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Tilt Stabilization by Energetic Beam Ions in a Field-Reversed Configuration

NISHIMURA Kazumi, HORIUCHI Ritoku and SATO Tetsuya
Theory and Computer Simulation Center,
National Institute for Fusion Science, Toki 509-5292, Japan

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Abstract

The stabilization of the tilt disruption in a field-reversed configuration by an ion beam is investigated by means of a three-dimensional particle simulation. The growth rate of tilt mode decreases as the beam current increases. It is also found that the drift kink mode grows in the vicinity of the field null line and saturates in the early phase.

Keywords:

field-reversed configuration, tilt instability, drift kink instability

1. Introduction

The compact torus is attractive for a fusion reactor because it has some superior features compared with the representative nominated reactor, e.g., tokamak. A field-reversed configuration (FRC) is grouped into the compact tori. Since the pressure of plasmas confined within the separatrix reaches its maximum value in the vicinity of the O-point (the field-null line) and the toroidal magnetic field does not exist ideally, the averaged plasma beta $\langle\beta\rangle$ tends to be high in FRC plasmas ($\langle\beta\rangle \sim 1$). In future, this configuration is especially expected for a D-^{3}He fusion reactor [1,2].

The tilt mode ($n = 1$) is known as one of the most dangerous instabilities to disrupt the configuration completely, where n represents the toroidal mode number. We focused on the two effects (ion finite Larmor radius (FLR) effect [3,4] and profile control effect [5,6]) and carried out the three-dimensional particle simulation in the previous paper [7]. The conclusion was that the growth rate of tilting instability decreases as the plasma beta value at the magnetic separatrix β_{sp} increases. In order to apply the FRC plasma for nuclear fusion device, not only stability but also confinement is improved to be better. The particle confinement is generally improved to be better as the β_{sp} decreases, while it becomes impossible to suppress the instability by decreasing β_{sp}. Then the other stabilizing method is needed for future devices. The main purpose of this paper is to investigate the properties of the tilt instability in the FRC plasmas including the beam ions by means of three-dimensional particle simulation.

2. Simulation Model

We consider the FRC plasma confined by a uniform external magnetic field within the cylindrical conducting vessel. The height of this vessel Z_D is always fixed to 6 times the vessel radius R_D in this paper. The time development of all particles (thermal ion, thermal electron, and beam ion) and field quantities are solved with using the three-dimensional electromagnetic particle simulation code [4]. It is assumed that the physical quantities are periodic at the boundary of z axis and the vessel wall is a rigid perfect conductor. The particles are elastically reflected at the vessel wall.

Two-dimensional MHD equilibrium solution is used as an initial condition. In the case where the beam ions exists, we adopt the MHD equilibrium including beam components,

$$-\nabla P + \frac{1}{c}\boldsymbol{j}_{\mathrm{d}} \times \boldsymbol{B} = 0, \quad (1)$$

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c}(\boldsymbol{j}_{\mathrm{d}} + \boldsymbol{j}_{\mathrm{b}}), \quad (2)$$

with the Cobb's pressure model [6], which can control both the current profile and the beta value at the separatrix easily. If the profile of beam current density is determined, the set of these equations can be solved numerically under the assumption that $n_b/n_i \ll 1$, where n_b and n_i are the number density of beam ions and that of thermal ions, respectively. The spatial distribution of beam current is assumed to be in a Gaussian form. The velocity and the center position of beam distribution are determined so as to satisfy the force balance equation. The total number of loaded thermal particles is fixed to 10^6. The beam ions are the same kind of thermal ions, *i.e.*, $q_b = q_i$. The number of beam ions can be changed freely as one of the controlled parameters in this simulation.

3. Simulation Result

The typical parameters are as follows: the mass ratio is $m_i/m_e = 50$, the ion cyclotron frequency defined by the vacuum magnetic field is $\omega_{ci} = 0.02\ \omega_N$ (ω_N: electron cyclotron frequency defined by the vacuum magnetic field), the ion thermal velocity is $v_{Ti} = 0.015\ c$ (c: velocity of light), the temperature ratio is $T_i/T_e = 1$, the radius of the cylindrical vessel is $R_D = 5.63\ c/\omega_N$, and the toroidal current of thermal plasma is $I_p = 8.9\ q_N\omega_N$ (q_N: elementary charge). The Alfvén transit time t_A (= R_D/v_A where v_A is the Alfvén velocity defined by the ion density at the field-null line and the magnetic field at the wall on the midplane) becomes about 200 ω_N^{-1}. The profile control parameters are fixed as $\beta_{sp} = 0.02$ and $D = -0.6$ for all cases, where D is the hollowness parameter which controls the current distribution. The profile given by these parameters becomes unstable against the tilt instability if the beam component does not exist [7].

There are two important parameters which we may change independently. One is the beam velocity v_b/c, and the other is the ratio of the number of beam ions to the number of thermal ions N_b/N_i. The parameters used for the simulation are listed in Table I. The simulation runs are classified into two types. One type is to vary the velocity of the beam ions v_b with keeping the total number of beam ions N_b/N_i constant (RA and RB in Table I), and the other type is to vary the total number of beam ions with keeping the velocity of the beam ions v_b constant (RC and RD in Table I).

Table 1 Characteristics of beam ions used in particle simulations, including beam velocity v_b/c; number ratio N_b/N_i; current ratio I_b/I_p.

RUN	v_b/c	N_b/N_i	I_b/I_p
R00	0.00	0.00	0.00
RA1	0.033	0.01	0.02
RA2	0.050	0.01	0.03
RA3	0.067	0.01	0.04
RA4	0.084	0.01	0.05
RB1	0.008	0.02	0.01
RB2	0.020	0.02	0.025
RB3	0.028	0.02	0.035
RB4	0.040	0.02	0.05
RB5	0.055	0.02	0.07
RB6	0.063	0.02	0.08
RC1	0.029	0.005	0.009
RC2	0.029	0.01	0.018
RC3	0.029	0.015	0.027
RC4	0.029	0.02	0.037
RC5	0.029	0.025	0.046
RD1	0.059	0.005	0.017
RD2	0.059	0.01	0.035
RD3	0.059	0.015	0.054

3.1 Drift kink instability in the early phase

Figure 1 shows the time development of the magnetic field on the midplane for the case RA4. The left panels are the contour plots of the z-component of the magnetic field B_z and the right panels are those of the z-component of the perturbed magnetic field ΔB_z defined by $B_z(t) - \langle B_z(t)\rangle$ (the bracket stands for the average in the toroidal direction) in the $\theta - r$ plane. The solid lines and the dashed lines represent the positive values and the negative values, respectively. The maximum and minimum values are plotted on the top part of the panels. The strong deformation of the magnetic profile occurs in the vicinity of the field null line, where the current density including the beam component steepens. The toroidal mode number of this instability is equal to 4 and the real frequency ω_r is equal to 0.1 ω_{ci}. This instability is saturated in the early phase of the simulation (about $t/t_A \approx 2$) for all cases. In Fig. 2, the maximum amplitudes of perturbed magnetic field are shown as a function of the current ratio I_b/I_p. The maximum amplitude or the growth rate decreases with the beam current I_b/I_p, and any significant

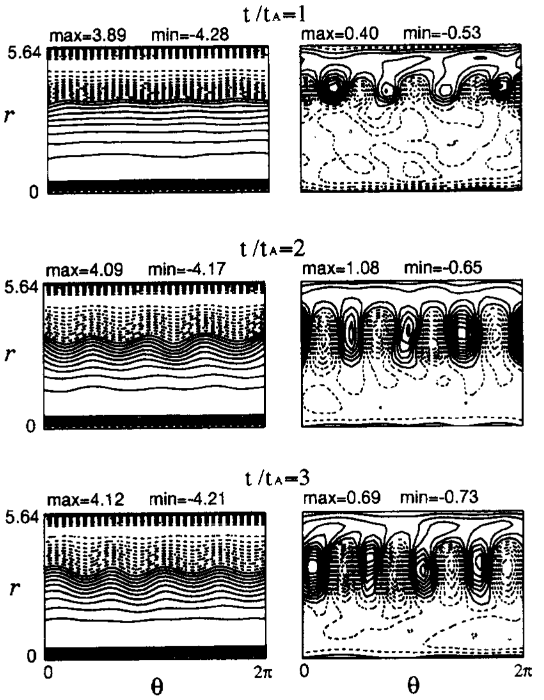

Fig. 1 Time sequential plots of (left) the magnetic field contours and (right) the perturbed magnetic field contours.

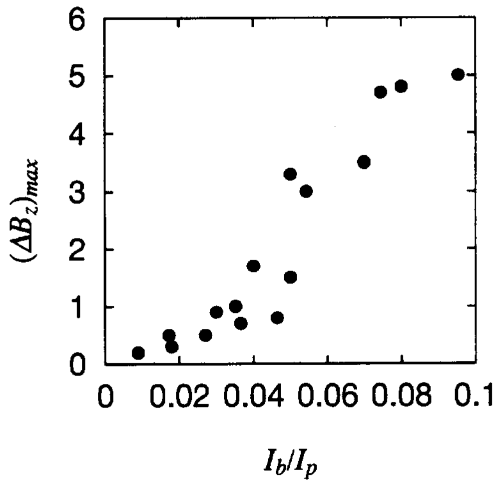

Fig. 2 Dependence of the saturation level of n = 4 drift kink instability on the current ratio I_b/I_p for all cases.

modification by this instability cannot be observed in the case without beam current. Thus, it is concluded that this mode is a kind of the drift kink instability driven by the beam current [8].

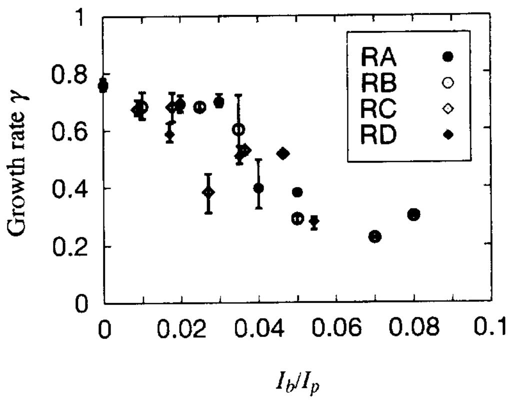

Fig. 3 Tilt growth rates as a function of the current ratio I_b/I_p for the cases where the beam velocity is changed (RA and RB), and the cases where the beam number is changed (RC and RD).

3.2 Tilt stabilization by the ion beam

The development of tilt instability is defined by using the Fourier amplitude of the z component of the fluid velocity $V_z^{(1)}(t)$ after the drift kink instability saturates. We follow the time development of this quantity and obtain the growth rate. The relation between the tilt growth rate and the current ratio is presented in Fig. 3. From this figure, it is found that the growth rate remains almost the same as that for no beam case (R00) for $0 < I_b/I_p < R_c(\approx 0.03)$. If the current ratio exceeds this critical value R_c, the tilt growth rate becomes small as the current ratio increases. There is no significant difference between the fixed number cases (RA and RB) and the fixed velocity cases (RC and RD). In other words, the influence of beam ions on the tilt growth rate can be evaluated by the current ratio I_b/I_p regardless of whether the beam current is controlled by the beam velocity or by the number of beam ions.

The values of the FLR parameter $\bar{s}$ roughly stands for the ratio of the plasma radius to the ion Larmor radius. It is found that $\bar{s}$ tends to become larger as the current ratio increases. As the beam current is stronger, the inclination of magnetic field at the field null is steeper and thus the magnetic field becomes stronger in the vicinity of the field null. In other words, the thermal ions becomes more strongly magnetized and the average ion gyroradius or the inverse of $\bar{s}$ becomes smaller with the beam current. Figure 4 shows the relation between the tilt growth rate and the parameter $\bar{s}$. It is important to note that the tilt mode is less destabilized due to the existence of the ion beam even in the high $\bar{s}$ region.

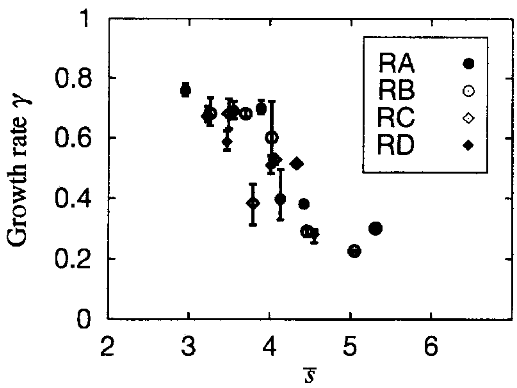

Fig. 4 Tilt growth rates as a function of the kinetic parameter $\bar{s}$ for the same cases as Fig. 3.

4. Summary

By carrying out the simulation runs with different values of I_b/I_p and N_b/N_i, the following new results were obtained:

(i) The localized instability due to the ion beam current in the FRC plasmas was generated along the field-null line and saturated in the early phase ($0 < t/t_A < 2$). The deviation of the profile mainly developed in the perpendicular direction of the magnetic field on the midplane. (ii) It was effective against the tilt instability to increase the current ratio I_b/I_p. The growth rate remained almost unchanged until the current ratio reached the critical value $R_c \sim 0.03$, and then it gradually decreased as the ratio exceeded R_c. (iii) Although the kinetic parameter $\bar{s}$ which evaluates the ion FLR effect became large as the current ratio I_b/I_p increased, the tilt mode can be stabilized due to the ion beam effect.

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