Effect of Initial-Plasmoid Density Reduction on Collisional Merging Process of Field-Reversed Configurations[*)]

Daichi KOBAYASHI, Taichi SEKI, Tomohiko ASAI, Yasuaki TAMURA, Hiroki SOMEYA,
Tsutomu TAKAHASHI, Jordan MORELLI[1)] and Shigefumi OKADA

College of Science and Technology, Nihon University, Tokyo 101-8308, Japan
[1)]*Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L 3N6, Canada*

(Received 10 January 2022 / Accepted 6 March 2022)

A super-Alfvenic/sonic collisional merging formation of field-reversed configurations (FRCs) with low-density and high-temperature initial-FRCs was attempted on the FAT-CM device at Nihon University. To vary the density and temperature of initial-FRCs, the low-density/high-temperature (LD/HT) FRC formation technique was applied to the initial-FRC formation. The electron density of initial-FRCs formed using the LD/HT FRC formation technique was reduced to about 50% of that in the standard cases. The ion temperature was increased as the electron density decreased because the plasma pressure completely balances with the external magnetic pressure in an ideal FRC. The ion mean-free-path also increased to the equivalent value of the diameter of the initial-FRCs. Therefore, the initial-FRCs will be collision-less. These collision-less initial-FRCs were successfully translated. The observation results of the collisional merging formation process of FRC from the internal magnetic probe array and two axially arranged interferometers indicate that the performance of the FRC formed after the collision and merging declined in cases with collision-less FRCs and it depends on the kinetic energy in the collision process.

© 2022 The Japan Society of Plasma Science and Nuclear Fusion Research

Keywords: field-reversed configuration, high beta plasma, FRC merging, collision-less plasma, energy regeneration

DOI: 10.1585/pfr.17.2402043

1. Introduction

A magnetically confined plasma with the highest volume-averaged beta value ($\langle\beta\rangle \sim 1$) is a field-reversed configuration (FRC) plasma. An FRC has only a poloidal flux maintained by the toroidal current flowing in the FRC itself [1, 2]. Ideally, the plasma pressure completely balances with the external magnetic pressure so that an FRC is known as an extremely high beta plasmoid. This feature will facilitate the realization of the development of a high-efficiency fusion reactor having aneutronic fuel capability.

The recent experiments in the C-2 series at TAE Technologies, Inc., have achieved the formation of FRCs having high enough magnetic flux for the tangential neutral beam injection (NBI) by a collisional merging formation method [3, 4]. In the collisional merging formation scheme, two oppositely formed initial-FRCs are accelerated and translated by a magnetic pressure gradient and collide with each other at a relative speed that exceeds both the Alfvén speed and ion sound speed [5]. After the collision, a single FRC is formed. The quasi-steady state sustainment of the resulting FRC for over 30 ms has also been achieved by combining the NBI and radial electric field biasing [6].

Experiments for observation of the collisional merging formation process have been conducted on the FRC amplification via translation-collisional merging (FAT-CM) device at Nihon University [7]. Shockwave excitation and heating have been suggested by the multi-point density measurement and neutrons/soft X-ray observations [8, 9]. The kinetic energy of initial-FRCs in the collision process can be converted to the internal energy of the formed FRC after merging via shock heating. Additionally, the internal magnetic observations and toroidal flow measurements have suggested the self-organized formation of FRC [10]. The initial-FRC's properties may affect the reformation process of FRC and/or energy conversion via shocks. In this work, the effect of the initial-FRC's properties on the collisional merging process and performance of merged-FRCs was evaluated. To vary the density and temperature of initial-FRCs without making any changes to the experimental device, the low-density/high-temperature (LD/HT) formation technique for field-reversed theta-pinch (FRTP) method [11] was applied to the initial-FRCs formation in the collisional merging formation scheme. The LD/HT technique had been developed to form a dilute and hot FRC using an FRTP formation method.

2. Experimental Setup

The FAT-CM device has two oppositely directed formation/acceleration sections and a central collision/

---

author's e-mail: kobayashi.daichi@nihon-u.ac.jp

[*)] This article is based on the presentation at the 30th International Toki Conference on Plasma and Fusion Research (ITC30).

© 2022 The Japan Society of Plasma Science and Nuclear Fusion Research

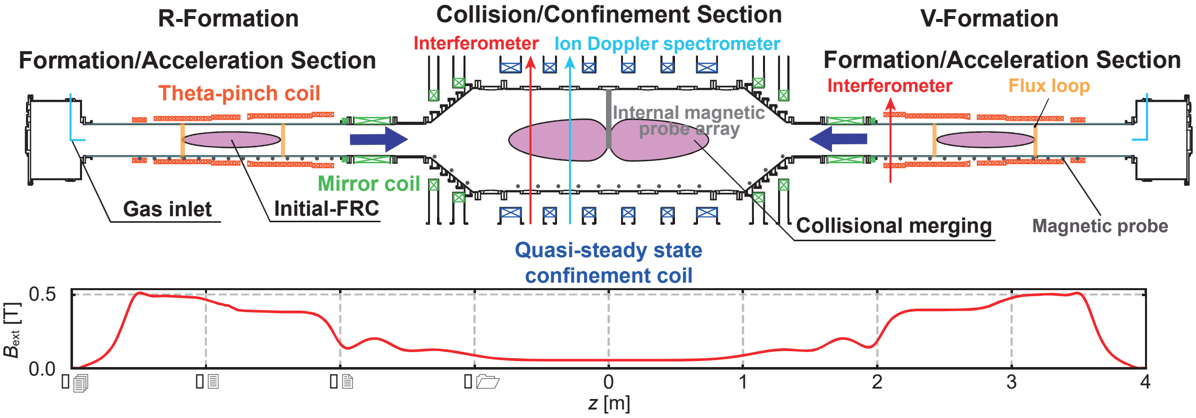

Fig. 1 Schematic view of the FAT-CM device with diagnostics setup and axial profile of external guide magnetic field.

confinement section as shown in Fig. 1. The initial-FRCs are formed using the FRTP method; a conventional technique of FRC formation. Each formation/acceleration section (V-/R-formation) consists of a conical theta-pinch coil and a discharge tube made of transparent quartz. In the FRTP formation scheme, an axial bias magnetic field (period of around 500 µs) is first applied to the discharge tube supplied with deuterium gas. The deuterium gas is locally supplied only to the formation sections by pulse solenoid valves 5 ms before applying the bias magnetic field. Second, the gas is pre-ionized by a fast-oscillating magnetic field (period of around 6 µs). Finally, a rapidly rising main compression magnetic field (rise time is around 3 - 4 µs) in the opposite direction to the bias magnetic field is applied at the timing when the bias magnetic field first peaks. This field radially compresses the pre-ionized plasma with its frozen-in bias magnetic flux. The closed poloidal magnetic flux is formed via magnetic reconnection at both ends of the formation/acceleration section; thus, forming the initial-FRCs. The initial-FRCs are accelerated by an external magnetic pressure gradient generated by a conical theta-pinch coil and is translated in the axial direction. The translation speed reaches up to ~200 km/s, and the relative speed in the collision process is 2 - 8 times the typical Alfvén and ion sound speed on the separatrix. The two initial-FRCs collide near the center of the device, where they merge to form a single FRC.

Magnetic probes arranged along the device wall were used to estimate the plasma shape and global motion in the axial direction. Two interferometers for the electron density measurement were installed on the confinement section ($z = -0.6$ m) and the muzzle of the V-formation section ($z = 2.1$ m). The installation location of the ion Doppler spectrometer for the ion temperature measurement was changed to the confinement section ($z = -0.3$ m) or on the muzzle of the V-formation section ($z = 2.1$ m) depending on the experimental conditions. The internal magnetic probe array [12], installed at the mid-plane of the device, can be used to observe the three components (x, y, and z directions) of the magnetic field and its radial profile and time evolution simultaneously.

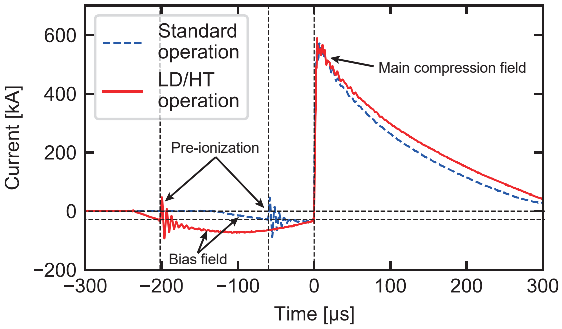

Fig. 2 Time evolution of current on the theta-pinch coil in standard and LD/HT operation.

3. Low-Density/High-Temperature FRC Formation

The LD/HT FRC formation technique had been developed for FRTP formed FRCs without translation on the Nihon University compact torus experiment (NUCTE) -III device [11]. In this technique, the temperature and density of the formed FRC can be varied by changing the current on a theta-pinch coil without changing the gas supply conditions. Figure 2 compares the current on the theta-pinch coil between the standard operation case and LD/HT operation cases. In the LD/HT operation, the bias magnetic field is strengthened, and the trigger time between the pre-ionization and main compression field is extended. The density of the FRTP formed FRC is reduced by diffusing the pre-ionized plasma frozen-in by the bias magnetic flux. Because the trapped flux, density, and temperature of an FRTP formed FRC depends on the intensity of the bias magnetic field [13, 14], the main compression field is applied at timing with the same intensity of the bias magnetic field as in the standard case. If the volume is not changed, the temperature increases as the density decreases to keep the balance between the plasma pressure and external magnetic pressure in an FRC. Therefore, the dilute and hot parameters are realized and the FRC will be a collision-less plasma. In the previous experimental cases on NUCTE-III, the density of the FRC was reduced from 1.1 to $0.56 \times 10^{21}\ \mathrm{m}^{-3}$ and the total temperature (sum of the electron and ion temperatures) was increased from 350 to 810 eV.

4. Experimental Results

4.1 Initial-FRCs formation/single-sided translation

The time evolution of the plasma volume, the averaged electron density and ion temperature of initial-FRC at the V-formation section is shown in Fig. 3. The red lines and blue-dashed lines denote the parameters averaged over five shots in the LD/HT and standard operations, respectively. The hatched area denotes the standard deviation. The LD/HT initial-FRCs were successfully formed and translated. The plasma volume at the time when the translation starts (the end of the line) was almost the same in each case. The volume of the FRC is determined by balancing the plasma pressure with the external magnetic pressure. Therefore, consistent plasma volume suggests that the plasma pressure is not changing. The electron density reduced from ~2.3 to $\sim 1.5 \times 10^{21}\ \mathrm{m}^{-3}$. The ion temperature increased from ~70 eV to ~130 eV with a reduction in density. These results also indicate maintaining the plasma pressure. The ion mean-free-path calculated from the measured values also increased from ~10 mm to ~50 mm. This value is comparable to the typical radius of initial-FRCs (~60 mm). Therefore, initial-FRCs become collision-less plasma.

The translation speed of the initial-FRCs was measured using the time-of-flight method with magnetic probes arranged along the device wall in single-sided translation cases. The average translation speed at the mid-plane of the device in the LD/HT cases was ~139 km/s, and it was slightly faster than in the standard case (~130 km/s). The internal energy of a single-sided translated initial-FRC at the confinement section was not changed in each case because the plasma pressure was almost the same in each case. In contrast, the kinetic energy during translation was decreased by the reduction in particle inventory as shown in Fig. 4. The average mass of the single-sided translated-FRC at the mid-plane in the standard and LD/HT cases were 36×10^{-9} and 18×10^{-9} kg, respectively.

4.2 Collisional merging process with LD/HT initial-FRCs

Figure 5 shows the time evolution of the plasma volume, the averaged electron density and ion temperature of the merged-FRCs in the confinement section. In contrast to the observation results of initial-FRCs in the formation/acceleration section as shown in Fig. 3, the electron density and ion temperature of the merged-FRCs were not changed. This indicates that the density and temperature of the merged-FRCs do not depend on those of the initial-FRCs. The volume and internal energy of merged-FRCs were small. These changes indicate the decrease in the plasma pressure (more precisely, the particle inventory). Figure 6 compares of the poloidal magnetic flux estimated from a direct measurement using the internal magnetic probe array in each case. The poloidal magnetic flux ϕ_p is estimated by

$$\phi_\mathrm{p} = -\int_0^R 2\pi r B_z dr = \int_R^{r_\mathrm{s}} 2\pi r B_z dr, \qquad (1)$$

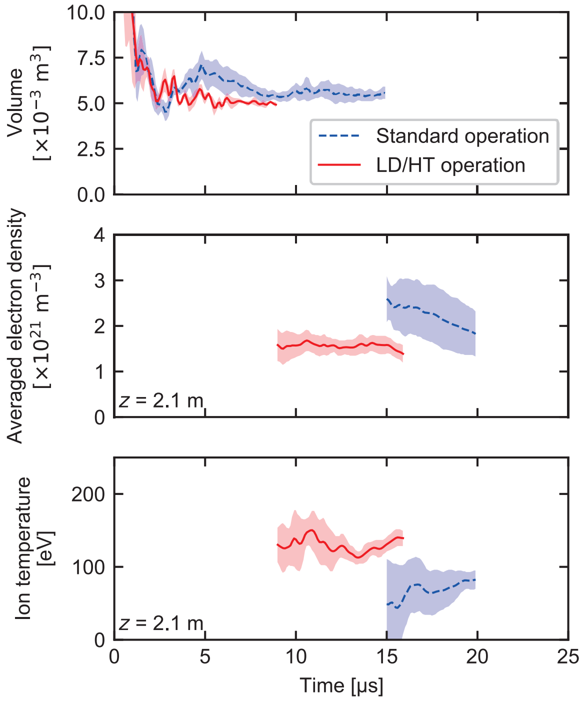

Fig. 3 Time evolution of current on the theta-pinch coil in standard and LD/HT operation.

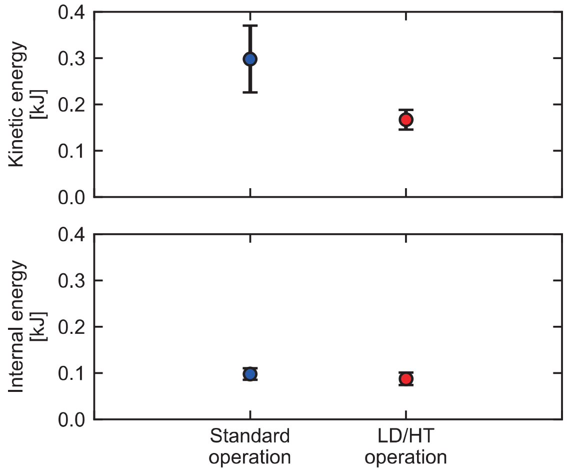

Fig. 4 Comparison of kinetic and internal (sum of thermal and magnetic) energy of a single-sided translated initial-FRC at the confinement section.

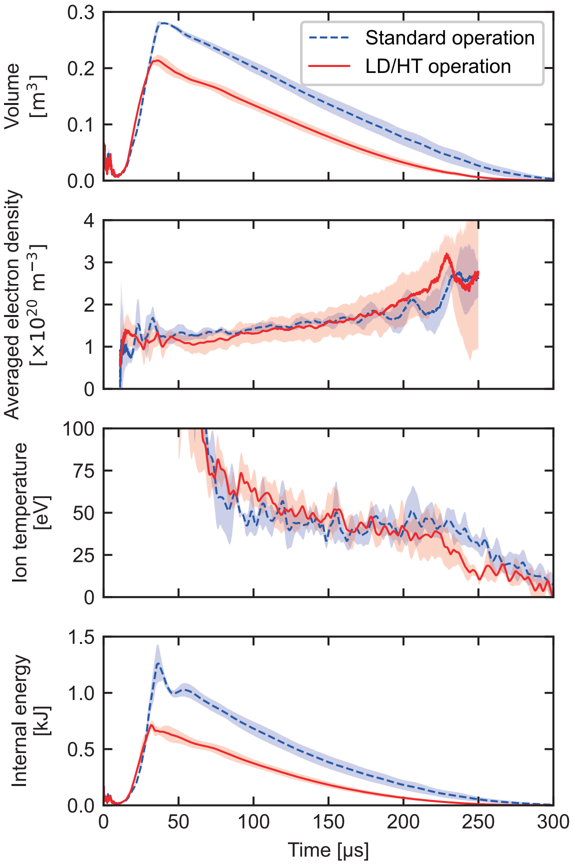

Fig. 5 Time evolution of each parameter of FRCs after merging in standard and LD/HT operations.

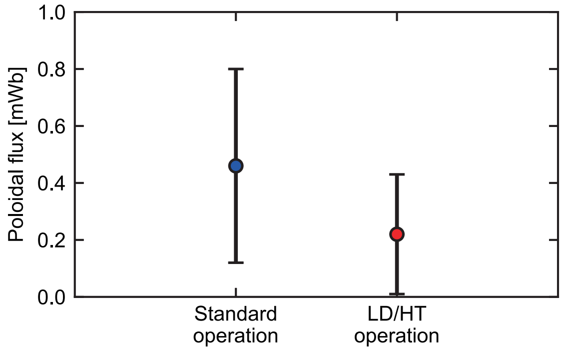

Fig. 6 Comparison of poloidal magnetic flux measured using internal magnetic probe array at the mid-plane.

where R is the magnetic axis, r_s is the separatrix radius, and B_z is the magnetic field in the z-direction. The decrease in the internal energy due to the reduction in the particle inventory and direct internal magnetic observation results indicate declining plasma performance in the LD/HT cases. The above results clearly indicated that the performance of merged-FRCs, such as the internal energy, depends on the kinetic energy of the initial-FRCs during the collision/merging process as shown in Fig. 7. It is unknown why the density and temperature of merged-FRCs were the same in each case. These may be determined by the boundary and/or collision conditions of the collision section, that were not changed in this work, such as the external magnetic field structure and relative speed of collision.

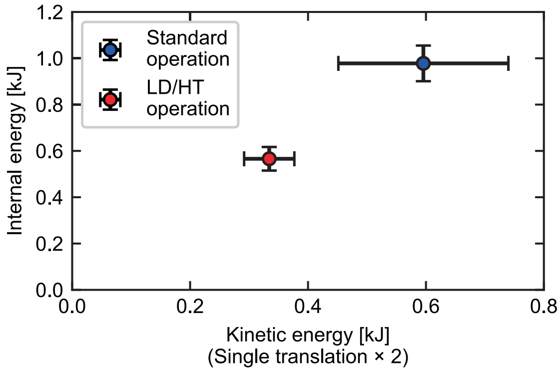

Fig. 7 Dependence of internal energy (25 μs after collision/merging) on the kinetic energy of initial-FRCs.

5. Summary

The LD/HT FRC formation technique was applied to initial-FRCs formed in the collisional merging formation scheme of FRC on the FAT-CM device. The LD/HT initial-FRCs were successfully formed and translated. The translation speed did not change much; however, the kinetic energy was decreased considerably due to the mass reduction.

The collisional merging formation of FRCs with LD/HT initial-FRCs was attempted for the first time. The decline in the performance of the merged-FRCs was observed by both the external and internal magnetic measurements in the LD/HT cases. The performance of merged-FRCs depends on the kinetic energy rather than the parameters of the initial-FRCs.

Acknowledgments

The authors would like to acknowledge all members of the Fusion-Plasma group, Nihon University. This work was partially supported by JSPS KAKENHI Grants Number JP19K21868, JP20H00143 and Nihon University, College of Science and Technology, Grant for Project Research.

[1] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[2] L.C. Steinhauer, Phys. Plasmas **18**, 070501 (2011).
[3] M.W. Binderbauer, T. Tajima, L.C. Steinhauer, E. Garate, M. Tuszewski *et al.*, Phys. Plasmas **22**, 056110 (2015).
[4] M.W. Binderbauer, H.Y. Guo, M. Tuszewski, S. Putvinski, L. Sevier *et al.*, Phys. Rev. Lett. **105**, 045003 (2010).
[5] D. Kobayashi and T. Asai, Phys. Plasmas **28**, 022101 (2021).
[6] H. Gota, M.W. Binderbauer, T. Tajima, A. Smirnov, S. Putvinski *et al.*, Nucl. Fusion **61**, 106039 (2021).
[7] T. Asai, T. Takahashi, J. Sekiguchi, D. Kobayashi, S.

Okada, H. Gota, T. Roche, M. Inomoto, S. Dettrick, Y. Mok *et al.*, Nucl. Fusion **59**, 056024 (2019).

[8] D. Kobayashi, T. Asai, T. Takahashi, A. Tatsumi, N. Sahara *et al.*, Plasma Fusion Res. **16**, 2402050 (2021).

[9] N. Sahara, T. Asai, D. Kobayashi, T. Takahashi, H. Ogawa *et al.*, Rev. Sci. Instrum. **92**, 063501 (2021).

[10] T. Asai, D. Kobayashi, T. Seki, Y. Tamura, T. Watanabe *et al.*, Nucl. Fusion **61**, 096032 (2021).

[11] Y. Ohkuma, M. Urano, M. Nakamura, Y. Narushima T. Takahashi *et al.*, Nucl. Fusion **38**, 1501 (1998).

[12] T. Watanabe, T. Asai, T. Takahashi, D. Kobayashi and D. Harashima, Rev. Sci. Instrum. **92**, 053541 (2021).

[13] T.S. Green and A.A. Newton, Phys. Fluid **9**, 1386 (1966).

[14] L.C. Steinhauer, Phys. Fluid **26**, 254 (1966).