Nonlinear Simulations of Internal Reconnection Event in Spherical Tokamak

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Abstract

Three dimensional magnetohydrodynamic simulations are executed in a full toroidal geometry to clarify the physical mechanisms of the Internal Reconnection Event (IRE), which is observed in the spherical tokamak experiments. The simulation results reproduce several main properties of IRE. The noticeable property in the linear growth of modes are the simultaneous excitation of multiple low n modes, which grow together with similar growth rates. Spontaneous phase-alignment mechanism among those excited modes is found in the nonlinear stage of the development, which causes bulge-like deformation of the torus and subsequent expulsion of heat energy to the ambient region through occurrence of external reconnection.

I. Introduction

The spherical tokamak has revealed itself several favorable properties such as compactness and excellent stability in high-β plasmas. As the progress of experiments, it has been shown that several unique features are observed in the dynamical processes of spherical tokamak plasmas. A phenomenon called Internal Reconnection Event (IRE) is one of such feature, which has been observed in the spherical tokamak experiments such as START [1-3] and CDX-U[4], and is considered to be an energy relaxation phenomenon, although physical mechanisms of the event has not yet been clarified. In this paper, three dimensional magnetohydrodynamic simulations are executed in a full toroidal geometry to investigate the physical mechanisms of the event.

IRE observed in experiments is characterized by the following properties. 1) The central value of the plasma pressure falls rapidly in a time scale of around 100 or 200 microsecond (thermal quench), and 2) the heat energy is transported from the core to the edge rapidly, but 3) the event is not so destructive as to destroy the whole torus, and a property of resiliency is observed. 4) The net toroidal plasma current increases in 10 percent or more like a spike, following the occurrence of the thermal quench. 5) The event is accompanied by low m and n modes. 6) Vertical elongation of the poloidal cross section is observed.

II. Simulation Modeling

We execute magnetohydrodynamic simulations in a toroidal geometry shown in Fig.1, where the computation region contains both the toroidal plasma region and the ambient vacuum field region. The

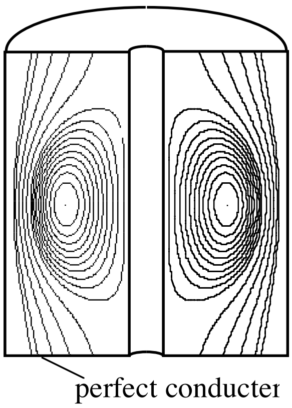

Fig.1 Simulation geometry.

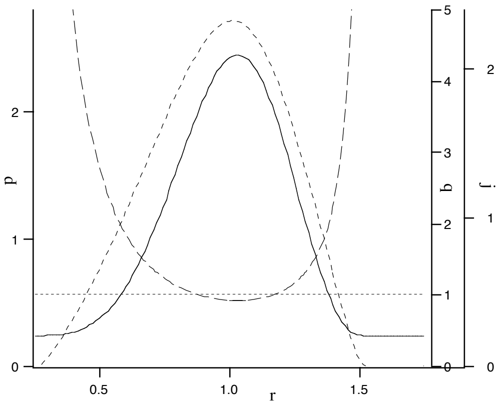

Fig.2 Initial profile of the safety factor q, plasma pressure p, and the plasma current j for case 1.

boundaries of the computation region are assumed to be a perfect conducting wall, on which the time derivative of the normal component of the magnetic field is set null. The governing equations consist of the full set of resistive and compressible magnetohydrodynamic equations as follows:

$$\frac{\partial \rho}{\partial t} = -\nabla\cdot(\rho\boldsymbol{v}), \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\boldsymbol{v}) = -\nabla\cdot(\rho\boldsymbol{v}\boldsymbol{v}) - \nabla p + \boldsymbol{j}\times\boldsymbol{B} + \mu(\nabla^2\boldsymbol{v} + \frac{1}{3}\nabla(\nabla\cdot\boldsymbol{v})), \tag{2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E}, \tag{3}$$

$$\frac{\partial p}{\partial t} = -\nabla\cdot(p\boldsymbol{v}) - (\gamma-1)p\nabla\cdot\boldsymbol{v} + (\gamma-1)(\eta\boldsymbol{j}^2 + \Phi - \nabla\cdot\boldsymbol{q}), \tag{4}$$

$$\boldsymbol{j} = \nabla\times\boldsymbol{B}, \tag{5}$$

$$\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \eta\boldsymbol{j}, \tag{6}$$

$$\Phi = 2\mu(e_{ij}e_{ij} - \frac{1}{3}(\nabla\cdot\boldsymbol{v})^2), \tag{7}$$

$$e_{ij} = \frac{1}{2}(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}), \tag{8}$$

$$\boldsymbol{q} = -\kappa\nabla_{||}(p/\rho). \tag{9}$$

The equations are solved in the cylindrical coordinate with a rectangular poloidal cross section. All the variables are normalized to the major radius of the simulation region and the toroidal magnetic field on the magnetic axis of the initial equilibria, therefore, the unit of time is the Alfven transit time(τ_A) encircling the magnetic axis. A finite difference scheme having fourth-order accuracy both in time and space is utilized. The numerical grid consists of, typically, 129x65x129 points. The initial condition is a two-dimensional axisymmetric equilibrium which is obtained by solving the Grad-Shafranov equation numerically under an assumption of polynomial pressure and current profiles. The equilibrium includes an externally opened vacuum magnetic field. The initial mass density is set to be unity over the whole region. The vacuum region is modeled as a very low temperature medium.

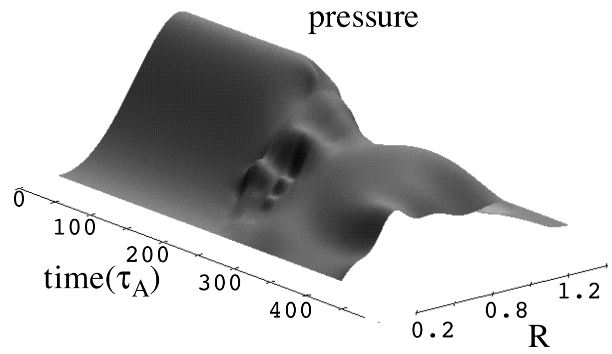

Fig.3 Sudden collapse in the plasma pressure profile on a midplane observed in the simulation (case 1).

III. Simulation Results

In this section, typical results in our simulations are shown. Shown in Fig.2 is the initial safety factor q profile for the first case (case 1), for which the central value of the safety factor, q(0), is slightly less than one. More specifically, the aspect ratio A is 1.35, the elongation κ is 1.6, the central beta $\beta(0)$ is 48%, and q(0) is 0.91 for the first case. As is shown below, the simulation results reproduce several main properties of IRE. As is shown in Fig.3, the central value of the plasma pressure falls in a time scale of around $100\tau_A$ (1 τ_A roughly corresponds to 1 microsecond), and the heat energy is transported from the core to the edge rapidly, but the event is not so destructive.

Shown in Fig. 4 is the time evolution of each Fourier component of the magnetic energy for case 1. A tiny perturbation .is given initially as a white noise to start the growth of instabilities. The level of the noise can be seen in the figure. As is plotted in Fig.3, the noticeable property in the linear growth of modes are the simultaneous excitation of multiple number of low n modes on the q=1 surface. In this case, m=1/n=1 and m=2/n=2 modes are the dominant ones, which grow together with the similar growth rates. Both of them are identified as the pressure-driven interchange mode. In this figure, the stage up to the time t = $150\tau_A$ may be called the "linear stage", where each mode grows independent of other modes; the phase of each mode is determined accidentally by the initial noise which is given in a random way. In the later stage, after t = $150\tau_A$, the mode coupling effects becomes significant, and many higher n modes are

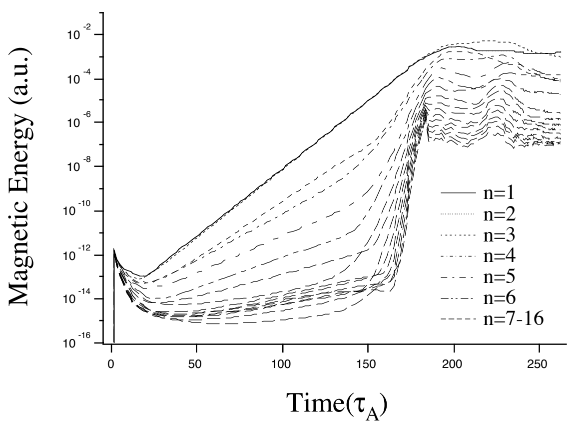

Fig.4 Growth of perturbation in the magnetic energy for each toroidal Fourier mode n (case 1).

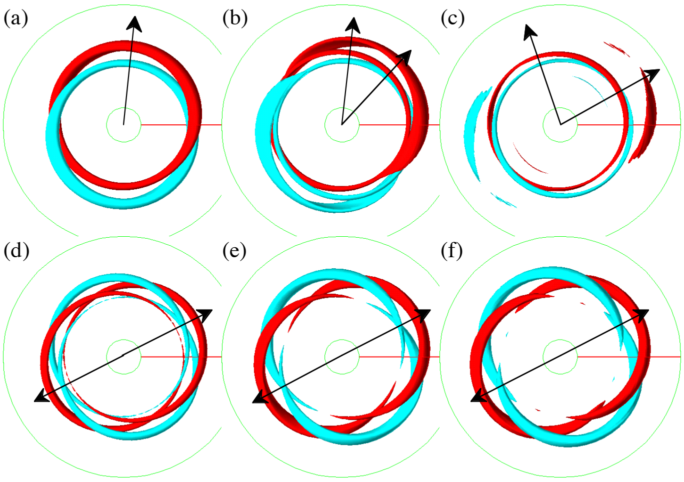

Fig.5 Temporal change in the mode structure of the n=1 mode ((a) to (c)), and of the n=2 mode ((d) to (f)), where red represents the positive perturbation, and blue represents the negative perturbation (case 1).

seen to be excited. This stage may be called the "nonlinear stage". In this stage, we find a notable property with respect to relative phase among the modes becomes apparent. Namely, a spontaneous phase-alignment mechanism is induced through nonlinear coupling between the dominant two modes, by which both modes develop while keeping a specific locked phase relation with each other.

Shown in Fig.5 is the temporal change in the mode structure of the n=1 mode ((a) to (c)), and of the n=2 mode ((d) to (f)), where the dark gray represents the positive perturbation, and the light gray represents the negative perturbation. The arrows in Fig.5 shows the direction of the positive perturbation for each mode, which defines the direction of the (positive) phase. It is observed that structure of the n=2 mode does not change so much. The structure of the n=1 mode, on the other hand, is eventually split into two parts, and the phase of the main part (the outer one) gradually rotates till it roughly aligns with the phase of the n=2 mode. This spontaneous phase-alignment mechanism is confirmed to be enhanced irrespective of the relative phase between the modes in the linear stage.

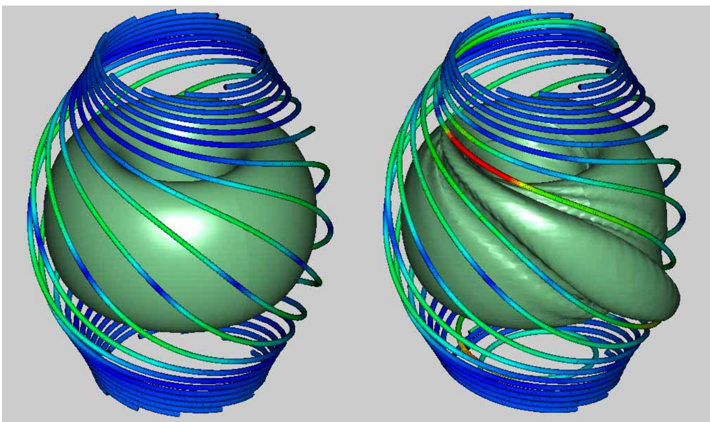

Fig.6 Time development of the three-dimensional profiles of the plasma pressure and magnetic field lines in the simulation result (case 1).

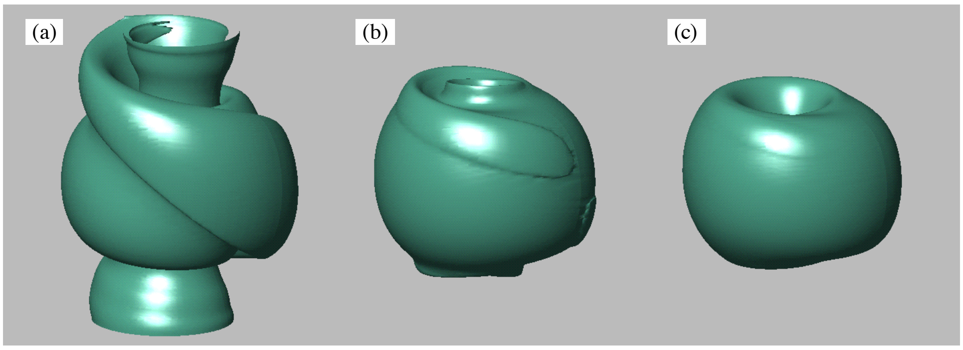

Fig.7 Time development of the pressure profile after the stage shown in Fig.6 (case 1).

Because of this nature, in real space, the perturbation in the torus does not grow uniformly around the torus, but expansive bulge-like deformation grows especially at a local region in the toroidal direction where the alignment in the positive perturbation occurs, as is shown in Fig.6. In the highly nonlinear stage, the heat energy is rapidly transported from the core to the edge region by convection due to the excited modes, which appears as the collapse in the pressure profile. It is interesting to note that a current sheet structure is formed on the periphery of the torus at the local toroidal region where the bulge-like perturbation mainly grows, and magnetic reconnection between the field lines in the torus and ambient fields are induced.

A part of field lines in the torus is directly connected with the external field lines due to the reconnection. The heat energy transported from the core to the edge of the torus is expelled to the external region along the reconnected field lines, which is found to occur rather impulsively. As is shown in Fig.7 (a), the expelled pressure is transmitted helically along the field lines in the external region, and the overall profile becomes a vertically elongated torus. The plasma shape which resembles Fig.7 (a) is actually observed in the experiment of START [5]. The excessive heat energy initially stored in the torus is expulsed from the torus in this way, and the torus plasma becomes linearly stable because of the expulsion and redistribution of the plasma pressure. Thus, the deformation of the torus caused by the unstable modes is gradually relaxed, and the torus comes back to an axisymmetric configuration, as is shown in Fig.7 (c).

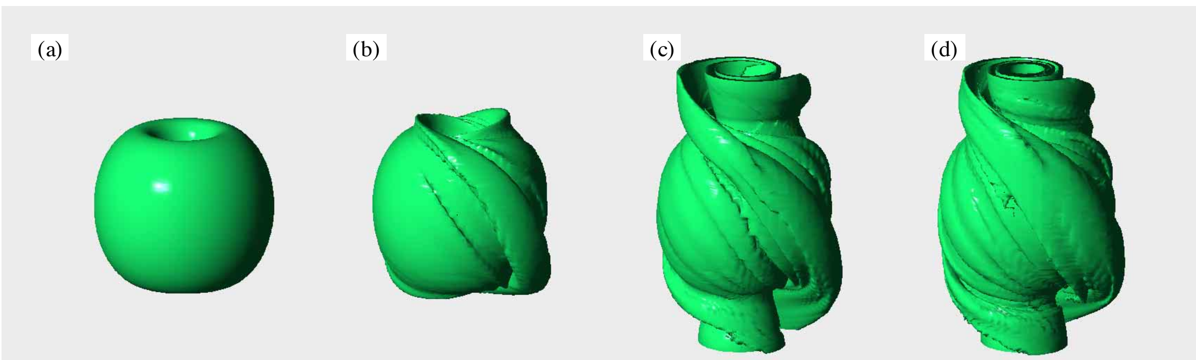

Fig.8 Time development of the pressure profile for case 2.

As a second example, we examine a case with q(0)>1 with a higher beta, where A is 1.42, the elongation κ is 2.4, the central beta $\beta(0)$ is 68%, and q(0) is 1.05 (case 2). As is shown in Fig.8, we obtain similar results of the quick expulsion of the heat energy to the external region also for this case. The dominant modes are n=2 (mainly m=3) and n=4 (mainly m=5), however, which have a nature of the ballooning mode. The bulge-like deformation is observed due to the similar phase-alignment property in the nonlinear stage, although two bulges appear for this case.

III. Summary and Discussion

Nonlinear simulations of Internal Reconnection Event in Spherical Tokamak were executed.

Scenario of IRE is proposed as follows.

1. Simultaneous excitation of multiple low n modes.
2. Local deformation of the torus due to a locked phase relation among modes caused by phase-alignment mechanism.
3. Occurrence of internal magnetic reconnection and external magnetic reconnection.
4. Expulsion of the excessive heat energy.
5. Return to a linearly stable axisymmetric equilibrium.

Those processes of the time development agree with the observations in spherical tokamak experiments in several points.

Our preliminary linear analysis shows that the property in the stability that a multiple number of low n modes are linearly unstable with similar growth rates is quite a general feature for pressure driven instabilities in the spherical tokamak configuration. The noticeable property of the spontaneous alignment in the relative phase of each mode, which is found in this paper, may have some generality in nonlinear dynamics, and is found only by executing nonlinear simulations as is described in this paper. For tokamak, Park et al have also numerically found formation of bulge-like structure, which was caused by excitation of localized ballooning modes as a result of kink type deformation of torus [6]. The mechanism in this paper, however, is different from the Park's case, in which the ballooning modes are excited as a "daughter" of the kink mode acting as a "mother". In the present case, on the other hand, the bulge is formed due to the phase-alignment among "sister" modes. Although the exact mechanism is still an open question, our computational experience on spherical tokamak indicates that such an alignment in phase often occurs after many e-folding times even for cases where the linear growth are slightly different.

We consider that the process observed in this paper is a mechanism that can expel "unnecessary" heat energy to the ambient region quickly. Owing to the existence of such mechanism, the spherical tokamak can efficiently readjust its own profile without destroying the whole torus while keeping the favorable property of the resiliency. Otherwise, a destructive process can occur, which may be called major disruption.

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