Rapid Communications

Beam Ion Loss Due to the Charge Exchange Process in the Open Field Region of a Field-Reversed Configuration

TAKAHASHI Toshiki[1)], HIRANO Yoichi[2)], ASAI Tomohiko[3)], TAKAHASHI Tsutomu[3)], TOMITA Yukihiro[4)],
MIZUGUCHI Naoki[4)] and KONDOH Yoshiomi[1)]

[1)]*Department of Electronic Engineering, Gunma University, Kiryu 376-8515, Japan*
[2)]*National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8568, Japan*
[3)]*College of Science and Technology, Nihon University, Chiyoda-ku, Tokyo 101-8308, Japan*
[4)]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*

(Received 25 March 2005 / Accepted 19 May 2005)

Beam ion loss due to the charge exchange with deuterium atoms in the open field region of a field-reversed configuration (FRC) is investigated by tracing its orbit. The beam ion is tangentially injected as neutral beams (NBs) into the FRC. The ionization process is reproduced by the Monte-Carlo method. Almost all of the 15 keV beam ions injected toward the field null are found to be confined in the case with an external magnetic field of 0.2 T. It is found that about 90% of the NB injection power is transferred to the plasma when the neutral atom density in the open field region is lower than 10^{17} m^{-3}.

Keywords:
Field-reversed configuration, Neutral beam injection, Loss by re-charge-exchange, Monte-Carlo

Poloidal flux maintenance in a field-reversed configuration (FRC) is important to prolong its lifetime. Two feasible methods are application of a rotating magnetic field (RMF) [1] and a neutral beam injection (NBI) [2-4]. Tangential neutral beam injection (TNBI) is an effective method to heat plasma electrons, and it is possible with this method to drive the toroidal diamagnetic current with only slight axial end loss of beam ions [5]. The beam ions carry a large angular momentum, and then draw the betatron orbits encircling around the geometric axis. Due to a radial betatron oscillation, the betatron orbits sometimes reach outside the separatrix. Since the electron temperature profile has a sharp drop near the separatrix [6,7], a significant neutral density may be possible; such a density results in a deleterious beam ion loss due to the charge exchange with neutrals. The present paper shows the effect of neutrals outside the separatrix on the deposition power by the NBI fast ions into the FRC plasma.

The equilibrium of FRC is computed by solving the Grad-Shafranov equation for the poloidal flux function $\psi(r,z)$ in the cylindrical coordinates system. Assuming a uniform temperature ($T_i = 100$ eV and $T_e = 50$ eV), we can obtain the plasma density profile. The obtained plasma density at the field-null magnetic axis for the external magnetic field B_{ex} of 0.1 T is 1.7×10^{20} m^{-3}, and the separatrix beta value is 0.52. Since the temperature is fixed, the density increases with B_{ex}^2. The hydrogen atom as an NB particle is injected tangentially to the circle with a radius of b (i.e., the impact parameter defined as the shift of the beam axis from the geometric axis). Ionization processes of neutral beam particles are simulated by the Monte-Carlo method. Depending on the ionization positions, the canonical angular momentum $P_\theta = mv^*_\theta r^* + q\psi^*$ of the beam ion is given, where m, q, and v_θ are the beam ion mass, charge and azimuthal velocity component, and the superscript * represents the value at the moment of ionization. In an axisymmetric and a steady-state system without either an electric field or Coulomb collisions, the accessibility of beam ions can be described as

$$\frac{1}{2}mv_b^2 \geq \frac{\left(P_\theta - q\psi(r,z)\right)^2}{2mr^2}, \tag{1}$$

where v_b is the speed of beam ions.

When a beam ion is accessible to the wall surface and/or the mirror end, orbit loss may occur from the wall and/or from the axial end. On the other hand, if the condition (1) is not satisfied at the wall and the end, the fast ion is confined. In order to search for the optimum external field B_{ex} and impact parameter b, the ratio in percentage α of the number of confined beam ions to the total number of test particles (10,000) is calculated and shown in Fig. 1. Here, the calculation is performed for the fixed beam energy of 15 keV and wall radius of 0.4 m. When $B_{ex} = 0.1$ T and $0 \leq b/r_w \leq 0.2$, the majority of beam ions are found to be lost on the wall surface. As their guiding center locates outside the separatrix, they can reach the wall. When $B_{ex} = 0.2$ T, almost 100% of

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author's e-mail: t-tak@el.gunma-u.ac.jp the fast ions injected toward the field null are confined. In the case of 0.3 T, since the plasma density outside the separatrix is high enough to ionize the neutral beams considerably, the beam ions are accessible to the mirror end; consequently α is smaller than in the case with 0.2 T.

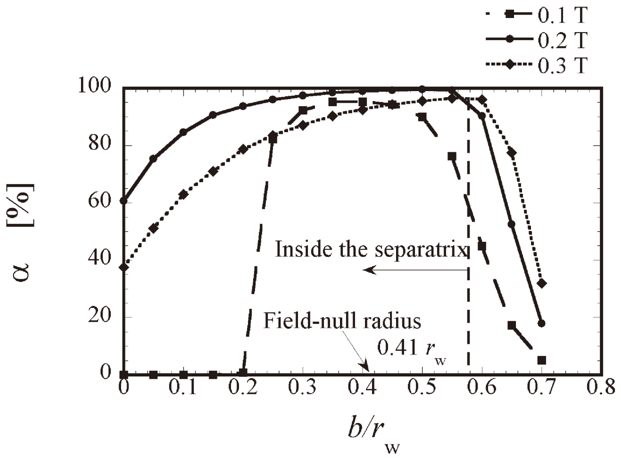

Fig. 1 The impact parameter dependence of the ratio of the number of confined ions to the total number of injected neutral beam particles. Dashed, solid, and dotted lines indicate an external magnetic field of 0.1, 0.2 and 0.3 T.

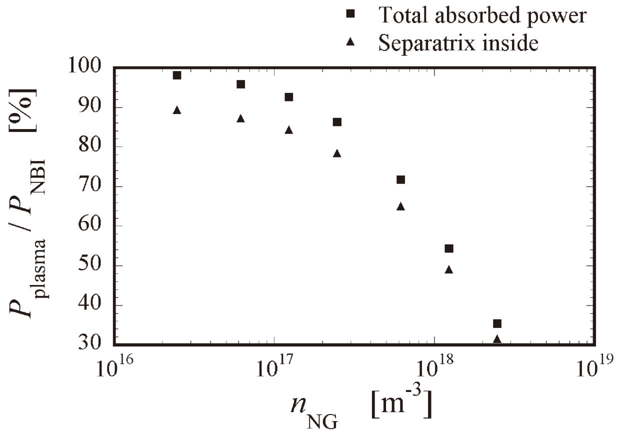

Fig. 2 The deuterium atom density dependence of the ratio of deposited power by fast ions to FRC plasma to the NBI power. The solid squares indicate the absorbed power by the plasma both inside the separatrix and in the open field region. The solid triangles represent the absorbed power only inside the separatrix.

The single particle orbit is traced in order to investigate the effect of the presence of neutrals on the deposition power. The deuterium atom is assumed to exist uniformly outside the separatrix at room temperature. If the fast ions suffer from the re-charge exchange process with deuterium atoms, they are assumed to be lost as fast neutral particles. Here, subsequent charge exchange processes are neglected. Varying parametrically the atom density, we study its influence on the deposition power by beam ions to plasma. The equation of motion for beam ions is

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = q[\mathbf{v}\times\mathbf{B}] - m\nu_{\mathrm{sl}}\mathbf{v} \ , \qquad (2)$$

where ν_{sl} is the slowing down collision frequency. The pitch angle scattering [8] is also considered.

For the optimum case in Fig. 1 (i.e., $B_{\mathrm{ex}} = 0.2$ T and $b/r_{\mathrm{w}} = 0.4$), the dependency of the ratio of the deposited power P_{plasma} to the NBI power P_{NBI} on the deuterium atom density n_{NG} is evaluated and shown in Fig. 2. Without the deuterium atoms, about 90% of the NBI power can be transferred to the plasma inside the separatrix. It is found that the deuterium atom density above 10^{18} m^{-3} (i.e., 0.15% of the field-null plasma density of $6.6 \times 10^{20}\,\mathrm{m}^{-3}$) results in a 50% decrease of the deposition power. It is concluded that the neutrals strongly affect the efficiency of TNBI into the FRC plasma due to the deleterious charge exchange process.

This work is performed with the support and under the auspices of the NIFS Collaborative Research Program.

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