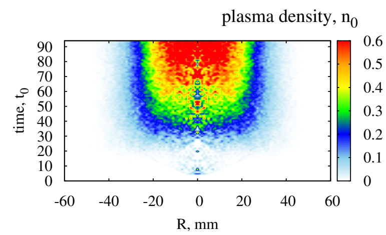


**FIGURE 4.** The change of plasma density at the end of the trap over time. Here $t_0 = 10^{-6}\ s$.

## CONCLUSION

In the work the plasma target trap with inverse magnetic mirrors and multipole magnetic walls developed in BINP is considered. Mathematical modeling of plasma dynamics at the trap is carried out. Distribution of plasma streams on the trap walls and through the face holes is received. As a result of calculations it is possible to establish that the inverse magnetic mirror rigidly holds particles and provides substantially lower plasma leaks, than through trap walls. According to the results of calculations, the generated plasma fills almost the entire length of the trap. The plasma outflow in end holes is sufficiently small, the loss of the plasma on the walls of the trap is inessential. Introducing of the recombination cross sections to the mathematical model will allow determining plasma lifetime and energy balance of the trap.

## ACKNOWLEDGMENTS

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