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Control of an FRC Translation Velocity by Resistive Metal Liner

Tsutomu Takahashi, Teruhiko Nihara, Yasuyuki Nogi

College of Science and Technology, Nihon University

Kanda-Surugadai 1-8-14, Chiyoda-ku, Tokyo, Japan 101-8308

1.Introduction

Successful translation experiments of field reversed configuration (FRC) plasmas have been achieved in several facilities. [1-3] In such experiments, an axial FRC motion is initiated by an uneven driven mirror magnetic field or a plasma formation in a slightly conical theta pinch coil. The axial kinetic energy of the plasma is converted from the internal energy of the plasma by reducing a magnetic field strength at a translation region and expanding the plasma. [4] The plasma is trapped in the confinement field after the several times inelastic reflection by the mirror field. But the confinement degradation caused by the interaction with the mirror field is observed at the reflection phase. [5]

In this paper, we report a translation experiment using resistive metal liners for the initiation of the axial motion and the control of the axial velocity of the translated plasmas. At the formation phase, the liner is used to control a magnetic reconnection and to ensure a position of the plasma formation. [6] By the adjustments of a penetration time and the position of the metal liner in the coil, an uneven magnetic reconnection is triggered and the axial motion is initiated. The velocity is dependent on the field strength under the liners determined by the penetration time. On the other hand, when the plasma injects in the liner with the penetration time (τ_0), which is longer than a plasma transient time (t_r) through the liner, a magnetic field excluded by the plasma is conserved in the liner. The magnetic field increases and the plasma is compressed. By the energy worked by the magnetic pressure, the plasma is decelerated.

In the following sections, a simple model of the velocity control by the metal liner, an experimental apparatus for the translation experiment, preliminary experiment results and summary are presented.

2.Model for velocity control by metal liner

The FRC plasma under the equilibrium injects in a metal liner with the penetration time of $\tau_0 > t_r$. Since the metal liner works as a perfect conductor, the magnetic field in the metal liner (B_e^{in}) increases and the plasma parameters change adiabatically, shown in Fig1. Cross sectional areas of the FRC plasma, the theta pinch coil and the metal liner are A, A_W, and A_C. The external magnetic field, the internal magnetic field in the plasma, the injected plasma length and translation velocity are B_e, B_i, l, and V, respectively. Subindexes of 1 and 2 represent plasma parameters before and after plasma injection.

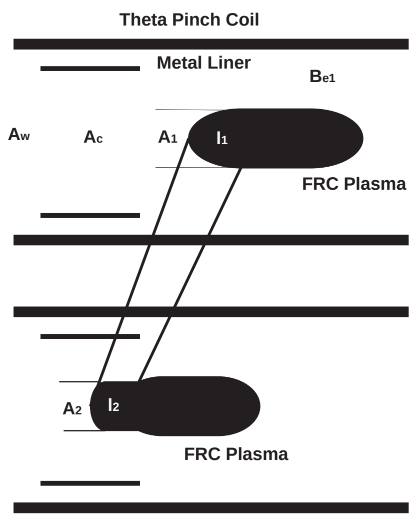

Fig.1 Model of the velocity control

When the magnetic field penetrates enough, the confinement magnetic field profile becomes a mirror one. The magnetic fields in and out the liner are the following equations

$$B_e^{out} = B_{e1}\frac{A_w - A_1}{A_w}\left\{\frac{A_w}{A_w - A_2} - \frac{A_2}{A_w - A_2}\exp\left(-\frac{(A_w - A_c)t}{(A_c - A_2)\tau_0}\right)\right\}$$

$$B_e^{in} = B_{e1}\frac{A_w - A_1}{A_w}\left\{\frac{A_w}{A_w - A_2} + \frac{A_2(A_w - A_c)}{(A_w - A_2)(A_c - A_2)}\exp\left(-\frac{(A_w - A_c)t}{(A_c - A_2)\tau_0}\right)\right\} \quad (1)$$

The change of internal energy of the FRC plasma (Δw_{int}) is defined as the sum of the changes of the external magnetic field energy, the internal magnetic field energy and the plasma thermal energy and is represented, in the case of $t << \tau_0$, by the following equation,

$$\Delta w_{\mathrm{int}} = \frac{B_{e1}^2}{2\mu_0}\left(1 - \frac{A_1}{A_w}\right)A_1 l_1\left(\frac{l_2 A_2 (1 - A_1/A_w)}{l_1 A_1 (1 - A_2/A_c)} - 1\right) + \frac{B_{e1}^2}{2\mu_0}\left(\frac{A_1}{2A_w}\right)A_1 l_1\left(\frac{l_2 A_1}{l_1 A_2} - 1\right)$$
$$+\left(\frac{B_{e1}^2}{2\mu_0(\gamma - 1)}\right)\left(\left(\frac{A_c(A_w - A_1)}{A_W(A_c - A_1)}\right)^2 A_2 l_2 - \left(\frac{A_1}{A_2}\right)^2 A_1 l_1\right) \quad (2)$$

By using NUCTE parameters, which B_{e1}, A_1, A_2, A_w, A_c and l_1 are 0.4T, 0.0785m^2, 0.0785m^2, 0.0907m^2, 0.0506m^2 and 0.25m, respectively, the ratio of B_e^{in}/B_{e1} is about 1.08 and the change of the internal energy is about 12.5J. The corresponded translation velocity of the deuterium plasma of 0.05mg is about 22.4km/s.

3. Experiment set up

The theta pinch coil of NUCTE III device is modified for the translation experiment. [7] The schematic view of the typical theta pinch coil arrangement is shown in Fig. 2. The mirror coil at the right side is removed and the center coil is prolonged from 1.0m to 1.5m. To form the FRC plasma in such an asymmetric theta pinch coil and initiate the FRC plasma to an axial motion, a pair of SUS 304 liners with the penetration time of about 12μs, the radius of 0.127m and the length of 0.25m, is installed at z=-0.645m and 0.260m. The time is defined as the time when the magnetic field strength inside the liner is equal to that outside liner. By the installation of the liners, the position of a magnetic field connection between a bias field and a compression field is confirmed. A radial compression and an axial contraction are also controlled.

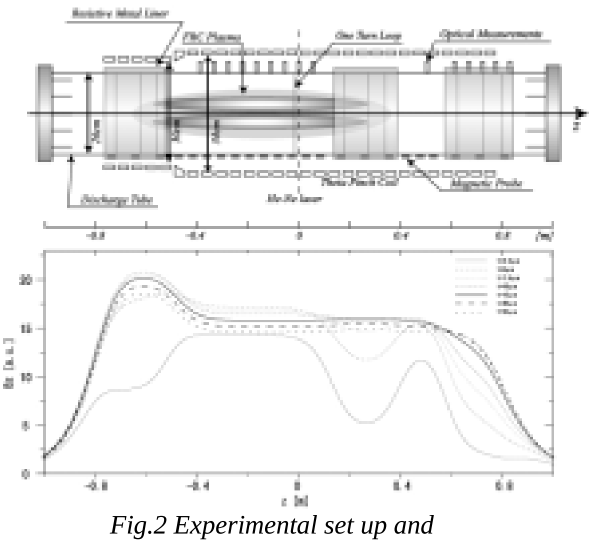

Fig.2 Experimental set up and Time history of the confinement field

Table 1 Coil Configuration

Coil No.	Mirror Coil Number	Radius (m)	B_0 (T)	t_0 (μs)
No.1	5	0.15	0.315	11
No.2	3	0.15	0.260	11
No.3	5	0.16	0.275	12
No.4	3	0.16	0.255	12
No.5	5	0.17	0.24	14

Table 2 Plasma Parameter at Formation Phase

	Vc(km/s)	r_{+min}/r_{0min}	Z+(m)	Z-(m)
No1	42	0.75	0.5	-0.7
No2	28	0.70	0.5	-0.7
No3	32	0.84	0.5	-0.4
No4	25	0.85	0.5	-0.7
No5	21	1.00	0.5	-0.4

An axial translation velocity is dependent on the compression field strength, which is adjusted by the penetration time of the metal liner and the theta pinch coil arrangement. The coil arrangements used in the experiments and the penetration time are listed in Table 1.

Another metal liner with the same geometrical parameters is also installed at z=0.71m to control the translation velocity. The penetration time is 25μs and two times longer than the other ones. The time evolution of the compression field strength at the geometric axis, which is estimated by a computer simulation is shown in Fig.2. The raise time of the magnetic field under the liner (about 10μs) is about twice longer by the effect of the liner. At about 10μs, the compression field penetrates enough into the former liners and at about 25μs, into the latter liner.

Deuterium FRC plasma is formed in a transparent discharge quartz tube, which is evacuated till 1.5×10^{-4} Pa by a turbo-molecular pump. The pre-heated plasma is produced by a I_z ringing discharge method. The I_z current is initiated before 40μs of the bias field initiated.

A profile of plasma radius (r_s(z)) is estimated from a diamagnetic measurement using a magnetic probe array and a flux loop. The left and right end positions of the plasma (z_+ and z_-) are defined as the plasma position at half-maximum of the plasma radius profile. The position and velocity of the center of gravity (z_G(t) and v_G(t)) is also obtained from the profile using the following equations,

$$z_G(t) = \int_{z_-}^{z_+} \pi r_s^2(z,t) z dz \Big/ \int_{z_-}^{z_+} \pi r_s^2(z,t) dz$$

$$v_G(t) = dz_G(t)/dt \quad (3)$$

The velocity of the axial contraction (v_+,v_-) is also estimated from the motions of the left and right plasma ends. A kinetic energy of the translation plasma (E_k) is also calculated by the following equation,

$$E_k = \frac{1}{2} m_d \bar{n}_e V_p v_G^2 \quad (4)$$

where $V_p = \int_{z_-}^{z_+} \pi r_s^2 dz$, $\bar{n}_e = \int n_e dl / 2r_s(0)$ and m_d are a plasma volume, an average density, and a mass of the deuterium atom, respectively.

4. Experimental Results

Typical time evolution of the plasma radius profile is shown in Fig. 3. The coil arrangement of the mirror coil consists of five coil elements with a diameter of 15cm and the metal liner for the velocity control is not installed. The FRC plasma is produced in the space between the metal liners. The field line connection between a bias and compression field occurs at the outside of the metal liners and, at 5μs, have been already completed. By the difference of the pinch time of the plasma under the each metal liner, the plasma unevenly contracts to the midplane of the device. The velocities of the contraction at the left and right plasma end are about v_-=40km/s and v_+=-20km/s, respectively. After 10μs, the plasma is translated for the right end of the device, with the almost constant velocity of 20km/s.

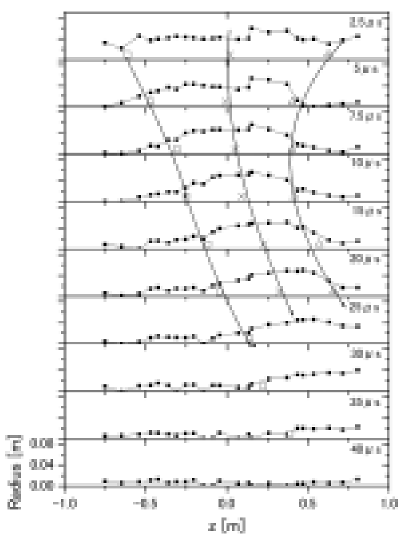

Fig.3 Time history of Plasma radius profile

The mass of the FRC plasma is about 0.04mg. The kinetic energy is about 8J.

Figure of 4 indicates the relation between the translation velocity (v_G) and the vacuum magnetic field strength under the liner (B_0). The translation velocity is defined as the velocity at the time when the plasma moves with the same velocities at the both ends and the center of the gravity. The value of B_0 is the vacuum magnetic field strength under the left liner at 4μs. The strength is related to the pinch radius and the axial contraction velocity, shown in the Table 1 and 2. The translation velocity is almost proportional to the magnetic field strength of B_0. Then, the magnetic field strength and the rising time are controlled by the penetration time of the liner. In the uniform magnetic profile without the mirror coil, the initiation of the axial motion will be possible by the liners with the different penetration times. By the method, the obtained translation velocity is from 10km/s to 40km/s and the kinetic energy is from 5J to 30J.

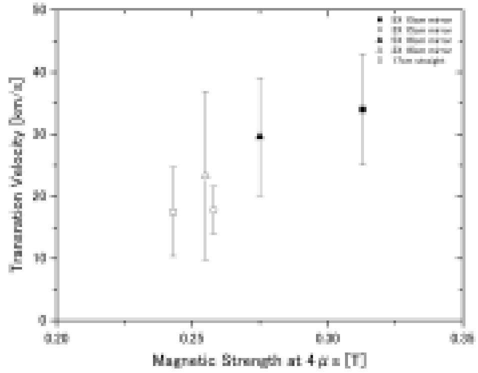

Fig.4 Relation between magnetic strength under the metal liner and translation velocity

When the translation velocity is less than about 15km/s, the plasma injects into the metal liner for the velocity control in 25μs. The compression field is enough penetrated into the metal liner and the profile of the magnetic field is a mirror one. The time evolution of the velocity and the positions of the center of gravity are shown in Fig. 5. The solid line indicates the transition of the center of gravity. When the head of the plasma injects into the liner (at about 28μs) with the velocity of about 13km/s, at fast the velocity increases and, after that, gradually decreases and the plasma is settled down at about 48μs. At the deceleration phase, the plasma length is decreases with keeping the plasma radius. The mass of the plasma is about 0.05mg. The deceleration force is about 65N. During about 10μs, the almost part of the kinetic energy (about 4.2J) is dissipated in the liner. Rotational instability of n=2 mode grows and the plasma is disrupted. The lifetime is about 55μs.

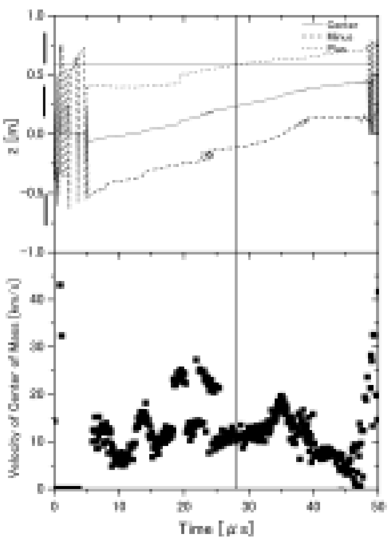

Fig.5 Time history of the plasma position and velocity in the deceleration case using the metal liner

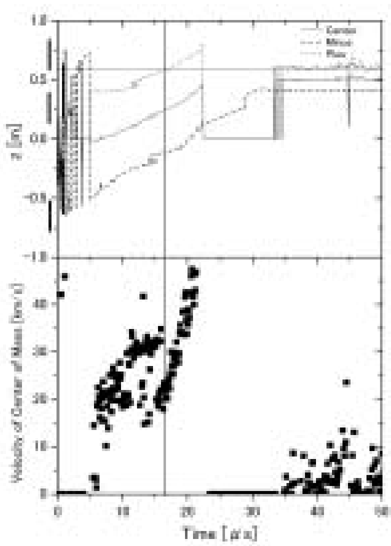

Fig.6 Time history of the plasma position and velocity in the acceleration case using the metal liner

On the other hand, the plasma injects into the liner before the complete penetration if the translation velocity is more than 20km/s. The plasma is accelerated and the velocity increases from about 30km/s to about 45km/s, shown in Fig.6. The mass is about 0.03mg. The acceleration force is about 96N. The plasma ejects from the right side coil end and terminates before the growth of n=2 rotational instability.

Figure of 7 shows the relation between the change of the kinetic energy in the liner (ΔE_k) and that of the external magnetic energy of W, which is calculated by the first term of the equation 1. The deference of data points from the relation of $W = \Delta E_k$ is caused by the assumption of the above simple model. The decay of the magnetic field in the liner, the decay of the plasma parameter and etc., are not included in the model.

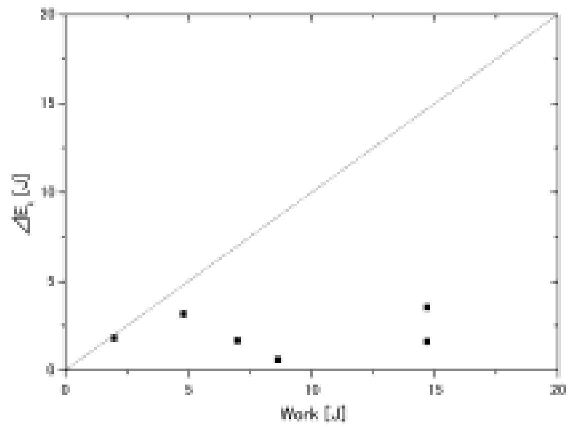

Fig.7 Relation between the change of the kinetic energy and the energy worked by the external magnetic field.

5. Summary

By using the metal liner, the initiation of the axial motion is possible. The obtained velocity is from 5km/s to 40km/s. The maximum velocity is about a half of the Alfven velocity. Though the magnetic field strength under the liner is controlled by the change of the coil radius in the preliminary experiments, the control of the strength is also possible by the penetration time of the liner. By the simple model calculation, the change of the penetration time of 5μs, 10μs and 15μs is corresponded to about 90%, 70% and 60% of the reduction, respectively.

The acceleration and deceleration of the translation plasma are also possible by the metal liner. When the injection time of the plasma into the liner is earlier than the penetration time, the plasma is accelerated by the gradient of the confinement field, which is created by the liner. Otherwise, the plasma is decelerated. In the case of the deceleration, the controlled kinetic energy is from about 5% to about 50% of the estimated value by the simple model. The deference is caused by the assumption of the model. It is needed to the precise model.

By the realization of our method, not only the translation in the uniform confinement field without the mirror coil but also the control of the global motion will be possible. [6] The new application field of the FRC will be also created.

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