Investigation of Electron Heating Effect in NB-injected FRC

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Abstract

The effect of neutral beam injection (NBI) in a field-reversed configuration (FRC) plasma has been investigated by using a newly developed Thomson scattering electron temperature measurement system. Experimental results hav shown that the FRC plasma with the NBI had 10-20eV higher electron temperature and longer flux confinement time than those without the NBI. The observeed flux confinement time show positive dependency on the electron temperature with $\tau_\phi \propto T_e^{1.32}$, which suggests that the FIX-FRC has a cross field diffusivity with classical-like dependency on T_e. These results may explain the anomalous lifetime extension due to the NBI.

1 Introduction

A field-reversed configuration (FRC) is a compact toroidal plasma with extremely high beta value[1]. The FRC has no toroidal field coils which are interlinked to the plasma and has the potential for axial translation of the plasma. In the FIX (FRC Injection Experiment) research project, several additional heating experiments on the high-beta FRC plasma have been carried out by using this translation technique.

A neutral beam injection (NBI) is an attractive candidate for FRC sustainment, such as plasma current drive, heating and fueling. Recently, NBI experiment has been performed on the FIX device and it led to some interesting results[2]. Remarkable extension of the FRC plasma lifetime was observed due to the NBI, and this extension of the lifetime was found to be much longer than expected from the NBI power of about 300kW. Therefore, it may be attributed to some confinement improvement caused by NBI, e.g. improvement by electron heating, stabilization of plasma global movement, or controlling the scrape-off plasma condition.

The NB effect on the edge plasma layer has previously been investigated by an end loss flux measurement, but no significant evidence which suggests the NB effect on edge plasma condition has been found[3]. On the other hand, the stabilization effect of NBI has been experimentally identified by magnetic measurement of plasma movement[4], although quantitative relationship between the stabilization effect and the confinement improvement has not been analyzed yet.

To investigate the mechanism of beam-plasma interaction, spatial profile measurement of the FRC plasma parameter is essential, and especially the electron temperature measurement is required to analyze both the electron heating effect and the mechanism of confinement improvement.

This article presents the results of electron temperature measurement performed on the NB-injected FRC plasma in the FIX device. The electron heating effect and the confinement improvement are analyzed and discussed.

2 Experimental Setup

2.1 The FIX Device and the NB Source

The schematic view of the FIX device[5] is shown in figure 1 together with the calculated trajectory of a sample high energy beam ion. The FIX device has a formation section which consists of a quartz vacuum vessel with a diameter of 27cm and theta pinch coils, and a straight confinement section made of a metal vacuum vessel which serves as a flux conserver.

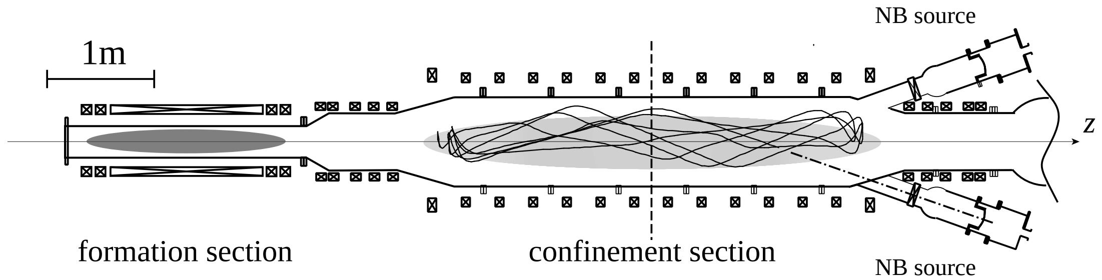

fig.1 Schematic view of the FIX device with NB sources and the calculated trajectory of a beam ion.

A FRC plasma is produced by the field-reversed theta pinch (FRTP) method with deuterium gas puffing system in the formation section and immediately translated into the confinement section by a magnetic pressure difference. Typical field strength is 0.7T in the formation section and 0.04T in the confinement section. The confinement section has a pair of mirror coils located on the both end. The mirror coils are spaced 3.4m apart, and the mirror field strength is 0.08-0.40T. Therefore the mirror ratio can be chosen to be 2-10.

NB injectors with concave electrodes are mounted on the tapered part of the FIX confinement chamber. The impact parameter is 100mm and the beam injection axis is inclined 19.25° to the geometric axis. This NB source can provide neutral hydrogen beam with injection power of up to 320 kW (14keV, 23A) and pulse width of 10msec. The injected H^0 neutrals are ionized mainly through the charge exchange reaction within 1m from the separatrix and trapped in the FIX confinement chamber by strong mirror field as shown in fig.1.

The energy relaxation time between the beam ions and the plasma electrons is expressed as

$$\tau_E^{be} = \frac{3\pi\sqrt{2\pi}\varepsilon_0^2 m_p m_e^{-1/2} T_e^{3/2}}{n_e e^4 \ln\Lambda} \sim 170\mu\text{sec} \tag{1}$$

for $n_e = 5\times10^{19}\text{m}^3$ and $T_e = 50\text{eV}$, and the relaxation time between the beam ions and the plasma ions is

$$\tau_E^{bi} = \frac{4\pi\varepsilon_0^2 m_p^2 v_b^3}{n_i e^4 \ln\Lambda} \sim 25\text{msec} \tag{2}$$

for $n_i = 5\times10^{19}\text{m}^3$ and $v_b = 1.6\times10^6$ km/sec (corresponds to H^+ ion with energy of 13keV). Therefore, the major part of the NB power is expected to be absorbed by plasma electrons during the FRC discharge.

2.2 Diagnostics

The axial profile of the separatrix radius is calculated from the excluded flux measurement by using 35 magnetic probes located just inside the metal chamber wall. Typical separatrix length l_s is about 3.2m and is almost constant during the equilibrium phase. Separatrix radius r_s of the FRC plasma just after the translation completion is about 0.2m, and separatrix volume is about 0.4m^3.

A Thomson scattering measurement system is installed on the midplane (z=0) of the FIX-FRC device. The system consists of several components, such as a Nd:YAG laser (1064nm) and laser optics, light collection optics, polychrometers and a data acquisition system. The scattered lights at r =0.1, 0.15, 0.2m are focused by collection lenses and introduced into the polychrometers with 4 wavelength channels by optical fiber bundles.

A multicoard CO_2 laser interferometer (10.6μm) and an impurity line (O_V:278.1nm) spectroscopy are employed to measure electron densities and ion temperature at $z = 0.6$m apart from the midplane of the FIX confinement section. Typical plasma parameters in the confinement section are; electron density $n_e \sim 5.0\times10^{19}\text{m}^{-3}$, total plasma temperature $T_{tot}(\simeq T_e+T_i) \sim 150\text{eV}$.

3 Experimental results

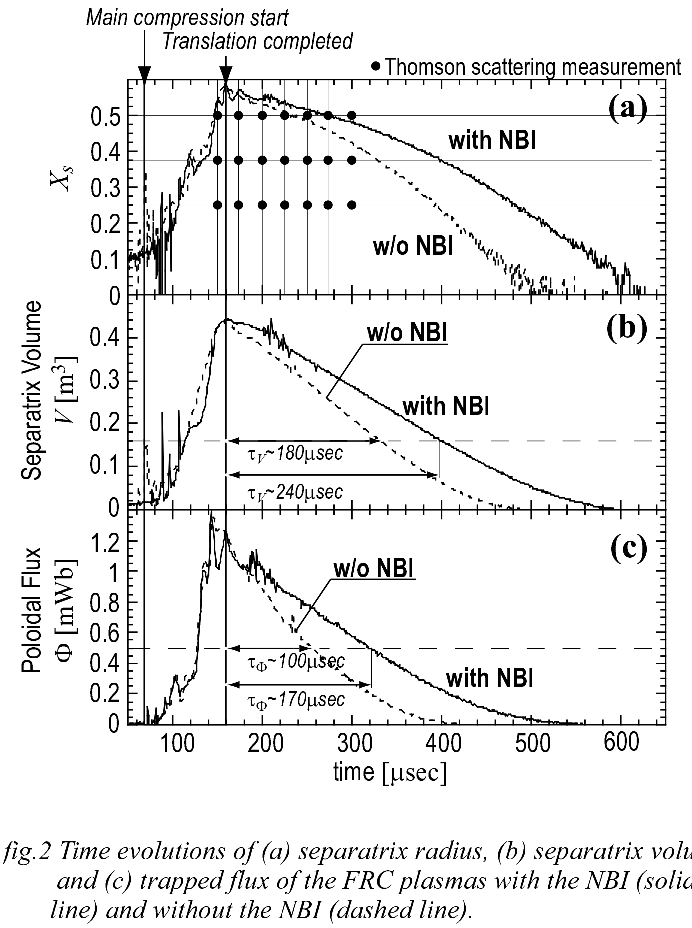

fig.2 Time evolutions of (a) separatrix radius, (b) separatrix volume, and (c) trapped flux of the FRC plasmas with the NBI (solid line) and without the NBI (dashed line).

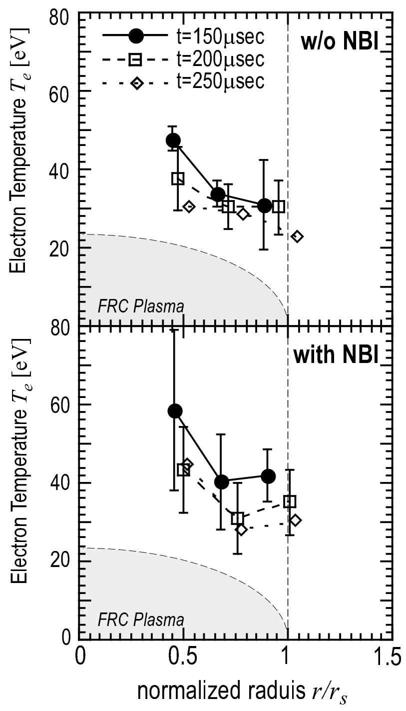

fig.3 Radial profiles of electron temperature in FRCs with the NBI (lower) and without the NBI (upper).

Figure 2 shows the typical waveforms of FRC discharge with and without the NBI measured in the FIX confinement section. The experimental conditions are; mirror ratio is set to $R_M = 7 \sim 9$, 13keV energy and $200 \sim 250$kW power of NB is injected. We have checked the axial symmetry of the FRC plasma by using the multichord interferometer, and chosen the operating condition to keep good plasma symmetry even in the case without the NBI in order to investigate the NB effect on the core plasma. In this experiment, we observed no significant changes caused by a plasma displacement or a deformation between the FRC plasmas with and without NBI. So we suppose we could exclude the possibility of the confinement improvement due to the stabilization effect of the NBI.

Figure 2(a) shows the separatrix radius r_s and (b) shows the separatrix volume V_p calculated from magnetic probe signals. An FRC is produced by field-reversed theta pinch method in the source section at about $t = 75\mu$sec and then translated into the confinement section. After the translation phase is completed at about $t = 160\mu$sec, the FRC begins to decay.

The FRC plasma with the NBI was observed to have a longer lifetime than that without the NBI. The plasma volume lifetime was extended from $\tau_V = 180\mu$sec to 240μsec by NBI. Fig. 2(c) shows evolutions of trapped fluxes of the FRC plasma with and without the NBI. The flux lifetime was also extended from $\tau_\phi = 100\mu$sec to 170μsec by the NBI. Since the total energy loss from the FRC plasma without NBI is in the order of several MW, the NBI with the input power of less than 300kW is not enough to explain the observed lifetime extension.

These results indicate that the electron heating caused be the NBI may bring this extension of the plasma lifetime, so we carried out the Thomson scattering electron temperature measurement at the time and position shown by black circles in Fig2 (a). The spatial profile of electron temperature was achieved in one discharge, and the time evolution of electron temperature was observed by changing the laser firing timing shot by shot. Figure 3 shows the radial profiles of electron temperature of the FRC with and without the NBI measured at t =150, 200, and 250μsec. The radial position is normalized to the separatrix radius.

The NB-injected FRCs have T_e of about $10 \sim 20$eV higher than the FRCs without the NBI. Since this temperature increment was observed even before the translation was completed (t=150 μsec), the beam power may be absorbed more efficiently during the translation phase due to the higher density. The electrons temperature shows significant increase at inner region ($r/r_s \sim 0.5$) and around the separatrix due to the NBI, although the electron temperature of the FRC without the NBI shows a flat gradient along the radial direction. This result suggests that the beam power deposition may be localized probabry due to the nonuniform distribution of the high energy beam ions.

Figure 4 shows the time evolutions of (a) electron temperature at r=0.1m and (b) ion temperature of the FRC plasmas with and without the NBI. The electron temperature of the NB-injected

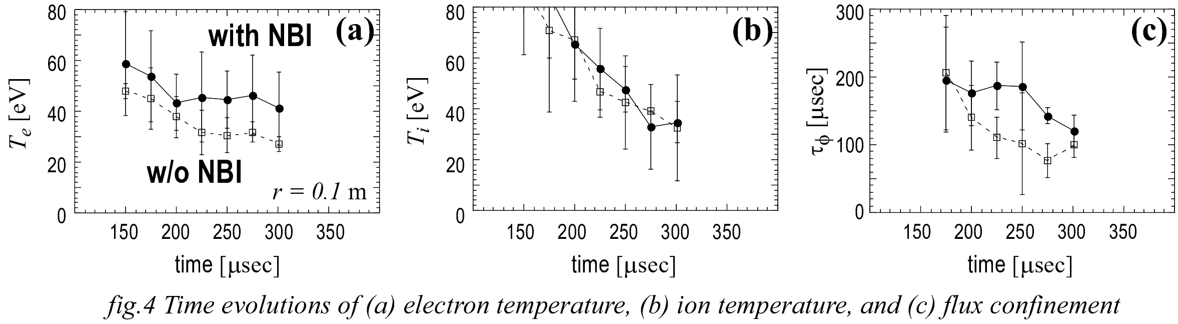

fig.4 Time evolutions of (a) electron temperature, (b) ion temperature, and (c) flux confinement time of the FRCs with th NBI (solid line) and without the NBI (dashed line).

FRC keeps $10 \sim 20$eV higher than that of the FRC without the NBI, whereas the evolutions of the ion temperature do not show any remarkable changes. Here, the total thermal loss power from plasma electrons and ions are calculated as $P_{Loss,e} = 100 \sim 300$kW and $P_{Loss,i} = 1 \sim 1.5$MW, therefore the NBI with power of 300kW has a potential to increase or sustain the electron temperature in the FRC plasma.

The NBI also brought the extension of the flux lifetime shown in fig.1. Time evolutions of the flux confinement time are shown in figure 4 (c). Improvement of flux confinement was observed in parallel with the increment of electron temperature by the NBI.

4 Discussion

In figure 5(a), the flux confinement time is plotted as a function of electron temperature. The

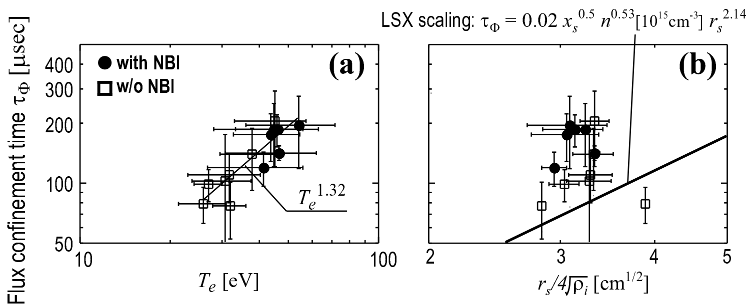

fig. 5 Flux confinement time versus electron temperature (left) and the empirical law $r_s/4\sqrt{\rho_i}$. (right)

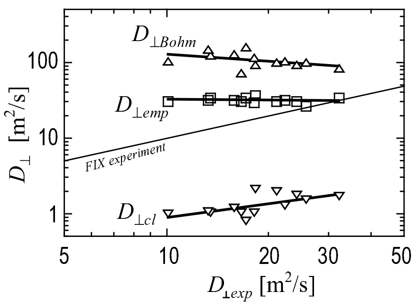

fig. 6 Cross field diffusivity based on classical model (downward triangle), Bohm model (upward triangle), and empilical scaling (open square) versus that calculated from τ_Φ in the FIX experiment.

flux confinement time was found to have a dependency on the electron temperature, proportional to $T_e^{1.32}$, which indicates the flux confinement time is almost proportional to the inverse of the classical resistivity, although the magnitude of the flux confinement time is much shorter than that expected from the classical resistivity.

On the contrary, the flux confinement time of the FIX-FRC does not agree with the empirical scaling by $r_s/4\sqrt{\rho_i}$, shown in fig. 5 (b). The FIX-FRC has the flux confinement time $2 \sim 3$ times longer than the empirical law[6].

Basic diffusivity $D_\perp$ in a FRC is expressed as $D_\perp = r_s^2/16\tau_\phi$ for a rigid rotor profile and a uniform resistivity. According to the equation, the diffusivity of the FIX-FRC is about 10-30 m^2/s, and is found to be approximately proportional to T_e^{-1}. Figure 6 shows the cross field diffusivities calculated from classical diffusivity $D_{\perp cl} = \eta_{\perp cl}/\mu_0$, Bohm diffusivity $D_{\perp Bohm} = \kappa T_e/(16eB)$, and the empirical scaling law obtained in LSX experiment[6] are plotted as a function of the diffusivity derived from the FIX experiment by $D_\perp = r_s^2/16\tau_\phi$.

The diffusivity of the FIX-FRC locates just between the classical diffusivity and the Bohm diffusivity. It is about 2-3 times smaller than the empirical scaling, but the dependency looks different. The diffusivity on the FIX-FRC has negative dependency on the electron temperature, similar to the classical one. Although further investigation of other possible mechanisms for the confinement improvement will be required, these results may imply a good interpretation of the confinement improvement due to the NBI.

5 Summary

The electron heating effect and the confinement improvement mechanism have been investigated on the NB-injected FRC plasma. The NBI brought a significant extension of plasma lifetime which may be caused by some improvement of confinement of the bulk plasma.

Thomson scattering T_e measurement has been carried out on NB-injected FRCs, and selective heating of plasma electrons due to the NBI was observed. This electron heating may contribute to the confinement improvement by the NBI. The flux confinement time and the diffusivity in the FIX-FRC was found to have a dependency on the electron temperature.

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