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Simple Model of Ion Beam Space Charge Generated Electric Field—Influence on Ion Trajectories in Asdex-Upgrade NBI Design

Uproszczony model pola elektrycznego wytwarzanego przez ładunek przestrzenny wiązki jonów. Wpływ na trajektorie jonów w systemie NBI Tokamaka Asdex-Upgrade

INTRODUCTION

In the paper the influence of space-charge-generated electric field on the ion trajectories in Asdex Upgrade Neutral Beam Injection (NBI) system is investigated. In the design, a hydrogen ion beam of 55 keV and 80 A is passed through a neutraliser (a gas chamber) to get a neutral beam, which is used to heat the tokamak plasma to high temperature. 50% of the beam, not neutralised, is reflected in a special magnet system and collected on actively cooled copper plates — ion dumps. This non-relativistic, still high current ion beam is difficult to transport, because of an electric field created by the high space charge. To decrease this field, the residual gas (the pressure up to 7×10^{-4} mbar) inside the magnet is used to produce the electrons and partially neutralise the space charge of the beam. In the paper, a simplified model of electric field inside the beam area is being used, assuming cylindrical space charge geometry. The degree of neutralisation of the ion beam, due to the compensation of its positive charge by the plasma electrons is simply taken as proportional to the local density of the beam. Such an electric field was introduced in the TRHN-code [1], which calculates the ion trajectories in the NBI design.

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CALCULATION METHOD

In our NBI system, the ion beam is deflected by the magnetic field — Figure 1. To simplify the calculations we neglect the focusing effects in the magnet region and assume that the space charge of the beam has cylindrical symmetry. The axial derivatives of field quantities are much smaller (here we assume them to be 0 than the derivatives in the radial direction.

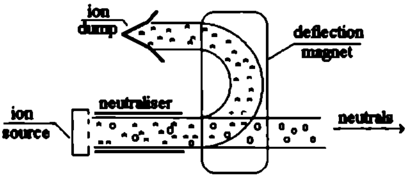

Fig. 1. The block scheme of the NBI design
Ryc. 1. Blokowy schemat systemu NBI

If the particle density $n(r)$ varies only in r direction, we can easily get the expression for the electric field [2]:

$$E(r) = \frac{q}{2\pi\varepsilon_0 r}\int_0^r 2\pi r' dr' n(r'), \tag{1}$$

where q is the ion charge. In ASDEX Upgrade NBI design, the ion beam has a particles density distribution across the beam similar to the Gaussian one:

$$n_i(r) = n_i^0 \exp\left(-\frac{r^2}{D_i^2}\right), \tag{2}$$

where n_i^0 is the maximal density just at the centre of the beam ($r = 0$), and $D_i^2 = 2d_i^0$ where d_i is the standard deviation.

The electric field for such a density distribution, calculated from eq. (1), is:

$$E_i(r) = \frac{D_i^2 q n_i^0}{2\varepsilon_0 r}\left\{1 - \exp\left\{-\frac{r^2}{D_i^2}\right\}\right\}.$$

The n_i^0 can be found from the normalisation procedure and is equal:

$$n_i^0 = \frac{i}{\Pi D_i^2 qv\left(1 - \exp\left(-\frac{R_0^2}{D_i^2}\right)\right)}, \tag{3}$$

where: i — is the current across the beam area; v — is the velocity of the beam particles; R_0 — is the radius of the cylindrical beam.

In the case when the ion beam passes through the gas and produces plasma, for the negative space charge of plasma, created due to the shift of electrons, we also assume, like in the case of ions:

$$n_e(r) = n_e^0 \exp\left\{-\frac{r^2}{D_e^2}\right\}. \tag{4}$$

The electric field connected with the negative charge is:

$$E_e(r) = \frac{D_e^2 q n_e^0}{2\varepsilon_0 r}\left\{1 - \exp\left\{-\frac{r^2}{D_e^2}\right\}\right\}. \tag{5}$$

Finally, the electric field $E(r)$ can be calculated from:

$$\begin{aligned} E(r) &= E_i(r) - E_e(r) = \frac{q}{2\varepsilon_0 r}\left[D_i^2 n_i^0 \left\{1 - \exp\left\{-\frac{r^2}{D_i^2}\right\}\right\}\right. \\ &\quad \left. - D_e^2 n_e^0 \left\{1 - \exp\left\{-\frac{r^2}{D_e^2}\right\}\right\}\right]. \end{aligned} \tag{6}$$

The full neutralisation of the beam will take place when for $D_i = D_e$, $n_i^0 = n_e^0$. In our calculations we always assume that $D_i = D_e$ and $n_i^0 > n_e^0$.

In the TRHN program, trajectories of the particle in the magnetic and electric fields are calculated using the 4 order Runge-Kutta method. The program requires the B_x, B_y, B_z and E_x, E_y, E_z components of both fields in every point of a uniform three-dimensional Cartesian mesh.

The calculations of the magnetic field created in the deflection magnet were performed using PROFI [3] code as installed at IPP.

To create the electric field according to equation (6) in every point of the 3–D Cartesian mesh, the expression for the central trajectory of the ion beam should be found. The central trajectory — which is also the centre of our cylindrical space charge area, where electric field $E = 0$ — was chosen as a trajectory of an ion emitted from the central point of the ion source. The standard numeric procedure was used for fitting the X, Y, Z set of coordinates of the central trajectory curve with the polynomials, and for the calculation of E_x, E_y, E_z in every mesh point.

RESULTS OF CALCULATIONS AND COMPARISON WITH THE EXPERIMENT

The calculations of the electric field created by the space charge of the ion beam in ASDEX Up NBI design, performed for the simplified cylindrical geometry, shows its quite high — in order of MV/m — value. The strong, space charge generated electric field is responsible for the discrepancy between the experiment and the calculations performed without taking into account the space charge effects [4]. In such a case (beam transported through the vacuum) most of the ion power did not hit the central part of the ion dump, but was found on its circumference, and especially on the liners of the magnet.

To decrease the space charge effects, the beam was directed through gas. In such a case, the power deposited on ion dumps and liners of the reflection magnet should be the function of the pressure of the gas. Increasing gas pressure results in the increase of the degree of neutralisation of the space charge of the beam. To illustrate the influence of pressure in the calculations we introduce the n_t parameter:

$$n_t = \left(1 - \left(\frac{n_i^0}{n_e^0}\right)\right) \cdot 100, \tag{7}$$

which is equal to the percentage of a not compensated (not neutralised) beam — with $D_i = D_e$. Here n_i^0 and $n_e^0$are the values determined in equations (3, 4) for ions and negative space charge respectively.

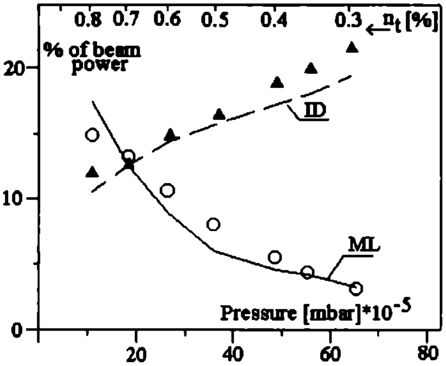

Fig. 2. The distribution of the electrical beam power on the central ion dump and liners of ion deflection magnet: a) as a function of pressure (experiment): - - - — central ion dump; — — magnet liners; b) as a function of n_t parameter (calculations): ▲▲▲ — central ion dump, ○○○ — magnet liners

Ryc. 2. Rozkład mocy wiązki jonów deponowanej na pułapce jonowej i osłonach nabiegunników elektromagnesu: a) jako funkcja ciśnienia gazu (eksperyment): - - - — pułapka jonowa; — — osłony nabiegunników elektromagnesu; b) jako funkcja parametru n_t (obliczenia): ▲▲▲ — pułapka jonowa; ○○○ — osłony nabiegunników elektromagnesu

In Figure 2 the distribution of electrical beam power on the ion dump and liners of the deflection magnet as a function of pressure in front of magnet is shown. Together with the experimental data, the results of power deposition calculations are plotted in the figure as a function of the n_t parameter. To adjust the n_t scale (logarithmic) to the scale of pressure (linear),the cross point of both curves ML — for magnet liners, and ID — for ion dump, was chosen as a fitting point.

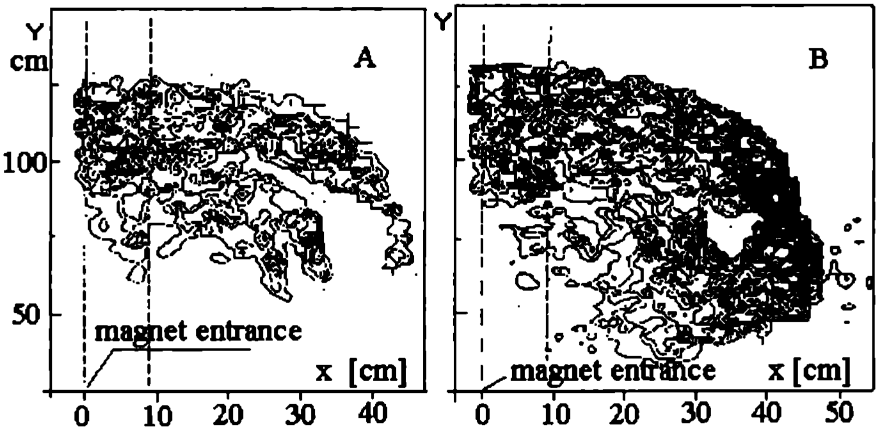

Fig. 3. The results of calculated power density deposited on the surface of outer pole liner: a) $n_t = 0.3\%$, b) $n_t = 0.7\%$. The power density contours are plotted with the step of 20 W/cm^2

Ryc. 3. Rezultaty obliczeń gęstości mocy deponowanej na powierzchni osłony nabiegunnika elektromagnesu: a) $n_t = 0.3\%$, b) $n_t = 0.7\%$. Poziomice gęstości mocy wykreślone są z krokiem 20 W/cm^2

In Figure 3 the results of the calculation of power density deposited on the surface of one of the copper liners of the magnet (outer pole) for n_t equal 0.7% and 0.3% are presented.

CONCLUSIONS

As it is clearly seen from the experiment and calculations, the strong electric field can be created by the ion beam space charge in the deflection system of NBI ASDEX Up. design, operating with the beam 55 keV and 40 A.

The simple method of the calculations of the electric field introduced to our TRHN code gives the results that reproduce quite well the tendencies of power deposition distribution in the main components of the ion removal system. To reduce significantly the influence of space charge of the beam, the degree of its neutralisation should be in the order of 99.5% — ($n_t = 0.5\%$).

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STRESZCZENIE

W niniejszym artykule badany jest wpływ pola elektrycznego ładunku przestrzennego wiązki jonów w systemie podgrzewania plazmy NBI (Neutral Beam Injector) w Tokamaku ASDEX-Upgrade na trajektorie jonów w układzie odchylania. Z prostego modelu rozkładu ładunku w wiązce, opartego na założeniu cylindrycznej geometrii i radialnej funkcji gęstości, wyliczana jest wielkość pola elektrycznego E w funkcji odległości od centrum wiązki. Wartości pola E w postaci III-wymiarowej macierzy wykorzystywane są w programie komputerowym TRHN symulującym trajektorie jonów w systemie NBI. Dokonano porównania wyliczonego w ten sposób rozkładu energii deponowanej na pułapkach jonowych z danymi eksperymentalnymi. Mimo przyjęcia prostego modelu zjawiska otrzymano zupełnie dobrą zgodność eksperymentu z symulacjami komputerowymi wpływu — na częściową neutralizację ładunku przestrzennego wiązki — wzrostu ciśnienia gazu (wodoru) w urządzeniu.