The Axial Expansion of a Field-Reversed Configuration Plasma as Induced by Neutral-Beam-Injected Fast Ions

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(Received 16 February 2006 / Accepted 17 March 2006)

An axially expanding motion of a field-reversed configuration plasma can be observed numerically. This motion is induced by fast ions reciprocating between field-null x-points; the ions are injected obliquely from the axial end as neutral beam particles. A two-dimensional hybrid simulation is employed by assuming axisymmetry, where the beam ions are treated as particles and the plasma ions and electrons are treated as fluid. The diamagnetic beam current formed around the x-points and in the open-field region reduces the magnetic pressure, and then the plasma is found to expand axially.

Keywords: field-reversed configuration, neutral beam injection, hybrid simulation, diamagnetic beam current, axial expansion

DOI: 10.1585/pfr.1.022

Among magnetic confinement plasmas, a field-reversed configuration (FRC) plasma is situated in an extremely high-beta regime; its average beta value exceeds 0.8. A firm grasp of the physics of FRC plasmas is necessary to achieve a high-beta operation in tokamaks and helical devices. Therefore, investigation of the equilibrium, stability, and transport properties in FRC plasmas gives us an essential expertise to be able to work with thermonuclear plasmas.

The lifetime of the FRC plasmas, however, is of the order of a few hundreds of a micro-second. A longer-life FRC plasma has the possibility of exhibiting an interesting kinetic feature. The neutral beam injection (NBI) into the FRC plasma is an effective way to achieve plasma sustainment. Asai *et al.* carried out a NBI experiment at the FRC injection experiment (FIX) machine [1]. Here, the neutral beam (NB) particles are injected at an oblique angle to the geometric axis. Asai *et al.* reported that the NBI can stabilize a precession movement of the FRC plasma because of a ring current that is formed around the field-null x-points [2]. Therefore, a detailed calculation of the electromagnetic interaction between the plasma and the beam ions is necessary to reproduce a global behavior of the FRC plasma with a NBI. Lifschitz *et al.* did a calculation in which the beam current is considered self-consistently on a quasi-steady-state magnetic field of NB injected plasmas, but they never discussed the effects from the electric field and flow velocity [3]. Therefore, a self-consistent magnetohydrodynamic (MHD) simulation is required in order to show the effect of the fast ions in creating a global movement of the FRC plasma.

In the present study, the one-fluid MHD equations along with the equation on the motion of fast ions are solved simultaneously. The finite difference method is used here. The density and flux of fast ions at grid points are calculated with the aid of the particle-in-cell (PIC) method. Axisymmetry is assumed, and then the two-dimensional simulation is carried out. Existence of the fast ions affects the electric field through the electron flow velocity as follows. The current density $\boldsymbol{J}$ that is calculated from the Ampere's law equals $en_i\boldsymbol{u}_i + en_b\boldsymbol{u}_b - en_e\boldsymbol{u}_e$, where n and $\boldsymbol{u}$ are the density and the flow velocity, and the subscripts i, b, and e represent deuterium ions, hydrogen beam (fast) ions, and electrons, respectively. In the definition of $\boldsymbol{J}$, $\boldsymbol{u}_i$ is calculated from the fluid equation of motion, and $\boldsymbol{u}_b$ is obtained by the PIC method. The ion and beam ion densities are calculated in the same manner. The quasi-neutrality condition gives the electron density. Because of this the electron flow velocity $\boldsymbol{u}_e$ can be calculated; it depends on the fast ion motion. The electric field is obtained by the use of a simplified Ohm's law as follows:

$$\boldsymbol{E} + \boldsymbol{u}_e \times \boldsymbol{B} = \eta \boldsymbol{J} \tag{1}$$

the electric field is obtained. Following Faraday's law, the magnetic field then evolves. Hence, the NB injected fast ions affect the structure of the electromagnetic field.

The external magnetic field B_{ex} and the wall radius r_w are 0.05 T and 0.4 m, respectively; they are identical to those obtained with the FIX machine. The mirror ratio R_M is about 2. The initial equilibrium state is obtained by solving the Grad-Shafranov equation. As an initial condition, the fast ions are assumed to be distributed uniformly inside the separatrix. Since the injection angle ϕ_0 to the geometric axis is 19.3 degrees in the FIX experiment [1], the axial component of initial velocity is set as $v_z = \pm v_b \cos\phi_0$,

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where v_b is the beam speed. The plus or minus sign is chosen by using the uniform random number. Here the beam current is 40 A, and the beam energy is 2 keV. These are, however, different from those in the FIX experiment. For the energy of 14 keV [1], the direct loss at the mirror end is significant for $R_M \approx 2$. Therefore, no effect of the 14-keV fast ions on the global motion of the FRC plasma can be observed.

On the other hand, the 2-keV ions can be trapped between the ends of the mirror; they can interact with the FRC plasma. A value of R_M higher than 8 is needed for the simulation results to be comparable with the experimental results in Ref. [1]. Unfortunately, for $R_M \geq 4$ numerical noise is unfavorably generated due to strong nonuniformity in the magnetic field, and no reliable results are available for a higher value for R_M. Therefore, our aim is to study an effect of the ring current formed by the 2-keV ions on the global behavior of FRC plasma even though the beam energy of 2-keV is impractical.

The color contour of the toroidal flux of the 2-keV ions is presented in Fig. 1. The flux is normalized by $n_0 v_{A0}$, where n_0 is the initial maximum density, and v_{A0} is the Alfvén speed defined by the external magnetic field and n_0 (i.e., $v_{A0} = B_{ex}/\sqrt{\mu_0 m_i n_0}$). The peak of the flux is found near the x-point, where it forms the ion ring current. Due to this diamagnetic ion current, the magnetic pressure in this vicinity is reduced. Comparison of the results with and without the NBI in the axial component of the magnetic field B_z is made in Fig. 2, where the difference of B_z (i.e., $\Delta B_z = (B_z)_{with} - (B_z)_{w/o}$) is evaluated. The value of B_z is normalized by the external magnetic field B_{ex} (i.e., 0.05 T). Since B_z is negative outside the separatrix in our model, a positive value means the absolute value of B_z is reduced by the NBI. Thus a reduction in the magnetic pressure is found around the ring current position.

The presence of the fast ions and their diamagnetic effect are found to induce the axial flow, which can be seen in Fig. 3. Here, the flow velocity is normalized by the Alfvén speed. In Fig. 3 (a) the axial flow toward the mirror ends is found only outside the separatrix. This axial flow along the open-field originates from the cross-field flow due to resistivity at the separatrix. On the other hand, in Fig. 3 (b), where the plasma inside the separatrix is also flowing toward the end, axial expansion of the FRC plasma is ob-

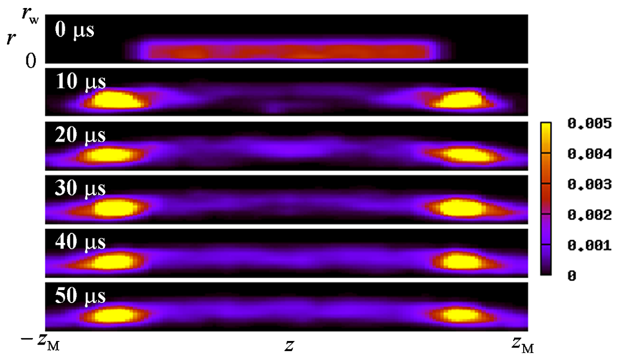

Fig. 1 Color contour of the toroidal flux of 2-keV fast ions at 0, 10, 20, 30, 40, and 50 μs from the top. The flux is normalized by $n_0 v_{A0}$. Every figure shows an upper half cross-section of the confinement region (i.e., $0 \leq r \leq r_w$ and $-z_M \leq z \leq z_M$, where r_w is the wall radius and z_M is the distance from the midplane to the mirror end).

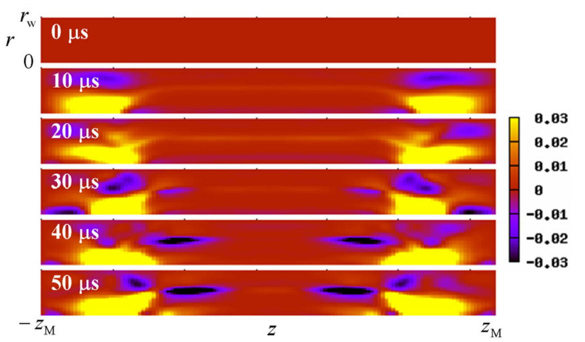

Fig. 2 Difference of the axial component of the magnetic field with and without fast ions at 0, 10, 20, 30, 40, and 50 μs from the top. The magnetic field is normalized by B_{ex}.

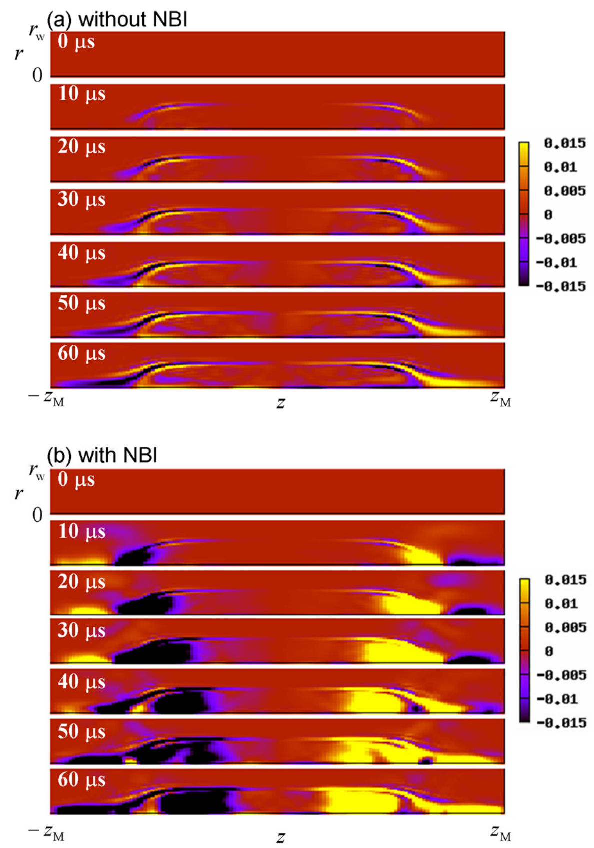

Fig. 3 Axial flow velocity of FRC plasma in cases (a) without and (b) with NBI. The time ranges from 0 to 60 μs from the top. The flow velocity is normalized by v_{A0}.

served in this case with the NBI. A global motion of FRC plasma caused by electromagnetic interaction between fast ions and the plasma is for the first time reproduced here. The beam ion current generated in the vicinity of the x-points reduces the strength of the magnetic field and results in the axial expansion of the FRC plasma.

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