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Neutral beam injection experiments in a high-beta FRC research

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I. Introduction

Neutral beam injection (NBI) has potentials for driving plasma current as well as for heating and fueling. Furthermore, the injected beam current may play an important role in suppressing instabilities, such as the rotational instability[1] and the tilt instability[2, 3]. The first experiment to apply NBI in an FRC has been performed on the FIX (FRC injection experiment) device[4]. The application of NBI is one of the most critical issues for progress in high-beta plasma research, both for FRCs and for STs.

NBI must be applied differently in high-beta plasmas than in Tokamaks, since high energy beam ions would merely pass through the high-beta (and hence low magnetic field) core region and strike the chamber wall. The development of an ion source which can produce large current neutral beams with relatively low energy is important for FRC research. As the beam current density is limited by the Langmuir-Child law, a high current, low energy beam requires electrodes with a large surface area. A beam with a large cross-sectional area is difficult to pass through a narrow port. To overcome this problem, we have developed an NB injector which has concave electrodes, so as to focus the beam. With this system, it is possible to produce more than 20 A of hydrogen neutrals with 14keV of energy, and to inject the beam into the plasma through a narrow port.

We have already reported initial experiments of NBI into the FIX-FRC[4], and the results show marked improvement in confinement. The configuration lifetime is extended by more than 100 % in the case of a 320 kW (23 A, 14 kV) beam. In the present work, we will experimentally evaluate the dependency of the FRC confinement on the beam current. We consider the beam-related electron heating as a possible mechanism for the improved confinement.

II. Experiments

The detailed property of FIX device has been described elsewhere[5]. In the formation region, the FRC is produced by the usual theta pinch method with a fast rising (T/4 ~ 4 ms) magnetic field of 1 T. In standard conditions with deuterium, the electron density, $\bar{n}_e$ ~ 5.0 x10^{21} m^{-3}, and the pressure balance temperature, T_{tot} (= T_i + T_e) ~ 440 eV. The magnetic confinement region has a straight guide field and also a mirror field at either end. The mirror field strength may be varied from 0.08 to 0.40 T, so that the mirror ratio can be chosen to be from 2 - 10. Typical plasma parameters in the confinement region are as follows; average electron density, $\bar{n}_e$ is 3.0 x 10^{19} m^{-3}, and pressure balance temperature, T_{tot} (= T_i + T_e) is about 200 eV.

The NB injector is installed on the tapered part of the confinement chamber at an angle of 19° off the geometric axis. This enables the Larmor radius to be effectively small, even for high energy beams of 14 keV. The ion Larmor radius is about 100 mm for an external magnetic field B_w of 0.04 T. The axis of the injector has an impact parameter of 100 mm from the geometric axis of the confinement region, in order to achieve a high efficiency of beam trapping between the external mirror fields.

Installed ion source is a bucket-type ion source, which has concave electrodes. This allows the beam to be extracted at high current from a large surface-area electrode and focused. The multi-aperture electrodes have an effective diameter of 218 mm and a radius of curvature of 800 mm. The beamlets are extracted from these apertures towards the focal point, 800 mm from the electrode.

The beam current extracted from the ion source may be varied by controlling the arc-plasma conditions, while holding the accelerating voltage constant. The beam current is controllable and is varied in this experiment from 10 to 23 A, with a fixed accelerating voltage of 14 kV. The duration of the beam is 10 ms.

We have conducted NBI experiments, focusing our attention on the ensuing improved confinement. Observations of the effects on confinement due to beam current have been performed. The configuration lifetimes τ_V vs. the input beam currents I_b are plotted in Fig. 1, where the beam-extracting voltage is fixed at 14 kV and the mirror field is R_M ~ 8. The extracted beam current is regulated by controlling the arc plasma conditions. The lifetime of τ_V is roughly proportional to the injected beam current I_b.

A pressure balance temperature T_{tot} (= T_e + T_i) has been also estimated for the same experimental shots as shown in Fig. 2. The initial plasma temperatures of translated FRCs at t = 80 μs are approximately the same value of 200 eV for all cases of I_b. The temperature T_{tot} in the case with NBI is higher than that without case, and the increment ΔT_{tot} in T_{tot} increases with time. The particle confinement time τ_N is also estimated, from the time evolution of the product of $\bar{n}$ and V_p. The confinement time τ_N for the case without NBI is approximately 110 μs, comparable to the lifetime τ_V of 104 μs. On the contrary, in the maximum NBI case, τ_N increases to 260 μs, which is significantly longer than the value of τ_V = 214 ms. This result indicates that the FRC particle confinement has been improved by NBI. It is unlikely that the supplied beam particles can compensate for the particle loss because the number of injected beam particles is 1.4 x 10^{14} ms^{-1} (for a beam current of 23 A) which is small compared to the global particle loss rate of 1.3 x 10^{16} ms^{-1} for the case of τ_N = 200 μs.

III. Discussion

We will discuss the possible basis of the improved confinement, which could be caused by the injected beam ions. Numerical simulations of the FRC predict that the global tilt mode instabilities can be suppressed by fast ions[2, 3]. In the present FIX experiments, the destructive global instabilities (including n=2 mode rotational instability) have not been observed in any case. We will omit discussion of the micro-instabilities here. In present experiment, the global energy loss rate of 5.5 MW is reduced to 2.3 MW, 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.

The increased lifetime τ_V could be caused by the rise in T_e, so we will now discuss the effect of electron heating. The heating rate of plasma ions is known to be very small. With our experimental conditions, the energy relaxation time of beam ions with plasma electrons and ions are estimated to be 170 μs and 4.2 ms respectively. We therefore make the following assumptions; the hot beam ions heat only plasma electrons, the internal structure of the FRC is not changed by the NBI, and the energy loss rate due to conduction is unchanged. The increment ΔT_{tot} in Fig. 2 is then to be regarded as the increment in T_e (ΔT_e).

Next, we make a simple estimate of the particle diffusion rate and how it is effected by the increase in electron temperature. We employ a power-law dependence of the diffusivity D on the electron temperature T_e, such as $D \propto T_e^{-3/2}$, according to the classical law. Moreover, for simplicity, we assume that the core FRC plasma has a cylindrical boundary shape. Under the assumption, the calculated dependence of τ_N on T_e is shown in Fig. 3. The curve in Fig. 3 is a least squares fit to the data, and is in good agreement with the experimentally estimated τ_N. These data indicate that the injected beam ions increase τ_V and τ_N through the electron heating process.

As another candidate to explain the experimental results, the spiraling-ions may improve the confinement through a beam enhanced potential in the edge plasma. In previous theoretical work[6, 7], 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, the 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.

IV. Summary

The dependency of the confinement on the beam current has been examined under the condition of a fixed beam energy E_b ~ 14 keV. The lifetime τ_V was found to be proportional to the injected beam current. It was also observed that the pressure balance temperature T_{tot} increases with the power-up of the beam. Based on these results, we have made a quantitative estimate of the electron heating by NBI. The pressure balance temperature was found to depend on the beam-current, and it is posited that the beam-current heats the electrons and that the rise in electron temperature leads to the improved confinement.

The electrostatic effects of fast beam ions on the edge plasma region might also be the potential of NBI to reduce the particle loss flow. Further studies; to capture the behavior of beam ions in the scrape-off layer and to measure parameter changing of edge plasma, are required to clarify the mechanism. Moreover, some micro-instabilities may effect the confinement, but this mechanism would be very difficult to treat experimentally. Investigation about microinstabilities is task for future study in FRC research.

As another effect of beam, centered FRCs and suppressed separatrix movement have been observed in the NBI experiments. This should be one of the important beam effects and it may reduce the interaction between stainless chamber wall and FRC plasmas. For further investigation, we are preparing a YAG-laser Thomson scattering system to measure the electron temperature in detail and B_θ probe arrays to observe global separatrix movement.

Refferences

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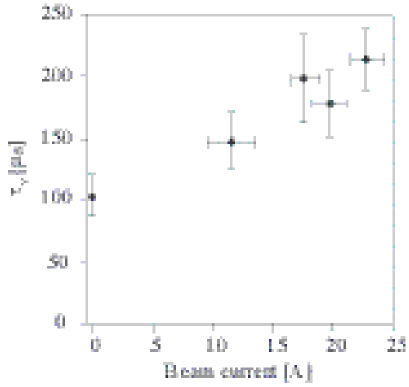

Fig. 1. Dependence of the lifetime on the beam current I_b; lifetime is found to increase with increasing beam current. The beam energy E_b is fixed at 14 keV. Horizontal error bars denote the repeatability of the beam current, and vertical error bars the dispersion in the lifetime.

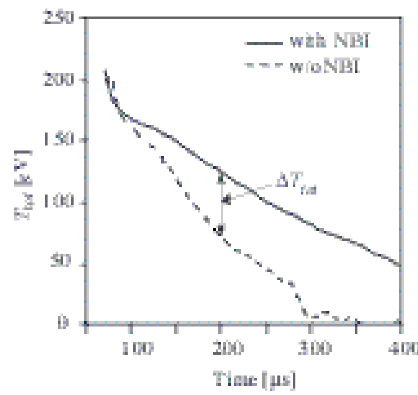

Fig. 2. Time evolution of the pressure balance temperature T_{tot} (= T_e + T_i) for the case of R_M~8 and P_b ~ 320 kW (solid line), and that of no NBI (broken line).

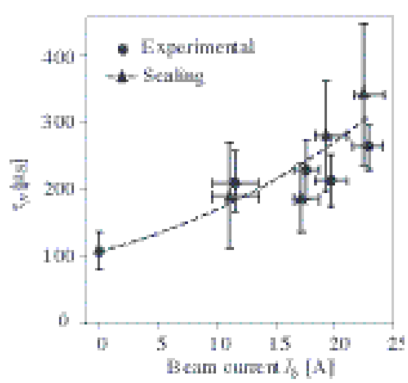

Fig. 3. Dependency of the experimental value of τ_N plotted *vs*. beam current I_b. Experimental values are denoted with circles, estimated values with triangles. The broken-line curve is fitted to the estimated values.