Flux Supply of a Field-Reversed Configuration by NBI Heating

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It is shown that the magnetic flux of a field-reversed configuration plasma can be supplied by neutral beam injection heating. Although the beam ion current leads a flux decay due to interaction between fast ions and electrons that carries the current dominantly, the thermal force affects sustainment of the flux. The azimuthal electric field is the only source of flux supply in the newly developed model.

Keywords: neutral beam injection, field-reversed configuration, flux supply, electron heating, resistive decay, thermal force, Monte-Carlo simulation

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1. Introduction

Neutral beam injection (NBI) is most effective way to maintain a field-reversed configuration (FRC) plasma. Because of its high-beta nature a commonly-used wave heating method is believed unfortunately inapplicable. Therefore, NBI is a key issue of steady state operation of FRC plasmas.

Recent numerical studies are focused on heating of FRCs. Takahashi *et al.* showed an FRC plasma with the trapped flux of 4.7 mWb confines well 15-keV beam ions injected tangentially to the plasma current [1]. A study of the flux supply by NBI, on the other hand, has not been as yet investigated. The theoretical model to discuss the flux supply of an FRC plasma is needed to develop.

It has been thought that the presence of the beam current could augment the confinement field according to the Ampère's law, and then the flux is thought to be supplied. However, the resistive force between beam particles and electrons can cause the flux decay, when one employs the simplified Ohm's law and the Faraday's law. This suggests that the azimuthal component of electric field should be modified. Being examined the azimuthal force on the electron fluid element the thermal force [2]

$$\boldsymbol{R}_{\mathrm{T}} = -\frac{3}{2}\frac{n_{\mathrm{e}}}{\omega_{\mathrm{e}}\tau_{\mathrm{e}}}\frac{\boldsymbol{B}}{B} \times \nabla T_{\mathrm{e}}, \tag{1}$$

can contribute to the flux supply of an axisymmetric FRC. Here, n_{e}, ω_{e}, τ_{e}, T_{e} are the electron density, the electron cyclotron frequency, the electron collision time, and the electron temperature in Joule, respectively. When the core plasma is heated by fast ions, the electron pressure gradient enhances; it can lead the flux supply.

In the present paper, we will develop a calculation model to discuss flux supply and show its possibility by NBI heating.

2. Estimation of the Thermal Force Effect

The order-of-magnitude estimate of the thermal force effect on flux supply is made here. The FRC is a deuterium plasma and in a quasi-steady equilibrium. We consider a case that the density is uniform, and the ion temperature is equal to the electron temperature. This estimate is focused on the effect in the midplane ($z = 0$), and then the magnetic field only has z-component. In our situation, the azimuthal component of electric field is

$$E_\theta = \eta J_\theta - \frac{3}{2}\frac{n_{\mathrm{e}} b}{e\omega_{\mathrm{e}}\tau_{\mathrm{e}}}\frac{\partial T_{\mathrm{e}}}{\partial r}\ . \tag{2}$$

Here, η, J_θ, b are, the classical resistivity, the azimuthal plasma current density, and the direction of magnetic field $B_z/|B_z|$, respectively. When the radial force balance is considered in Eq. (2), we obtain

$$E_\theta = \frac{1}{4}\eta J_\theta\ . \tag{3}$$

Therefore, inclusion of the thermal force reduces the azimuthal electric field by quarter. This means that the resistive flux decay suppressed by the presence of the temperature gradient. If an external heating would enhance the electron temperature gradient, it is possible to maintain the magnetic flux of an FRC plasma. Noting the property of the thermal force, we find NBI heating near the field-null point is favorable to supply the magnetic flux.

3. Heating by NBI

Neutral beam injection into the FRC plasma is firstly demonstrated at the FIX (FRC Injection Experiment) machine [3]. The FRC lifetime is extended by NBI; it is thought that it results from suppression of a global motion of the FRC by a beam ion ring formed near the X-point [4]. Power deposition by beam ions to the plasma is calculated by tracing orbits of beam ions [5, 6]. Since the beam ions are injected obliquely with respect to the geometric axis,

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they suffer from the end loss significantly. Therefore, the deposition power is at most 10% of the injection power [6].

Contrary to the axial injection, tangential NBI (TBNI) can suppress orbit losses of beam ions drastically [1]. We study now electron heating by beam ions with Coulomb collisions.

An equilibrium state is calculated by the Grad-Shafranov equation. Neutral beam particles are injected tangentially as shown in Fig. 1. In order to reduce a numerical oscillation generated by the thermal force, we ignore here the thermal force which will be discussed in the Sec. 4. Consequently, the field resistively decays as

$$\frac{\partial\psi}{\partial t} = -r\eta J_\theta \,. \tag{4}$$

Ionization of neutral particles is reproduced by a Monte-Carlo method [5]. Orbits of beam ions are calculated by integrating numerically the equation of motion that includes the slowing-down collision term. The heat acquired by the electrons in collisions with beam ions is written as

$$Q_{\mathrm{eb}} = -\boldsymbol{R}_{\mathrm{eb}} \bullet (\boldsymbol{u}_{\mathrm{e}} - \boldsymbol{u}_{\mathrm{b}}) \,, \tag{5}$$

where $\boldsymbol{R}_{\mathrm{eb}}$ is the friction force by beam ions acting on the electron fluid. The heat acquired by the beam ions in collisions with electrons is neglected here. The R. H. S. of Eq. (5) is calculated from the friction force of individual beam ion by using the PIC method [7].

Numerical calculation is carried out for an FRC plasma as shown in Table 1. Here, $\Phi_{\mathrm{w}}, E_{\mathrm{B}}, P_{\mathrm{NBI}}$ are the wall flux, the beam energy, and the NBI power. The plasma parameters are chosen from the Nihon University Compact Torus Experiment (NUCTE)-III. The beam energy is determined so as the beam ions to be confined in the NUCTE-III plasma. A typical trajectory of a beam ion is drawn in Fig. 2. It is found that the beam ion is well confined inside the separatrix and does not suffer from re-charge exchange process [1] with neutral atoms in the open-field region.

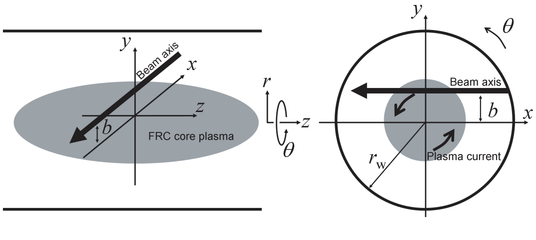

Fig. 1 Geometry of tangential neutral beam injection.

Table 1 The plasma and beam parameters

Parameters	Units	Values
r_{w}	m	0.17
z_{M}	m	0.75
T_0	eV	124
n_0	m^{-3}	2.6×10^{21}
$\Phi_{\mathrm{w}} = 2\pi\lvert\psi_{\mathrm{w}}\rvert$	Wb	36×10^{-3}
E_{B}	eV	15×10^{3}
P_{NBI}	W	360×10^{3}

Numerical results of the beam ion profiles are shown in Fig. 3, 4, and 5, where neutral beam particles are injected at $r = 0.24r_{\mathrm{w}}$ and $z = 0.1z_{\mathrm{M}}$. Here, r_{w} and z_{M} are the wall radius and the axial length from the midplane to the mirror end. The beam ion density is shown in Fig. 3. In our calculation, injection is done only at $t = 0$ (the top figure). We show also the case $t = 10t_{\mathrm{A0}}$ (the middle) and $t = 20t_{\mathrm{A0}}$ (the bottom). It is found that beam ions moves axially toward the midplane; this implies beam ions exhibit the betatron orbit. The azimuthal flow velocity of beam ions is also presented in Fig. 4. The current of beam ions generates the poloidal field, and it contributes to flux supply. On the other hand, interaction between beam ions and electrons cause the azimuthal electric field. This re-

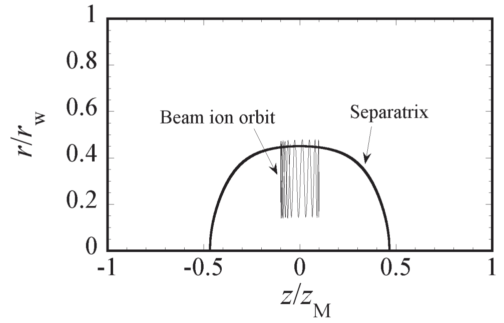

Fig. 2 A typical trajectory of the 15-keV beam ion.

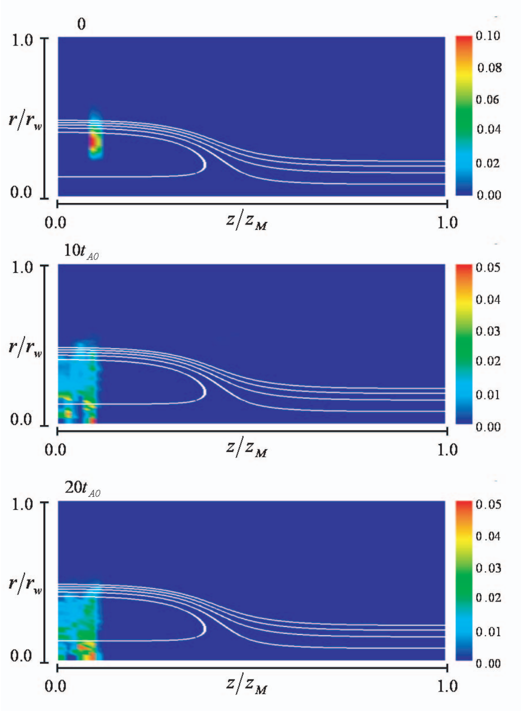

Fig. 3 Color contours of the beam ion density that is normalized by n_0. (Top) $t = 0$, (middle) $t = 10t_{\mathrm{A0}}$, and (bottom) $t = 20t_{\mathrm{A0}}$.

sults in the electron current and flux decay. From Fig. 4, the flow of beam ions directs in the ion diamagnetic current initially. A paramagnetic beam flow can be found in $0.1z_{\mathrm{M}} \leq z \leq 0.5z_{\mathrm{M}}$. The orbit of beam ions changes from the betatron to gyrating motion with time. By comparing with Fig. 3, the number of gyrating particle is relatively few, because the beam ion density is low in this region. Profiles of NBI electron heating power are shown in Fig. 5. Electron heating occurs dominantly near the midplane and geometric axis. If the injection geometry is optimized, it is possible that the electron temperature increases near the field-null at $t = 0$ (the top figure). If so, the electron temperature gradient enhances with time. By the thermal force written in (1), the magnetic flux can be augmented.

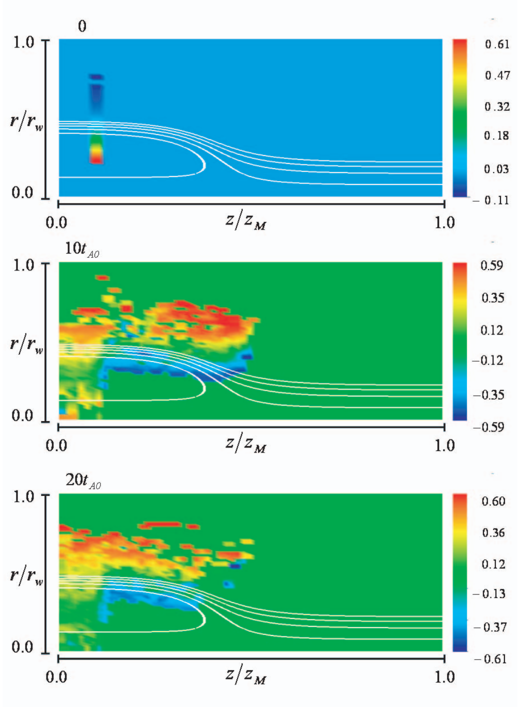

Fig. 4 Color contours of azimuthal flow of the beam ion. The flow normalized by r_{w}/r, and $r = m_{\mathrm{i}}r_{\mathrm{w}}/(q_{\mathrm{i}}|\psi_{\mathrm{w}}|)$. (Top) $t = 0$, (middle) $t = 10t_{\mathrm{A0}}$, and (bottom) $t = 20t_{\mathrm{A0}}$.

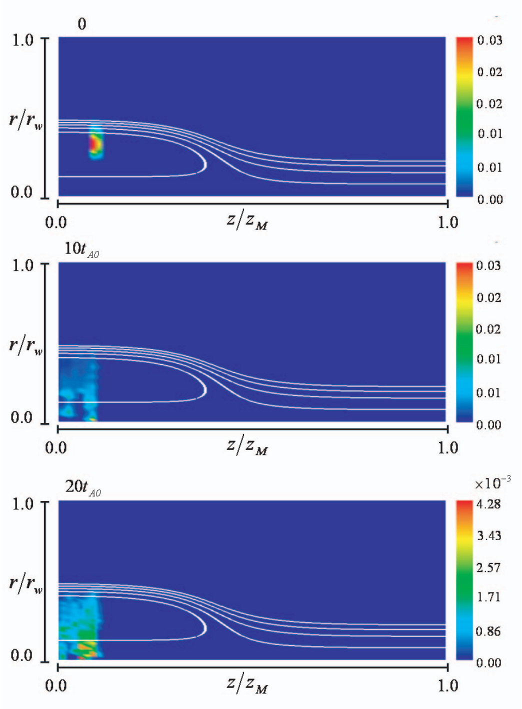

Fig. 5 Color contours of NBI electron heating power in a unit volume, it is normaliozed by n_0T_0/τ, (Top) $t = 0$, (middle) $t = 10t_{\mathrm{A0}}$, and (bottom) $t = 20t_{\mathrm{A0}}$.

4. Flux Supply by Heating

We will demonstrate maintenance of the magnetic flux of an FRC plasma numerically, when the thermal force is considered. The electron temperature is calculated by the heat balance equation. In the present study the equation is simplified to confirm flux supply by electron heating. The heat balance equation is written as

$$\frac{3}{2}n_{\mathrm{e}}\frac{\partial T_{\mathrm{e}}}{\partial t} = Q_{\mathrm{e}} \,. \tag{6}$$

The initial temperature assumed to be uniform in the present calculation. Suppose that electron heating power per unit volume is done as

$$Q_{\mathrm{e}} = Q_{\mathrm{e0}}\left(\frac{r}{r_{\mathrm{w}}}\right)^2\left[1-\left(\frac{r}{r_0}\right)^2\right]\exp(-\beta z^2)\,, \tag{7}$$

where Q_{e0}, r_0, β are parameters that control amount of heat and a region where electrons can be heated. When we consider the thermal force, the time derivative of the flux function becomes

$$\frac{\partial\psi}{\partial t} = -r\left(\eta J_\theta + R_{\mathrm{T}\theta}\right)\,, \tag{8}$$

where η, $R_{\mathrm{T}\theta}$ are the anomalous resistivity and the azimuthal component of the thermal force written in (1). We employ the Runge-Kutta method for time integration of Eqs. (6) and (8).

The electron temperature profile in $r-z$ plane is shown in Fig. 6. The peak value becomes 1.6 times higher than the

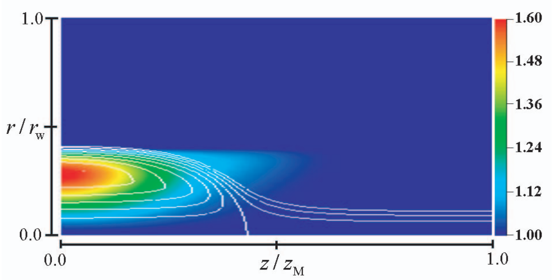

Fig. 6 Color contour of the electron temperature at $t = 18.7t_{\mathrm{A0}}$. The maximum of the temperature reaches 1.6 times higher than the initial.

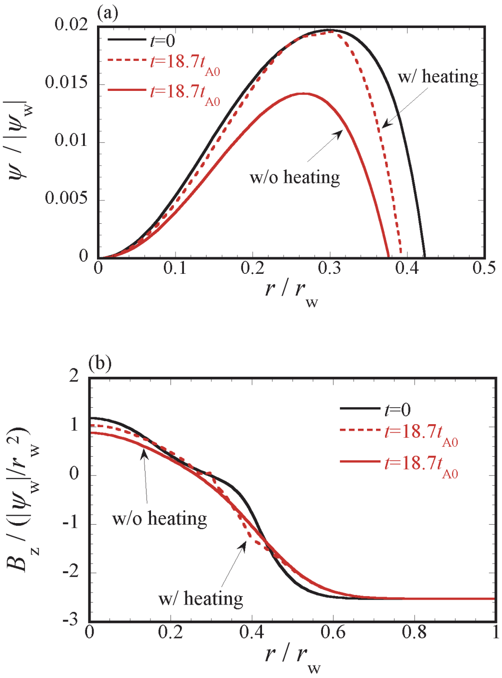

Fig. 7 The midplane ($z = 0$) profiles of (a) the magnetic flux function and (b) the magnetic field. The black solid lines indicate the initial profiles.

initial temperature T_0 (124 eV). In this calculation, we set

$$Q_{e0} = 5 \times 10^{-2} \frac{n_0 T_0 q_i |\psi_w|}{m_i r_w^2} ,$$

$$r_0 = 0.4 r_w , \quad \beta = 15/z_M^2 .$$

Here, n_0, ψ_w, m_i, q_i are the initial electron density at the field-null, the flux function at the wall and midplane, the ion mass, and the ion charge, respectively. To show the possibility of flux supply by heating, we examine the effect of electron heating on time evolution of flux function. The midplane profiles of the flux function and magnetic field are shown in Fig. 7. When we neglect the heating term, the flux decays with time as is drawn by the red solid line. On the other hand, if electron heating is present, the flux can be sustained. Time evolution of the maximum trapped flux is shown in Fig. 8. When the FRC plasma is heated, no decay of the trapped flux is found. Therefore, we can show successfully the possibility of flux supply by electron heating.

5. Summary

Electron heating by tangential neutral beam injection into a field-reversed configuration has been calculated numerically. Electron heating has been found near the field-null point.

Taking into account the electron thermal force, we have shown the possibility of the FRC flux supply by the electron heating. Numerical results evidently show sustainment of the magnetic flux, when the heat generation is present.

From our result, not only NBI but also such as the electron cyclotron wave heating is also possible method to drive the diamagnetic plasma current.

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