TWO-DIMENSIONAL MODELING OF PLASMA CONFINEMENT IN A TOROIDAL ELECTROMAGNETIC TRAP

O.A. Lavrent'ev, V.A. Maslov, S.V. Germanova, B.A. Shevchuk, N.A. Krutko

Institute of Plasma Physics, NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine, e-mail: lavr@ipp.kharkov.ua

Two-dimensional modeling of plasma confinement in a toroidal electromagnetic trap with transverse magnetic slits is carried out. The spatial distributions of electrons and ions density, magnetic and electrostatic potentials are obtained. Diamagnetic currents of electrons and ions, responsible for shielding of a vacuum magnetic field in plasma, and borders of the superseded vacuum magnetic field are determined.

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ALGORITHM OF TWO-DIMENTIONAL MODELING

The magnetic configuration of a toroidal electromagnetic trap with transverse magnetic slits is created by eight twin coils located in a toroidal vacuum chamber. The sizes of coils: radius R_0 = 0.35 m, cross section – 0.1 x 0.2 m^2, ampere conductors – I_0 = 1 MA, radius of a toroidal chamber along the axis line – R = 1.6 m.

Two-dimensional modeling was made on a base of solution of Vlasov's stationary equation. The method described in the paper [1] was used.

The integrals of motion of charged particle with energy ε_κ and angular momentum l_κ in the cylindrical coordinate system r, φ, z is given by the following expression:

$$\varepsilon_\kappa = \tfrac{1}{2} m_k \left(\dot{r}^2 + r^2 \dot{\varphi}^2 + \dot{z}^2 \right) + q_k \Phi(r,z), \quad (1)$$

$$l_\kappa = m_k r^2 \dot{\varphi} + q_k r A_\varphi(r,z), \quad (2)$$

where m_k and q_k are mass and charge of particle, Φ is an electrostatic potential, A_φ is a constituent of the magnetic potential $\vec{A}$, $A_r = A_z = 0$.

The stationary equation for electrostatic potential is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial \Phi}{\partial r} \right) + \frac{\partial^2 \Phi}{\partial z^2} = -4\pi \left(q_e n_e + q_i n_i \right), \quad (3)$$

and for magnetic potential:

$$\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(r A_\varphi) \right] + \frac{\partial^2 A_\varphi}{\partial z^2} = -\frac{4\pi}{c}\left(j_{e\varphi} + j_{i\varphi} \right). \quad (4)$$

Here $n_e = \int f_k d^3 v$, $j_{k\varphi} = \int q_k v_\varphi f_k d^3 v$,

$$f_k(\varepsilon, l) = c_k \cdot \exp\left(-\frac{\varepsilon_k}{kT_k} \right) \cdot \exp\left(-\frac{l_k^2}{2 m_k a_k^2 kT_k} \right).$$

The integration is carried out in the velocity space $-\infty < v_r < \infty$, $-\infty < v_\varphi < \infty$, $-\infty < v_z < \infty$,

$$n_k = n_{k0}\left(1 + \frac{r^2}{a_k^2} \right)^{-1/2} \cdot \exp\left\{ -\frac{1}{kT_k}\left[q_k \Phi + \frac{q_k^2 A_\varphi^2 r^2}{2 m_k \left(a_k^2 + r^2 \right)} \right] \right\}, \quad (5)$$

$$j_{k\varphi} = -\frac{n_k q_k^2 A_\varphi r^2}{m_k \left(a_k^2 + r^2 \right)}. \quad (6)$$

The solution of the equations (3) and (4) is realized using the method of grids.

By virtue of symmetry, it is enough to choose the area consisting of a quarter of the space between the neighbour magnetic slits of the toroidal electromagnetic trap, Fig. 1.

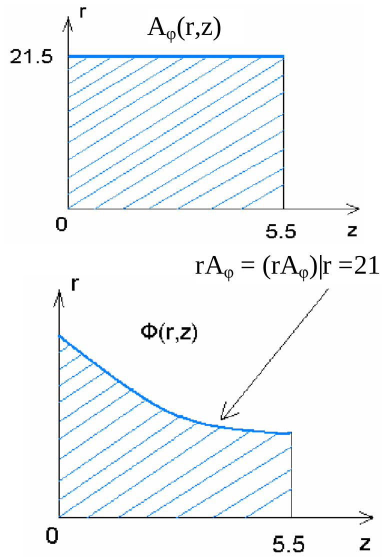


Fig. 1. Area of integration

The initial condition for magnetic potential is the vacuum magnetic field, produced by the coils of magnetic system of the toroidal trap:

$$A_\varphi = A_{\varphi 0}(r,z). \quad (7)$$

The boundary conditions:

$$A_\varphi(0,z) = A_\varphi(z,0) = 0,$$

$$\frac{\partial A_\varphi}{\partial z}(0,z) = \frac{\partial A\varphi}{\partial z}(r,0) = \frac{\partial A\varphi}{\partial z}(r,5.5) = 0. \quad (8)$$

The initial condition for electrostatic potential:

$$\Phi(r,z) = 0. \quad (9)$$

The boundary conditions Φ=0 at an outermost magnetic surface supporting on the anode diaphragm in the magnetic slit:

$$rA_\varphi = (rA_\varphi) \text{ at } r = 21.5 \text{ cm}, z = 0.2 \text{ cm}, \quad (10)$$

$$\frac{\partial \Phi}{\partial r}(0,z) = \frac{\partial \Phi}{\partial z}(r,0) = \frac{\partial \Phi}{\partial z}(r,5.5) = 0. \quad (11)$$

The equations for electrostatic and magnetic potentials that are brought in through the finite differences:

$$\Phi(r,z)=\frac{h^2k^2}{2(h^2+k^2)}\left\{\left(\frac{1}{h^2}+\frac{1}{2rh}\right)\Phi(r+h,k)+\right. \tag{12}$$
$$+\left(\frac{1}{h^2}-\frac{1}{2rk}\right)\Phi(r-h,z)+\frac{1}{k^2}\left[\Phi(r,z+k)+\Phi(r,z-k)\right]+$$
$$\left.+4\pi\left(q_e n_e+q_i n_i\right)\right\},$$

$$A_\varphi(r,z)=\left(\frac{1}{r^2}+\frac{2}{h^2}+\frac{2}{k^2}\right)^{-1}\cdot\left\{\left(\frac{1}{h^2}+\frac{1}{2rh}\right)A_\varphi(r+h,z)+\right. \tag{13}$$
$$+\left(\frac{1}{h^2}-\frac{1}{2rh}\right)A_\varphi(r-h,k)+\frac{1}{k^2}\left[A_\varphi(r,z+k)+A_\varphi(r,z-k)\right]+$$
$$\left.+\frac{4\pi}{c}\left(j_{e\varphi}+j_{i\varphi}\right)\right\},$$

with the boundary conditions:

$A_\varphi(r,k) = A_\varphi(r,-k)$; $A_\varphi(r, 5.5+k) = A_\varphi(r, 5.5-k)$;

$\Phi(r,k) = \Phi(r,-k)$; $\Phi(r, 5.5+k) = \Phi(r, 5.5-k)$. (14)

The uncertainty on the axis r = 0, $\frac{1}{r}\frac{\partial\Phi}{\partial r}=\frac{0}{0}$,

is opened by the Lopital's rule:

$$\frac{1}{r}\frac{\partial\Phi}{\partial r}=\frac{\partial^2\Phi}{\partial r^2}.$$

The electrostatic potential on the axis r = 0:

$$\Phi(0,k)=\frac{h^2k^2}{2h^2+4k^2}\left(\frac{4}{h^2}\Phi(h,z)+\frac{2}{k^2}\Phi(0,z+k)+\right.$$
$$\left.+4\pi\left(q_e n_e+q_i n_i\right)\right). \tag{15}$$

The equations (12) and (13) were found by the method of iterations for magnetic field in the magnetic slit B = 5 kGs, density of plasma $n_{e,i}$ = 10^{10}-10^{11} cm^{-3}, electron temperature T_e = 5 keV, ion temperature T_i = 1.5 keV. In Fig. 2 the spatial distribution of potential in a toroidal trap is shown.

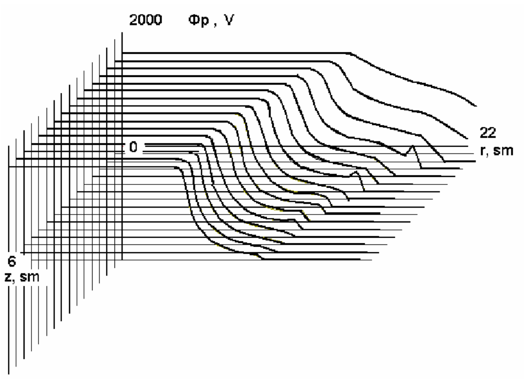


Fig. 2. Electrostatic channel $\Phi_p(r,z)$, $n_{e0} = 10^{11}$ cm^{-3}, $n_{i0} = 10^8$ cm^{-3}, T_e = 1000 eV, T_i = 300 eV

The plasma is confined within the limits of the boundary magnetic surface with a sharp decrease of density of electrons and ions in the frontier area, Fig. 3.

The density of plasma grows to the centre, to axis r=0.

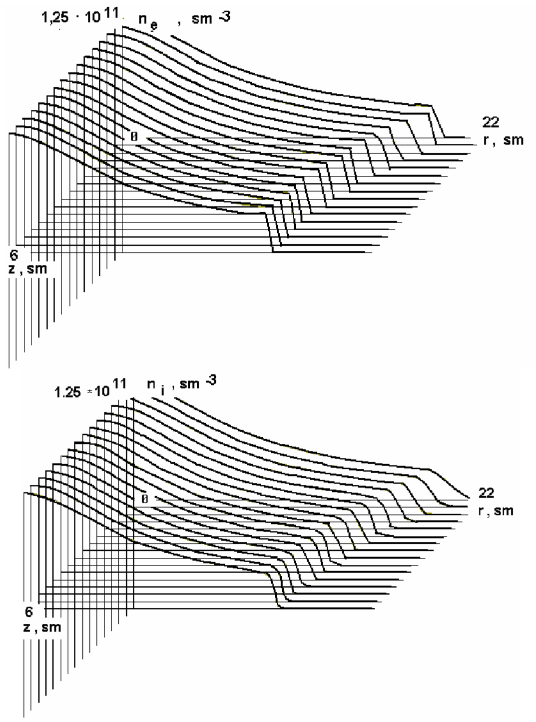
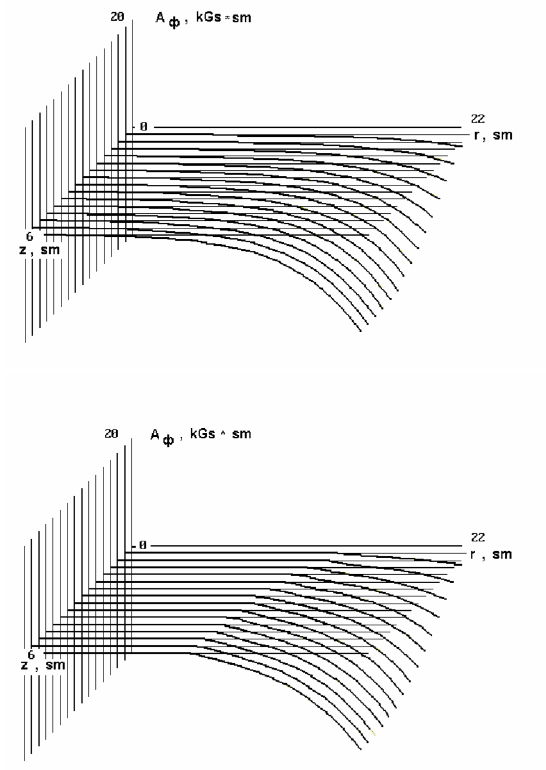


Fig. 3. Density of plasma $n_{e,i}(r,z)$, T_e = 5000 eV, T_i = 1500 eV

The plasma supersedes out a vacuum magnetic field from the centre of the trap up to the border determined by balance of magnetic and gas-dynamic pressures, Fig. 4.



a

b

Fig. 4. Magnetic potential $A_\varphi(r,z)$, T_e = 5000 eV, T_i = 1500 eV;
a) n_{e0} = 0, n_{i0} = 0,
b) $n_{e0} = 5\cdot10^{11}$ cm^{-3}, $n_{i0} = 5\cdot10^8$ cm^{-3}

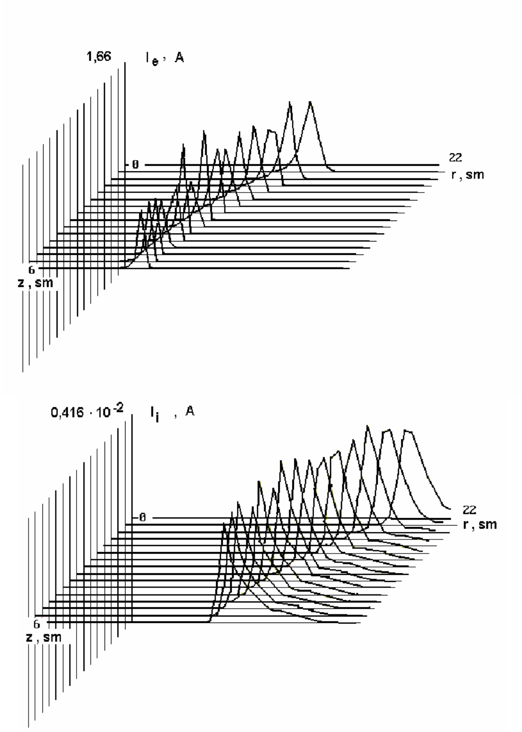


Fig. 5. Currents of charge particles: I_e – electron current, I_i – ion current

Together with a vacuum magnetic field the plasma currents are superseded out to the surface of plasma: both the electron and ion currents, Fig. 5.

These diamagnetic currents are responsible for the screening of a vacuum magnetic field in the plasma.

CONCLUSION

Two-dimensional modeling based on the solution of the Vlasov's stationary equation has allowed to find spatial distribution of plasma density, electrostatic and magnetic potentials, to determine borders of the superseded vacuum magnetic field - cross sizes of the electrostatic channel for capture and accumulation of ions in an ion ring.

REFERENCES

1. F. Brunel, G. Lafrens, H. Burkhart, B. Gregory. The Vlasov's equation in electrostatic closed magnetic geometry // *Can. J. Phys*. 1974, v.52, p.21-57 (in Russian).

ДВУМЕРНОЕ МОДЕЛИРОВАНИЕ УДЕРЖАНИЯ ПЛАЗМЫ В ТОРОИДАЛЬНОЙ ЭЛЕКТРОМАГНИТНОЙ ЛОВУШКЕ

О.А. Лаврентьев, В.А. Маслов, С.В. Германова, Б.А. Шевчук, Н.А. Крутько

Проведено двумерное моделирование удержания плазмы в тороидальной электромагнитной ловушке с поперечными магнитными щелями. Получены пространственные распределения плотности электронов и ионов, магнитного и электростатического потенциалов. Определены диамагнитные токи электронов и ионов, ответственные за экранирование вакуумного магнитного поля в плазме, и границы вытесненного магнитного поля.

ДВОМІРНЕ МОДЕЛЮВАННЯ УТРИМАННЯ ПЛАЗМИ В ТОРОЇДАЛЬНІЙ ЕЛЕКТРОМАГНІТНІЙ ПАСТЦІ

О.О. Лаврентьєв, В.О. Маслов, С.В. Германова, Б.О. Шевчук, Н.О. Крутько

Проведено двомірне моделювання утримання плазми в тороїдальній електромагнітній пастці з поперечними магнітними щілинами. Отримані просторові розподіли густини електронів і іонів, магнітного та електростатичного потенціалів. Визначені діамагнітні токи електронів та іонів, відповідальні за екранування вакуумного магнітного поля в плазмі, і межі витиснутого магнітного поля.