Increased Relative Velocity due to Enhanced Magnetic Pressure Gradient for the Collision Experiment of High-Beta Plasmoids*)

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The FAT-CM device at Nihon University has been modified to expand the experimental relative velocity range of the collisional merging of high-beta plasmoids. This experiment focuses on the ensuing collisionless shockwave that is generated. The relative velocity was increased by making modifications to enhance the magnetic pressure gradient at the exit from the formation regions of the device. The purpose of this modification is to increase the relative velocity up to ∼1000 km/s at the collision of the plasmoids. This is selected to be comparable to the expansion speed of a supernova remnant that generates collisionless shocks. To generate collisionless shocks, the high-temperature and low density plasmoid generation technique is also required. After the modification, the relative velocity is nearly doubled, reaching up to 600 km/s by increasing the magnetic pressure gradient and reducing the mass of the plasmoid. The mean free path became longer than the length of a plasmoid due to increased ion temperature. The experimental range of the FAT-CM device has been expanded to the collisionless region successfully.

Keywords: field-reversed configuration, high-beta plasma, shockwave, magnetic acceleration, collisionless shock

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1. Introduction

The collisionless shocks, observed in supernova remnants, have been thought to be one of the origins of high-energy cosmic rays [1, 2]. The corresponding particle acceleration and shock heating mechanism have been under intense study. To verify these mechanisms, some experimental approaches were proposed. In the case of the experiment using intense lasers [3], metal foils sublimated by the lasers form the plasma flow, and the collision of these flows generates the shocks. The collision experiment of high-beta plasmoids also has been proposed as one of the methods for experimentally verifying phenomena in generating collisionless shocks.

A collisional merging experiment of high-beta plasmoids is conducted in the FAT-CM device at Nihon University [4, 5]. The relative velocity of the plasmoids at the collision exceeds both the Alfvén and the ion sonic speeds and results in shockwaves being produced. The original FAT-CM device can produce the plasmoids collision with the following typical parameters: relative velocity of 200 - 400 km/s, density of $\sim 10^{20}\,\mathrm{m}^{-3}$, and ion temperature of 50 - 70 eV. To simulate the conditions such as those found in supernova remnants in this device, expansion of the experimental relative velocity range is required. In this study, the FAT-CM device has been modified to increase the relative velocity at the collision and to produce the conditions required to generate collisionless shocks.

Before the modification, two preliminary experiments have been conducted. These experiments propose the plasmoid acceleration technique [6, 7] and the high-temperature and low-density plasmoid formation method [8, 9]. They are included in the modification presented in this paper. The relative velocity of the plasmoids at the collision increases to ∼600 km/s by applying higher magnetic pressure gradients in the formation sections and the mean free path is extended to be a few times the plasmoid length. The initial experimental results of the modified FAT-CM device have been presented in this paper.

The outline of the paper is as follows. Section 2 describes the mechanism of plasmoid acceleration, details of the preliminary experiments, and configurations of the newly modified FAT-CM device. Section 3 shows the experimental setup including the diagnostics, early experimental results after the modification, and the comparison of the expanded experimental range with those of the unmodified configuration. Section 4 concludes with a summary.

2. Modification of the FAT-CM Device

Figure 1 is the schematic view of the modified FAT-CM device with the axial magnetic field profiles. The mag-

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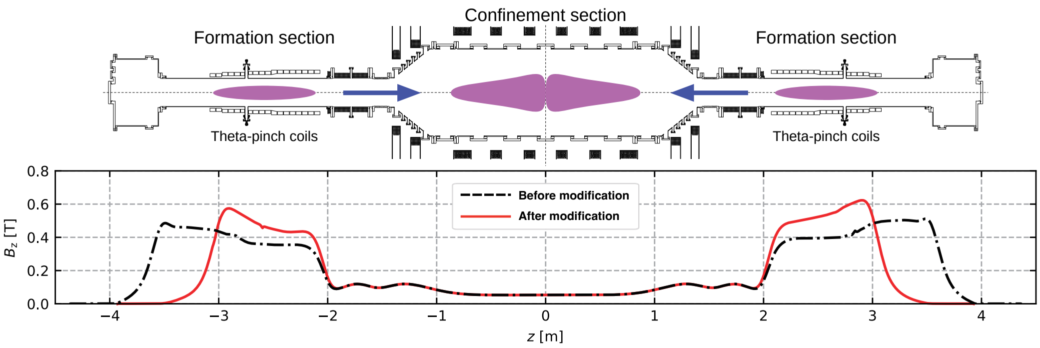

Fig. 1 Schematic view of the modified FAT-CM device and the axial magnetic profiles before/after the modification.

netic field in the formation sections is greater than that in the confinement section. The magnetic pressure gradient between the formation sections and the confinement section affects the acceleration of the plasmoids. The field-reversed configuration (FRC)-like high-beta plasmoids are generated by the field-reversed theta-pinch (FRTP) method in the formation sections on both ends of the device. The formed plasmoids are accelerated towards the confinement section. The translation velocity in the formation section is comparable the Alfvén speed. After that, the translation velocity increases up to 100 - 200 km/s by the magnetic pressure gradient between the formation and confinement section. The details of this acceleration mechanism have been explained in Ref. 6, the relationship between magnetic pressure and kinetic energy in the translation process is written as:

$$\int \frac{\Delta {B_z}^2}{2\mu_0} dV = \int \frac{1}{2}\rho {v_z}^2 dV_{CT}. \quad (1)$$

Where ΔB_z, V, ρ, v_z, and V_{CT} are the axial magnetic pressure gradient, volume which a plasmoid passed through, particle density, increment of translation velocity, and volume of a plasmoid respectively. In Fig. 1, The axial magnetic field profile in the formation sections has a slight asymmetry, and there is a large magnetic pressure gradient between the formation and confinement sections. The equilibrium of an FRC is determined so as to always keep the plasma pressure balance with the external magnetic field pressure, and also there is no axial structure that fixes the FRC position. If the plasmoid is formed in the formation section, which is the higher external magnetic field region, it is pushed out to a lower magnetic field region because of asymmetric axial pressure balance. This process gives kinetic energy to the plasmoid.

In the preliminary experiment of plasmoid acceleration [7], the results show that the plasmoid translation velocity is increased to ~300 km/s when the higher magnetic pressure gradient is applied. The theta-pinch coils consisted of a set of single wound coils that are connected in parallel with the discharge circuit. The current density per coil was increased by reducing the number of coils. Therefore, the magnetic field of the formation section was in-

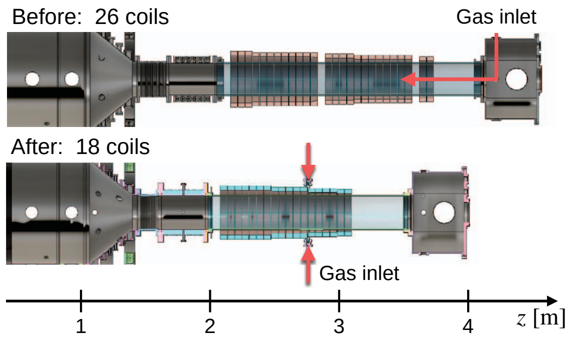

Fig. 2 Image of the formation section setup before/after the modification. The number of theta pinch coils is reduced to 18 from 26 coils. The location of gas inlet is moved to the center of the quartz tube from the end of the formation section.

creased. In the present modification, the same technique has been applied to increase magnetic pressure. Figure 2 shows the image of the formation section before/after the modification. The number of coils is reduced to 18 from 26 in the modified setup. A theta pinch coil, consisting of parallel-connected single-turn coils of 30 - 34 cm diameter, is connected to a capacitor bank of ~67.5 μF capacitance. Total inductance of the theta pinch coils after the modification is ~100 nH, it forms the main reversal field in ~2 μs for the FRC formation and acceleration. The strength of the magnetic field increases by ~30% of its value before the modification as shown in Fig. 1. In other words, the magnetic pressure difference between the formation section and the confinement section increases by ~1.7 times (the square of 1.3).

The high-temperature and low-density formation (HTLD) method for the FRTP was demonstrated in Ref. 8. The external magnetic pressure and plasma pressure are balanced on an FRC plasma [10, 11]. When the density is reduced, the temperature increases to keep the same plasma pressure. In typical FRTP formation, the formation gas, pre-ionized under the bias magnetic field, is pinched by the main reversal compression field, and an FRC plasma is formed. The pre-ionization plasma is diffused by taking a longer time between pre-ionization and main compression, and thus a low-density plasma can be generated in the HTLD formation method. In the present modification, the HTLD formation method has not been applied to the new setup. Instead, the amount of formation gas is reduced by adjusting the gas injection timing. The gas injection points are moved to the center from the end of the formation sections as shown in Fig. 2. The formation gas is directly injected under the theta-pinch coils, and it becomes possible to fine-adjust the amount of gas by controlling the gas injection time. The gas injection time indicates the time interval from gas injection to the start of discharge, the amount of gas injected into the formation section is reduced in the case of a shorter gas injection time. This experiment compares the translation velocity at gas injection times of 9, 10, 11, 12, and 13 ms. All data in this paper are obtained from single translated FRCs passing through the midplane of the device to estimate parameters just before the collision.

3. Experimental Results after the Modification

3.1 Increasing translation velocity

The translation velocity is compared in the single side translation case. In the confinement section, the magnetic probes lined up in the axial direction, and the interferometer is installed in the mid-plane. The parameters of a translated plasmoid are measured by this diagnostic setup. The plasmoid accelerated by the magnetic pressure gradient between the formation and confinement section move in almost uniform linear motion within the confinement region, and the smaller the amount of gas, the faster the plasmoid reaches the central cross-section of the device. The translation velocity estimated by signals from the magnetic probes in each case is shown in Fig. 3. The translation velocity averaged over some number of shots and its standard deviation in the original unmodified setup is indicated by the dashed line and the filled area. In cases of gas injection time greater than or equal to 12 ms, translation velocity is comparable to before the modification, or increased by several tens of km/s. However, in the most gas reduced case (gas injection time is 9 ms), there are shots that the velocity increases up to over 300 km/s. By adjusting the gas injection time, it became possible to select any translation velocity in the achievable range without changing other discharge conditions.

The total particle inventory in each case is estimated by the product of the averaged density (as shown in Fig. 4) and the volume of a plasmoid. This parameter is related to mass of the plamoid. In the case that the gas injection time is 12 ms, the total particle inventory is roughly the same as typical particle inventory before the modification. When the gas injection time is shortened, the total particle inventory tends to decrease, and in the most reduced case, it decreases to less than 50% of the typical particle inventory. This result shows that the mass of the plasmoid is reduced by changing the amount of initial gas. The translation velocity may be changed by not only the increase in magnetic pressure, but also the change in the mass of the plasmoid.

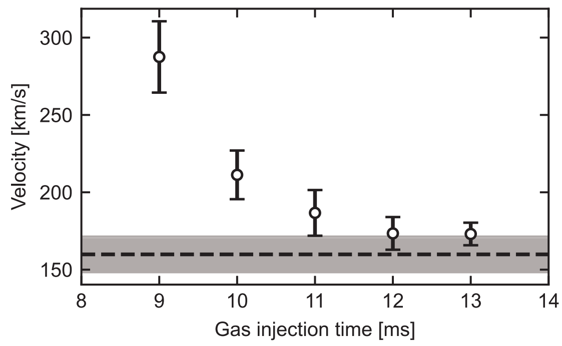

Fig. 3 Comparison of translation velocity in the confinement section. Filled area is the typical velocity range before the modification.

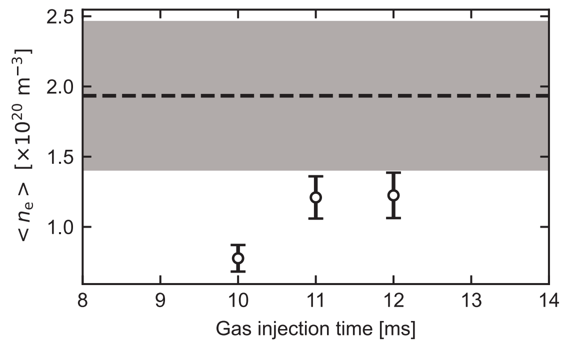

Fig. 4 Comparison of averaged electron density in the confinement section. Filled area is the typical density range before the modification.

3.2 High-temperature and low-density plasmoid

To reproduce the conditions required to generate a collisionless shock, temperature and density must also be compared in each case. The averaged electron density estimated by line integrated density measured by the interferometer and plasma radius is shown in Fig. 4. In all cases after the modification, the density is smaller than that of the original condition. Especially, the case of 10 ms, for which the density is reduced to under half of its value in the original case.

The ion temperature has been estimated by Doppler broadening of the line spectrum of CV (227.65 nm) as impurities in a deuterium plasmoid [12]. As an accelerated FRC is passing in front of the measurement point z = 0, the ion temperature is measured. The typical ion temperature of the translated plasmoid was 50 - 70 eV before the modification. However, the ion temperature has been greatly increased in cases after the modification as shown in Fig. 5.

Table 1 Comparison of experimental range of before/after the modification.

	Separatrix radius [m]	Separatrix length [m]	Relative velocity [km/s]	Density [$\times 10^{20}\,m^{-3}$]	Ion temperature [eV]	Mean free path [m]
Before	~0.1	1 – 1.7	200 – 400	~2.0	50 – 70	~0.05
After	0.08 – 0.16	1 – 1.7	200 – 600	~0.7	100 – 400	3 – 5

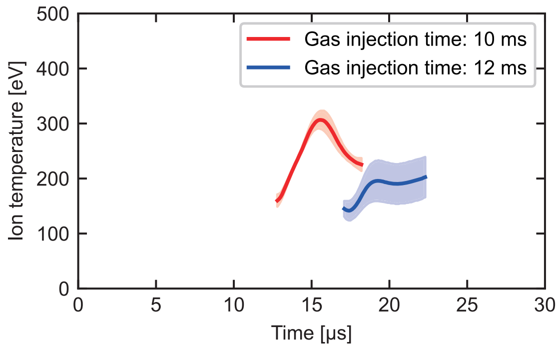

Fig. 5 Ion temperature of single translated plasmoid in the confinement section.

The temperature tended to be higher as the amount of gas is smaller, and it reaches 100 - 300 eV after the translation process. According to FRC equilibrium, plasma pressure should balance with the external magnetic field. Temperature is increasing to maintain the plasma pressure in the low-density case. The amount of increase in temperature is larger than the maximum temperature expected by the effect of reducing density (~140 eV) [9]. In the formation process, the heating effect by the pinch may increase under the higher magnetic field condition.

Table 1 is a comparison of experimental results in the single translation case before/after the modification. In order to generate a collisionless shock, it is necessary to reduce collisions between particles as much as possible in the collision process of plasmoids. The mean free path for collisions with particles contained in the other plasmoid is calculated from the parameters above. After the modification, the mean free path becomes 3 - 5 m, which is a few times larger than the plasmoid length. This means that particles inside one plasmoid do not collie with particles in the other one, and a collisionless shock will be generated.

4. Summary

The experimental range of the collisional merging experiment in the FAT-CM device has been expanded to a collisionless region. The high-magnetic pressure gradient for the plasmoid acceleration has been applied to the newly modified formation sections and the HTLD plasmoid has been generated. Improvement of acceleration performance has been experimentally verified in the single translation case. The high magnetic pressure gradient and reduction in mass of the plasmoid increase the translation velocity; it reaches ~300 km/s in the fastest case. In the case of reducing density to half its original value, the ion temperature increases to ~300 eV. In the collision of plasmoids, mean free path, calculated by using these parameters, is 3 - 5 m, which is longer than the separatrix length of a plasmoid, the parameters during collision exist in the collisionless region.

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