Kinetic Behaviors of Energetic Ions in Oblate Field-Reversed Configuration

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Abstract. Energetic ion behaviors in oblate FRC plasmas are investigated using spontaneously driven toroidal flow shear produced by the counter-helicity merging spheromaks and tangential neutral beam injection (NBI). The decay rate and the electron density profile of the oblate FRC are strongly affected by the direction of the toroidal flow, indicating that the global bahavior of the FRC plasma is controlled by the preferential particle loss of the energetic ions. Hydrogen neutral beam with energy of ~13keV and current of ~5A was injected tangentially to the oblate FRC plasma for the first time. The observed improvement of the magnetic energy decay rate is much larger than the input NBI power, suggesting that global stability of the FRC is improved by the NBI fast ions.

1. Introduction

Field-reversed configuration (FRC) is a toroidal plasma confined solely by a poloidal diamagnetic field. Unlike the other magnetically confined toroidal system such as tokamaks, RFPs and spheromaks, the FRC does not permit any low beta state. The absence of the low beta equilibrium restricts the FRC formation scheme to a few particular methods, the field-reversed theta pinch [1], the rotating magnetic field [2], and the counter-helicity spheromak merging [3]. On the other hand, the extreme high beta (β>80%) nature has attracted our attention on the FRC as a possible candidate of a core plasma for advanced fuel fusion, if remarkable breakthrough can be achieved on stability, confinement and current drive. Kinetic behaviors of energetic ions are keys to solve some of these issues. Many numerical studies pointed out that the energetic ions in the FRC plasma give improvements on global stability [4,5]. In the plasma merging method, high-power ion heating is provided by anti-parallel reconnection of two initial low-beta spheromak plasmas, forming the high-beta FRC equilibrium within a short reconnection period. The reconnected field line is accelerated up to the Alfvén velocity of the upstream regime, dragging the plasma in which the reconnected field line is frozen. Thus, the accelerated ion's kinetic energy reaches about 3-5 times larger than the initial ion temperature of the low-beta spheromaks, exerting kinetic effects on the formed FRC. Energetic particles will also provide a most promising FRC heating/current driving tool; the neutral beam injection (NBI). One advantage of the plasma merging method is that it can produce large-bore oblate FRC plasma with large amount of poloidal magnetic flux, which is essential to trap the energetic beam ions injected into the FRC plasma. In this paper, kinetic behaviors of energetic ions are comprehensively investigated using reconnection-driven sheared toroidal flow and tangential NBI.

2. Experimental setup

Fig. 1 shows the schematic view of the TS-4 plasma merging device [6]. Two flux cores inside the vacuum vessel with octagonal cross-section have both poloidal and toroidal windings inside them to inject the toroidal flux (TF) and poloidal flux (PF) into a plasma, respectively. They can produce two initial spheromaks whose polarities of the toroidal fields are determined by those of the currents flowing in the TF coils. Pairs of internal PF coils named separation coils and acceleration coils are used to control the dynamic process of the plasma merging. Typical major radius, separatrix radius and separatrix length of the formed FRC are 0.5 [m], 0.7 [m] and 0.4[m], respectively. A two-dimensional magnetic probe array is used to measure the axial (B_z) and toroidal (B_t) components of the internal magnetic field and to calculate the two-dimensional profiles of the poloidal magnetic flux and the toroidal current density. An example of a poloidal flux contour plot is superimposed in Fig. 1. An eight-chord CO_2 interferometer was introduced to measure the line-integrated electron density on the midplane. The Abel inversion technique is employed to reconstruct the radial profile of the local electron density.

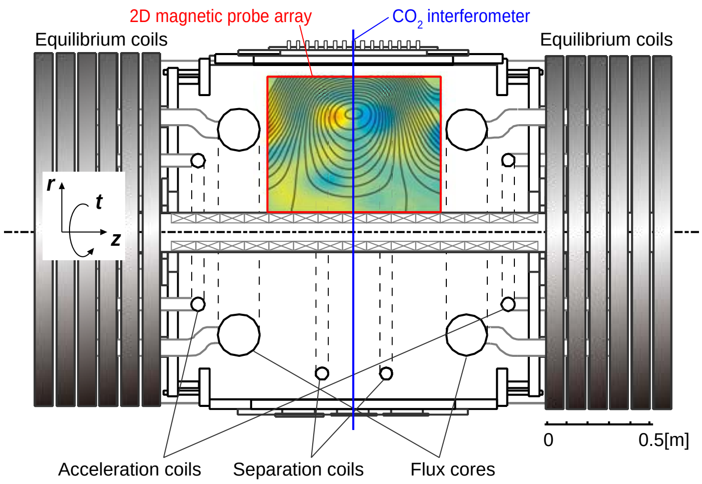

FIG. 1. Schematic view of the TS-4 plasma merging device.

The stabilization effects of kinetic ions on oblate FRCs have been intensively investigated on plasma merging experiments [7,8]. In the plasma merging method, two initial spheromak plasmas must have toroidal plasma currents in the same direction to attract each other. Therefore, two cases of magnetic reconnection occurs during the merging of two spheromaks with opposing toroidal magnetic field (counter-helicity merging) [6,9] with respect to the toroidal field polarities of the initial spheromaks, in other words, the direction of radial reconnection current, as shown in Figs. 2 (a) and (b). In both two cases, the toroidal magnetic fluxes of the initial spheromaks vanish and high-beta FRCs are formed. Though the formed FRC has null toroidal flux, the reconnected field lines just after the reconnection are stretched in the toroidal direction, as illustrated in Figs. 2 (c) and (d). The tension of the toroidally stretched magnetic loop exerts an azimuthal force on the plasma, driving a sheared toroidal flow whose direction changes its sign in accordance with the radial position. The two cases of the counter-helicity merging have opposing sheared toroidal flows [6] driven by the shrinking force of differently stretched magnetic loops. Figs. 2 (e) and (f) show the radial profiles of the toroidal flow velocity $V_t(r)$ calculated as the Alfvén velocity for the downstream density and the toroidal magnetic field at the corresponding upstream regime, $|V_t(r)| = B_{t,i}(r)/\sqrt{\mu_0 m_i n_{i,f}(r)}$, where $B_{t,i}(r)$ is the toroidal magnetic field of the initial spheromaks and $n_{i,f}(r)$ is the ion density after plasma merging. The toroidally stretched magnetic loops in the case A accelerate the ions parallel to the plasma current on the outside of the magnetic axis and anti-parallel on the inside, and vice versa in the case B. This sheared toroidal flow helps to stabilize the global low-n modes in the oblate FRC [6].

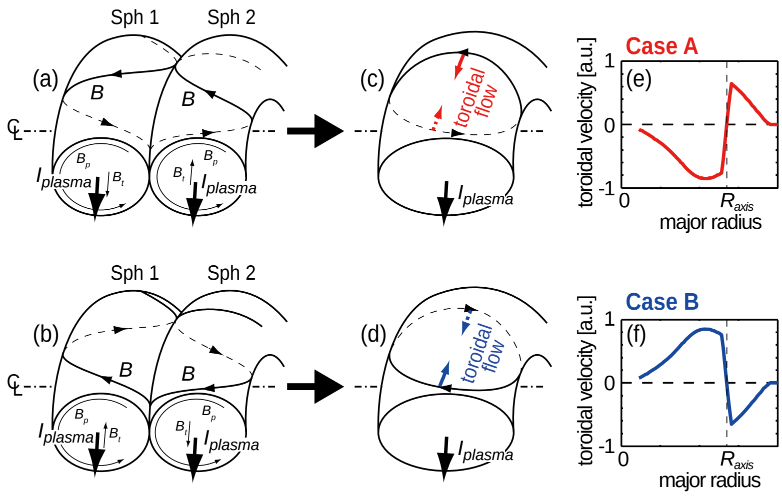

FIG. 2. The magnetic field line structures of the two types of counter-helicity spheromak merging (a)–(d), and the radial profiles of the toroidal shear flows driven by the tension force of the toroidally stretched magnetic loops (e) and (f).

3. Experimental results

Figs. 3 (a)-(c) show the time evolutions of stored magnetic energies of FRCs produced by the case A and B counter-helicity mergings in neon, argon, and krypton gas discharges, respectively. The merging formation of FRC completed at around 400μs in each discharge. The formed FRC suffered from large energy loss since no additional heating nor current drive was applied in this experiment. There is large discrepancy between the cases A and B; the case B has larger decay rate in each ion species, although the initial spheromaks had almost same conditions for both cases. Fig. 3 (d) shows the mass dependency of the magnetic energy decay rates for the cases A and B. The krypton FRC with the case B polarity shows largest decay rate, though it was observed in the previous experiments [7,8] that the krypton FRC was more stable than neon and argon ones due to its longer Alfvén transit time of ~100μs than neon (~50μs) and argon (~75μs) discharges, and smaller $\bar{s} = \int_R^{r_s} R/(r_s \rho_i) dr$ value, where R is the major radius, r_s is the separatrix radius, and ρ_i is the ion gyroradius. In this experiment, the krypton FRC generally revealed better global stability than the FRCs with lighter gas as observed in the previous experiment, nevertheless, large energy loss was observed in the krypton FRC formed as a consequence of the case B counter-helicity merging.

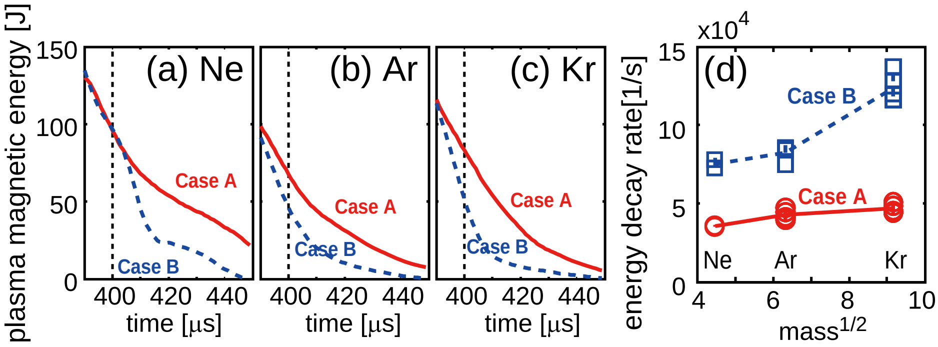

FIG. 3. Time evolutions of stored magnetic energies of FRCs in (a) Ne, (b) Ar, and (c) Kr discharges, and (d) magnetic energy decay rate averaged for 10μs after the merging completion as a function of square root of ion mass number.

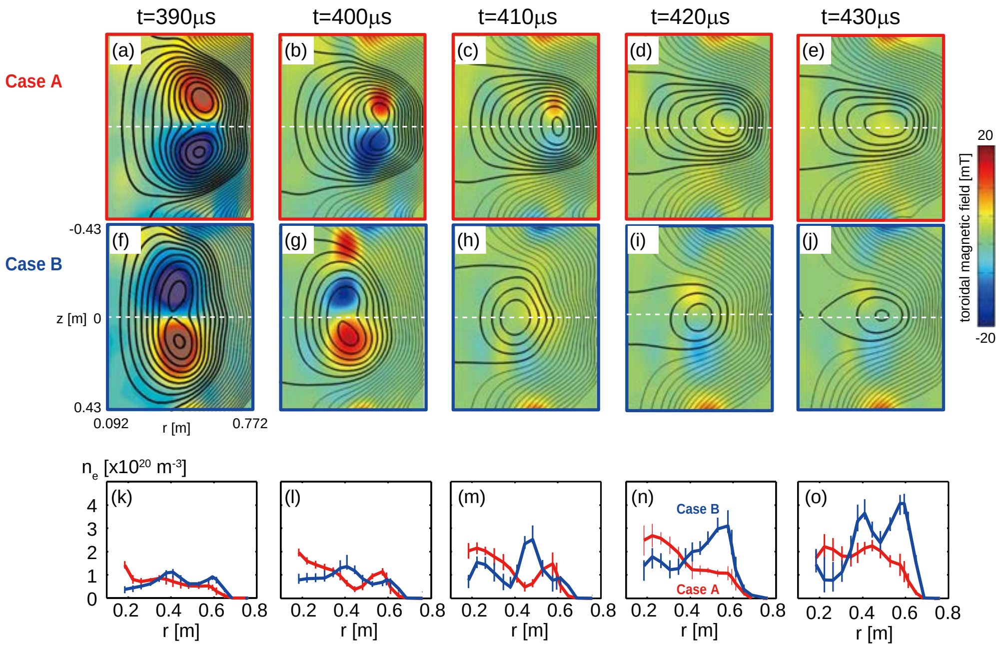

FIG. 4. Snapshots of poloidal magnetic flux surfaces of krypton FRC with case A polarity (a)-(e) and with case B polarity (f)-(j). Corresponding radial profiles of electron density are shown in (k)-(p).

Snapshots of the poloidal magnetic flux surfaces (contour spacing:1mWb) with toroidal magnetic field (color coded) of the krypton FRC are shown in Figs. 4 (a)-(e) for the case A and (f)-(j) for the case B. In the case A, the upper side initial spheromak had a positive toroidal field and lower side one had a negative toroidal field, as shown in Fig. 4 (a), resulting in a positive radial reconnection current $\mu_0 j_r = -\frac{\partial B_t}{\partial z}$, and vice versa in the case B. The merged plasma in the case B shows faster decay than that in the case A during and after the plasma merging. Figs. 4 (k)-(o) show the radial electron density profiles measured by an eight-chord CO_2 interferometer on the midplane ($z = 0$). A steep density peak appeared on the outside of the magnetic axis in the formed FRC in the case B, while the density in the case A had a peak inside the magnetic axis. These observations are interpreted as follows. The energetic heavy ions accelerated by the magnetic reconnection have large kinetic energy so that its gyro-motion reach the separatrix radius ($\bar{s} \sim 1$) particularly in the krypton discharge.

In such a situation, the ions travelling in the toroidal direction parallel to the plasma current are stably confined near the null point like a betatron, while the ions travelling anti-parallel to the plasma current move away from the null point, eventually escaping from the plasma region. This preferential particle loss in the velocity-space [10] will become dominant in the discharge with heavy gas.

4. Discussion

Particle orbits of the energetic ions are calculated for a numerical equilibrium of an oblate FRC. Figs. 5 (a) and (b) show the results of trajectory calculation of Kr^+ ions in the case A and B mergings with initial sheared toroidal flow velocity shown in Figs. 2 (e) and (f). Just after merging, the ion's kinetic energy reaches 30eV, which is 3-5 times larger than the initial ion temperature of the two spheromaks. The red and blue arrows correspond to the test ion's trajectories for 30μs. In the case B, all test particles begin to move toward outboard side and most of them hit the vessel wall in a short period. Figs. 5 (c)-(e) show the radial profiles of the energetic ion density in the cases A and B. These numerically calculated densities with higher inboard and outboard density qualitatively agree with the experimentally measured electron density profiles in the case A and B, respectively. Thus, the case A polarity of the counter-helicity merging with moderate $\bar{s}$ gives better fast-ion confinement, resulting in a long-lived FRC plasma with large magnetic flux.

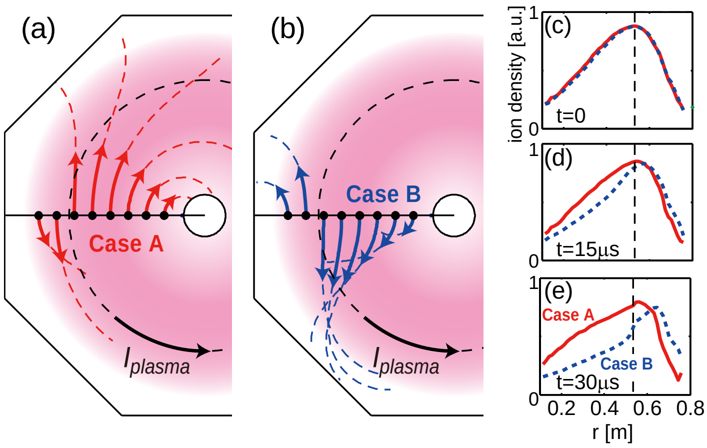

FIG. 5. Trajectories of Kr^+ ions on the TS-4 cross section with initial toroidal sheared produced by (a) case A and (b) case B counter-helicity mergings, and corresponding density profiles calculated from static equilibria (c)-(e).

5. Neutral beam injection to an oblate FRC

The neutral beam fast ions must be trapped inside the separatrix for a long time for efficient transfer of the ion's kinetic energy to the plasma thermal energy. The speculation about the energetic ions' motion in the FRC plasma discussed above is also applicable to the confinement of the neutral beam fast ions. Co-injection of the neutral beam into a FRC plasma formed by the case A counter-helicity merging would bring about the best performance for the NBI additional heating. Fig. 6 (a) shows the neutral beam source equipped on the TS-4 device. This beam source employs a washer gun discharge as a substitute for an arc discharge with hot filaments [11]. The design ratings of the acceleration voltage and current are 15keV and 30A, respectively. The concave extraction electrodes have a curvature radius of 2 [m] and the extracted beam focuses on the center of the target torus at r ~ 0.4 [m], as illustrated in Fig. 6 (a). Fig. 6 (b) shows the evolutions of the beam current and acceleration voltage. Hydrogen beam with energy of ~13keV and current of ~5A is tangentially injected to the argon FRC plasma formed by the case A counter-helicity merging. Fig. 6 (c) shows that the NBI significantly decrease the decay rate of the FRC plasma. The improvement of energy decay rate is much larger than the input NBI power of ~65kW, suggesting that global stability of the FRC is improved by the NBI fast ions.

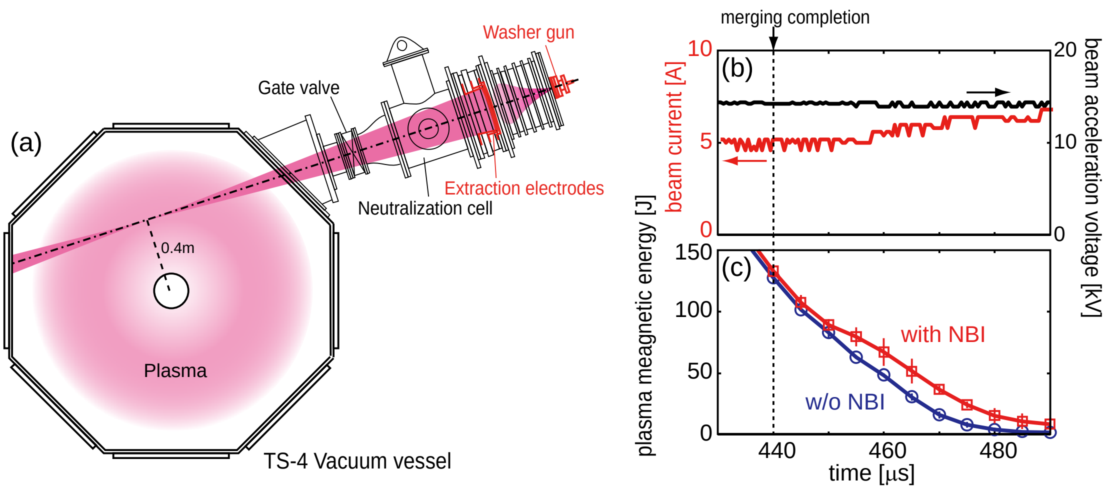

FIG. 6. Cross-sectional view of the TS-4 device with neutral beam source (a). Evolutions of neutral beam voltage and current (b) and FRC stored energy (c).

6. Summary and conclusions

Kinetic behaviors of energetic ions in FRC plasmas are comprehensively investigated using spontaneously driven sheared toroidal flow and tangential NBI. During the counter-helicity merging, significant ion heating is provided by magnetic reconnection of both poloidal and toroidal fields of the initial spheromaks. The reconnection outflow then has both radial and toroidal components, resulting in generation of sheared toroidal flow whose direction is determined by the polarity of the toroidal fields of the two initial spheromaks. Since the accelerated ion's kinetic energy reaches 3-5 times larger than the initial ion temperature, the ion's gyroradius becomes comparable to the plasma size particularly in krypton discharge. The experimental results show that the decay rate and the electron density profile of the oblate FRC are strongly affected by the direction of the toroidal flow. When the direction of the toroidal flow is parallel to the plasma current on the outside of the magnetic axis, the electron density peaks at the inboard side and the FRC shows small energy decay rate. However, when the toroidal flow is anti-parallel to the plasma current on the outside of the magnetic axis, the electron density peaks near the plasma edge with large gradient and the FRC suffers from rapid decay especially caused by the heavy ion loss. Numerical calculation of the fast ion’s trajectory shows that most of the ions in the latter case drift toward outboard side and escape from the plasma region in a short period, indicating that the differences in the decay rate and the density profile are possibly induced by the preferential particle loss of the energetic ions. Confinement of the energetic ions is also essential for the NBI heating of the FRC plasma. Hydrogen beam with energy of ~13keV and current of ~5A was injected tangentially to the oblate FRC plasma for the first time. The observed improvement of the magnetic energy decay rate is much larger than the input NBI power, suggesting that global stability of the FRC is improved by the NBI fast ions.

Acknowledgements

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