Extended-MHD modeling of tokamak disruptions and resistive wall modes with M3D-C1

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Introduction

Disruptive instabilities in tokamaks are often strongly affected by the coupling between the plasma and surrounding conducting structures. This coupling plays an important role in both the linear threshold of disruptive instabilities such as resistive wall modes (RWMs), and also in the subsequent nonlinear evolution of the disruption, which generally involves a large and rapid displacement of the plasma and penetration of magnetic flux through the wall.

A new capability to model these interactions using the extended-MHD code M3D-C1 [1, 2] has recently been demonstrated [3]. This model includes the capability to model resistive walls of arbitrary thickness, to spatially resolve current density in the wall, and to allow currents to flow from the plasma to the wall and back. Both eddy currents induced in the wall by the plasma motion and Halo currents driven on magnetic field lines that intersect the wall are naturally captured in this model.

Here we show recent applications of this model to RWMs and vertical displacement events (VDEs) in tokamaks. It is found that the electromagnetic forces on the wall due to the VDE are weakly sensitive to the wall conductivity, although the impulse delivered to the wall increases with the wall conductivity. A current spike is also routinely observed in the simulations when the vertical motion of the plasma is halted upon impact with the upper or lower divertor. The three-dimensional evolution of the plasma undergoing an initially axisymmetric VDE is also explored. Furthermore, the effect of rotation on RWMs is considered. It is found that the RWM may be fully stabilized by rotation, and that the growth rate essentially follows the quadratic dependence on rotation predicted in the thick-wall limit [4].

Model

The mesh in M3D-C1 is divided into three parts, as shown in figure 1. The innermost region is the "extended-MHD" region in which the extended-MHD equations [3] are solved for density, pressure, the fluid velocity, and the magnetic field. Surrounding the "extended-MHD" region is the "resistive wall" region in which only the magnetic field is solved, subject to the equation $\partial_t\vec{B} = -\nabla\times(\eta_w\vec{J})$, where $\vec{J} = \nabla\times\vec{B}/\mu_0$. Surrounding the "resistive wall" is the "vacuum

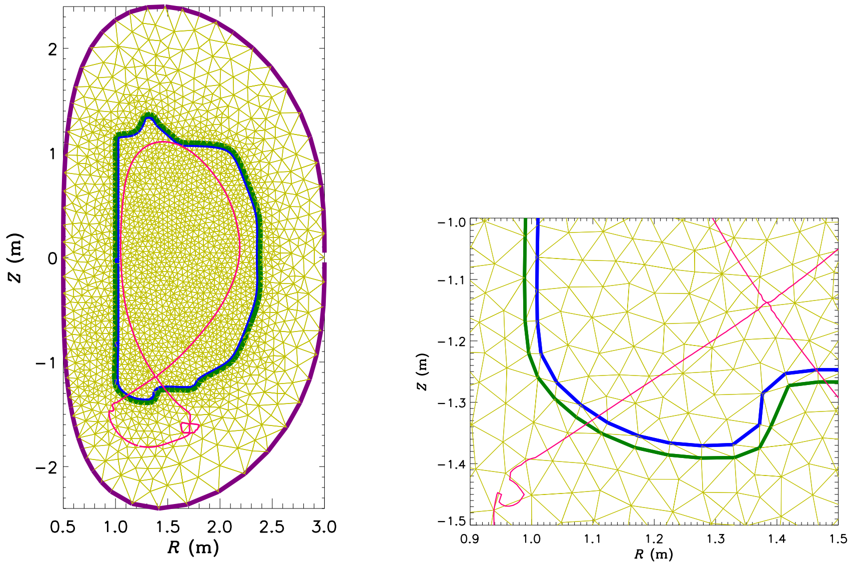

Figure 1: An example of a mesh in which the resistive wall region takes roughly the shape of the DIII-D first wall. The extended-MHD region is enclosed by the blue curve; the resistive wall region lies between the green and blue curves, and the vacuum region lies between the purple and green curves. The separatrix of a typical DIII-D plasma is shown in magenta.

region" in which only $\vec{J} = 0$ is solved. The outer extent of the vacuum region is the computational domain boundary, where superconducting boundary conditions are applied. Treating the resistive wall in this way and not as a boundary condition has the advantage of maintaining purely local coupling between mesh elements, which is advantageous for parallelization. The equations in all three mesh regions are solved simultaneously and implicitly.

Resistive Wall Modes

In Ref. [3], the RWM stability in a Shafranov equilibrium was considered using a reduced (two-field) model in order to validate M3D-C1 against analytic theory. It was shown that M3D-C1 reproduces the analytic result in both the resistive-wall and inertial limits of the instability for arbitrary wall thickness. Here we additionally consider the effect of toroidal rotation on the RWM stability of this equilibrium. In these simulations, an equilibrium toroidal rotation of the form $\omega = \omega_0(1-\Psi_N)$ is included, where Ψ_N is the normalized poloidal flux.

In figure 2, the growth rate γ calculated by M3D-C1 for a range of ω_0 is compared to a thick-wall model published by Pustovitov [4]: $\gamma = \gamma_0(1-\omega^2/\omega_c^2)$, where γ_0 is the growth rate in the absence of rotation and $\omega_c = 2\gamma_0/n$. Even in the thick-wall limit, quantitative agreement between M3D-C1 and Pustovitov's model is not expected here due to some differences in assumptions (for example, the radial dependence of the rotation profile).

Nevertheless, decent agreement is found in the thick-wall case when we take ω to be the rotation frequency at $\Psi_N = 0.5$. While the growth rate in the thin-wall case is also roughly quadratic in the rotation, the calculated cutoff differs from the model's prediction here by roughly a factor of four.

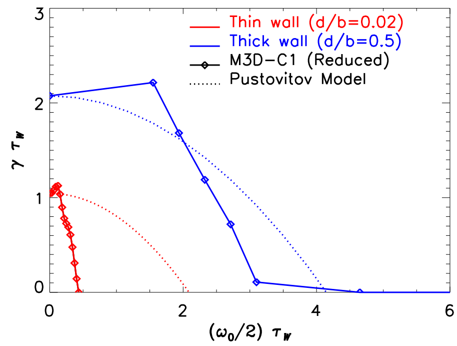

Figure 2: The RWM growth rate normalized to the resistive wall time $\tau_W = \mu_0 db/\eta_W$ as calculated by M3D-C1, as a function of $\omega(\Psi_N = 0.5) = \omega_0/2$. Here d, b, and η_W are the thickness, minor radius, and resistivity of the wall, respectively. The dotted lines show the prediction of Pustovitov's thick-wall model, given the growth rate of the non-rotating case.

Vertical Displacement Events

VDEs result from the loss of control of the vertical position of the plasma. They may follow (as in a "cold VDE") or induce (as in a "hot VDE") a thermal quench (TQ) in which the thermal energy of the plasma is mostly lost. We have carried out simulations of both hot and cold VDEs in order to examine the currents and forces induced by these events in the resistive wall. In particular, the non-axisymmetric forces which may arise due to secondary instabilities in the plasma are of interest, as these present a greater threat to the structural integrity of the device than axisymmetric forces.

The plasma is initialized in a vertically unstable axisymmetric equilibrium. Here, the plasma is initially stable to non-axisymmetric modes, and is observed to remain axisymmetric until after it makes contact with the wall. Upon contact with the wall, the plasma begins to be scraped-off by the wall at a rate set by the wall resistivity. By removing the outer layers of the plasma, this process tends to reduce the limiting value of the safety factor, q_a.

In simulations of cold VDEs, in which a large anomalous perpendicular thermal conductivity (> 100 m^2/s) cools the entire plasma to ~ 70 eV within 1 ms, the rapid resistive decay of the plasma current I_P causes q_a to rise more quickly than the scraping-off process can reduce it. Therefore, these cases are expected to remain stable to non-axisymmetric modes.

In contrast, in simulations of hot VDEs, in which thermal conductivity is taken to remain at ~ 10 m^2/s and the plasma remains at keV temperatures even after contact with the wall, the resistive decay of I_P is slow, and the scraping-off of the plasma causes q_a to drop (while the q profile in the plasma core remains essentially fixed). In these cases, the plasma is observed to go unstable to non-axisymmetric modes. It is found that the plasma remains dominantly axisym-

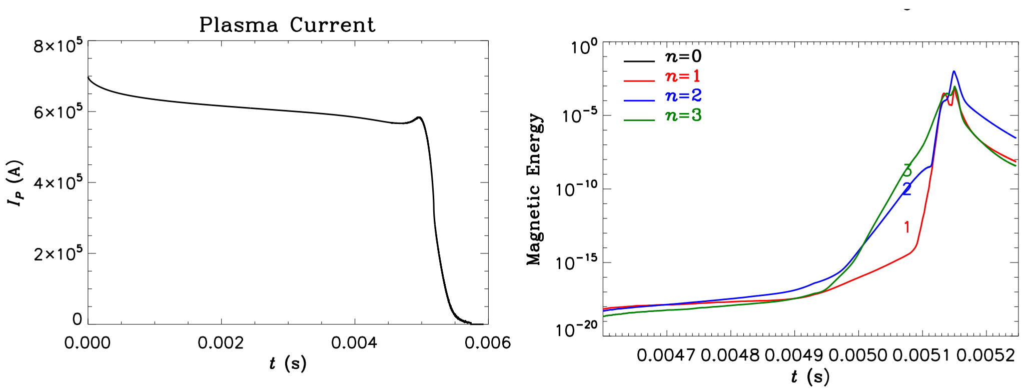

Figure 3: *Left*: I_P in a VDE simulation in NSTX geometry, showing a spike just before the current quench. *Right*: the energy associated with the $n = 1$–3 components of the magnetic field. For reference, $q_a = 2$ at roughly 4.89 ms, and $q_a = 1$ at roughly 5.03 ms.

metric until q_a drops below 1, at which point an $n = 1$ instability rapidly grows. Subsequent investigation has found that the anomalously high temperature of the scrape-off layer (SOL) in these calculations $\sim$ 100 eV may be spuriously stabilizing kinks that would otherwise be expected to grow at lower values of q_a. Work to treat the SOL more realistically, in order to capture the non-axisymmetric evolution of the plasma more accurately, is ongoing.

Both simulations of hot and cold VDEs show a clear spike in I_P when the plasma makes contact with the divertor wall (*c.f.* figure 3). This spike is associated with the rapid loss of counter-I_P currents that are induced on the surface of the plasma by the motion of the plasma toward the wall. In hot-VDE simulations, the plasma remains hot during the spike (*i.e.* the thermal quench occurs after the spike). In cold-VDE calculations, the thermal quench is complete before the plasma has displaced appreciably, and no current spike is observed at the time of the thermal quench. These observations are apparently at odds with the conventional understanding that the current spike is associated with the change in internal inductance following the thermal quench. This surprising result is under investigation.

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