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End Loss Measurement of Neutral-Beam-Injected Field-Reversed Configuration Plasma

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Abstract

End loss flux measurements have been performed by using ion energy analyzer in order to investigate the confinement improvement in a field-reversed configuration (FRC) plasma sustained by neutral beam injection (NBI). The experimental results show that the energy confinement time of FRC has been extended by about 100 % compared with the no NBI case. To understand these experimental phenomena, some measurements have been performed on end loss flux. Previous theoretical studies predict injected hot beam ion walls would play a role in improving the confinements on the edge layer by some electrostatic effects. However, significant evidences suggesting these electrostatic effects on the edge layer due to NBI have never been observed in this work.

Keywords:
field-reversed configuration, neutral beam injection, improved confinement, end loss flux, particle energy analysis

1. Introduction

A Field-reversed configuration (FRC) plasma would have many advantages as a fusion reactor core because of its high-beta nature and engineering simplicity. Unfortunately, current FRCs are operated only in a pulsed fashion. Therefore, in the present stage of FRC researches, application of a neutral beam injection (NBI) is one of the most critical issues for steady state operation of the configuration.

The first results of using NB systems marked improved confinement [1]. In the case of mirror ratio $R_M \sim 8$ and 320 kW (23 A, 14 kV) of NBI, configuration lifetime is extended by more than 100 % compared with the case of no NBI. Furthermore, these lifetime extensions are also observed to be dependent on beam current I_b. However, these NB effects on confinement improvement are too large to consider that it is the only act of current driving and/or electron heating, because the injected beam power of several hundred kilo watts is much smaller than the reduced global energy losses of several mega watts.

We calculated the trajectories of re-ionized beam particles in the magnetic configurations with an experimentally achieved equilibrium of FIX-FRC in the previous work [1]. According to the calculation, it is possible to infer that the dense region of beam ions are formed at the entrance of the mirror regions, and therefore space charge would be formed around these regions of around minimum $|\boldsymbol{B}|$. Or the beam particles ionized in the core plasma region have large orbits and stay mostly in the edge plasma region, and these ions might charge up the core plasma generating significant potential. These electrostatic developments would affect on ion particle loss from FRC plasma along open magnetic field line, leading to some change in total

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confinement property. In order to investigate these electrostatic effects, we measured the time evolution, spatial distribution and velocity distribution of ion loss flux at the end region of FIX device.

In this paper, we present the details of end loss flux measurements in FIX-FRC with NBI. We will also discuss about the electrostatic effect of large orbit beam ions as one of the mechanisms of confinement improvement in these experimental results.

2. Experimental Setup

A. FIX Device

These experiments were carried out on the FIX device [2]. The schematic view of the device is shown in Fig. 1. The FIX has unique plasma confinement properties: translation technique, metal confinement chamber, relatively low plasma density and strong mirror field in which an FRC equilibrium is attained. The FRC plasma is produced by the field reversed theta pinch method with a deuterium puffing system, and is instantaneously moved along a guiding magnetic field into the metal confinement chamber, which serves as a flux conserver, and then reforms to a quasi-steady equilibrium state. Typically applied magnetic field in the straight confinement region is 0.04 T. Each mirror coils are spaced 3.4 m apart; the mirror field strength is 0.08 ~ 0.40 T, and so the mirror ratio can be chosen to be 2 – 10. Typical plasma parameters in the confinement region are; electron density $n_e \sim 5.0 \times 10^{19}$ m^{-3}, plasma temperature T_{tot} ($= T_i + T_e$) ~ 150 eV, separatrix radius r_s ~ 0.2 m, and separatrix volume V_p ~ 0.4 m^3. The poloidal shape of the confined FRC is calculated from excluded flux measurement by using an array of 35 magnetic probes located just inside flux conserver wall. A CO_2 laser interferometer (10.6 μm) is installed parallel to the y axis at z = 0.6 m from the midplane.

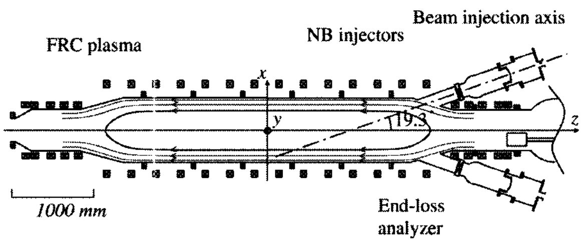

Fig.1 Sectional drawing of the confinement part of the FIX device. The NB injectors are mounted on the tapered part of the confinement chamber. The impact parameter is 100 mm and the beam injection axis is inclined 19° with respect to the geometric axis.

B. Neutral Beam Injection System

Two NB injectors with concave electrodes are employed in our study. Extracted neutral beams focus at a distance of 800 mm from the electrodes on the beam injection axis. Power supplies for the beam sources are the capacitor banks which are switched on-off with Insulated-Gate Bipolar Transistor (IGBT) units. By using this system, neutral hydrogen beams with 770 kW of power (14 keV, 55 A) and 10ms pulse width are produced. The injected neutral beam has a 77 % degree of neutralization and a 5.3 mm radius at the focal point. In our experiment, The neutral beam injectors have been mounted as shown in Fig. 1. The injectors are installed at an angle of 19° to the geometric axis so that the beam particles ionized in the separatrix are outside the loss cone of the mirror field in the case of the strongest mirror ratio of over 9.

C. End Loss Analyzer

A cross-sectional view of the particle energy analyzer is shown in Fig. 2. This analyzer has a set of retarding potential grids. By sweeping the retarding bias

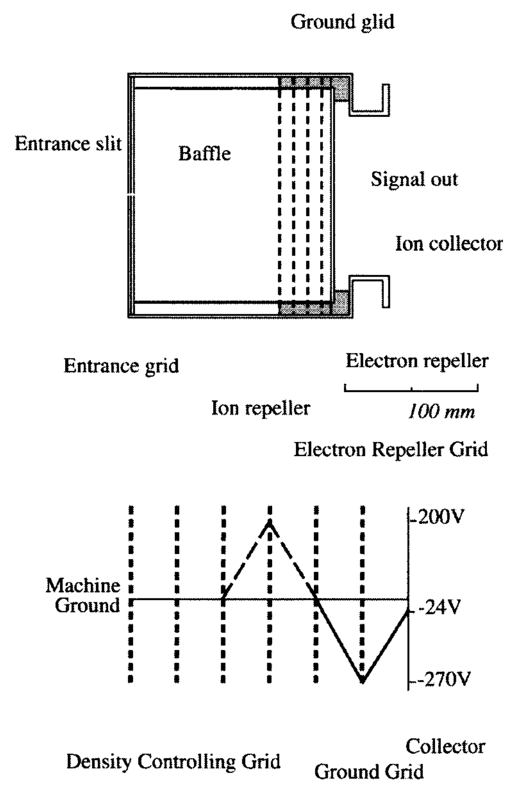

Fig. 2 Schematic view of the energy analyzer and grid potential. The ion repeller bias voltage can be swept to measure axial velocity distribution.

voltage, parallel component of energy $E_{\parallel}$ of loss ions is measured. A typical collector current under the condition of swept bias voltage shown in Fig. 3. A typical axial velocity distribution measured by using this system is shown in Fig. 4. The horizontal axis shows the axial velocity and the vertical axis shows the collector current signal differentiated by the ion repeller voltage which corresponds to $v_{\parallel} f(v_{\parallel})$ where $f(v_{\parallel})$ is axial velocity distribution function. The distribution is approximated by a shifted Maxwellian velocity distribution function

$$f(v_{\parallel}) \propto \exp\left[-\left(v_{\parallel} - v_{\text{flow}}\right)^2 / v_{\text{th}}\right], \qquad (1)$$

where v_{flow} is the axial flow velocity and v_{th} is the axial thermal velocity. The measured velocity distribution shows a good agreement with a shifted Maxwellian (solid line).

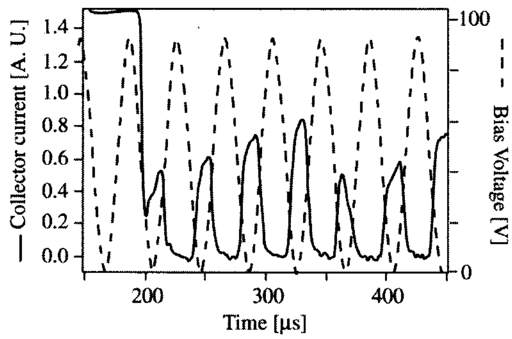

Fig. 3 Typical time evolution of the collector current signal (solid line) and bias voltage on the ion repeller grid (dashed line).

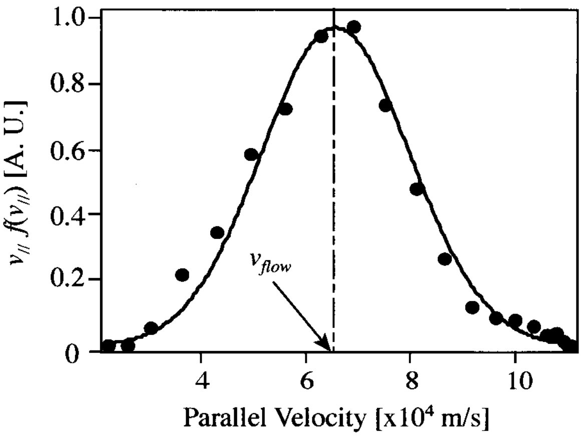

Fig. 4 Typical axial velocity distribution obtained from the energy analyzer. The solid line is fitted one using a shifted Maxwellian distribution function.

The detailed propriety of this system have been tested in our previous study [3,4]. The cutoff angle of the entrance aperture is 85 degree *i.e.* the ratio $E_{\perp}/E_{\parallel}$ = 132, and the measurable range is enough to obtain the energy distribution in our case.

3. Experimental Results

We have conducted NBI experiments focusing our attention on ensuing improved confinement and dependency of end loss flux on the improvement. In following experiments, the beam pulse of NBI has been started about 2 ms before FRC formation because the output of the beam injector reaches a stable and reproducible value 1–2 ms after it is turned on. Even in this situation, the formation and the first-pass of the FRC translation are not influenced by the beam. The injected beam power and mirror ratio are fixed to 320 kW (14 keV, 23 A) and $R_M \sim 8$ respectively.

Typical time evolutions of total particle inventory $N(t)$ ($= \bar{n}_e(t) \cdot V_p(t)$) of FRC plasmas with/without NBI are shown in Fig. 5. Here, time evolution of the separatrix volume $V_p(t)$ is calculated from axial distribution of the excluded flux and averaged electron density $\bar{n}_e(t)$ is estimated from interferometric measurement as $\int n_e d\ell / 2r_s$. The translated FRC plasmas have almost same initial value of N before 80 μs regardless of NBI. After 80 μs, the beam effect on the inventory change appears and the value of N decays at a drastically different rate. Here, we define the particle confinement time τ_N as the e-folding time of the particle inventory decrease, just after 80 μs. The particle confinement time τ_N has increased from 160 μs to 270 μs with the application of NBI. This result shows that

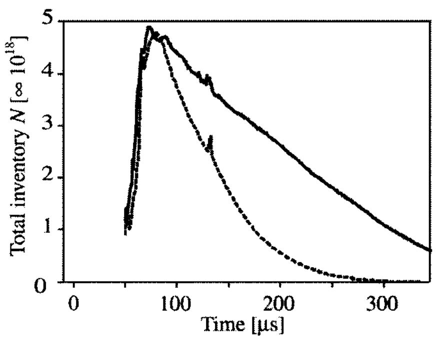

Fig. 5 Time evolution of total particle inventory N in FRC plasmas with/without NBI. The injected beam power P_b estimated from the extracting voltage and the current is about 320 kW (14 keV, 23 A).

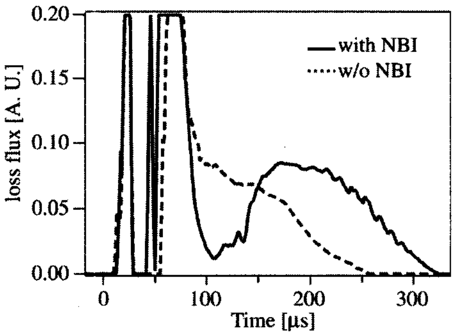

Fig. 6 Time evolution of the amount of end loss flux from FRC plasmas with $R_M \sim 8$ for the case with NBI ($P_b \sim 320$ kW) (solid line), and with no NBI (broken line).

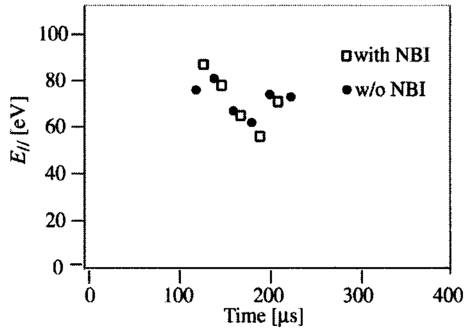

Fig. 8 Time evolution of parallel energy of end loss ions $E_\parallel$ from FRC plasmas with $R_M \sim 8$ for the case with NBI ($P_b \sim 320$ kW) (open square), and with no NBI (closed circle).

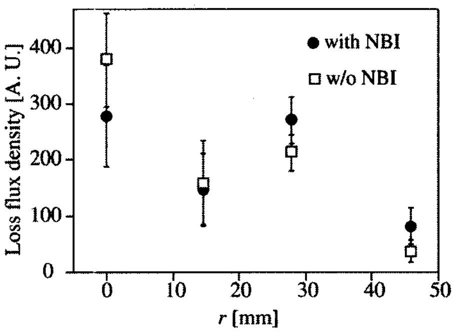

Fig. 7 Spatial distribution of end loss flux from FRC plasmas with NBI ($P_b \sim 320$ kW) (closed circle), and with no NBI (open square).

NBI leads to good confinement in the FRC plasma, because the total beam particle deposit to the core plasma is too small to explain this increase of particle confinement time.

The end loss flux has been measured for same plasma conditions by using the end loss analyzer to observe the electrostatic effects which may be enhanced by NBI. Time evolution of end loss flux amount is shown in Fig. 6. The loss flux has been reduced by NBI especially in the early equilibrium phase (100 μs~150 μs). Measured total amount of loss flux is consistent with the time evolution of particle inventory in Fig. 5.

Spatial distribution of end loss flux has also been measured at the equilibrium phase. Figure 7 shows the spatial distribution at 150 μs. Here the vertical error bars indicate the standard deviations of loss flux over several plasma shots. The spatial distribution shows no significant change due to NBI. Time evolution of parallel energy of loss ions $E_\parallel$ (= 1/2 $m_i(v_{\rm flow}^2 + v_{\rm th}^2)$) has also been estimated by using this energy analyzer as shown in Fig. 8. However, significant difference between cases, both with and without NBI, has never been observed.

4. Discussion

We will discuss the possible basis of the improved confinement, which could be caused by the injected beam ions. The issues discussed here will be the generation of plasma potential or potential barriers in the edge plasma region. The particle confinement time τ_N is increased from 160 μs to 270 μs by the NBI as shown in Fig. 6. In this experiment, the global energy loss rate of 5.5 MW in normal FRC is reduced to 2.3 MW due to NBI, indicating that the energy confinement time τ_E is increased by a factor of approximately two. The injected NB power is 0.3 MW and is not sufficient to directly make up for the diminution of 3.2 MW in global energy loss.

In previous theoretical work [5,6], it was predicted that the electrostatic potential arising in the edge plasma would reduce the particle loss. In our case, because of the high mirror ratio, open field lines around the FRC resembles a magnetic mirror configuration, and especially the configuration near the X points may be regarded as magnetic cusps. During NBI, the electrostatic potential could be enhanced by the beam ions.

The density of the fast beam ions increases at both ends of the confinement chamber as estimated by numerical calculation [1]. The hot beam ions near the X points can possibly create an enhanced potential. This beam-assisted potential could reflect the plasma ions which leak onto the open field lines. This would especially admit the possibility of improving the particle confinement in the mirror region and around the X points. In our case, it is possible that the loss reduction in the edge plasma region decreases the pressure gradient on the separatrix, and thereby improves the core FRC plasma confinement.

In a FRC plasma, it is known that the parallel energy component of end loss ions are accelerated by the pressure drop between core plasma region and the end region [7]. If the potential change decelerates loss ions, its parallel velocity distribution could change and/or the cross sectional area of loss flux could narrow down. However, end loss flux measurements in this work have indicated that the beam ions have no significant effect on plasma potential or potential barriers at the edge plasma region. Therefore, it is considerable that some other mechanisms such as electron heating and/or global stabilization due to fast beam ions may be responsible for the improved confinement property in NB-injected FRCs.

5. Summary

End loss flux measurements have been performed in order to investigate the mechanism of improved confinement in NB-injected FRC. The total amount of loss flux measured by the end loss analyzer is reduced in the early equilibrium stage due to NBI, which is consistent with the time evolution of total particle inventory. However, obvious changes have never been observed on the spatial and velocity distribution of the loss ion flux. Therefore it is concluded that the NBI in this experiment does not cause significant change of plasma potential or potential barriers. As another candidate to explain the improved confinement, the hot beam ions could heat the electrons [8] and suppress micro/macro instabilities. For further investigation, we are preparing a YAG-laser Thomson scattering system to measure the electron temperature in detail.

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