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Particle Transport Properties in the Edge Plasma of a Field-Reversed Configuration

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Abstract

Particle loss properties in the edge plasma of a field-reversed configuration (FRC) are investigated by changing the boundary condition in the end mirror region; the magnetic mirror field strength and the material boundary. In the high mirror ratio regime of 3 to 7 the particle end loss time in the edge plasma is shown to have linear dependence on the mirror ratio, as suggested by the MHD prediction of the particle end loss.

The axial current of 0.8kA flowing inward toward the FRC edge is found when conducting end wall is mounted and terminated to the confinement vacuum vessel through 0Ω. This current is equivalent to 13% of the global particle loss rate of the FRC and its origin may be in the central part of the edge plasma.

Keywords:

FRC, edge plasma, particle loss, MHD flow, mirror confinement

1. Introduction

A field-reversed configuration (FRC) [1] is an elongated compact toroid that ideally contains no toroidal magnetic field.

In the FRC, plasma particles lost across the separatrix will be carried along the open field lines in the edge layer outside the separatrix. Therefore, the particle loss in the edge layer is of great importance in confinement study. Tuszewski and Linford [2] pointed out a strong scaling of the particle confinement time τ_N with the thickness of the edge layer, which depends on the open-field-line confinement. Hoffman and Milroy [3] derived an analytical formula for τ_N which has strong dependence on open-field-line confinement in present FRCs.

The edge plasma measurments, conducted on the FRC Injection experiment (FIX) machine [4], revealed the MHD-like behaviour of the end loss implying the possibility that the end configuration affects the particle transport in the edge layer [5].

The purpose of this experiment is to investigate the particle loss process in the edge plasma by changing the configuration in the end mirror region, such as magnetic mirror field strength and the material boundary conditions.

2. Experimental Facility

Experiments are conducted on the FIX shown in Fig. 1. Detailed explanation of the FIX machine is described in Ref. [4]. The FRC plasma is produced by a reversed-biased theta-pinch in the source region and is translated to the confinement region. The confinement region is in a stainless steel vessel. The quasi-static magnetic field of 0.03 ~ 0.06T and 0.12 ~ 0.35T are applied in the central part and the end part of the

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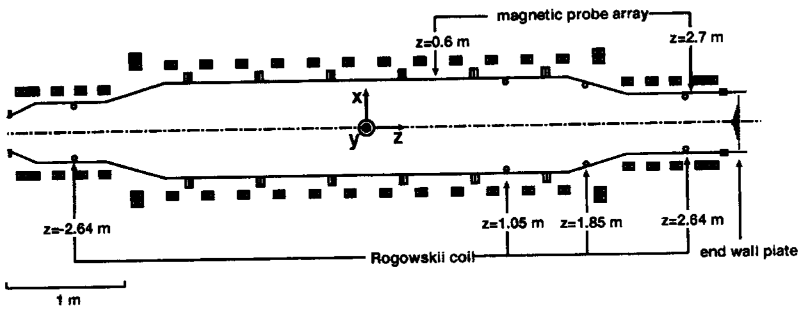

Fig. 1 Schematic diagram of the confinement region of FIX. The origin of the *z* axis is on the midplane of the central confinement vessel.

confinement region respectively.

The separatrix profile of the translated FRC is determined [6] with the axially arrayed magnetic probes located just inside the vacuum vessel wall. Side-on laser interferometer is used to measure the electron line density at the axial midplane of the confinement region. Radially arrayed magnetic probes are mounted in the central part (z = 0.6m) and the end part (z = 2.7m) of the confinement region to obtain detailed radial profiles of the local magnetic field and to measure the local pressure. Rogowski coils are mounted at axial positions of −2.64, 1.05, 1.85, and 2.64m to determine the axial net current and the direction of the current. The end wall plate is mounted on the downstream end mirror region (z = 3.0m) as the material boundary. This plate is an array of concentric conducting stainless steel rings each of which is terminated to the conducting confinement vessel through a resistance of 0, 11, 100, 1k, 10k, and 1MΩ. The current collected by each conducting ring is also measured with the Rogowski coil (Fig. 2).

Typical plasma parameters of the FIX-FRC in the confinement region is as follows: the electron density $n_e \sim 6 \times 10^{19} \mathrm{m}^{-3}$, total temperature $T_i + T_e \sim$ 100eV, and the separatrix radius $r_s \sim$ 0.2m.

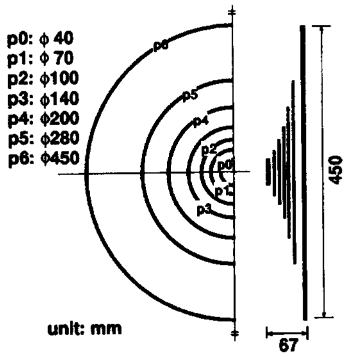

Fig. 2 Schematic drawing of the end wall plate. The end wall plate is an array of 7 concentric conducting stainless steel rings. Each ring is named from p0 (the innermost ring) to p6 (the outermost ring).

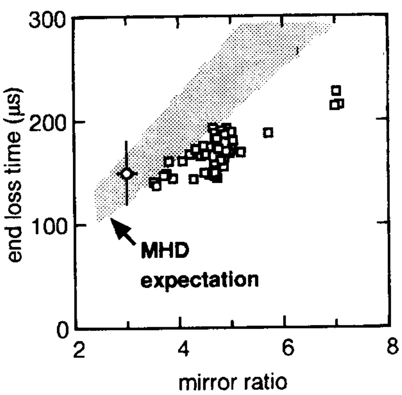

Fig. 3 End loss time plotted against the mirror ratio obtained at t = 230μs, together with the MHD expectation of the end loss time (shaded region). The experimental values are indicated by □ and ○.

3. Experimental Results

In Fig. 3, the average end loss time $\langle 1/\tau_{\parallel} \rangle^{-1}$ parallel to the magnetic field of line is plotted against the effective mirror ratio. The value of $\langle 1/\tau_{\parallel} \rangle$ is the beta-weighted average of $1/\tau_{\parallel}$ over the volume outside the separatrix. It is given [5] as

$$\left\langle \frac{1}{\tau_{\parallel}} \right\rangle = \frac{2\langle \beta \rangle}{\tau_{\mathrm{N}}} \left(\int_{1}^{u_{\mathrm{w}}} \beta \mathrm{d}u \right)^{-1}, \qquad (1)$$

where u_{w} is the value of $u (\equiv 2r^2/r_s^2 - 1)$ at the confinement wall, τ_{N} is the particle confinement time of the FRC, and $\langle \beta \rangle$ is the average of the plasma beta inside the separatrix. Here, the radial particle flux to the

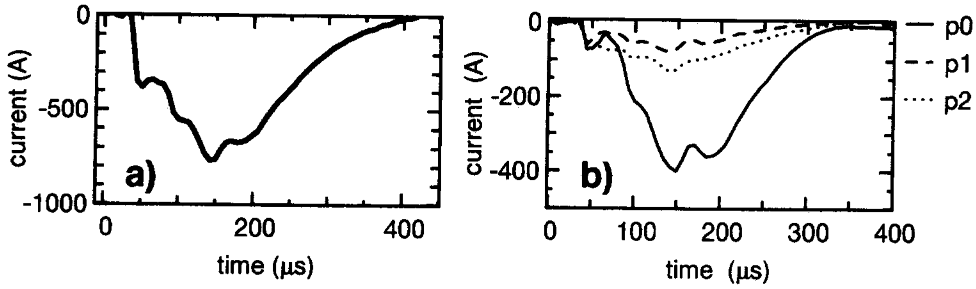

Fig. 4 Time evolution of a) the axial net current at z = 2.64m and b) the collected current by the ring named p0, p1, and p2.

confinement wall is assumed to be zero. The effective mirror ratio in Fig. 3 is defined as $[(1/R_- + 1/R_+)/2]^{-1}$ in order to include the difference of the upstream and downstream end mirror field strength, where R_- and R_+ is the upstream and downstream mirror ratio defined by $R_\pm \equiv B(z = \pm 2.7\text{m})/B(z = 0\text{m})$.

MHD prediction of the particle end loss time $(\tau_\parallel)_{MHD}$ [7] parallel to the open magentic field has a strong dependance of the magnetic mirror ratio. The mirror ratio is more than 3 and the plasma beta at the separatrix is about 0.5 in our experiments. In these conditions, $(\tau_\parallel)_{MHD}$ is proportional to the mirror ratio within the error of 5%. In Fig. 3, the experimental data of the end loss time in the edge plasma are plotted against the mirror ratio, together with the MHD prediction of the end loss time. There seems to be a proportional relationship between the end loss time and the mirror ratio in the high mirror ratio regime as predicted by the MHD theory, although the relation factor differs.

The non-ambipolar radial loss rate in the open field line region can be estimated by measuring the axial net current [8]. The axial net current is measured by the grounded end wall plate and the Rogowski coils. The time evolution of the axial net current measured at the downstream end is shown in Fig. 4. The sign of the current at the downstream end region is negative.

In Fig. 5, the axial net current measured at z = −2.64, 1.05, and 1.85m are plotted against the axial net current at z = 2.64m obtained at t = 230μs. Those data are obtained by 20 plasma shots, and are divided into two groups of points according to the current I at z = 2.64m. One is the group where the termination resistance is 0Ω and $I(z = 2.64\text{m})$ is about 0.5kA, while the other is the group where the termination resistance is more than 11Ω and $I(z = 2.64\text{m})$ is about 0A.

In the case that the termination resistance is 0Ω, the

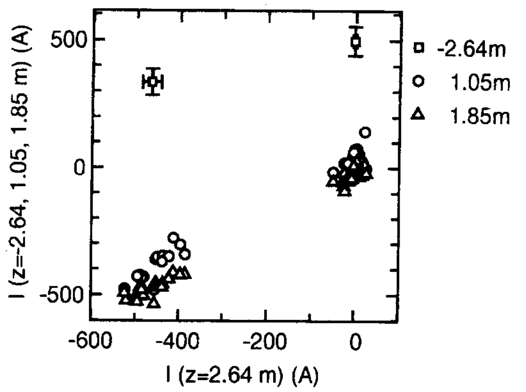

Fig. 5 Axial net current at z = −2.64, 1.05, and 1.85m plotted against the axial net current at z = 2.64m obtained at t = 230μs.

sign of the axial current is positive at the negative z location and negative at the positive z location. The origin of the current may be in the central part of the edge plasma; more precisely, the origin of about 80% of the axial current detected at the downstream end region may be in the portion of the edge plasma where the axial location is less than 1.05m. The total current flowing through both ends is about 0.8 kA at t = 230μs. If this current is assumed to be carried by electrons, the same amount of the ion current out to the vacuum vessel may exist under the ambipolarity condition. This current is equivalent to 13% of the global particle loss rate of the core plasma ($4 \times 10^{22}\text{s}^{-1}$) as the particle inventory is 9×10^{18} and the particle confinement time is 220μs in FIX-FRC.

The floating condition at the downstream end is achieved by increasing the termination registers. In our experiments, the net current at the downstream end becomes closer to zero with the termination resistance of more than 11Ω. As shown in Fig. 5, the net current

$I(z = -2.64\text{m})$ that is about 320A in 0Ω case increases to 500A when $I(z = 2.64\text{m})$ is about zero. However, the non-ambipolar radial loss rate decreases to 60% of that in the 0Ω case by increasing the termination registers.

The current density collected by the ring named p0 (the innermost ring, ϕ40) is about $2.0 \times 10^5 \text{A/m}^2$ at t = 230μs, while the others are only less than 10% of it (Fig. 4). This result implies the importance of the edge plasma just outside the separatrix for the non-ambipolar radial diffusion.

One possible process of the non-ambipolar radial loss is ion radial loss due to the like-particle collision, because the pressure gradient scale length just outside the separatrix in FIX-FRC is 7 ~ 8cm and is comparable to the local ion gyro radius (3 ~ 4cm).

4. Conclusions

The particle loss properties in the edge plasma of a field reversed configuration are investigated under the condition that the mirror ratio is increased and the conducting end wall plate is mounted at the end of the device.

The particle end loss time in the edge layer has linear dependance on the mirror ratio in the high mirror ratio regime, as predicted by the MHD treatment.

The axial net current is detected in the edge plasma and the direction of the current is the direction from the end part to the central part. The axial net current is measured to be 0.8kA and is about 13% of the global particle loss rate of the FRC plasma. The origin of the current seems to be in the central part of the edge plasma, mainly at just outside the separatrix.

The major particle loss process in the edge plasma of FIX-FRC is the axial end loss with hydro-magnetic flow in the magnetic loss channel, but non-ignorable amount of nonambipolar radial loss process may be present in the edge plasma.

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