M3D Simulations of ITER Halo Currents

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ITER Halo Currents

Preliminary work is presented on halo current simulations in ITER.

The first step is the study of VDE (vertical displacement event) instabilities[1]. The growth rate is consistent with scaling inversely proportional to the resistive wall penetration time. The simulations have self consistent resistivity proportional to the $-3/2$ power of the temperature. Simulations have been done with temperature contrast between the plasma core and wall of 100, to model the halo region between the core and resistive shell. Some 3D simulations are shown of disruptions competing with VDEs. The toroidal peaking factor can be as high as 3, and the halo current fraction as high as 40%.

The part of the mesh adjacent to the outer wall (the ITER - FEAT first wall) was made using the ellipt2d package [2].

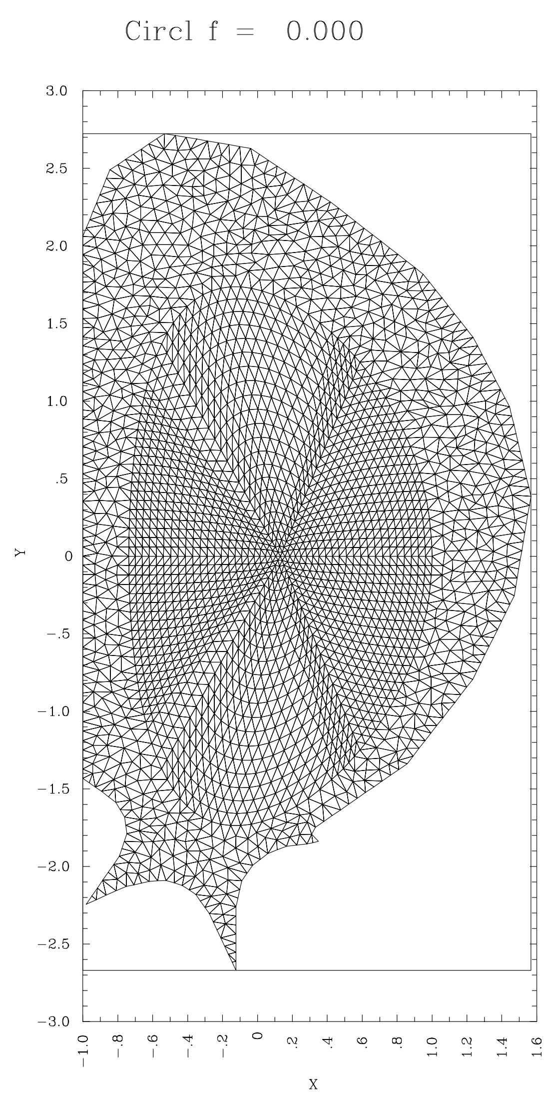


Fig.1 Mesh in poloidal plane

The code includes a temperature equation, with thermal conduction along the magnetic field modeled by the artificial sound method. The resistivity is proportional to $T^{-3/2}$, where T is the temperature. The halo region between the plasma core and the wall is modeled as a cold resistive plasma. Simulations have been done with core temperature 100 times the halo temperature, for a resistivity contrast of 1000.

The M3D code includes resistive wall boundary conditions, which match the solution inside the resistive wall to the exterior vacuum solution. The exterior problem is solved with a Green's function method, using A. Pletzer's GRIN code.

Resistive Wall Boundary Conditions

On the resistive wall boundary, integrating $\nabla \cdot \mathbf{B}$ across the thin shell gives

$$\hat{n} \cdot \mathbf{B}^v = \hat{n} \cdot \mathbf{B}^p \tag{1}$$

where $\hat{n}$ is the outward normal from the plasma.

The vacuum field is solved by the GRIN code. For an axially symmetric wall, the vacuum field is first Fourier expanded. From Green's identity one has an integral equation relating $\hat{n} \times \mathbf{B}^v$ to $\hat{n} \cdot \mathbf{B}^v$ on the boundary contour.

Now the magnetic field components in the plasma have to be matched using resistive evolution at the inner boundary, which is a thin resistive shell of thickness δ and resistivity η_w.

Ohm's Law in the plasma adjacent to the resistive wall is

$$\frac{\partial \mathbf{A}}{\partial t} = \nabla \Phi + \frac{\eta_w}{\delta} \hat{n} \times (\mathbf{B}^v - \mathbf{B}^p). \tag{2}$$

Vacuum currents are modeled with a "virtual casing" condition, requiring $\hat{n} \times \mathbf{B}^v = \hat{n} \times \mathbf{B}^v$ in the initial equilibrium.

VDE Simulations

The VDE instability growth rate is inversely proportional to the wall resistive penetration time, or η_w. This scaling is consistent with simulations, as will be shown below. To get the scaling it seems necessary to be in a regime in which the core resistive decay time is long compared to the wall penetration time, which in turn is longer than the halo current resistive decay time,

$$\tau_{core} > \tau_w > \tau_{halo}.$$

Here $\tau_{core} = S\tau_A$, and $\tau_{halo} = (T_{halo}/T_{core})^{3/2}\tau_{core}$, where $\tau_A = R/v_A$ is the Alfvén time, R is the major radius, v_A is the Alfvén velocity, $S = a^2 v_A/(\eta R) = 10^4$ in the simulations, where a is the geometric half width in the midplane, and S is the initial value at the magnetic axis. In the following, $T_{halo} = 10^{-2}T_{core}$, where T_{halo} and T_{core} are halo and core temperatures, and $\tau_w = \delta_w/\eta_w S\tau_A$. We have chosen parameters in the regime

$$1 > \frac{\tau_w}{\tau_{core}} > 10^{-3} = \frac{\tau_{halo}}{\tau_{core}}$$

For over two orders of magnitude variation in η_w/δ_w, the growth rate of the VDE scales as

$$\gamma = 4.0\eta_w/\delta_w. \tag{3}$$

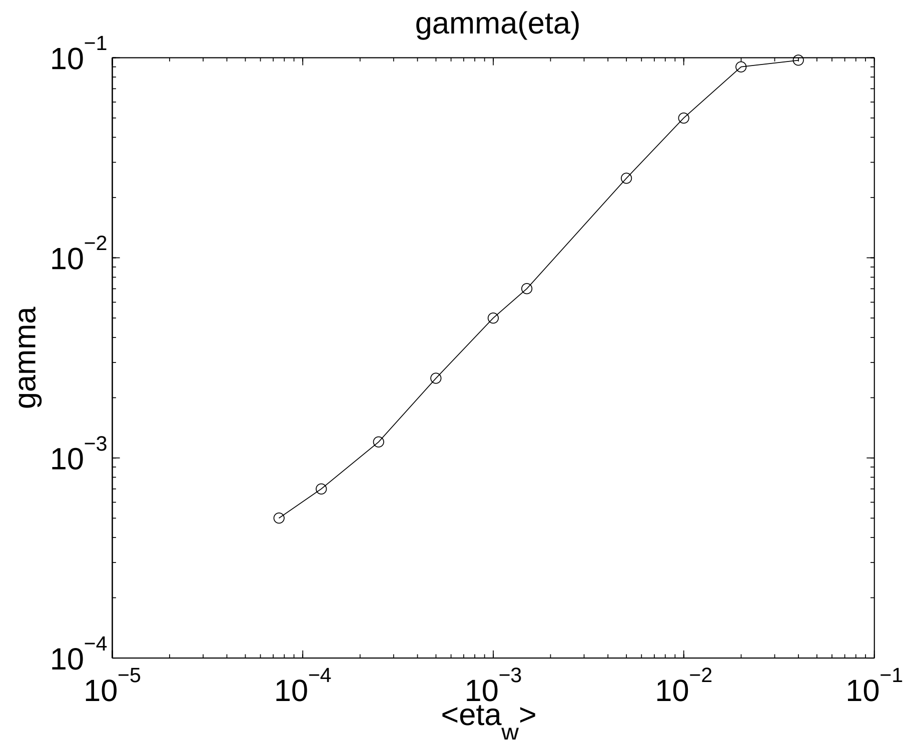


Fig.2 Growth rate of VDEs vs. η_w/δ_w

The nonlinear stage of the VDE is shown below at time $t = 103\tau_A$.

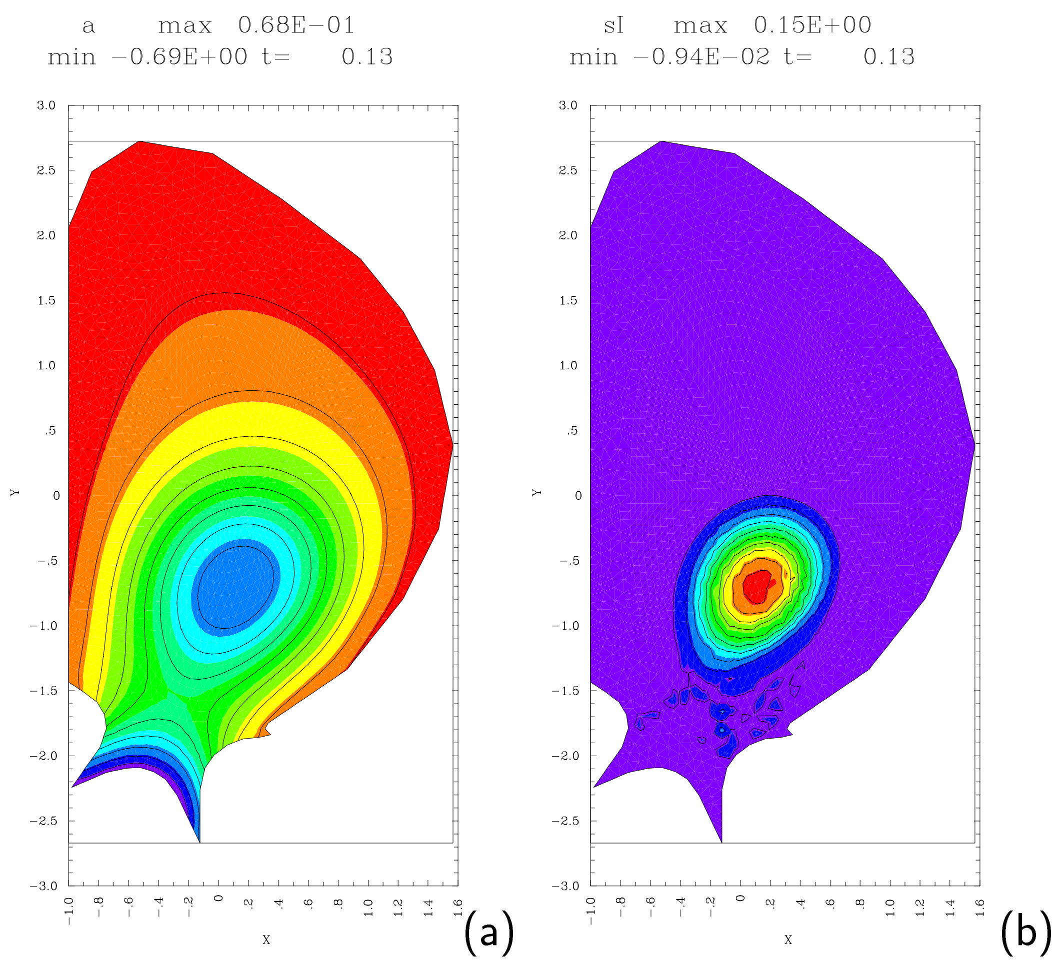
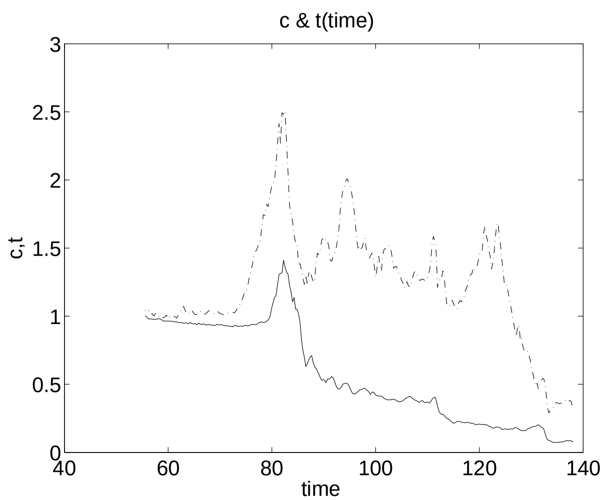


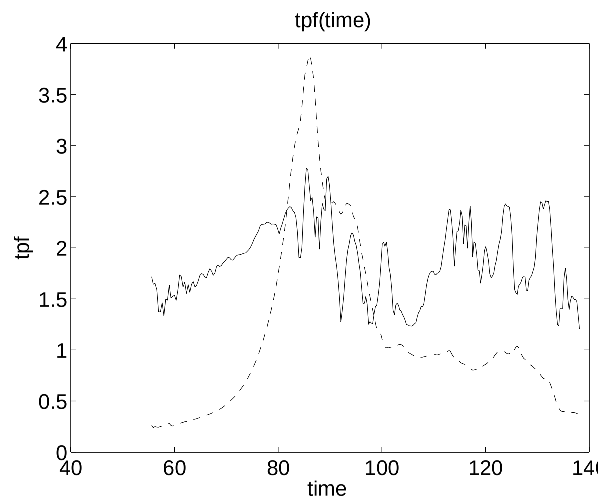
Fig.3 (a) Poloidal Flux (b) Toroidal Flux at t $= 103t_A$

Disruption Simulations

In three dimensional simulations, disruptions can occur. In one scenario, a disruption causes a thermal quench, which in turn causes a current quench. This is accompanied by a VDE. The initial state has $q = 0.6$ on axis, with an inversion radius including most of the core plasma. This is internal kink unstable. When the instability is sufficiently nonlinear, toroidal coupling to other modes causes a disruption. The plasma cools because of transport along stochastic field lines. This raises the resistivity and dissipates the current.



(a)



(b)

Fig.4 (a) normalized peak toroidal current (dotted line) and peak temperature vs. time (b) toroidal peaking factor (tpf) and halo current fraction $\times 10$ (dashed line) vs. time.

The temperature quench proceeds the current quench. The current, plotted with a dashed line, declines in value more slowly than the temperature, shown as a solid line. The toroidal peaking factor almost reaches 3, but most of the time oscillates around 2. The peak current fraction is 40%. The halo current is the normal component of the poloidal current integrated over the wall,

$$I_h(\phi) = \frac{1}{2}\int |\hat{n} \cdot \mathbf{J}| R d\ell$$

The toroidal peaking factor is the maximum of $I_h(\phi)$ divided by its toroidal average $< I_h >= 1/(2\pi)\int I_h d\phi$,

$$tpf = I_{h(max)} / < I_h >. \tag{4}$$

The total toroidal current is $I_\phi = \int J_\phi dRdZ$ and the ϕ average is $< I_\phi >$. The halo current fraction is the ratio $< I_h > / < I_\phi >$.

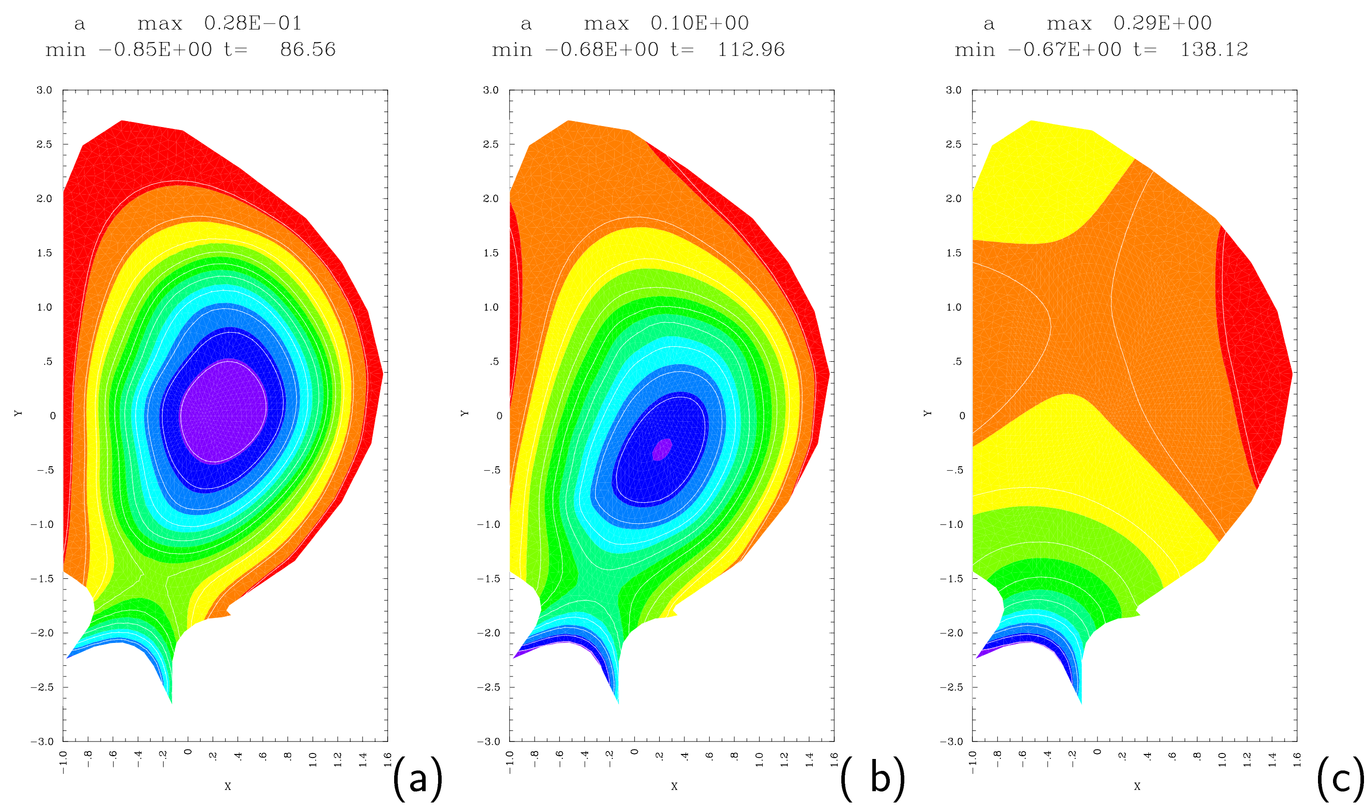


Fig.5 Poloidal Flux at $t =$ (a) $87t_A$ (b) $113t_A$ (c) $138t_A$

The disruption occurs at time $t = 87\tau_A$. The VDE occurs later at time $t = 126\tau_A$. The VDE is caused by the loss of poloidal flux in the plasma, while the poloidal flux in the divertor is unchanged. This moves the toroidally averaged magnetic axis into the divertor.

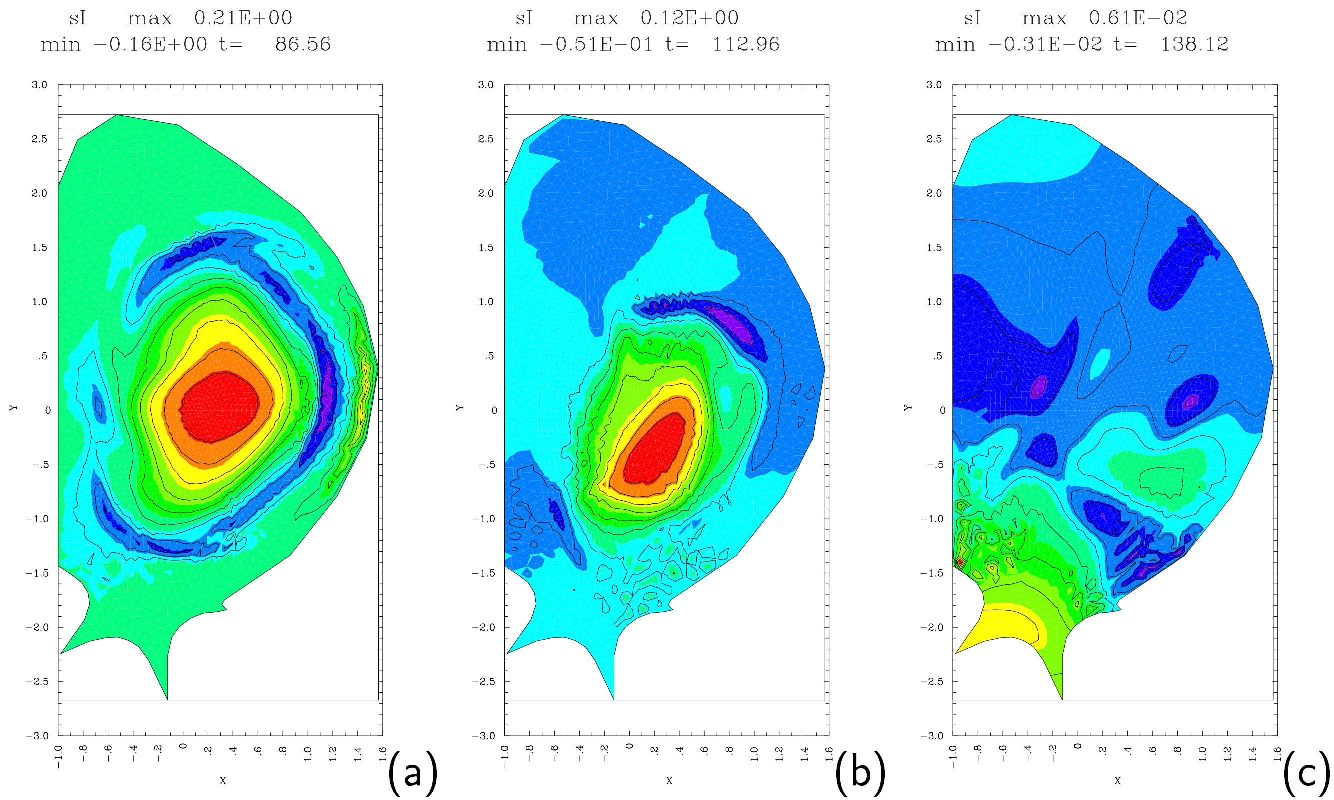


Fig.6 Toroidal Flux at $t =$ (a) $87t_A$ (b) $113t_A$ (c) $138t_A$

1. Sayer, R.O., Peng, Y-K. M., Jardin, S. C., Kellman, A. G., Wesley, J. C., Nuclear Fusion 33, 969 (1993).

2. Pletzer, A., Dr. Dobb's Journal 334, p. 36 (March 2002)