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R. Horiuchi, K. Nishimura and T. Watanabe

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KINETIC STABILIZATION OF TILT DISRUPTION IN FIELD-REVERSED CONFIGURATIONS

Ritoku Horiuchi, Kazumi Nishimura, Tomohiko Watanabe, and Tetsuya Sato
Theory and Computer Simulation Center,
National Institute for Fusion Science,
Toki 509-52, Japan

Abstract

The kinetic stabilization process of the tilt disruption in a field-reversed configuration is investigated by means of a three-dimensional particle simulation. For the case of no ion beam the growth rate of tilt instability decreases as the plasma beta value at magnetic separatrix β_{sp} increases. This stabilization effect originates from the character of anchoring ions which exist in the vicinity of the magnetic separatrix and play a role as an "anchor" to hold the internal plasma to the external plasma. The tilt mode is also found to be stabilized by injecting an ion beam with about 20% of the ion thermal energy at the neighborhood of the null point even for small β_{sp} plasmas.

1 Introduction

An ideal magnetohydrodynamic (MHD) theory[1] predicts that a field-reversed configuration (FRC) becomes unstable against internal tilt modes if its shape is prolate. On the other hand, many experimental observations[2] show that FRC plasmas remain stable much longer than the tilt growth time. Many papers have so far tried to explain this contradiction by examining non-ideal MHD effects in FRC plasmas, such as the finite ion Larmor radius (FLR) effect[3,4], the ion beam effect[5], and so on. However, the contradiction can not be fully solved up to the present. For example, the kinetic simulations[3,4] have disclosed that the tilt mode can be stabilized for the kinetic plasma of $\bar{s} \approx 1$, but it tends to be unstable as $\bar{s}$ increases. Here, the FLR parameter $\bar{s}$ is defined by

$$\bar{s} = \int_R^{r_s} r dr/(r_s \rho_i), \tag{1}$$

r_s is the separatrix radius, R is the radius of the field null, and ρ_i is the local ion gyroradius. Thus, there remains a big discrepancy between the experiments and the theories in the moderately kinetic plasma of $2 \leq \bar{s} \leq 5$. This paper will discuss the tilt stabilization of FRC plasmas due to the FLR effect, the current profile control effect, the ion beam effect, and the effect of vacuum toroidal field, based on the results obtained from a three-dimensional full particle simulation and an MHD simulation.

2 Simulation model

Let us consider the FRC plasma confined by a uniform external magnetic field within the cylindrical conducting vessel with the periodic length $2Z_d$ along the z-axis and the radius R_d. The dynamical evolution of FRC plasmas is solved by making use of the three-dimensional electromagnetic particle simulation code which relies on the semi-implicit scheme[4,6]. As an initial condition we adopt two-dimensional equilibrium solution which satisfies the equations

$$-\nabla P + \frac{1}{c}\mathbf{j}_d \times \mathbf{B} = 0, \tag{2}$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}(\mathbf{j}_d + \mathbf{j}_b), \tag{3}$$

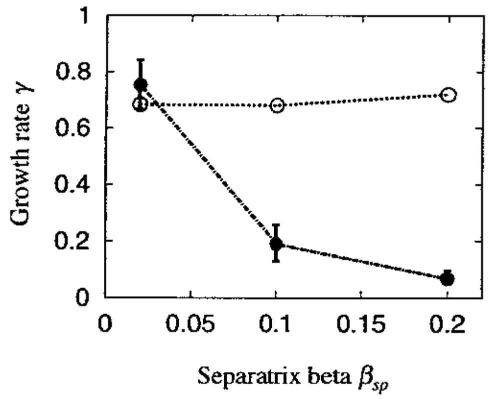

Figure 1: Dependence of growth rate on separatrix beta for peaked current profiles where $D = -0.6$, $\bar{s} = 3$. Open and closed circles correspond to the results obtained from the MHD simulation and the particle simulation, respectively.

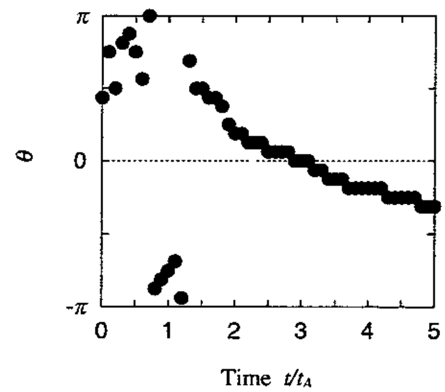

Figure 2: Temporal evolution of azimuthal angle of tilt mode for the case of $\beta_{sp} = 0.02$ where the parameter θ stands for the azimuthal angle at which the tilt amplitude becomes maximum.

where $\mathbf{j}_d$ and $\mathbf{j}_b$ are the diamagnetic component and the beam component of an electric current, respectively, and the pressure profile $P(\Psi)$ is given by[7]

$$P(\Psi) = \begin{cases} P_0(K_0 - \chi - \frac{1}{2}D\chi^2) & \text{for } \chi \leq 0 \\ P_0 K_0 e^{-\chi/K_0} & \text{for } \chi > 0, \end{cases} \quad (4)$$

Ψ denotes the poloidal flux function, $\chi = \Psi/|\Psi_{ax}|$, Ψ_{ax} is the value of Ψ at the field null, P_0 is constant, $K_0 = \beta_{sp}(1 - D/2)/(1 - \beta_{sp})$, $\beta_{sp}[= P(0)/P(\chi = 1)]$ is the normalized pressure value at the magnetic separatrix, and D is the hollowness parameter. The parameter β_{sp} represents roughly the plasma beta value at the separatrix. The current profile is spatially peaked for $D < 0$, flat for $D = 0$, and hollow for $D > 0$. The ion beam with zero temperature is injected along the toroidal(azimuthal) direction near the field null point so that it satisfies the radial force balance equation. We carry out several simulation runs for a moderately kinetic plasma of $2 \leq \bar{s} \leq 5$. In the present model, five parameters can be controlled independently. The first three are the FLR parameter $\bar{s}$, the plasma beta value at magnetic separatrix β_{sp}, and the hollowness parameter D. The ion beam is controlled by the total beam current I_b and the total number of beam ions N_b.

3 Stabilization by anchoring ions

The dependence of the tilt instability on the parameters $\bar{s}$, D and β_{sp} are examined for the case of no ion beam ($I_b, N_b = 0$). The growth rate of tilt mode is slightly affected by the FLR parameter $\bar{s}$ and the hollowness parameter D. On the other hand, it is found that the growth rate strongly depends on the plasma beta value at magnetic separatrix β_{sp}. The normalized growth rate is plotted as a function of the parameter β_{sp} in Fig. 1 for the case where $\bar{s} = 3$, $D = -0.6$, and the growth rate obtained from the MHD simulation is plotted with open circles for comparison. The kinetic growth rate decreases as the parameter β_{sp} increases, while the MHD growth rate is almost independent of β_{sp}. It is also found that the number flux of gyrating ions crossing the magnetic separatrix repeatedly ("anchoring ions") increases in proportion to β_{sp} and the tilt stability is realized for a large number flux of anchoring ions.

The kinetic stabilization mechanism by anchoring ions is as follows. Tilt instability is triggered by the internal mode, i.e., the collective motion of plasma is generated inside the magnetic separatrix. The ions which make a gyrating motion across the separatrix do not follow the collective motion when they are moving outside the separatrix. On the other hand,

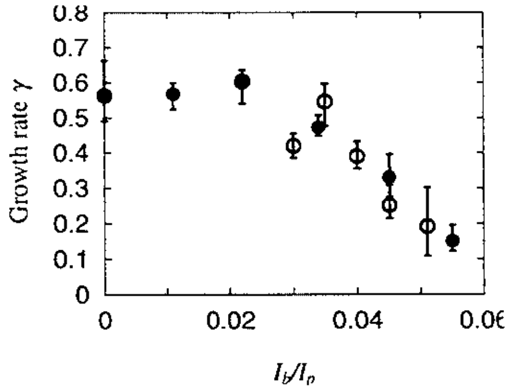

Figure 3: Dependence of growth rate on the beam current I_b for the cases where the beam number is changed (closed), and the cases where the beam velocity is changed (open).

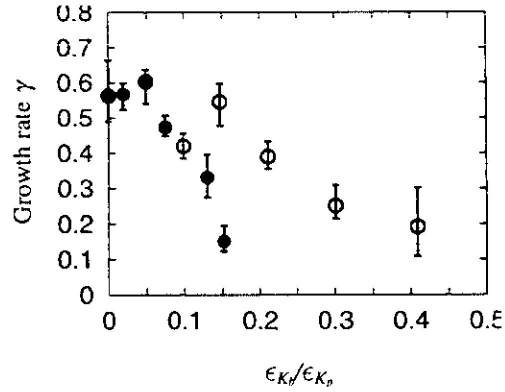

Figure 4: Dependence of growth rate on the energy ratio of beam ions to thermal ions $\epsilon_{K_b}/\epsilon_{K_p}$ for the same cases as Fig. 3.

the unstable internal motion grows while drifting slowly towards the azimuthal direction due to the finite Larmor radius effect, as is shown in Fig. 2. In this way, the phase difference is created between the motion of anchoring ions and the unstable internal motion. When anchoring ions come back inside the separatrix, the internal tilting motion is disturbed by the motion of anchoring ions. The stabilization effect by anchoring ions becomes more effective as the number flux increases. Consequently, the tilt stability is realized for a large beta at the separatrix ($\beta_{sp} > 0.2$). In other words, the anchoring ions play a role as an "anchor" to hold the internal plasma to the external plasma, thus stabilizing the tilting motion through their "anchor" effect.

4 Stabilization by ion beam

The beam stabilization effect for small β_{sp} plasmas is examined by controlling the total beam current I_b in two ways. First by changing the beam particle number and the other by changing the beam particle velocity. Figure 3 shows the dependence of growth rate on the total beam current I_b for the case where $D = -0.6$, $\bar{s} = 3$, $\beta_{sp} = 0.02$, and I_p is the total current of thermal plasmas. For both cases the growth rate remains almost unchanged until the beam current reaches a critical value ($I_b < 0.03 I_p$). The growth rate gradually decreases as the beam current increases above the critical value. Figure 4 shows the dependence of growth rate on the ratio of beam ions to thermal ions energy $\epsilon_{K_b}/\epsilon_{K_p}$ for the same cases as Fig. 3. For the cases where the beam velocity is changed (open circles), the tilt stabilization is realized when $\bar{s}_{eff} \approx 1$ and the beam energy is about 50% of the ion thermal energy. Here, the effective $\bar{s}$ value, $\bar{s}_{eff}$, is defined by using the average velocity of all ions instead of the only thermal ions. For the cases where the beam number is changed (closed circles), the tilt stabilization is realized when the beam energy is about 20% of the ion thermal energy. It is concluded that the beam stabilization effect is evaluated in terms of the beam current, and the effective stabilization with a relatively small beam energy is realized by controlling the total number of beam ions.

5 Stabilization by vacuum toroidal field

Let us examine the MHD stabilization effect when the vacuum toroidal field is applied to an FRC type configuration with a center conductor in which an axial current flows[8]. Figure 5 shows the results obtained from the linear analysis where the growth rate is plotted as a function of the toroidal mode number n for five different magnitudes of vacuum toroidal field B_{t0} and the magnitude B_{t0} is normalized by the typical value of the equilibrium magnetic field. It is clearly seen that the low-n global MHD modes such as the tilt mode are made less unstable

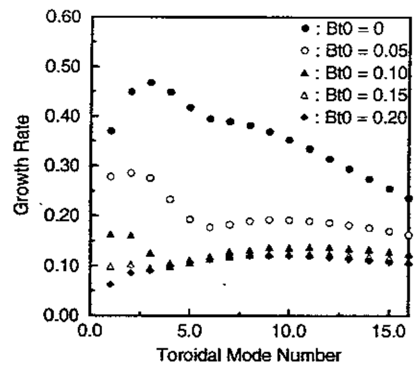

Figure 5: Dependence of MHD growth rate on toroidal mode number for five different toroidal fields.

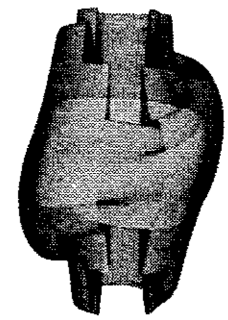

Figure 6: Perspective view of pressure profile at $t = 40t_A$ for the case of $B_{t0} = 0.5$.

by imposing the strong toroidal field, while the ballooning type modes localized in the bad-curvature region remain unstable. It is also found that the ballooning modes continue to be unstable as the toroidal field is decreased to zero where the linear eigenfunction consists of convection vortices elongated vertically. The nonlinear MHD simulation confirms that, for a relatively strong toroidal field, the ballooning mode is predominantly excited and deforms the global pressure profile, as is seen in Fig. 6. One can clearly see a big bulge of the pressure pushed out into the vacuum region.

6 Conclusions

We have investigated the tilt stabilization mechanism of FRC plasmas by means of a three-dimensional particle simulation and an MHD simulation. The tilt stabilization in the moderately kinetic regime ($2 \leq \bar{s} \leq 5$) is attributable mainly to the character of anchoring ions which exist in the vicinity of the magnetic separatrix and play a role as an "anchor" to hold the unstable internal plasma to the stable external plasma. Injecting the ion beam with about 20% of ion thermal energy or imposing the vacuum toroidal field with a center conductor leads to the tilt stabilization even for small β_{sp} plasmas.

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