J. Plasma Fusion Res. SERIES, Vol. 2 (1999) 97–100

Complex Behavior of Internal Collapse Due to Self-Generated Radial Electric Field

MATSUMOTO Taro, TOKUDA Shinji, KISHIMOTO Yasuaki, TAKIZUKA Tomonori and NAITOU Hiroshi[1]
Naka Fusion Research Establishment,
Japan Atomic Energy Research Institute, Naka 311-0193, Japan
[1]Department of Electrical and Electronic Engineering,
Yamaguchi University, Ube 755-8611, Japan

(Received: 11 December 1998 / Accepted: 13 May 1999)

Abstract

The density gradient effect is taken into account in the gyro-kinetic nonlinear simulation of the kinetic $m = 1$ internal kink mode to clarify the nonlinear behavior of the internal collapse. Even when the density gradient is not so large enough to change the process of the full reconnection, the later process is changed considerably due to the self-generated radial electric field. The nonlinear growth of the 0/0 mode after the internal collapse violates the symmetrical flow of the parallel current, restricting the secondary reconnection.

Keywords:

$m = 1$, internal kink mode, gyro-kinetic model, particle simulation, internal collapse, tokamak, radial electric field, poloidal rotation

1. Introduction

In tokamaks with high current density where the safety factor at the magnetic axis (q_0) is less than unity, the $m/n = 1/1$ mode ($m = 1$ mode) evolves and causes the internal collapse, where m and n are the poloidal and the toroidal mode numbers, respectively. The physics of the $m = 1$ mode is affected by many effects of the plasma. Among such effects the electron inertia, density and temperature gradients, ion Larmor radius and high energy ions are some of examples. Because of this inherent properties of the $m = 1$ mode, it is not so easy to understand the nonlinear development of the mode. Therefore, it is desirable that the basic physics of the $m = 1$ mode is clarified by simulations describing appropriately such effects.

Naitou *et. al.* performed a nonlinear gyro-kinetic particle simulation [1] of the $m = 1$ mode in a cylindrical geometry with an uniform plasma pressure. They showed the collisionless magnetic reconnection caused by the electron inertia and that the magnetic configuration where q_0 is less than unity can be reconstructed after the full reconnection [2-3]. This model is modified to take the density gradient into account by Matsumoto *et. al.* [4].

In this paper, we study the density gradient effect on the collisionless $m = 1$ mode by the gyro-kinetic nonlinear simulation. The process after the internal collapse is found to be changed due to the self-generated radial electric field, *i.e.* the $m/n = 0/0$ mode induced by the nonlinear interaction.

This paper is organized as follows. In Section 2, we described the simulation model and parameters briefly. In Section 3, the simulation results with a non-uniform density profile are shown and compared with those obtained with the uniform density profile. Finally, a

Corresponding author's e-mail: tmatsumo@naka.jaeri.go.jp

brief summary is given in Section 4.

2. Simulation Model and Parameters

In the gyro-kinetic model, plasma can be described with the equations which do not include any frequency higher than the ion cyclotron frequency, since the physical phenomena are averaged with respect to the ion Larmor radius by the gyro-kinetic ordering [1]. The gyro-kinetic model permits the time step much longer than the electron plasma frequency, and is appropriate to the analysis for the phenomena whose frequency is the same order of Alfvén frequency such as the internal kink mode.

The gyro-kinetic equations used in this simulation are obtained in Ref. [4]. We choose safety factor profile which is 0.85 on the magnetic axis and unity near the half radius. The main parameters are listed on Table 1. In the present simulation, we choose the skin depth ($\delta_e = c/\omega_{pe}$) as $\delta_e = 4\rho_{si}$. The diamagnetic frequency in the non-uniform density simulation is $\omega_* \sim 1.12 \times 10^{-3}$ $(\omega_{ci}) \sim 0.208(V_A/L_Z)$ at the q = 1 surface.

3. Simulation Results

In the uniform density case, the electrostatic potential energy of the uniform density case are shown in Fig. 1(a). The full reconnection occurs at the end of the linear growth of the $n = 1$ mode ($\omega_{ci}t \sim 4300$). The growth rate is the order of the Alfvén frequency because $V_A/L_Z \sim 187\omega_{ci}$. The $n = 1$ mode decreases after the full reconnection, however it is still dominant until the end of the simulation. In the poloidal direction, the electrostatic potential has the $m = 1$ mode dominantly. As shown in Fig. 2(a), this 1/1 mode drives the symmetrical flow of the parallel current which is swept

Table 1 The main parameters used in this simulation.

Configuration Shape	Rectangular Box
Poloidal Mesh Width	1 (ρ_{si})
System Size ($L_X \times L_Y \times L_Z$)	64 × 64 × 32
Number of Particle in a Node	32,768 × 2
Number of Nodes	128
Number of Total Particles	4,194,304 × 2
Electron Thermal Velocity	0.25 (V_A)
Time Step : Δt	2.33×10^{-3} (L_Z/V_A)
Skin Depth : (c/ω_{pe})	4 (ρ_{si})
Toroidal Mode Numbers : n	–4 ~ + 4

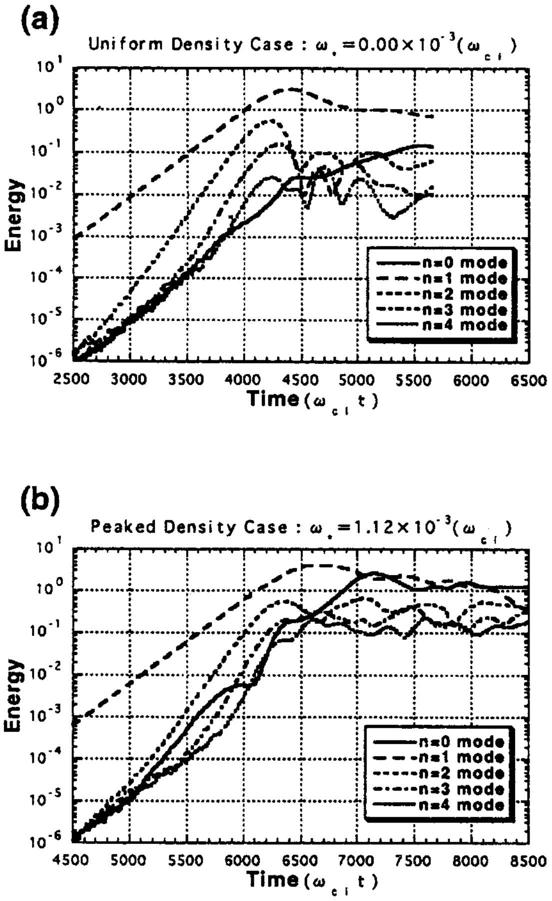

Fig. 1 The electrostatic potential energy decomposed into the toroidal modes in (a) the uniform density case and (b) the non-uniform density case.

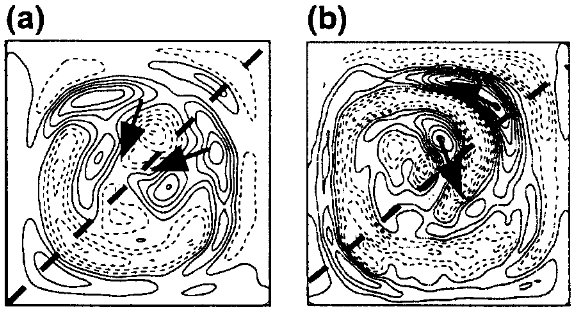

Fig. 2 The contours of the perturbation of the parallel current in (a) the uniform density case ($\omega_{ci}t = 4575$) and (b) the non-uniform density case ($\omega_{ci}t = 6449$). The solid and dashed lines indicates the plus and minus contour lines, respectively. The thick dashed line show the symmetrical plane described by the electrostatic potential just after the full reconnection. The arrows indicate the direction of motion of the parallel current.

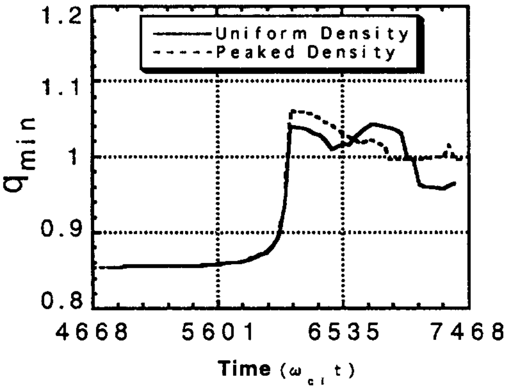

Fig. 3 The variation of the minimum safety factor in the both cases.

out from the central region as a result of the full reconnection, and causes the current concentration which induces the magnetic reconnection again [2-3]. Figure 3 shows the reconstruction of $q < 1$ configuration after the internal collapse. This is the mechanism of the secondary reconnection.

In the non-uniform density case, The full reconnection occurs without saturation ($\omega_{\mathrm{ci}}t$ ~ 6500), because the diamagnetic frequency is less than the linear growth rate in the uniform density case. However, even when the density gradient is not so large enough to change the process of the full reconnection, the later process is changed considerably due to the self-generated radial electric field. The $n = 0$ mode is found to exponentially grow after the saturation of the dominant $n = 1$ mode, and reach to the same level as the $n = 1$ mode, as shown in Fig. 1(b). In the poloidal direction, the nonlinear $m = 0$ mode is also observed [4]. This 0/0 mode drives a $\boldsymbol{E} \times \boldsymbol{B}$ plasma rotation in the ion diamagnetic direction which violates the symmetry of the plasma flow, as shown in Fig. 2(b). As a result, the current reconcentration which induces the secondary reconnection is restricted. Therefore, it is a delicate problem whether the minimum safety factor becomes less than unity again, as shown in Fig. 3. The 0/0 mode is maintained until the end of simulation, although the $n = 1$ mode decreases gradually.

Next, the deviation of the energy from the equilibrium value is shown in Fig. 4. The conservation of the total energy is good for both cases ($\Delta E/E \leq 0.02\%$). The behaviors of the electrostatic, magnetic, and kinetic energies are the almost same in the process of the full reconnection. However, in the non-uniform density case, the gain of the magnetic energy after the internal collapse due to the secondary reconnection is not observed. Instead, the electrostatic potential energy is increased due to the nonlinear growth of the 0/0 mode.

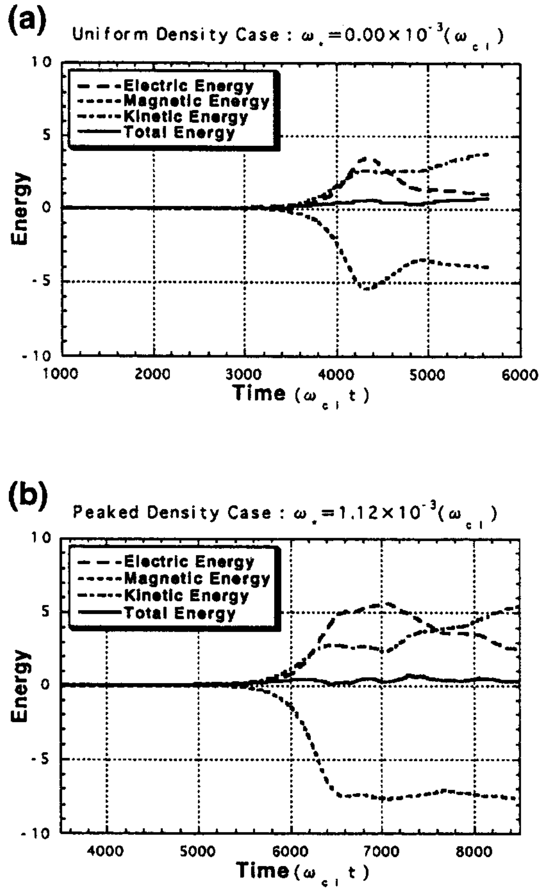

Fig. 4 The energy history for (a) the uniform density case and (b) the non-uniform density case.

4. Summary

We have studied the effect of density gradient on the energy transfer in the nonlinear process of the internal collapse by the nonlinear gyro-kinetic simulation of the collisionless $m = 1$ mode in a cylindrical plasma.

Even when the density gradient is not so large enough to change the process of the full reconnection, the later process is changed considerably due to the self-generated radial electric field, *i.e.* the $m/n = 0/0$ mode, induced by the nonlinear interaction. The radial electric field is found to exponentially grow after the saturation of the dominant 1/1 mode, and to reach to the same level as the 1/1 mode. The generation of radial electric field which is not included in the conventional MHD model leads to the complex behavior in the process of the internal collapse. It should be noted that the radial electric field is observed after the internal collapse in JIPP-TII tokamak [5].

This 0/0 mode drives a $\boldsymbol{E} \times \boldsymbol{B}$ plasma rotation in the ion diamagnetic direction which violates the symmetry of the plasma flow. As a result, the current reconcentration which induces the secondary reconnection is restricted. Therefore, it is a delicate problem whether the minimum safety factor becomes less than unity again. The 0/0 mode is maintained until the end of simulation, although the $n = 1$ mode decreases gradually.

References

[1] W.W. Lee: Phys. Fluids **26**, 556 (1983).

[2] H. Naitou, K. Tsuda, W.W. Lee and R.D. Sydora: Phys. Plasma, **2**, 4257 (1995).

[3] H. Naitou, T. Sonoda, S. Tokuda and V.K. Decyk: J. Plasma and Fusion Research **72**, 259 (1996).

[4] T. Matsumoto, S. Tokuda, K. Kishimoto, T. Takizuka and H. Naitou: J. Plasma and Fusion Research, to be published.

[5] Y. Hamada, A. Nishizawa, Y. Kawasumi, *et. al.*: Nucl. Fusion **36**, 515 (1996).