Three-Dimensional Simulation of the Vertical Displacement Event in Tokamaks

K. J. Shin, Y. Y. Lim, C. H. Shon, and J. K. Lee

***Abstract*— Tokamak plasmas with highly elongated cross sections are subject to a vertical displacement event (VDE). The nonlinear magnetohydrodynamic (MHD) evolutions of tokamak plasmas during VDE are visualized by a three-dimensional MHD simulation. The nonlinear evolution during VDE is strongly affected by the relative amplitude of the nonaxisymmetric to the axisymmetric mode.**

***Index Terms*— Magnetohydrodynamic (MHD), simulation, tokamak, vertical displacement event (VDE).**

A tokamak with high pressure and high plasma currents demands vertically elongated plasma, which is inherently unstable to vertical displacements. During such an event, the vacuum vessel may be subject to large vertical forces and the observed distribution of the halo current is not toroidally axisymmetric [1]. Most of the previous studies are carried out assuming an axisymmetry in the toroidal direction, thus inadequate for explaining the nonaxisymmetry of the experimental observation. The tool employed in the present study to simulate a vertical displacement event with three-dimensional nonaxisymmetry is a magnetohydrodynamic (MHD) simulation code CART [2], [3], which can be used to calculate the time development of the MHD instability and the equilibrium of the plasma during the vertical displacement event (VDE).

The tokamak model used in this paper has fourteen poloidal current coils and two quadrupole current coils which are located at a vertically symmetric position in Fig. 1, with major radius $R_{\rm major} = 1.4$ m and plasma radius $R_{\rm minor} = 0.25$ m. The modeled tokamak has two up–down symmetric divertors and a rectangular wall boundary.

Given the coil distribution, reference MHD equilibria are computed using the free boundary MHD equilibrium code FBT [4] which calculates highly elongated and arbitrarily shaped equilibria with separatrices and multiple magnetic axes. The plasma shape is chosen to have elongation $\kappa = 2.0$ to allow for adequate vertical stabilization.

The equilibrium state is for the plasma horizontal radius 0.25 m, the plasma vertical radius 0.5 m, the plasma elongation $\kappa = 2.0$, the toroidal vacuum magnetic field $B_{\rm tor} = 3.5$ T, the toroidal plasma current $I_{\rm plasma} = 0.51$ MA, the plasma peak pressure 1.37×10^4 pascal, the plasma $\beta_{\rm toroidal} = 0.06\%$, the plasma $\beta_{\rm poloidal} = 7.8\%$, and the safety factor q at 95% flux surface $q_{95} = 3.8$.

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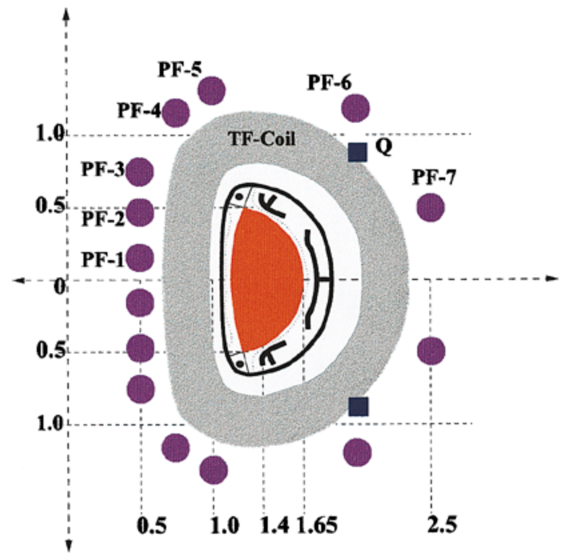

Fig. 1. The high-pressure and high-current elongated tokamak model.

The coordinates used here are (R, Z, ϕ) Cartesian coordinates and the spectral representation in the toroidal direction has been used. The equations are the MHD equations as in [2] and [3]. In the linear mode, the equations are linearized about the equilibrium, and the perturbation solution is iterated in time for each toroidal harmonic N until it grows with an exponential time dependence $e^{\gamma t}$. In the nonlinear mode, the linear eigenfunctions are used to initialize the nonlinear evolutions. Several N modes are coupled, and the full nonlinear equations are iterated in time until the predetermined number of timesteps is reached. 65 grids are used in each R and Z direction.

As shown by Fig. 2, the plasma moves vertically downward. The plasma current shows a similar feature to the poloidal magnetic stream function A.

Our simulations start from the linear eigenmodes with $N = 0$ and $N = 1$ (with variable relative starting amplitudes) to observe a nonlinear state exhibiting a substantial displacement of the plasma center. $N = 2$ and $N = 3$ are the first and the second nonlinear harmonics, respectively, growing from these linear ($N = 0$ and $N = 1$) eigenmodes.

There have been experimental observations that the comparable magnitude of the $N = 1$ mode is mixed with the $N = 0$ mode during VDE [1]. The simulation of mixed $N = 0$ and $N = 1$ modes can give some physical insight to understand the VDE. Various ratios of $N = 0$ to $N = 1$ are used in our nonlinear simulations. It can be seen that the displacement of the magnetic axis is gradually suppressed as the amplitude of $N = 1$ mode becomes larger. The toroidal plasma current

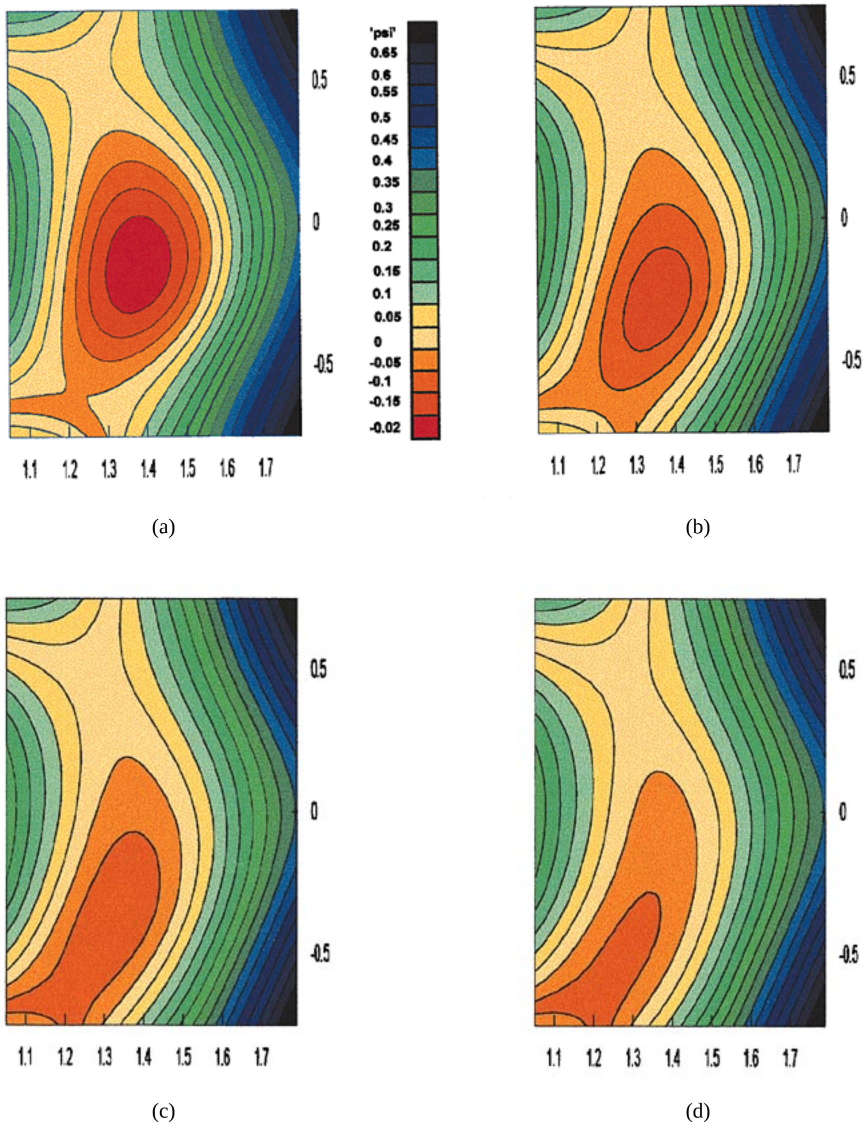

Fig. 2. Nonlinear evolution of the total plasma cross section at time (a) =0.734 msec, (b) 1.100 msec, (c) 1.467 msec, (d) 1.834 msec.

decreases slower and the scrape-off layer current increases slower when the $N = 1$ perturbation becomes larger.

In summary, the finite-pressure and high-current noncircular tokamak equilibria are calculated by the FBT program to be used for the linear and nonlinear resistive MHD simulations by the CART code. The vertical displacement of the plasma results from the axisymmetric $N = 0$ alone. Varying proportions of the nonaxisymmetric $N = 1$ mode, included along with the $N = 0$ mode, elucidate the physical phenomena and the consequences of the instability initiated by a vertical displacement instability leading to a nonaxisymmetry. No prior nonaxisymmetric nonlinear simulation has been carried out on this aspect of VDE despite the experimental observation of a significant amplitude of the nonaxisymmetry. A typical nonlinear calculation on a Cray-2 takes 2–4 h on 65 by 65 grids with 4–5 toroidal mode numbers.

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