3D MHD disruptions simulations of tokamaks plasmas

R. Paccagnella[1], H. Strauss[2], J. Breslau[3]

CONSORZIO RFX
Ricerca Formazione Innovazione

[1] Ass. Euratom/ ENEA
Consorzio RFX and CNR
Padova, Italy

[2] New York University
Courant Institute of
Mathematical Sciences

PPPL

[3] Princeton Plasma Physics
Laboratory Princeton (NJ)

Motivations

- For ITER construction it is needed to know how big will be the

horizontal unbalanced forces due to asymmetric VDEs/Disruptions

- ITER **should NOT** have disruptions in the **(D-T) phase**

-> Disruptions physical mechanisms should be clarified
and avoidance techniques developed

M3D Extended MHD CODE

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}_i) = 0$$

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} + \left(\mathbf{v}_i^* \cdot \nabla\right)\mathbf{v}_\perp\right] = -\nabla \mathbf{p} + \mathbf{J}\times\mathbf{B} + \mu\nabla^2\mathbf{v}$$

$$\mathbf{E} + \mathbf{v}\times\mathbf{B} = \eta\mathbf{J} - \frac{\nabla_\parallel p_e}{ne}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$$

$$\mathbf{J} = \nabla\times\mathbf{B}$$

$$\frac{\partial p}{\partial t} + \mathbf{v}\cdot\nabla p = -\gamma p \nabla\cdot\mathbf{v} + \nabla\cdot n\chi_\perp\nabla\left(\frac{p}{\rho}\right) - \mathbf{v}_i^*\cdot\nabla p - \gamma p\nabla\cdot\mathbf{v}_i^* + \frac{\mathbf{J}\cdot\nabla p_e}{ne} + \gamma p_e \mathbf{J}\cdot\nabla\left(\frac{1}{ne}\right)$$

$$\frac{\partial p_e}{\partial t} + \mathbf{v}\cdot\nabla p_e = -\gamma p_e\nabla\cdot\mathbf{v} + \nabla\cdot n\chi_{\perp e}\nabla\left(\frac{p_e}{\rho}\right) + \frac{\mathbf{J}_\parallel\cdot\nabla p_e}{ne} - \gamma p_e\nabla\cdot\left(\mathbf{v}_e^* - \frac{\mathbf{J}_\parallel}{ne}\right)$$

where

$$\mathbf{v}_e^* \equiv -\frac{\mathbf{B}\times\nabla p_e}{neB^2}, \quad \mathbf{v}_i^* \equiv \mathbf{v}_e^* + \frac{\mathbf{J}_\perp}{ne},$$

$$\mathbf{v} \equiv \mathbf{v}_i - \mathbf{v}_i^* = \mathbf{v}_e - \mathbf{v}_e^* + \frac{\mathbf{J}_\parallel}{ne}$$

Artificial sound wave model for $\kappa_\parallel$:

$$\frac{\partial T}{\partial t} = s\frac{\mathbf{B}\cdot\nabla u}{\rho}$$

$$\frac{\partial u}{\partial t} = s\mathbf{B}\cdot\nabla T + \nu\nabla^2 u$$

Boundary conditions

$$\mathrm{B_v} = \nabla\psi_v \times \nabla\phi + \nabla\lambda + I_o \nabla\phi$$

Vacuum magnetic field

GRIN Solver:

$$\left(\frac{\partial\psi_v}{\partial n}\right)_i = \sum_j K_{ij}^{o}\,\psi_{pj} + S_i \quad \rightarrow \quad \frac{\partial\psi_w}{\partial t} = \frac{\eta_w}{\mu_o\delta_w}\left[\frac{\partial\psi_w}{\partial n}\right]$$

Thin shell BC

$$(\lambda^n)_i = \sum_j K_{ij}^{n}(\mathbf{B}_p \cdot n)_j \quad \rightarrow \quad \frac{\partial B_{n\,pw}}{\partial t} = \frac{\eta_w}{\delta_w}\left[\frac{\partial B_{n\,w}}{\partial n}\right]$$

Virtual "case"

VIRTUAL CASING METHOD

The source term S_i can be obtained from the applied external currents, or else using the ``virtual casing" method.

In this method we first perform an ideal equilibrium calculation, with $\psi=0$ on the boundary.

Then equating

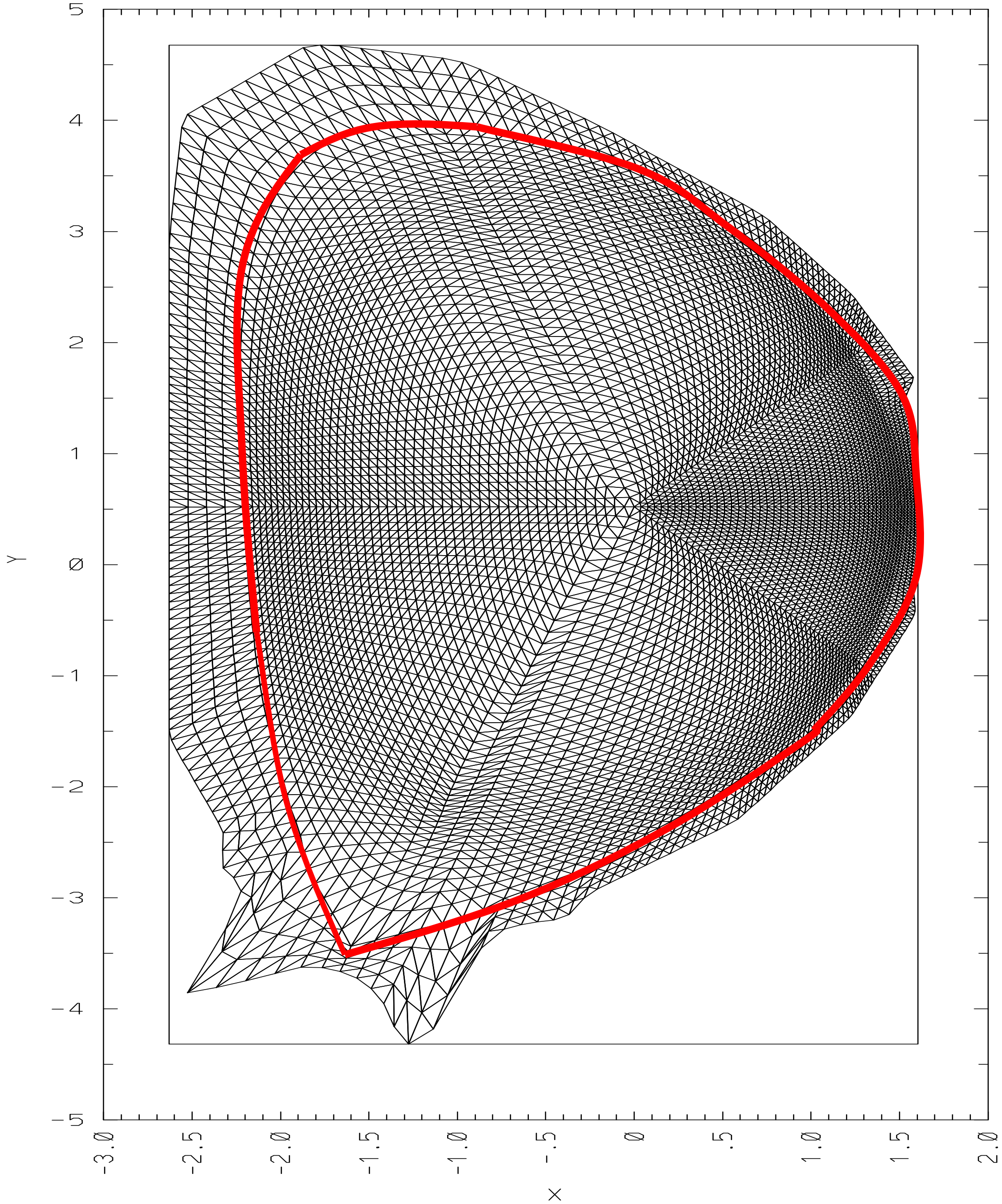
$$\frac{\partial \psi_v}{\partial n} = \frac{\partial \psi_p}{\partial n}$$

the source term required for equilibrium is found from

$$S = \frac{\partial \psi_p}{\partial n} \qquad @\ t=0$$

where the right side is obtained from the ideal equilibrium.

THE MESH : PLASMA AND EDGE REGIONS



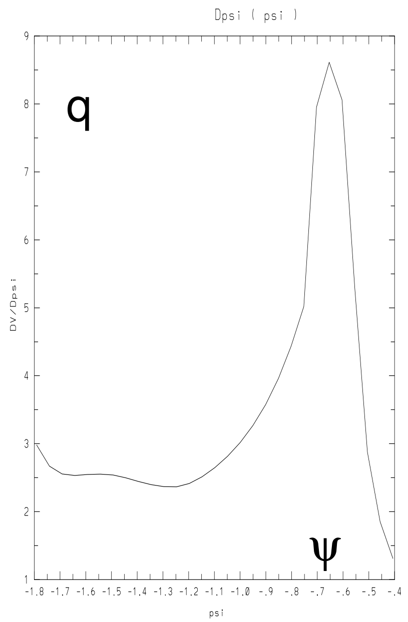
The mesh is builded in the two regions:

Inside the separatrix
(plasma with low resistivity)

and outside the separatrix
(plasma with resistivity
***100-1000 times larger**)*

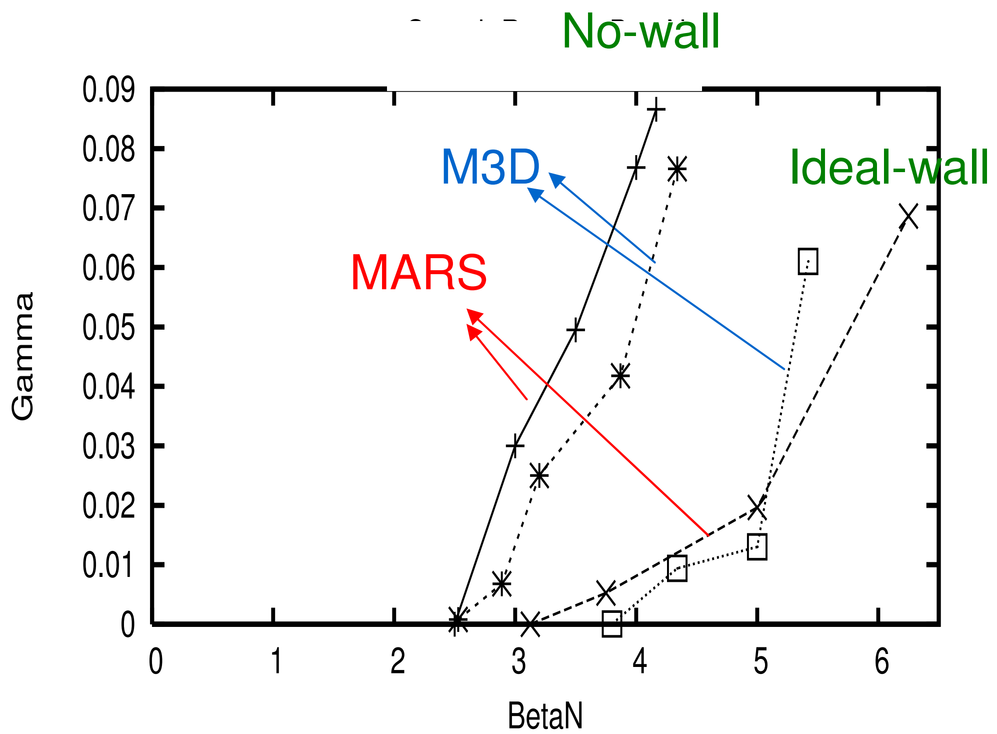
The mesh can be structured (field aligned) or unstructured

RWM LINEAR BENCHMARK AGAINST MARS (&CHEASE)



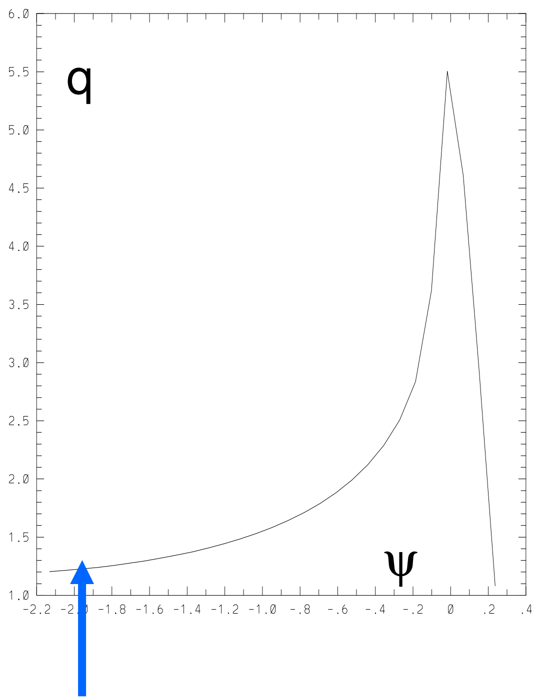
ITER AS

SCENARIO

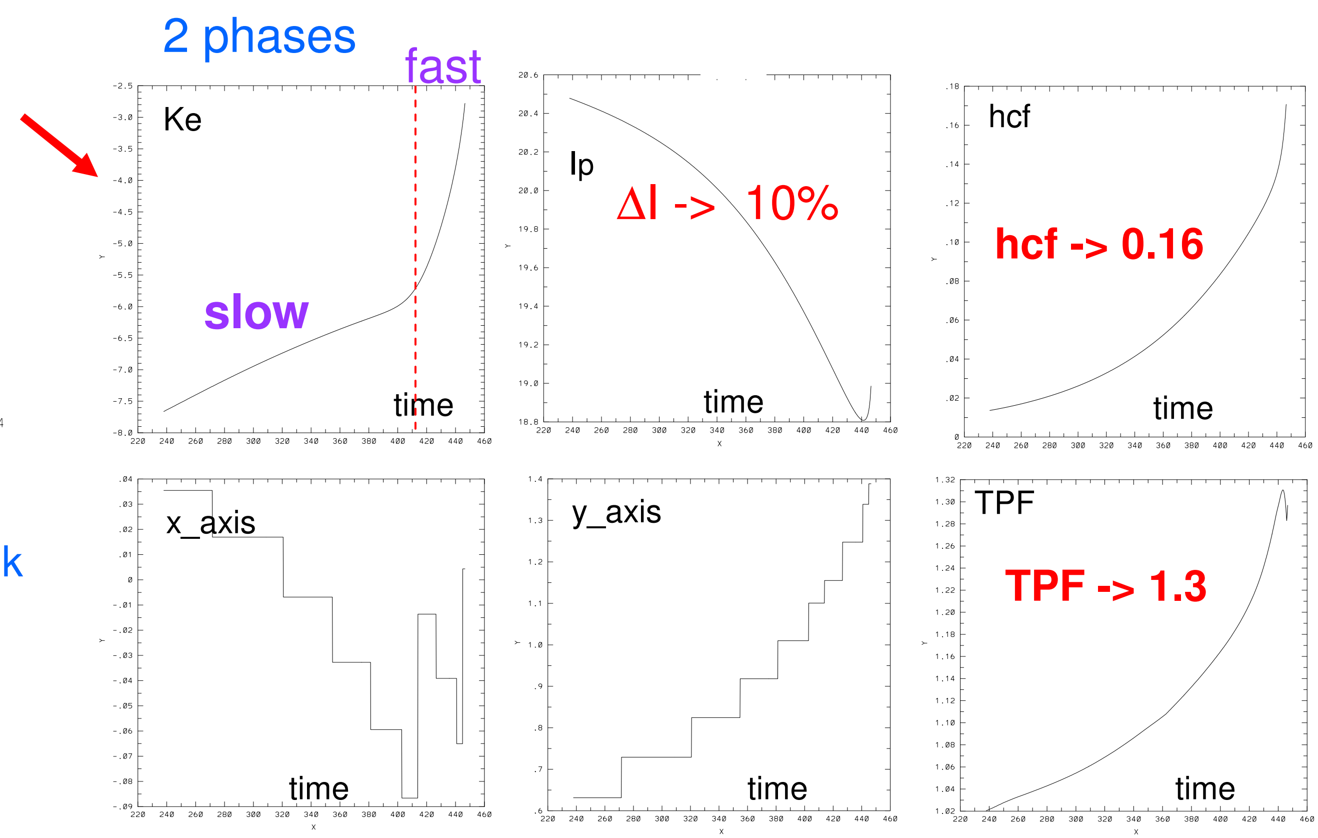


(the benchmark and runs are done with the **OMP M3D version**)

ITER REFERENCE SCENARIO



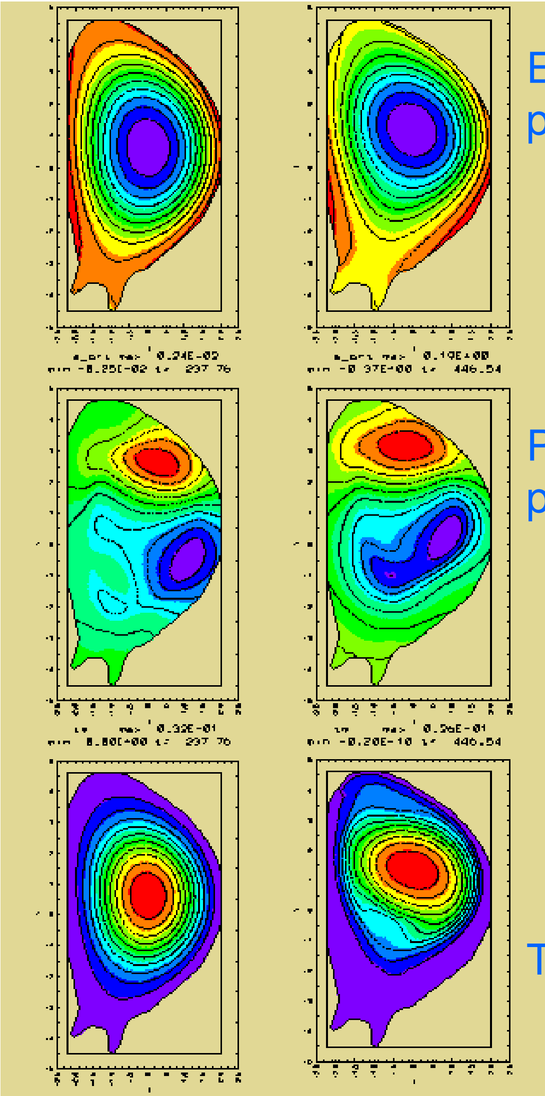
q(0) >1 to avoid the internal kink



ITER REFERENCE SCENARIO

(no vertical control)

- dominant n=1 mode
- localization near the plasma-wall contact region



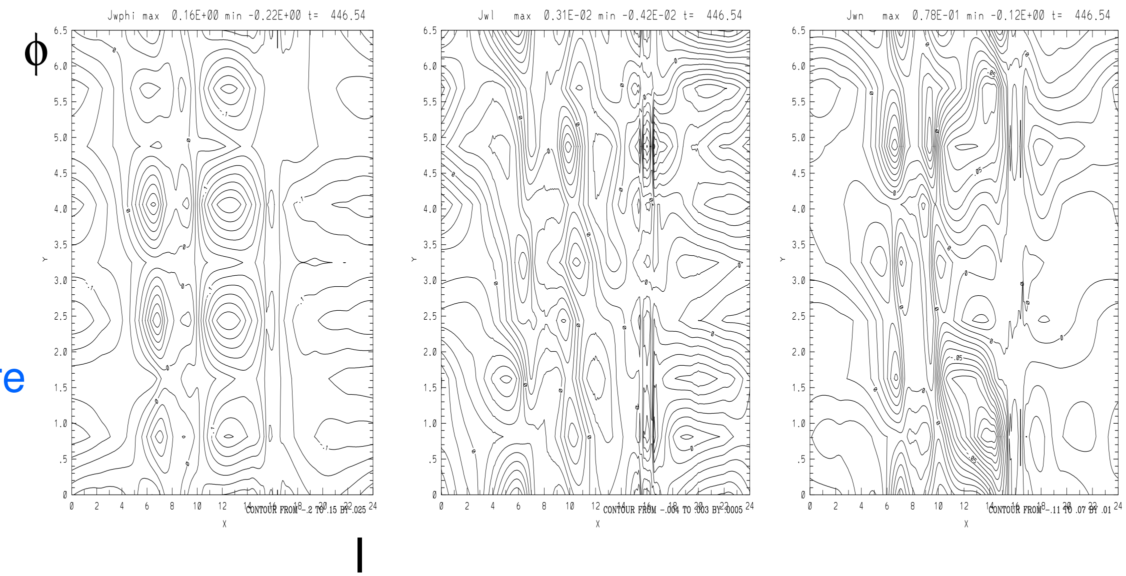
Equilibrium poloidal flux

Perturbed poloidal flux

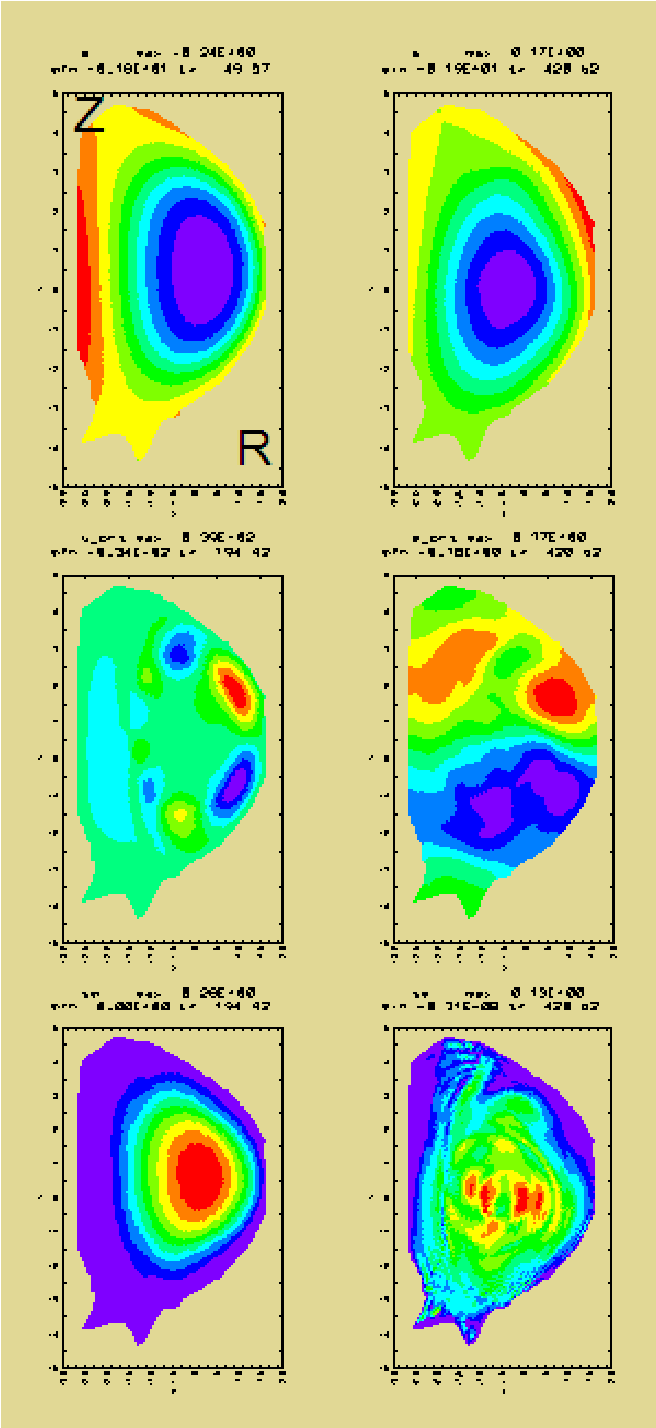
Temperature

2D map of the current at the wall

toroidal poloidal normal



(y=ϕ tor. angle and x=l poloidal length)



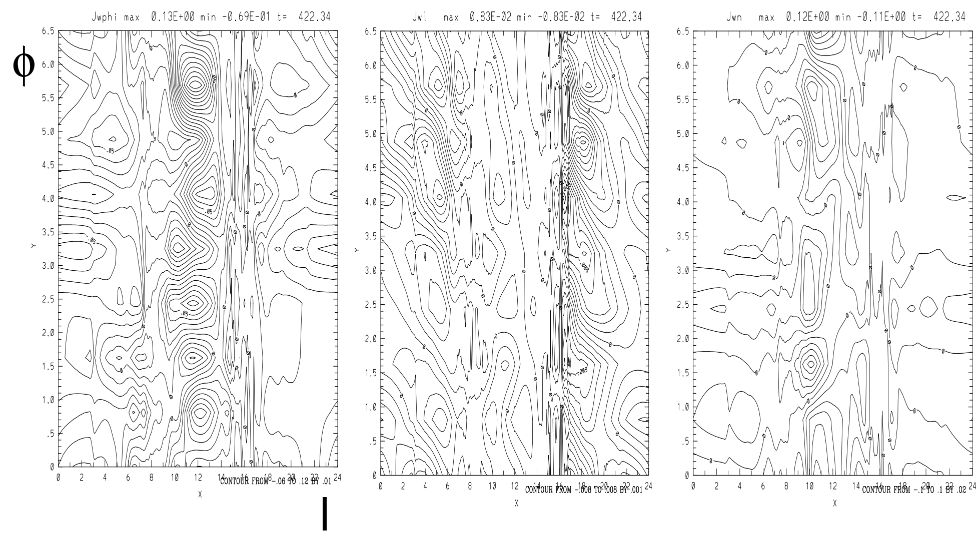
ITER Advanced Scenario

$\beta_N = 3.5$

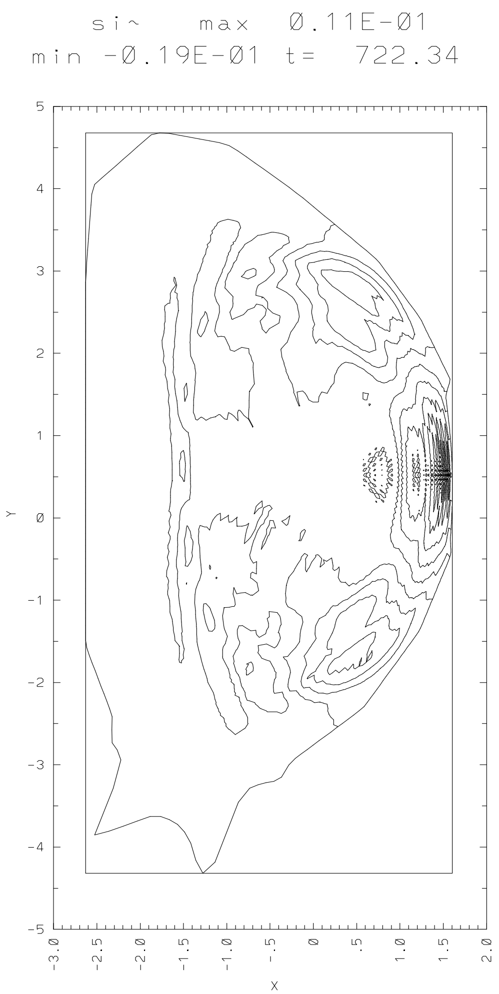
RWM unstable

- Current localized at the edge
- Resiliance to VDE
- signs of n>1 activity

Current localization



ITER Advanced Scenario



Perturbed toroidal field

- Convergence problems :

Localization of magnetic field and current (generally at the edge) can make the simulation to blow up

Toroidal Peacking and halo fraction

$$I_h(\phi) = \frac{1}{2}\int |n \cdot J|\; R\; dl$$

Halo current: normal current at the wall

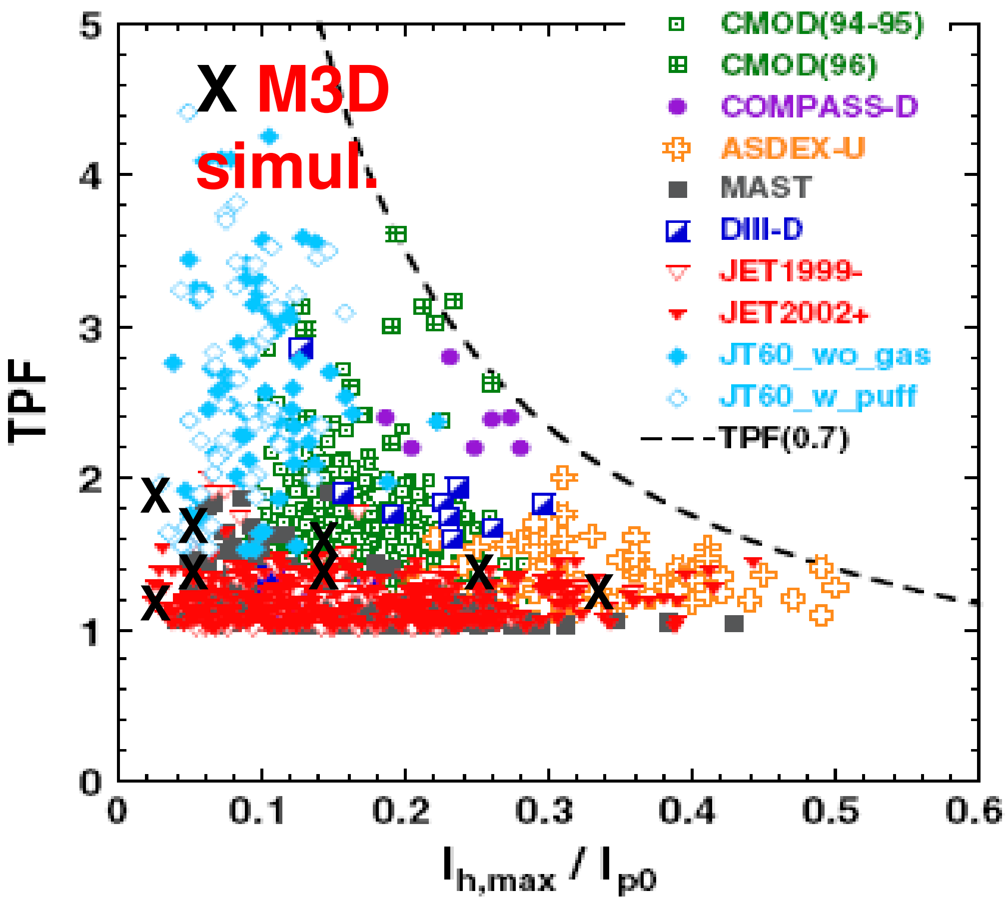
$$TPF = \frac{I_h^{\max}}{< I_h >} = \frac{I_h^{\max}}{\frac{1}{2\pi}\int \; I_h(\phi)\, d\phi}$$

Toroidal peacking Factor

$$F_h = \frac{< I_h >}{< I_\phi >} = \frac{\int \; I_h(\phi)\, d\phi}{\int \; J_\phi \; dRdZd\phi}$$

Halo fraction

Toroidal Peacking vs halo fraction



When the current quench precedes the thermal quench **(normal VDE)**, the high beta produces a relatively **high TPF** (modes are more unstable).
Since the current was already partially lost, the **hcf is not** particularly **high**.

Vix. versa if the thermal quench happens first **(standard disruption)** the **TPF** becomes **lower** (external kink is mitigated) but the **hcf can be** relatively **high** due to the high current still flowing in the plasma.

Conclusions

- Relatively slow disruptions driven by RWMs have been studied in 3D (dominants n=0,1)

- linear benchmark of M3D with MARS is ok

- Qualitative trends that confirm experimental findings are found.
  Figure of merit (TPF*hcf) for ITER seems appropriate

PROBLEMS still to be addressed:

- Lundquist in simulations much lower (up to 10^5) than in experiments

- Numerical convergence is critical (especially for the advanced scenarios)

- **Fully parallel MPI simulations are required**