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Neutral Beam Injection to a Field-Reversed Configuration
磁場反転配位への中性粒子ビーム入射

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The effect of energetic beam ions on oblate field-reversed configurations (FRCs) has been studied experimentally in the TS-4 plasma merging device. In order to examine its kinetic effects, we developed a novel economical high-power pulsed neutral beam injection (NBI) system by use of a washer gun as a plasma source. We found for the first time that two merging high-*s* hydrogen spheromaks with opposite helicities relaxed into the large scale FRC with poloidal flux as high as 15 mWb under the assistance of the 0.6 MW NBI. This fact indicates importance of ion kinetic effects for the FRC stability.

1. Introduction

A Field-reversed configuration (FRC) is a compact toroid with small or zero toroidal magnetic field and dominant poloidal field. The FRC has some potential for future fusion reactors due to its high beta and simple geometry. Plasma heating and current drive by neutral beam injection (NBI) are important research subjects for FRC. Although the NBI for prolate FRCs was introduced sorely to the FIX (FRC Injection Experiment) device at Osaka University [1], its heating efficiency was low since the theta pinch formation method with poor formation efficiency could not produce the poloidal flux large enough to trap fast beam ions inside the FRC. On the other hand, oblate FRCs formed by merging spheromaks have an advantage in the large amount of poloidal flux which can be amplified easily by a center solenoid coil.

It is important to experimentally elucidate the physics of kinetic effects of energetic beam ions in oblate FRCs. A numerical study shows that NBI is useful not only for heating but also for an improvement of stability by the energetic ions [2]. The stabilization effects of kinetic ions have been investigated in our TS-4 plasma merging experiments. We found for the first time that two merging high-*s* (average number of ion gyroradii in the separatrix) hydrogen spheromaks with opposite helicities relaxed into the large scale FRC with poloidal flux as high as 15 mWb under the assistance of the 0.6 MW NBI. This fact suggests that some ion kinetic effects are essential to the FRC stability.

2. Plasma Merging Device TS-4

The plasma merging device, TS-4, was utilized to produce two spheromaks with opposing helicities, to merge them axially by means of magnetic reconnection, and to relax to an oblate FRC [3]. Its cylindrical vessel with a diameter of 1.6 m and a length of 2.2 m has two flux cores whose internal poloidal and toroidal field coils produce poloidal and toroidal magnetic fields of the two initial spheromaks, respectively. The center conductor, equipped with center solenoid coils, is located along the center axis to reduce toroidal mode $n = 1$ (tilt, shift) activities. Its typical FRC plasma parameters are as follows: $\Psi \sim 15$ mWb, $I_p \sim 30$ kA, $n_e \sim 10^{20}$ m^{-3}, $T_e \sim 10$ eV, $T_i \sim 40$ eV, $R \sim 0.5$ m, and $A \sim 1.5$.

3. NBI System with Washer Gun Plasma Source

In order to investigate the kinetic effects, we developed a novel high-power pulsed NBI system. In the conventional plasma sources, the neutral gas is pre-ionized by hot electron emission from filaments. Their arc discharge requires high-capacity water-cooling system to remove heavy heat loads to the permanent magnets on the exterior wall of the vessel. In the new system, we replaced the filaments by a gas-injected stainless-steel washer gun placed on the bottom of the vessel as a plasma source. It enables us to remove the conventional filaments and water cooler from the system and to adopt neodymium magnets for the cusp field.

We already completed the development of the NBI system. It is observed that the beam current exceeds 20 A over approximately 0.5 ms, which is suitable for our target plasma in TS-4. Our experimental results reveal the successful beam extraction up to 15 kV, 40 A and 0.6 MW. Recently, two new

NB sources with acceleration voltage and current of 15 kV and 20 A are also under development.

4. Numerical Simulation of the NB in an Oblate FRCs

Numerical orbit calculation has been performed for the purpose of checking whether the newly developed NBI system can be applicable to the oblate FRC in TS-4 and whether fast neutral beam particles can yield the kinetic energy to the plasma. The ionization positions of tangentially injected 15 keV neutral beam particles are calculated on the midplane of TS-4 using the Monte Carlo code. Figure 1 shows the particle trap rate in the FRC, indicating that most of fast beam ions are trapped between the axis and the separatrix due to the gyroradius of the beam ion as long as the separatrix radius and the radially inward Lorenz force $\boldsymbol{v} \times \boldsymbol{B}$.

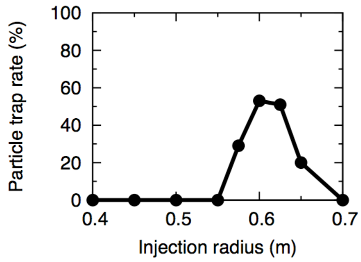

Fig.1. Particle trap rate calculated by the orbit code.

5. Initial Results of Merging Formation of Large-size FRCs with the Assistance of NBI

The neutral beam injection was performed during the merging formation of an FRC in TS-4. Poloidal flux and plasma current were increased as much as possible by a solenoid coil for the purpose of trapping the beam ions efficiently. Figure 2 shows poloidal flux contours and toroidal field of merging spheromaks with and without NBI. Figure 3 also shows their radial profiles of electron densities as a function of time. A new finding is that two merging high-*s* hydrogen spheromaks with opposing helicities relax into the large scale FRC with poloidal flux as high as 15 mWb under the assistance of the 0.6 MW NBI. However, they did not relax to an FRC without the assistance of the NBI. Although the beam ion density was almost a few percent of the plasma density, n_e around the magnetic axis of the FRC with NBI was almost twice as much as that of the FRC without NBI. These facts suggest that some ion kinetics effects such as toroidal ion flow are essential to FRC stability.

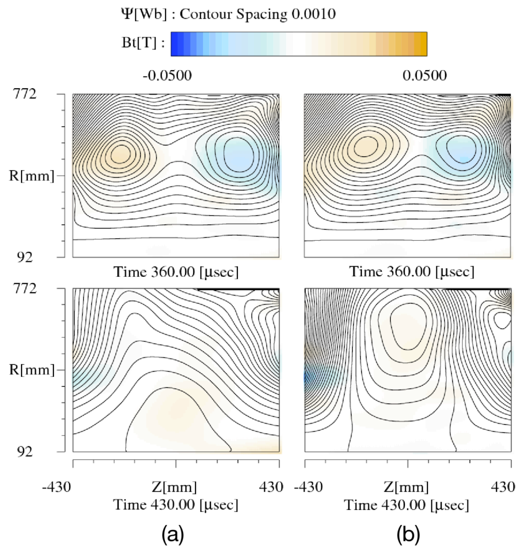

Fig.2. *R-Z* contours of poloidal flux and toroidal field (in color) of counter-helicity merging spheromaks (a) without and (b) with NBI. In the case (b), the merging spheromaks relax into a single FRC.

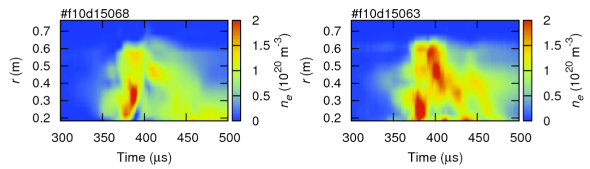

Fig.3. Radial profiles of electron density n_e of hydrogen FRCs without NB and with NB as a function of time.

6. Summary

The effect of energetic beam ions on oblate FRCs was studied experimentally for the first time in TS-4. We found that two merging high-*s* hydrogen spheromaks with opposite helicities relaxed into the large scale FRC with poloidal flux as high as 15 mWb under the assistance of the newly developed NBI with the beam power of 0.6 MW. This fact suggests that kinetic effects are essential to FRC stability. We will perform the upgraded FRC experiments using three NB sources under development whose total output power exceeds 1 MW.

Acknowledgments

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References

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