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Particle Simulation Study on Profile Relaxation in Field-Reversed Configurations

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Abstract

The purpose of this study is to investigate the relaxation process of the field-reversed configuration (FRC) from an initial MHD profile to a kinetic one by means of the three dimensional electromagnetic particle simulation. It is found that the relaxation oscillation takes place when the profile relaxes from an MHD profile to a kinetic one. The relaxation oscillation with the frequency $\omega \sim 2\omega_{ci}$ is gradually damped in $\omega_{ci}t \sim 3\pi$ (ω_{ci} is the ion cyclotron frequency). The hollow current profile is realized in the full kinetic FRC plasmas after the relaxation. The hollow profile of the current density is realized only in an ion meandering region. In the full kinetic case with the hollow current profile, the shift mode is dominant and the tilt instability is stabilized.

Keywords:

field-reversed configuration, electromagnetic particle simulation, kinetic effect, hollow profile, tilt mode

1. Introduction

The dangerous tilt instability in the field-reversed configuration (FRC) plasmas, which leads to the disruption of plasma confinement, is predicted by the MHD theory [1,2], but it has not been observed in the experiments [3]. This contradiction between the experiments and the MHD theory has not been elucidated yet [4-8]. On the other hand, Steinhauer and Ishida [9] pointed out that most experimental equilibrium configurations tend to take a hollow current profile.

The purpose of this study is to investigate the relaxation process of the FRC plasmas from an initial MHD profile to a kinetic one by means of the three dimensional electromagnetic particle simulation. We clarify the physical properties of the kinetic profile and the relationship between the tilt mode and the kinetic profile.

2. Method and Condition

We perform the three-dimensional full electromagnetic particle simulation with the semi-implicit algorithm in the cylindrical coordinates [7,10,11]. An initial profile is given by a one-fluid MHD equilibrium which is controlled by the hollowness parameter (D_{hj}), the separatrix beta value (β_{sp}) and the finite Larmor radius parameter ($\bar{s}$).

3.1 Profile Relaxation

3.1.1 Relaxation from MHD to kinetic

Figure 1 shows the time evolutions of the null point (R) and separatrix (r_{sp}) radii. In the full kinetic case (left), the oscillation with frequency $\omega \sim 2\omega_{ci}$ (ω_{ci} is the ion cyclotron frequency.) is excited in the radial direction in the early period and damped gradually until $\omega_{ci}t \sim 3\pi$. The plasma beta value at the separatrix (β_{sp}) jumps from an initial small value ($\beta_{sp} = 0.2$) to about

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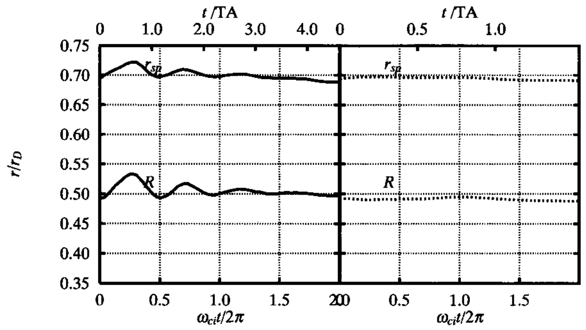


Fig. 1 Time evolution of the radii of the null point (R) and separatrix (r_{sp}). The left panel shows $\bar{s} = 1$ and the right panel shows $\bar{s} = 3$, respectively. r_D is the vessel radius and TA is the Alfvén time.

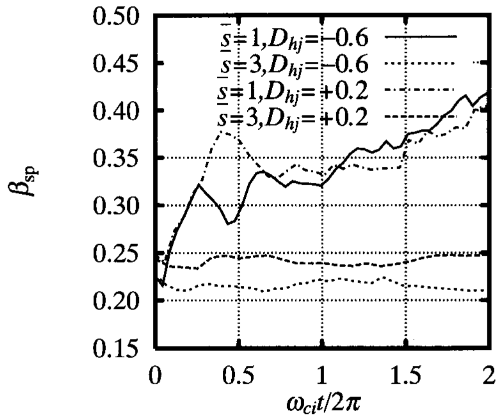
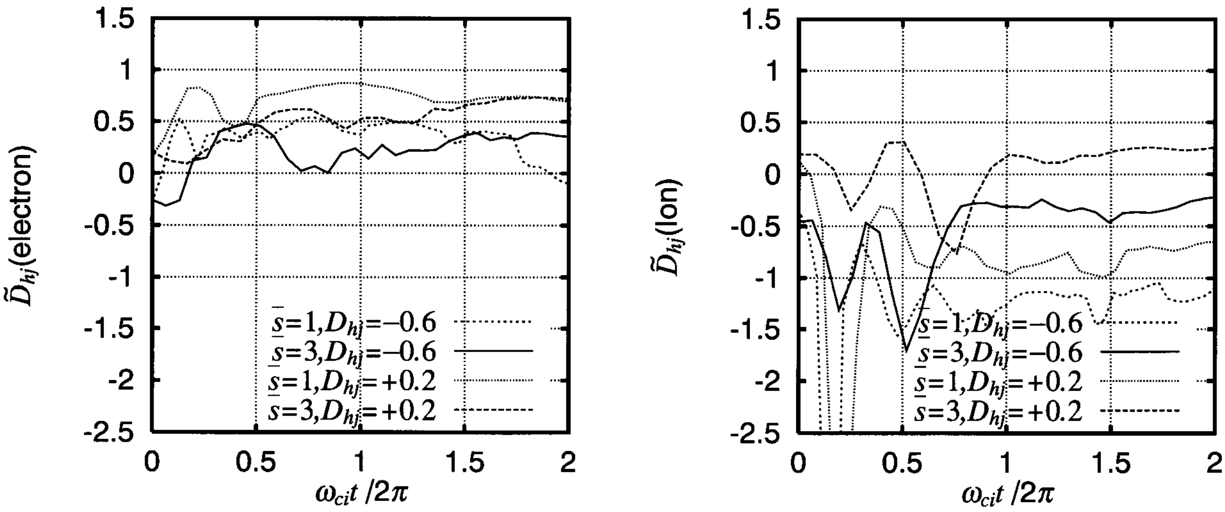


Fig. 2 Time evolution of the separatrix beta value (β_{sp}). The solid line shows $\bar{s} = 1$ and $D_{hj} = -0.6$, the dotted line shows $\bar{s} = 3$ and $D_{hj} = -0.6$, the dashed-and-dotted line shows $\bar{s} = 1$ and $D_{hj} = 0.2$ and the broken line shows $\bar{s} = 3$ and $D_{hj} = 0.2$.



(a) Electon.

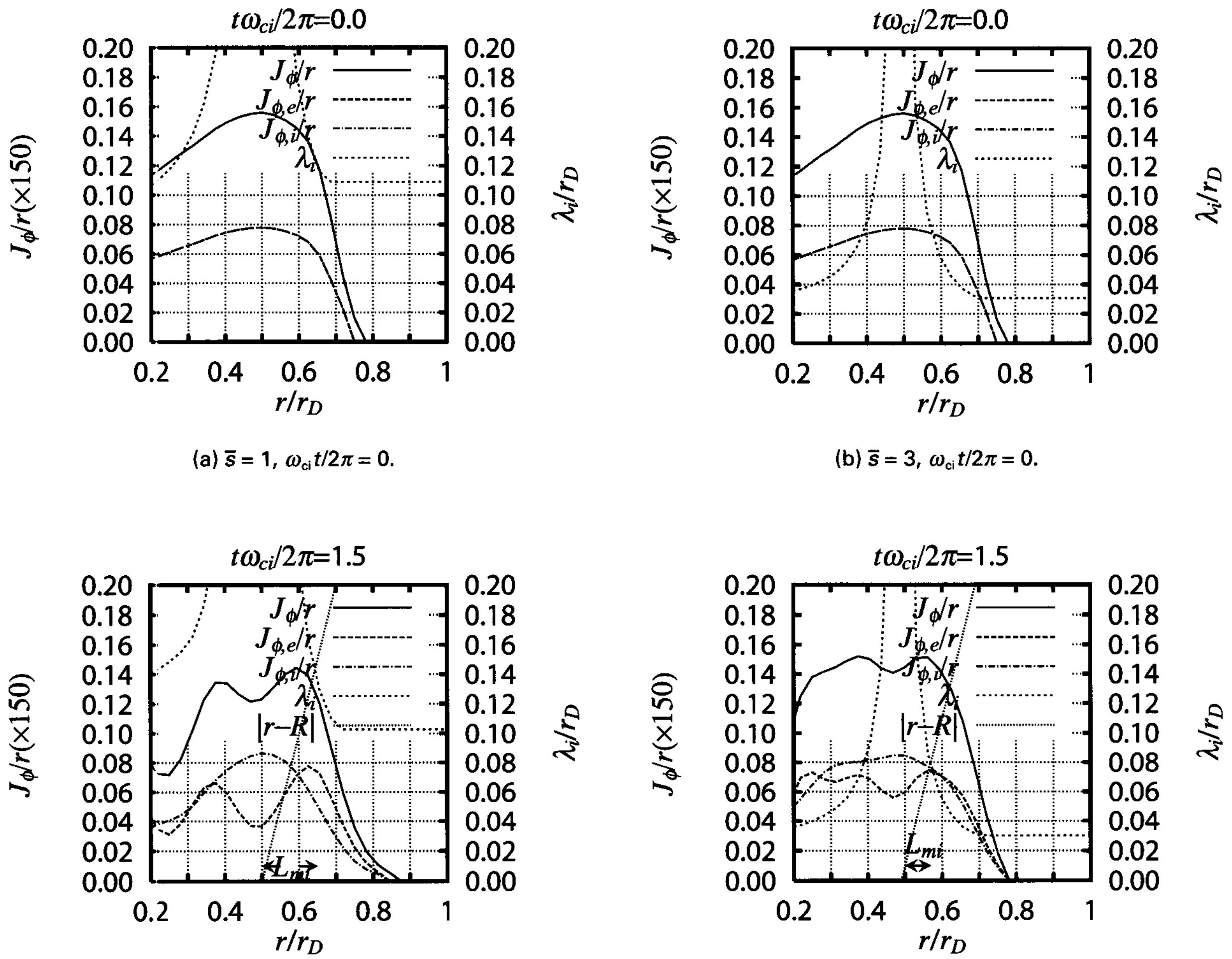
(b) Ion.

Fig. 3 Time evolution of the hollowness parameter ($\tilde{D}_{hj}$). The solid line shows $\bar{s} = 1$ and $D_{hj} = -0.6$, the dotted line shows $\bar{s} = 3$ and $D_{hj} = -0.6$, the dashed-and-dotted line shows $\bar{s} = 1$ and $D_{hj} = 0.2$ and the broken line shows $\bar{s} = 3$ and $D_{hj} = 0.2$, respectively.

0.35, and keeps this value for a while (Fig. 2). In the moderate kinetic case (right), on the other hand, no oscillation appears and β_{sp} keeps an initial value. The radial oscillation takes place in order to relax an excess energy in an MHD profile. When $\bar{s}$ is small, the energy difference between an MHD profile and a kinetic one is so large that a relaxation oscillation is excited.

3.1.2 Hollowness parameter

Figure 3 shows the hollowness parameter ($\tilde{D}_{hj}$). Since the finite spatial mesh is used in the simulaiton, $\tilde{D}_{hj}$ at $t = 0$ is different from D_{hj} given as the initial parameter. The electron hollowness parameter ($\tilde{D}_{hj,e}$) in the full kinetic case ($\bar{s} = 1$) changes from the negative value to the positive one, that is, the electron current profile is changed from the peaked one to the hollow



(a) $\bar{s} = 1$, $\omega_{ci}t/2\pi = 0$.

(b) $\bar{s} = 3$, $\omega_{ci}t/2\pi = 0$.

(a) $\bar{s} = 1$, $\omega_{ci}t/2\pi = 1.5$.

(a) $\bar{s} = 3$, $\omega_{ci}t/2\pi = 1.5$.

Fig. 4 Current distribution in the radial direction for $\bar{s} = 1$ and 3 at $\omega_{ci}t = 0$ and 3π. The solid line shows the total current (J_ϕ/r), the broken line shows the electron current ($J_{\phi,e}/r$), the dashed-and-dotted line shows the ion current ($J_{\phi,i}/r$), respectively. The dashed line shows the local ion Larmor radius ($\lambda_i(r)$), and the dotted line shows the distance from the null point ($|r-R|$), respectively.

one. The ion hollowness parameter ($\tilde{D}_{hj,i}$) in $\bar{s} = 1$ decreases and the ion current profile becomes more peaked both in the hollow and peaked initial profile after the profile relaxation.

3.1.3 Current profile in kinetic equilibrium

We show the radial profiles of current density at $\omega_{ci}t = 0$, 3π for $\bar{s} = 1$ in Fig. 4. After the relaxation oscillation ($\omega_{ci}t > 3\pi$), the electron current density near the separatrix increases, and near the null point decreases. An initial peaked profiles changes to a hollow profile. On the other hand, the ion current density becomes more peaked. So one can see in Fig. 4 that the initial peaked profile of the total current becomes the hollow profile. Let us consider what determines the spatial scale of the hollow region. Figure 4 also shows the local ion Larmor radius ($\lambda_i(r)$). Ions becomes unmagnetized in the vicinity of field-null point. The size of unmagnetized region is determined by the ion meandering orbit amplitude (L_{mi}) which is defined by the relation

$$L_{mi} \equiv \lambda_i(r) = |r - R| . \qquad (1)$$

One can see that the hollow profile is realized only in an ion meandering region. The scale of the hollow region in $\bar{s} = 1$ is larger than that in $\bar{s} = 3$. The change in the scale of the hollow region is related to the change in the ion meandering orbit amplitude (L_{mi}). It is reasonable to suppose that the effect of the meandering ions have an influence on the equilibrium current distribution near the null point. Consider now the increase of the electron current density near the separatrix. The finite ion Larmor radius effect generates the radial electric field in the narrow periphery region near the separatrix. The size of this region is shorter than the ion Larmor radius there for $\bar{s} = 1$. Because the generated $E \times B$ drift has the same sign as the electron diamagnetic drift, the electron current density increases in the periphery. On the other hand, the electric field acts on ions less effectively since the ion Larmor radius is larger than the size of a strong electric field region. That is, the modification of ion current profile becomes relatively smaller. In this way an initial MHD equilibrium with a peaked current profile relaxes to a kinetic equilibrium with a hollow current profile through the ion meandering orbit and finite Larmor radius effect. The details will be discussed in other paper.

3.2 Tilt instability

We investigate the tilt mode in the kinetic profile with the hollow current distribution. Table 1 shows the growth rate of toroidal mode number $n = 1$ mode. In the full and moderate kinetic cases with the hollow current profile as the initial condition ($\bar{s} = 1$ and 3 with $D_{hj} = 0.2$) and the full kinetic case with the hollow current profile after the relaxation oscillation ($\bar{s} = 1$ and $D_{hj} = -0.6$), the growth rates of the $n = 1$ mode are smaller than the moderate kinetic case with the peaked current profile ($D_{hj} = -0.6$ and $\bar{s} = 3$). In other words, the $n = 1$ mode of the configuration with the hollow current profile can be stabilized. We separate the $n = 1$ mode into the tilt and shift modes by assuming that the flow velocity is symmetric about an equatorial plane in the tilt mode and anti-symmetric in the shift mode. Table 2 shows the growth rate of $n = 1$ symmetric (tilt) mode. In the case of the full kinetic and hollow current profile ($D_{hj} = 0.2$ and $\bar{s} = 1$), the tilt mode is stabilized and the shift mode is increased, that is, the shift mode is dominant. The tilt mode can be stabilized in the case of the hollow current profile.

Table 1 Growth rate of the toroidal $n = 1$ mode.

	$D_{hj} = -0.6$	$D_{hj} = 0.2$
$\bar{s} = 1$	0.267	0.0315
$\bar{s} = 3$	0.512	−0.109
MHD	2.08	1.20

Table 2 Growth rate of the symmetric $n = 1$ mode.

	$D_{hj} = -0.6$	$D_{hj} = 0.2$
$\bar{s} = 1$	0.735	shift domain
$\bar{s} = 3$	0.804	0.0289
MHD	2.08	1.20

4. Conclusions

We perform the 3D full electromagnetic particle simulation to investigate the profile relaxation of the field-reversed configurations (FRCs) and the profile effect on the tilt instability.

(i) The relaxation oscillation takes place when the profile relaxes from an MHD profile to a kinetic one. In the full kinetic case when the relaxed state is far from the MHD equilibrium, the large relaxation oscillation takes place. The relaxation oscillation with the frequency $\omega \sim 2\omega_{ci}$ is gradually damped in $\omega_{ci}t \sim 3\pi$.

(ii) The hollow current profile is realized in the full kinetic FRC plasmas after the relaxation from MHD profiles to kinetic profiles. The hollow profile of the electron current is realized only in an ion meandering region (L_{mi}). The ion finite Larmor radius effect generates the radial electric field in the narrow periphery region near the magnetic separatrix. Because the generated $E \times B$ drift has the same sign as the electron diamagnetic drift, the electron current density increases in the periphery.

(iii) In the case of $\bar{s} = 3$, the plasma confinement is broken by the tilt instability. In the case of $\bar{s} = 1$ with the hollow current profile, however, the shift mode is dominant and the tilt instability is stabilized.

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