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Simulation Research on Runaway Electrons in Tokamak Disruption Events
ディスラプション時の逃走電子シミュレーション研究

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The goal of our project “DISRUPT” using the Helios supercomputer at IFERC-CSC is to develop an integrated simulation code for describing whole duration of major disruptions including its 3D nature. Our current scope is runaway electrons (REs), which may unacceptably shorten the lifetime of the plasma facing components in ITER and DEMO. The present experiments have pointed out that low-order MHD instabilities play a significant role in the RE generation as well as the RE current plateau termination. We propose two different approaches to incorporate MHD events into RE modeling, which is based on (1) nonlinear MHD codes for internal modes and (2) linear MHD codes for external modes.

1. Introduction

Runaway electrons (REs) produced during major disruptions can gain the energies above 10 MeV and their localized wall loads may unacceptably shorten the lifetime of plasma facing components. In ITER, even a small seed current can be amplified by an avalanche mechanism, and the formation of multi-MA RE beams poses a serious problem. Therefore, the development of mitigation schemes has become one of the most important topics in ITER.

Up to present, 2D axisymmetric modeling of disruptions has widely been used, which are powerful tools for the parametric study to interpret the experiments and to predict the disruption scenarios. On the other side, the necessity of improved modeling taking into account 3D nature of disruptions is recognized especially if we focus on the toroidal asymmetry of the energy deposition on the vessel wall as well as of the electromagnetic loads. Concerning REs, enhanced RE losses have been observed with the excitation of magnetic fluctuations, typically being n = 1 mode (n: toroidal mode number), which results in toroidally localized wall loads in the RE discharge termination phase. In addition, the proposed mitigation schemes such as massive gas injection and resonant magnetic perturbations require 3D modeling of disruptions and RE generation processes.

From 2012, we have initiated a project “DISRUPT” in IFERC-CSC, which is aimed at describing whole duration of major disruptions including its 3D nature by simulations. Under this project, ETC-Rel [1,2] has been developed and continuously improved as 3D modeling of REs, which solves relativistic guiding-center equations for Monte-Carlo test particles. In this paper, our recent progress is described especially focusing on the study for examining how REs respond to the excitation of low-order MHD instabilities.

3. Redistribution of REs by Internal Modes

The MHD modes that arise in the early phase of a current quench has been considered to mitigate the RE generation [3]. Because REs are produced predominantly in the core region near the magnetic axis, the main contribution is expected to be due to internal modes. When we consider their impact on the RE confinement, the saturated island widths are a key parameter because REs are redistributed at a large parallel velocity along the stochastic magnetic fields once magnetic islands at different radial locations are overlapped. For treating such a phenomenon, we integrate a nonlinear reduced MHD code Extreme [4] (based on the spectral method in the poloidal and toroidal directions) with ETC-Rel. Figure 1 shows the evolution of (a) magnetic energy, and (b) radial profile of seed REs calculated, where a resistive kink mode is considered as an example of the MHD mode that causes the RE redistribution in the core plasma. Here, an initial MHD equilibrium with the peaked current profile ($q(0)$ ~ 0.6) is chosen for the resistive kink to be unstable. The simulation has shown that REs immediately respond to the change of magnetic field topology associated with the kink growth, and the timescale of RE redistribution is dominated by the mode growth, independently of the RE energy. The physics involved is considered to be similar to the relaxation of fast-ion densities in the presence of sawteeth and fishbone. On the other side, since REs are sensitive to the perturbing fields because of its small gyroradii, short-wavelength magnetic turbulence can also enhance the radial transport of REs. To improve the resolution, an application of R4F [5] which can treat higher n modes on the basis of pseudo-spectral method with massively parallel computer is also underway.

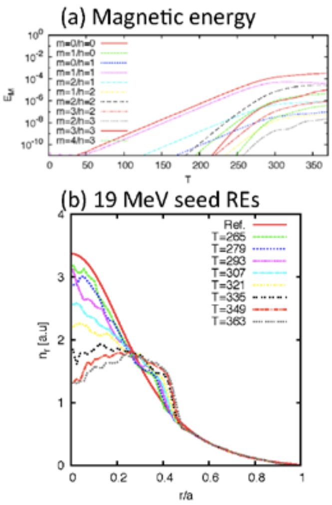

Fig.1. Evolution of magnetic energy and of the radial profile of 19 MeV REs in the nonlinear saturation phase of resistive kink mode calculated by Extreme [5], where the time T is normalized by the Poloidal Alfvén unit.

3. RE Loss Flux Driven by External Modes

Another important contribution of MHD modes to REs is the RE current plateau termination driven by external modes. Although the stability properties of the RE current plateau have not yet been elucidated, the experimental correlation of prompt RE losses with the surface safety factor values are rather clear. It suggests the contribution of external-kink type modes. Following this idea, we develop a simulation model combining the linear stability code MARG2D [6] with ETC-Rel. Figure 2 shows the Poincaré map of the RE drift orbit recorded on the outer equatorial plane in the presence of m = 4 external kink perturbations for $\delta B/B$ ~ 1%. (Here, $q(a)$ is selected to be 3.8.) Near the plasma edge, such a strong perturbation causes a prompt loss of REs even in the absence of stochastic fields. For edge perturbations like RMPs and external MHD modes, the energy dependence of RE losses are dominated by horizontal shift of the resonant position against the MHD modes due to the curvature drift motion. The simulation show that REs are lost to the vessel wall as if the current channel outside $q_K > 3$ is scraped off, where q_K is an effective safety factor measured along the drift surface. Because the loss pattern to the wall is governed by the radial magnetic field that is felt by particles [7] when they are lost from the boundary between closed and open field lines, the wall loads exhibit the n = 1 toroidal asymmetry.

4. Summary and Future Work

Progress in the project "DISRUPT" has been reported, focusing on the RE physics. As the next step, the simulation codes will be extended as an MHD+PIC hybrid model for studying the interaction between REs with MHD. Another important task is to treat slow plasma boundary evolution on the transport timescale, taking into account vertical displacement events (VDEs), which dominates a final loss position of REs. In addition, for the development of RE control scheme such as collisional dissipation [8], the equilibrium and linear stability models for the RE current plateau will also become important.

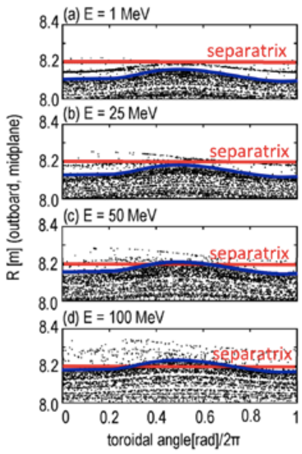

Fig.1. Poincaré map of 1-100 MeV RE drift orbit on the outer equatorial plane in the presence of external kink mode calculated by MARG2D, where $\delta B/B$ ~ 1%. Red segments indicate the magnetic separatrix and the blue curve indicates q_K = 3 drift surface.

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