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Shape Control of Field-Reversed Configuration Plasma by Axial Compression

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Abstract

We propose and carry out an axial magnetic compression experiment to control the separatrix shape of a Field-Reversed Configuration (FRC) plasma. The axial compression is done in a manner as decreasing the mirror distance. By this compression, the separatrix shape will become short and fat. According to the empirical scaling law, the particle confinement time is expected to lengthen. An additional compression coil is installed into the chamber to raise the strength of the magnetic field at a certain section next to one of the mirrors. The coil with the crowbarred capacitor bank produces the compression field with the rise time of 34μs to change the mirror distance from 3.4m to 2.4m. The shape profile of the FRC becomes short and fat with the extension of plasma lifetime.

Keywords:
FRC, magnetic compression, scaling, shape control, tilt instability

1. Introduction

The field-reversed configuration (FRC) plasma is a high-β, prolate compact toroid (CT) with purely poloidal magnetic field. As a CT is free from any linking object, it can be translated into another chamber along the guide field. The separation from high voltage theta-pinch system makes it convenient to mount some additional components. The separatrix shape of the translated FRC is affected by the external field shape. The separatrix shape plays an important role in plasma confinement properties. The empirical scaling law $\tau_N \sim r_s^2 / \rho_i$ (τ_N; particle confinement time, r_s; separatrix radius, ρ_i; ion gyro radius) contains a parameter of separatrix radius [1]. Small separatrix elongation (separatrix length / separatrix radius) may bring tilt instability [2]. In the FRX-C/LSM facility, the high-power magnetic compression experiment was accomplished by increasing the confinement magnetic field strength from 0.4T to 1.8T [3]. The heating was successful and nearly consistent with the expected adiabatic scaling. But the confinement became poor, which agreed with the scaling law. On the other hand, our shape control experiment is planed to improve the confinement property.

The separatrix length of the translated FRC is limited by the distance between mirror fields. By shortening the mirror distance, the FRC is compressed axially and the plasma pressure increases. The separatrix shape is expected to become short and fat. According to the scaling law, fat FRC has a good confinement property. This was evaluated for the translated FRC parameters of the FIX device under the assumption of the adiabatic model [4]. Though the heating is expected to be small, the confinement time is calculated to become 2 times against the compression of shortening

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the mirror distance half. But the effect of the reduction of the separatrix elongation and the production of instability is not considered. The translation is a sort of shape control. In our FIX machine, the formed FRC is translated into the confinement region with super Alfvén speed. When the translating FRC with super Alfvén speed is reflected by the mirror field, rethermalization is caused by a shock wave and the volume expands by a factor of ~100 [5]. This irreversible process is nearly uncontrollable. The axial compression can be done adiabatically. This is a novel scheme to control the separatrix shape.

2. Apparatus

The FIX machine consists of the formation and the confinement region [6]. A schematic diagram of the entire device is shown in Fig. 1. The FRC is formed in a quartz tube by the field reversed theta-pinch method with the magnetic field of 1.0T. The formed FRC is translated into the confinement chamber made of stainless steel, which also functions as a flux conserver. In the confinement region, the bias field of 0.04T and the mirror fields of 0.13~0.17T are applied. This translation process is caused by the difference of magnetic field strength and the FRC expands by a factor of 100. The confined FRC is affected by the shape of the confinement magnetic field and the separatrix length is decided by the distance between mirrors. The axial compression experiment is done in this region.

In order to control the separatrix shape, the axial compression is carried out by shortening the mirror distance with the additional compression coil, which can increase the strength of the bias confinement field in some section next to the mirror. For the adiabatic compression, the rise time (one-forth of a period) of the compression field should be longer than the particle collision time (~20μs). Moreover, the rise time should be shorter than the particle confinement time of ~100 μsec. As such a fast rise magnetic field cannot penetrate into the metal chamber, the compression coil is set inside the chamber. After the experimental estimation of the mutual inductance between the chamber and the compression coil, the compression coil and the power source are developed. By the mutual inductance, the strength of the produced magnetic field becomes one-third than the coil alone. The cross sectional view of the compression coil is illustrated in Fig. 2. In order to keep good vacuum inside the chamber and to insulate the current on the coil, the cable for high voltage usage (~25kV) is wired inside the stainless steel duct. To break a circuit for induced current on the conductive coil duct, the nylon insulator is inserted. A compression coil unit consists from three coil ducts and a straight backbone duct. Three ducts are connected perpendicularly to the backbone duct. A branch pipe of the backbone duct is attached to the vacuum port of the chamber. The high voltage cable goes away from there. The radius of the duct is 3.4×10^{-2}m and the internal radius of the chamber is 4.0×10^{-2}m. The compression ratio can be easily changed by the addition of the coil unit. At present, the compression experiment is performed with two coil units of six turn coil. The distance between each duct is 2.0×10^{-2}m respectively. This coil shortens the mirror distance from 3.4m to 2.4m. Power source consists of the crowbarred capacitor bank with total capacitance of 108μF and the maximum charge voltage of 25kV. The discharge waveform is shown in Fig. 3. The rise time of 34 μs and the magnetic strength of 0.10 T is obtained with the charge voltage of 25kV.

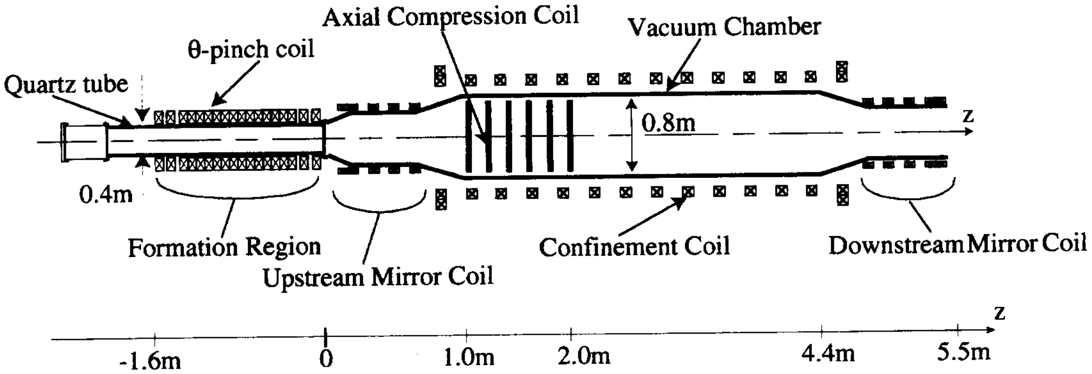

Fig. 1 A schematic diagram of the FIX machine.

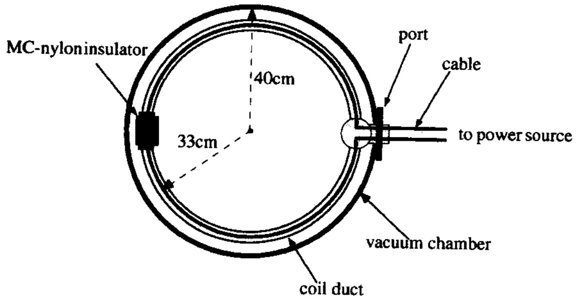

Fig. 2 The cross sectional view of the compression coil and the chamber.

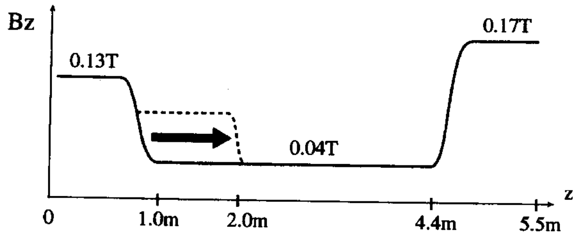

Fig. 4 Strength of magnetic field before and after compression in confinement region. With compression coil, field profile changes as dashed line and mirror distance shortens.

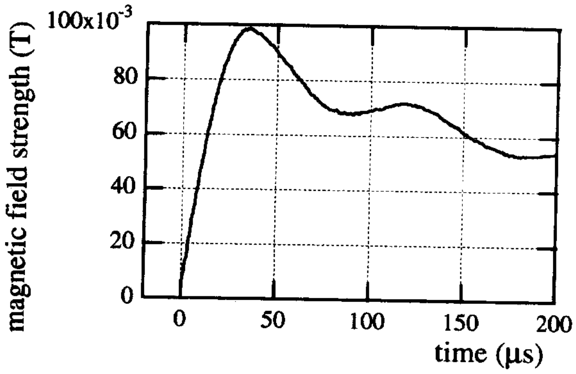

Fig. 3 The discharge waveform of the compression coil with crowbarred capacitor banks.

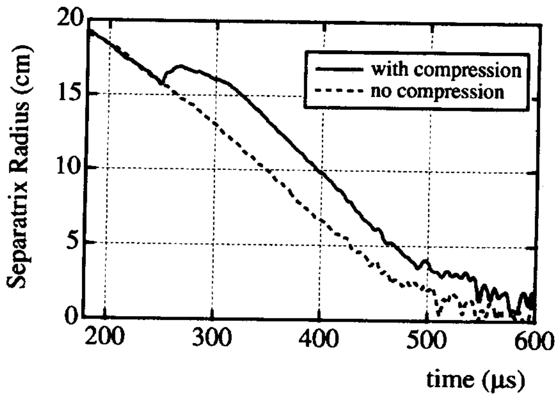

Fig. 5 The time evolution of the separatrix radius at a distance of 1.2m from the compression coil.

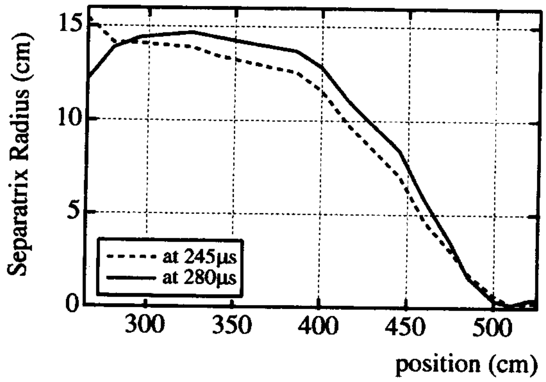

Fig. 6 Separatrix shapes before (at 245μs) and after (at 280μs) the compression. Compression starts at 245μs.

3. Experimental Results

The FRC formed at 0μs is translated into the confinement region after 50μs from the formation. Moving FRC bounds off several times between mirror fields and settles down at ~220μs to a quasi steady state. The separatrix radii gradually decrease with its length almost the same. The compression is done after the settlement. The compression coil changes the mirror distance from 3.4m to 2.4m, as is shown in Fig. 4. As the confinement chamber functions also as a flux conserver, the separatrix radii are easily estimated from the excluded flux measured by the magnetic probe array located just inside the chamber. But the probes near the compression coil pick up the compression field besides. The separatrix radii are obtained only from 2.5m to 5.5m.

The compression field with the strength of 0.04T and the risetime of 34μs is applied at 240μs. The time evolution of the separatrix radius at a distance of 1.2m from the compression coil is shown in Fig. 5 with and without the compression. This position corresponds to the midplane after the compression. The separatrix radius begins to increase from 248μs. After the peak compression, the decay rates of the separatrix radii are almost the same. The plasma lifetime extends by the

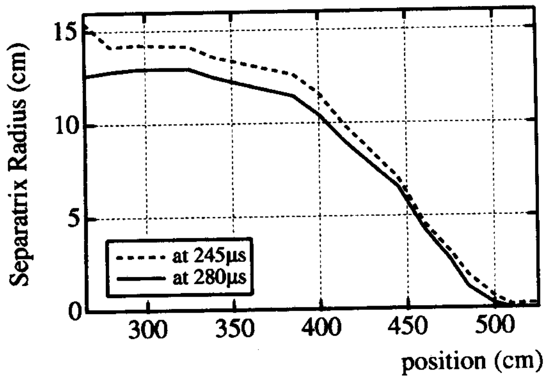

Fig. 7 Separatrix shapes without compression at the same times as Fig. 6.

axial compression. Separatrix radii nearer the compression coil increase faster. The separatrix shapes before and after the compression are shown in Fig. 6 and these without compression at the same times are in Fig. 7. By the compression, separatrix radii increase at all measured position except around at 2.5m. This suggests that the FRC becomes short and fat. But the separatrix radii increase with the faster rise time of ~19μs than that of the compression field. Since the axial compression is done by changing the mirror distance, the compression time is not equivalent to the rise time of the compression field. According to this experimental result, it is thought that the compression comes to an end and the separatrix radius begins to decrease within the rise of the compression field. The compression may have to be done slowly. The line integrated electron density is measured by CO_2 interferometer at 3.4m. As the separatrix radius increases after the compression, the line density also increase. But, the increment of the average density (0.5 × line density / separatrix radius) is as small as the estimation from the adiabatic model with this compression ratio. The rotational instability is not observed by the compression. Though the compression is done with various strength of the compression field with the same rise time, the shape control is successful with the compression field of about 0.04T. Considering that the strength of the confinement bias field is 0.04T and that of the mirror field is 0.13~0.17T, the separatrix shape can be controlled by the weaker strength of the compression field than the mirror field.

4. Conclusions

We developed the axial compression coil and its power source for the axial shape control of the FRC. With this coil, the effective mirror distance changes from 3.4m to 2.4m. The separatrix radius at the midplane increases by 7 percent. After the compression, the separatrix radius decreases with the same decay rate as that without the compression. The plasma life time extends by the axial compression. The separatrix shape becomes short and fat without instability. It is still unknown how this extension is brought by the shape control. The translated FRC is prolate with $E \sim 9$ and $s \sim 2$ (E; the ratio of the separatrix length to the separatrix diameter, s; the ratio of the separatrix radius to the average ion gyro-radius). Large number of theoretical studies have been made on the global stability of the FRC and it is predicted that tilt stability of the prolate FRC depends on s/E [7]. The axial compression reduces E with almost same s. According to these studies, the FRC with small s can be compressed axially to become oblate without instability. Farther experiments are required with the rise time, the strength and the ratio of the compression field in a wide range to investigate the shape control by the axial compression. The development of the technique to measure separatrix radii near the compression coil is also needed not only for the evaluation of the particle confinement time against the empirical scaling but also for the investigation into the dynamics of the compressed FRC.

References

[1] K.F. McKenna, W.T. Armstrong, *et al*, Phys. Rev. Lett. **50**, 1787–1790 (1983).

[2] M. Tuszewski, D.P. Taggart, *et al*, Phys. Fluids B**3**, 2856, (1991).

[3] D.J. Rej, D.P. Taggart, *et al*, Phys. Fluids B**4**, 1909, (1992).

[4] S. Okada, M. Ohnishi, Y. Tomita and H. Momota, Proc. 1996 *Int. Conf. on Plasma Physics, Nagoya*, 1182, (1996).

[5] H. Himura, S. Okada, S. Sugimoto and S. Goto Phys. Plasmas **2**, 191, (1995).

[6] A. Shiokawa and S. Goto, Phys. Fluids B**5**, 534, (1993).

[7] H. Ji, M. Yamada, R. Kulsrud, N. Pomphrey and H. Himura, Phys. Plasmas **5**, 3685, (1998).