Drift kink instability excited by ion beam injection in FRC plasmas

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abstract

The drift-kink instability for a strong ion beam case and the profile relaxation phenomenon for no ion beam case in FRC plasmas are investigated by means of a three-dimensional particle simulation. The unstable mode with the toroidal mode number $n = 4$ grows with the rate $\gamma \sim 0.1 - 1.0\omega_{ci}$ for a strong beam current and deforms the plasma profile along the beam orbit in the vicinity of the field-null line. This mode is nonlinearly saturated as a result of the relaxation of current profile. An initial MHD equilibrium with a peaked current profile relaxes to a kinetic equilibrium with a hollow current profile in a half period of ion gyration in the absence of an ion beam. It is also found that the relaxation oscillation in the radial direction takes place in the early period for a kinetic plasma ($\bar{s} = 1$).

A. Drift-kink instability by ion beam injection

Recent particle simulation studies[1,2] have revealed that the tilt mode is stabilized for a large plasma beta value at the magnetic separatrix ($\beta_{sp} \geq 0.2$) by the anchoring ions which play a role to hold the unstable internal plasma to the stable external plasma.

A beam injection has been considered as an effective method to keep FRC plasmas stable against the tilt mode in a good confinement device with a small β_{sp} value. Horiuchi *et al.*[2,3] found from the three-dimensional electromagnetic (EM) particle simulation that the beam injection is effective to keep FRC plasmas stable, but a peaked current profile with a strong beam component becomes unstable against the drift kink (DK) instability.

Figure 1 shows the radial distributions of the current density at three different time periods. The typical profile of the current density with a beam component has a sharp peak in the vicinity of the field-null line at the initial stage. The peaked current profile changes gradually towards the smoothed one as the DK instability grows up. It is observed that the DK instability is nonlinearly saturated when the initial peaked current profile of $L \ll \rho_{i0}$ relaxes to the smoothed profile of $L \geq \rho_{i0}$ (L is the half-width of current profile and ρ_{i0} is the typical ion Larmor radius). That is, the ion beam which is localized in an unmagnetized narrow region ($L \ll \rho_{i0}$) spreads over the magnetized wide region ($L \geq \rho_{i0}$) as a result of the nonlinear evolution of the DK instability, and thus the ion magnetization effect can stabilize the DK mode.

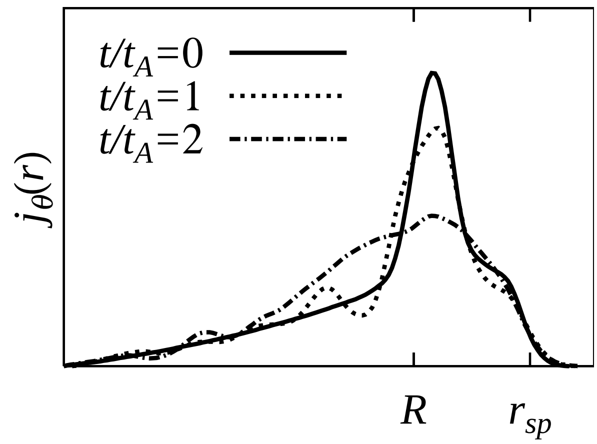

Figure 1: Radial profile of the averaged toroidal current density on the midplane at three different time periods.

In Fig. 2, the maximum saturation amplitude of the perturbed magnetic field is shown as a function of the beam velocity v_b/v_{Ti} for the cases of $N_b/N_i = 0.01$ and $N_b/N_i = 0.02$, where N_b and N_i are the total number of beam ions and that of thermal ions. The maximum amplitude increases with the beam velocity v_b/v_{Ti} for both cases. It is interesting to note that the growth rate is negligibly small for $v_b < v_{Ti}$ and it starts to increase with v_b as soon as v_b becomes larger than v_{Ti}, regardless of the value of N_b/N_i. This phenomena can be explained in the followings.

We have a rough relation $v_d/v_{Ti} \sim \rho_{i0}/L$ for an MHD equilibrium, where v_d is the average drift velocity. Let us suppose that the beam is injected in a narrow region near the field-null [$L \sim (r_{sp} - R)/5 < \rho_{i0}$]. For a weak beam ($v_b < v_{Ti}$), the average width of current profile L is given by $r_{sp} - R$ ($> \rho_{i0}$), i.e., $v_d/v_{Ti} \sim \rho_{i0}/L < 1$, where r_{sp} and R are the separatrix radius and the radius of the field-null, respectively. The DK mode is stabilized in the current profile with a weak beam of $v_b < v_{Ti}$ due to the ion magnetization effect ($\rho_{i0}/L < 1$). The average width decreases as the beam velocity or the beam current increases. We have the relations as $v_d/v_{Ti} \sim v_b/v_{Ti} \sim \rho_{i0}/L > 1$ for a strong beam ($v_b > v_{Ti}$). Thus, the strong beam of $v_b/v_{Ti} \gg 1$ destabilizes the DK instability because $\rho_{i0}/L \gg 1$.

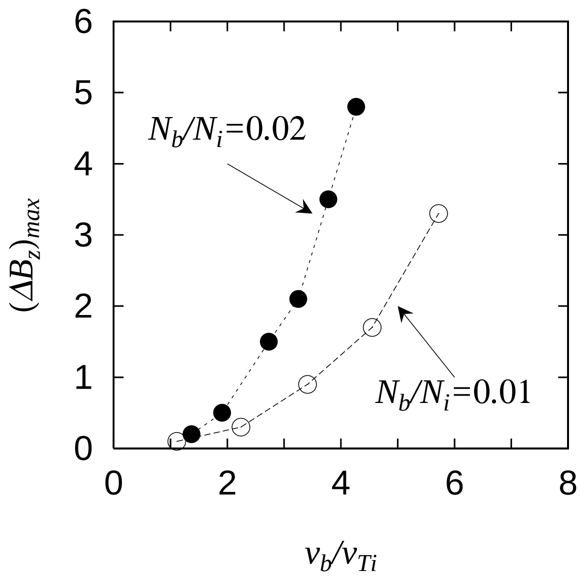

Figure 2: Dependence of the saturation levels of the drift kink mode on the beam velocity v_b/v_{Ti} for two different values of N_b/N_i : $N_b/N_i = 0.01$ (open circles) and $N_b/N_i = 0.02$ (closed circles).

B. Self-generation of a hollow current profile in kinetic FRC plasmas

Steinhauer and Ishida[4] have pointed out that a hollow current profile is realized in most of experimental FRC plasmas, which makes itself stable against the tilt instability. In our simulation model for no ion beam an initial profile is given by a one-fluid MHD equilibrium which is described by the hollowness parameter D, the separatrix beta value β_{sp}, and the finite Larmor radius (FLR) parameter $\bar{s}$. It is easy to expect that an initial MHD profile relaxes to a kinetic one while changing the three key parameters with time.

In order to investigate the relaxation process of FRC plasmas for no beam case, we start the full EM particle simulation from an MHD equilibrium with a peaked current profile, in which the average flow velocity is equal to the diamagnetic velocity and $T_i = T_e$. Figure 3 plots the radial profiles of

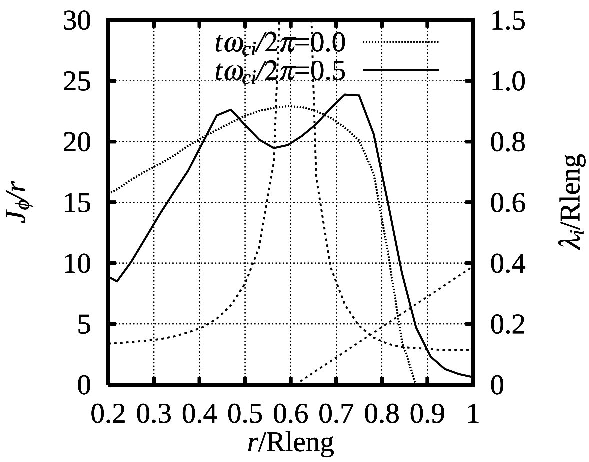

Figure 3: Radial profiles of current density at $\omega_{ci}t = 0, \pi$ for $\bar{s} = 1$ where dotted lines represent the local ion Larmor radius and the radial distance from a field-null point, respectively.

current density at $\omega_{ci}t = 0, \pi$ for $\bar{s} = 1$. One can see in Fig.3 that an initial peaked profiles changes to a hollow profile only in a half period of ion gyration. It is interesting to note that the hollow profile is realized only in an ion meandering region in which a local ion Larmor radius is larger than a radial distance from the field-null point. The ion and electron current profiles are the same at $\omega_{ci}t = 0$. The ion FLR effect generates the radial electric field in the narrow periphery region near the magnetic separatrix. The size of this region is shorter than the ion Larmor radius there for $\bar{s} = 1$.

Because the generated $\mathbf{E} \times \mathbf{B}$ drift has the same sign as the electron diamagnetic drift, the electron current density increases in the periphery and thus its profile tends to a hollow one. 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 FLR effect.

Let us discuss other interesting phenomena in the profile relaxation. Figure 3 shows the temporal

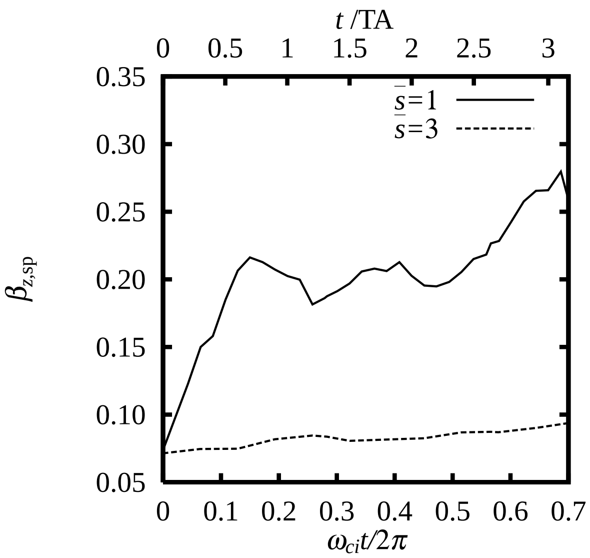

Figure 4: Temporal evolution of the separatrix beta value β_{sp} for $\bar{s} = 1$ (solid) and 3 (dashed).

evolution of the separatrix beta value β_{sp} for $\bar{s} = 1$ and 3. For $\bar{s} = 1$, β_{sp} jumps from an initial small value to about 0.2 during an initial short period ($\omega_{ci}t/2\pi < 0.15$), and keeps this value for a long period. On the other hand, for $\bar{s} = 3$, the value increases fairly slowly while being kept smaller than 0.1. This result suggests that a profile with a small β_{sp} value cannot be maintained in a kinetic plasma, and it relaxes into a kinetic profile with a relatively large β_{sp} value.

In Figure 4, we plot temporal evolutions of the separatrix radius r_{sp}, field-null radius R, and turning points of ion meandering motion $R \pm L_{mi}$ for $\bar{s} = 1$ (left) and 3 (right). The relaxation oscilla-

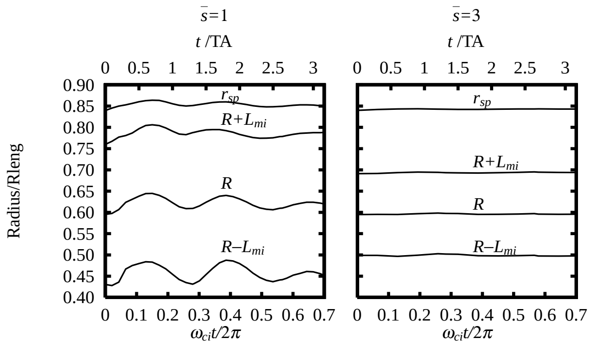

Figure 5: Temporal evolutions of the separatrix radius r_{sp}, field-null radius R, and turning points of ion meandering motion $R \pm L_{mi}$ for $\bar{s} = 1$ (left) and 3 (right).

tion with the frequency $\omega \approx 4\omega_{ci}$ is excited in the radial direction in the early period and damped gradually for $\bar{s} = 1$, while no oscillation appears for $\bar{s} = 3$. It is concluded from this result that the adopted MHD profile is far from a kinetic equilibrium for $\bar{s} = 1$ and the radial oscillation is excited in order to relax an excess energy.

References

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