

The RFP discharges were improved by nonresonant helical fields. It is shown that the external helical current layer has a stabilizing effect on external kink modes. Another mechanism such as improved pitch at the edge is being examined.

The production of unidirectional field-aligned electron beam was confirmed with a MST type electron injector. No deterioration or slight improvement of the RFP discharges was observed with poloidal current injection up to 1 kA. The decrease in the local reversal parameter was observed. The results implies that global change in $F - \Theta$ plot needs current injection at plural toroidal locations.

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Ideal/Resistive Modes Analysis in Reversed Shear Configuration Plasmas

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In the reversed shear configurations, high- n ballooning mode can be stabilized by strongly negative magnetic shear. However, the ideal/resistive interchange modes become destabilized, and the double-tearing mode is induced due to the spatially close two rational surfaces. In this work, an attempt is made to seek stable domain and to clarify the roles of double tearing mode in the reversed shear tokamak operation, and the diagram for the linear stability and nonlinear behaviors are given.

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1. Introduction

It is one of the most important issues to improve the magnetohydrodynamic (MHD) stability for the enhancement of plasma performance and realization of tokamak reactor. A strongly negative magnetic shear configuration with a large bootstrap current¹ is considered to be one of the promising configuration to realize it. Recently reversed shear configuration with internal transport barrier shows very high performance confinement.² However, this configuration always terminated by MHD event and it is an agent task to clarify the mechanism and to develop the methods to sustain the high performance configuration for a long time. In negative shear configurations, the high- n ballooning modes can be stabilized by a negative magnetic shear. However, the infernal mode can be unstable for weak or zero shear regions³ and the ideal/resistive interchange modes become destabilized by a reduced magnetic well.⁴ The double-tearing mode is induced due to the current density gradient and the spatially close two rational surfaces. It is believed that these modes induce a collapse and limits the reversed shear operation. In this work, We applied the classical tearing mode theory to the reversed shear tokamak configurations, and an attempt is made to clarify the role of double tearing mode and to seek stable domains.

2. Model

We use the nonlinear reduced set of resistive MHD equations for the stream function Φ and the flux function Ψ in cylindrical geometry, because $m \geq 2$ (m : a poloidal mode number) double tearing modes are current driven modes and are not much influenced by toroidal geometry or finite beta effects. Basic equations are

$$\frac{\partial \Psi}{\partial t} = \{\Psi, \Phi\} + \frac{B_0}{R_0} \frac{\partial \Phi}{\partial \varphi} + \eta J - E^w,$$

$$\frac{\partial U}{\partial t} = \{U, \Phi\} + \{J, \Psi\} + \frac{B_0}{R_0} \frac{\partial J}{\partial \varphi} + \nu \Delta_{\perp}^* U,$$

$$U = \Delta_{\perp}^* \Phi, \quad J = \Delta_{\perp}^* \Psi,$$

$$\Delta_{\perp}^* = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2},$$

$$\{a, b\} = \frac{1}{r} \left(\frac{\partial a}{\partial r} \frac{\partial b}{\partial \theta} - \frac{\partial a}{\partial \theta} \frac{\partial b}{\partial r} \right),$$

$$\mathbf{v} = \mathbf{z} \times \nabla_{\perp} \Phi,$$

$$\mathbf{B} = \mathbf{z} \times \nabla_{\perp} \Psi + B_0 \mathbf{z},$$

In the following calculations, the helical symmetry is assumed because the effects of toroidal geometry and the perturbations with the different helicity are not take into account. The following equilibrium q -profile (q : safety factor) of reversed shear case is used;

$$q(r) = q_0 \left[1 + \left(\frac{r}{0.412} \right)^2 \right] \left[1 + (\Re - 1) \exp \left\{ - \left(\frac{r}{0.273} \right)^2 \right\} \right].$$

Here, $\Re (\equiv q(0)/q_0)$ is a parameter which represents the degree of shear reversal and several examples of q -profile with different value of \Re are shown in Fig. 1.

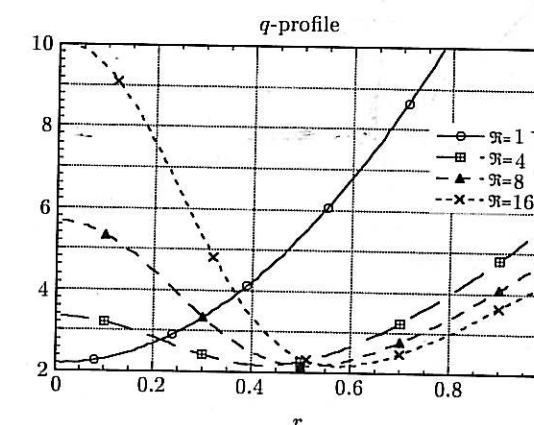


Fig. 1. Safety factor q profile for different shear reversal parameter \Re . $\Re = 1, 4, 8, 16$.

3. Stability Diagram

The nonlinear, two-dimensional time evolutions with an initial perturbation of linear eigen-function profile are computed. Simulations are performed mainly for a plasma with $\eta = 10^{-5}$ and $\nu = 10^{-6}$ and with flat density profile. We can divide the simulation results for the equilibrium configuration with two resonant surfaces into 4 classes.

(1) Double tearing mode is destabilized and reconnection occurs. Two chains of magnetic island grow in the initial phase. In the next stage, current sheets are formed between outer islands and core plasma and between inner islands and outer plasma and merging between them occur. The clash extends to plasma center (major clash). Safety factor profile/current profile is completely flattened from outer resonant surface to the magnetic axis in the final stage.

(2) Double tearing mode is destabilized and reconnection occurs and two chains of magnetic island merge. However, only minor part of the plasma is replaced (minor clash). Safety factor profile is flattened from inner resonant surface to outer one in the final stage.

(3) Final state is two island chains (saturated tearing mode) and equilibrium current profile is weakly flattened near the resonant surfaces. Only one of resonant surface, the outer one in the normal shear region, contributes to destabilization.

(4) A resonant surface in the negative shear region contributes to destabilization and final state is almost the same as previous case.

In Fig. 2, we show the diagram of final stage of nonlinear calculations for $m = 3/n = 1$ mode in $\mathcal{R} - q_{\min}$ plane (n , a toroidal mode number). We can see that there exists stable region for $m = 3$ double tearing mode in the region which q_{\min} is just above 2 and moderate $\mathcal{R} (< 10)$. In the case of $q_{\min} < 2$, we must consider the possibility of $m = 2$ mode excitation, $m = 2$ mode is more unstable than $m = 3$ mode and easily induce major disruption. The $m \geq 4$ modes are more stable and do not induce major clash even when it become unstable. Linear growth rate for case (1) is $1.37 \times 10^{-2} \tau_A$ for $\mathcal{R} = 4$, $q_{\min} = 2.72$ and it is proportional to $\eta^{1/3}$. The clash time (from the formation of current sheets to complete the reconnection) is also of the same order.

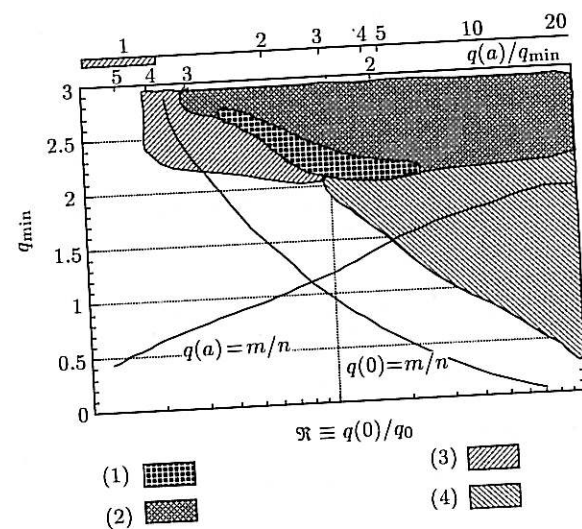


Fig. 2. Stability diagram for $m = 3/n = 1$ mode (m/n are poloidal and toroidal mode number, respectively). In region (1), double tearing mode induces a major clash. In region (2), double tearing mode induce only a minor clash. In region (3) and (4), the saturation of tearing mode is realized in the final stage. Destabilization comes from outer resonant surface and positive shear region in case (3) and from inner one in case (4).

4. Discussion and Conclusion

The existence of stable zone for $m = 3$ double tearing mode is shown in this work. The application of feedback control systems for reconnection events, for cases (1) and (2), is difficult for its fast time scale. For saturated case (3), local electron cyclotron heating (ECH) or electron cyclotron current drive (ECCD) can be applied as usual tearing case,⁷ if we choose a proper side of islands and proper direction for current drive. Local (O -point) ECH can stabilize the islands only for normal shear case and ECCD must be driven in the opposite direction in the reversed shear case.

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Nonlinear Simulations of Relaxation Phenomena in Spherical Tokamak

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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 the 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 torus and subsequent expulsion of heat energy to ambient region.

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1. 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 START¹⁻³ 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 200 microsecond, 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. (5) The event is accompanied by low m and n modes. (6) Vertical elongation of the poloidal cross section is observed.

2. Simulation Modeling

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

erning equations consist of the full magnetohydrodynamic equations.

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 Alfvén 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, $129 \times 65 \times 129$ 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.

3. Simulation Results

In this section, typical results in our simulations are described. We examine a case 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. 1, the central value of the plasma pressure falls in a time scale of around $150 \tau_A$ ($1 \tau_A$ 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. 2 is the time evolution of each Fourier component of the magnetic energy for the case