Neutral Beam Injection to Oblate FRC Formed by Plasma Merging Method

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1. Introduction

The field-reversed configuration (FRC) is an attractive high-beta concept among magnetically confined systems, however, difficulties in current drive and additional heating have prevented improvements on FRC's confinement properties. Recently, the rotating magnetic fields are applied to demonstrate quasi-steady sustainment of prolate FRC plasmas [1-4, rotamak, TCS, FIX, PFRC]. Another promising power input method is a neutral beam injection (NBI), which is most commonly used to heat the magnetically confined fusion plasmas. The NBI was applied to the FRC plasmas in the FIX apparatus for the first time. The extension of plasma lifetime [5], suppression of the FRC's global motion [6] and electron heating [7] were reported by using a 12kV, 240kW NBI on FRC plasmas translated into a metal confinement section. Since the trapped flux of the translated FRC about 1mWb, the 15kV fast ions cannot be confined if they are injected tangentially. Oblique injection with 19.25 degree to the geometrical axis and large mirror ratio of 9 were employed to confine the energetic ions, nevertheless, the ion's trajectories spread out of the FRC's separatrix leading to a substantially low power deposition rate of less than 50% due to the orbit and re-charge exchange losses. In this paper, we describe the utilization of oblate FRCs formed by counter-helicity spheromak merging method as a better target plasma for NBI.

The counter-helicity merging of spheromaks is an alternative method to form a high-beta FRC plasmas [8]. Pronounced features of the merging method are occurrence of significant ion heating due to magnetic reconnection, applicability of a center solenoid current drive, and oblate plasma shape with large major radius. These features enhance the potential for NBI heating in high-beta FRC plasma, because the large plasma radius and the resulting large magnetic flux are essential for good confinement of produced fast ions as well as efficient ionization of beam neutrals. Effective tangential injection of 15 keV hydrogen beam requires target FRC plasma with magnetic flux more than 20 mWb. The NBI is also expected to improve the global stability of FRC plasma by providing azimuthally rotating fast ions near the magnetic null [9].

2. Experimental setup

In the TS-4 device (figure 1), large FRC plasma with major radius of about 45 cm is produced by the counter-helicity spheromak merging method. Because of the large S* number (ratio of minor radius to ion skin depth), the counter-helicity merging with hydrogen gas in the TS-4 device usually exhibits severe low-n instability just after the merging. On the other hand, the plasma mergings with heavier gases such as neon and argon are more stable and show clear relaxation to FRC plasma with small poloidal eigenvalue [10]. The produced argon FRC has trapped flux of more than 8 mWb and the magnetic energy loss power of about 1 MW, as shown in figure 2. It is consequently expected to become a good target plasma for the tangential NBI.

A washer gun type neutral beam source [11] was developed and installed on the midplane of the TS-4 device to inject the beam tangentially into the FRC plasma with variable impact parameter of 0.4-0.6 m by changing the incident angle of the beam, as shown in figure 3. The acceleration voltage is 15 kV and maximal obtained beam current is about 40A, providing more than 0.5 MW input power of hydrogen neutral beam.

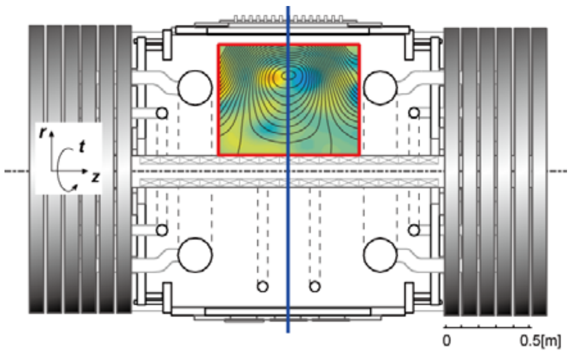

Figure 1. Schematic view of TS-4 device.

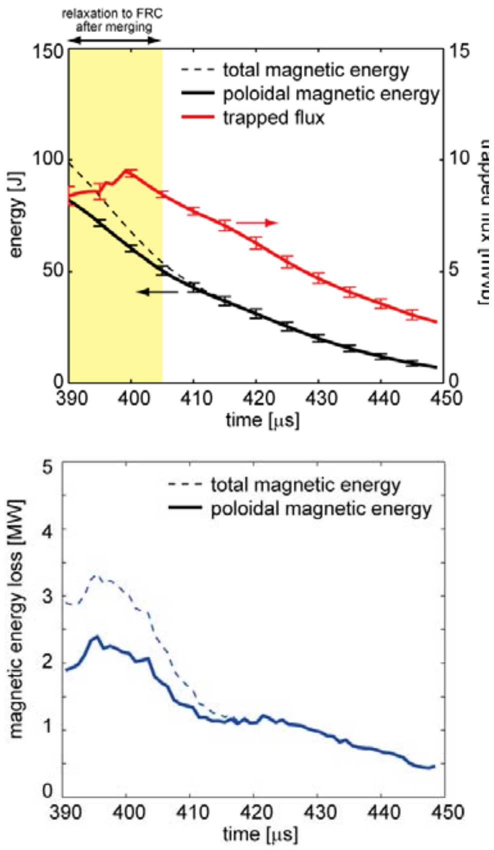

Figure 2. Time evolution of magnetic energy, trapped flux (top), and magnetic energy loss rate (bottom).

3. Experimental results

Figure 4 shows the evolution of beam current, voltage and the magnetic energy of the argon FRC plasmas with and without NBI. The argon FRC typically has the density of 1x10^{20} m^{-3}, ion and electron temperatures of 10 eVs, and the trapped magnetic flux of 8 mWb. The injection of 15keV 5A hydrogen neutral beam extended the argon FRC's decay time.

Another primary result from NBI experiments was that the stability of hydrogen FRC formation process was drastically improved by the tangential injection of 15 keV hydrogen beam with peak input power of 500 kW. Figure 5 shows the evolutions of flux surfaces together with the toroidal magnetic fields of the FRC formation process with and without NBI. The hydrogen FRC simply formed by merging method in TS-4 becomes unstable just after the merging process is over at t = 380 μs, and loses its equilibrium quickly. The NBI drastically changes the situation, as shown in the bottom panels in figure 5. The formed FRC with NBI remains stable after the merging and shows moderate decay.

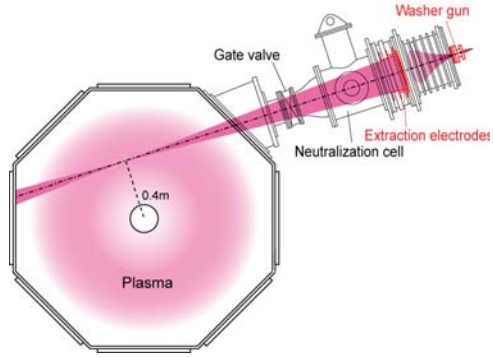

Figure 3. Cross-sectional view of the TS-4 device and the beam source.

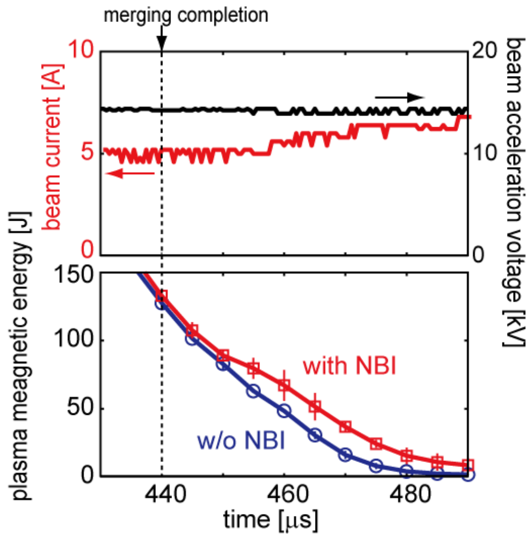

Figure 4. Time evolutions of beam current and voltage (top) and the FRC's magnetic energy with and without NBI (bottom).

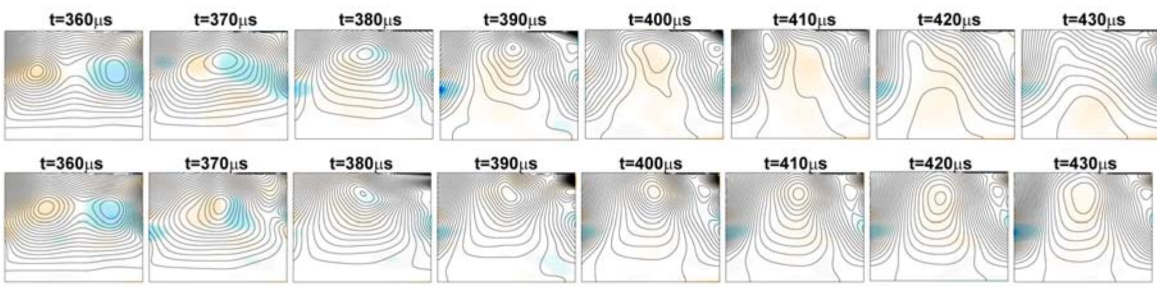

Figure 5. Evolutions of 2-D magnetic field structure of hydrogen FRC without NBI (top) and with NBI (bottom).

The NBI has two major impacts on oblate FRC; first, it provides better stability against low-n modes which usually brake the equilibrium quickly after the formation of large S* oblate FRC. And it also provides extended lifetime in which the reduced loss power is much larger than the NBI input power. These results indicate that the beam-plasma direct interaction other than the energy transfer to plasma electrons via viscosity plays important roles on the FRC's lifetime extension.

4. Summary

The first NBI experiment to the oblate FRCs produced by plasma merging was conducted. The NBI provided a stable formation of hydrogen FRC with trapped flux of up to 15 mWb. NBI also reduces the flux decay rates of FRC plasmas with various gases such as hydrogen, helium, and argon. Since the decrease of energy loss rate is much larger than the input NBI power, the stabilization of the low-n modes provided by beam-plasma direct interaction is possibly responsible for the lifetime extension observed in the NB-injected FRC plasmas.

Recently, two other ion sources with acceleration voltage and current of 15 keV and 20 A, respectively, were moved from Osaka University (FIX device) and installed on the TS-4 device for tangential injection on the midplane. Full-scale NBI experiments with injection power up to 1 MW are in preparation to achieve non-inductive sustainment of oblate FRC.

[1] I.R. Jones, Phys. Plasmas **6**, 1950 (1999).

[2] A.L.Hoffman, et al., Nucl. Fusion **45**, 176 (2005).

[3] S.A. Cohen, et al., Phys. Rev. Lett. **98**, 145002 (2007).

[4] M. Inomoto, et al., Phys. Rev. Lett. **99**,.175003 (2007).

[5] T. Asai, et al,. Phys. Plasmas **7**, 2294 (2000).

[6] T. Asai, et al., Phys. Plasmas **10**, 3608 (2003).

[7] M. Inomoto, et al., Nucl. Fusion **48**, 035013 (2008).

[8] Y. Ono, et al., Nucl. Fusion **39**, 2001 (1999).

[9] E. Belova, et al., Phys. Plasmas **13**, 056115 (2006).

[10] E. Kawamori and Y. Ono, Phys. Rev. Lett. **95**, 085003 (2005).

[11] T. Asai, et al., Rev. Sci. Instrum. **79**, 063502 (2008).