Simulations of asymmetric VDEs with M3D: model validation and comparison with experimental cases

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CONSORZIO RFX
Ricerca Formazione Innovazione

PPPL

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OUTLINE:

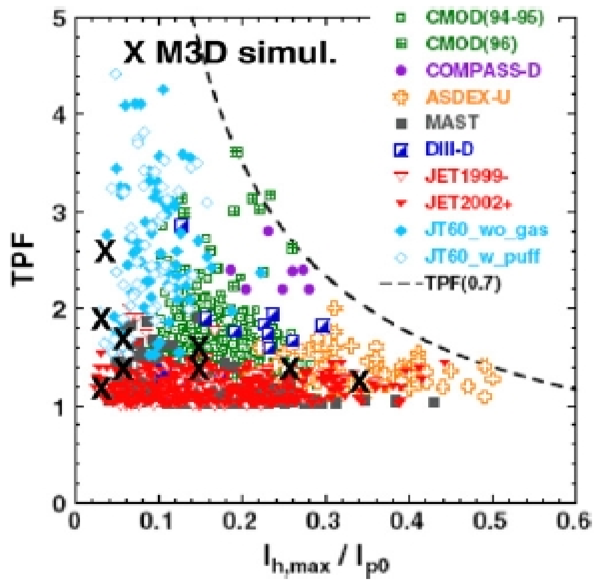
- Motivation of the work
- M3D & ASDEX
- M3D & JET
- M3D & ITER
- Conclusions

Motivations:

- M3D 3D MHD simulations of disruptions already produced published results (R. Paccagnella et.al. NF 2009, H. Strauss et. al. PoP (2010) & NF (2013))

- necessity of code validation against experiments
- AUG, JET and DIIID, NSTX are relevant cases
- F4E issued GRT-334 in 2011 for AUG and JET comparison and ITER cases simulations (this presentation)

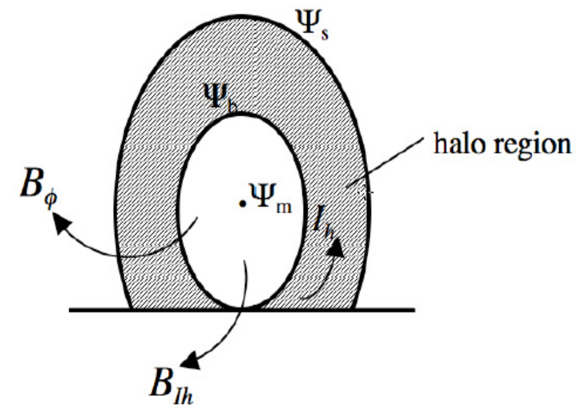
Some of the previous results

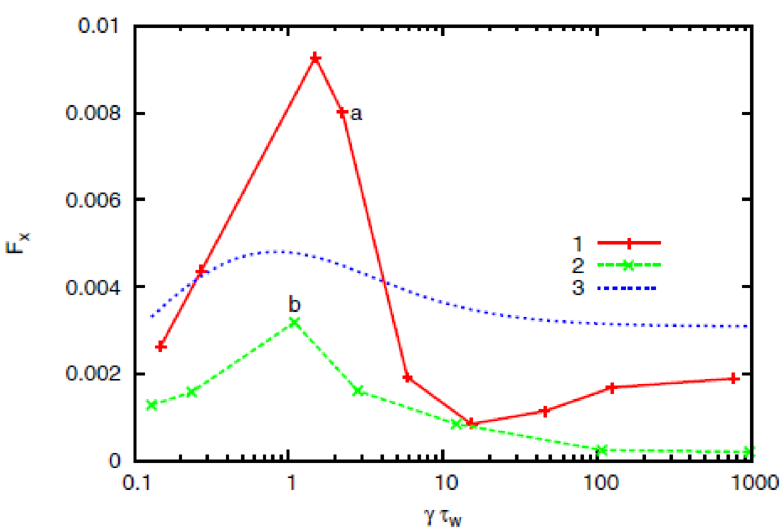


from NF (2009)

$$I_{\mathrm{halo}}(\phi) = \frac{1}{2}\int |\hat{n}\cdot\mathbf{J}| R\,dl,$$

$$\mathrm{TPF} = \frac{2\pi I_{\mathrm{halo(max)}}}{\int I_{\mathrm{halo}}\,d\phi}.$$



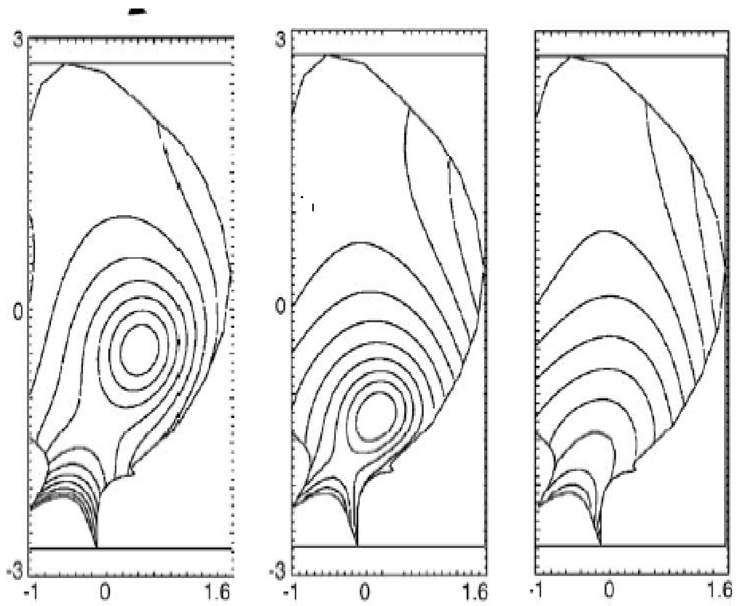


from PoP (2010)

Horizontal force is maximum for $\gamma\,\tau_W = 1$

..what does this means really in ITER?

Eddy vs halo



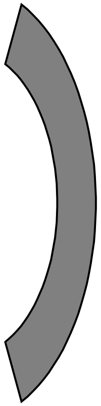
Halo currents are **stabilizing** and therefore they **enhance the eddy** component **opposing flux penetration** through the material wall

- *which physical model for Jn : 1F MHD, 2F MHD, ..??*

If Jn = 0

only

Eddy currents are induced

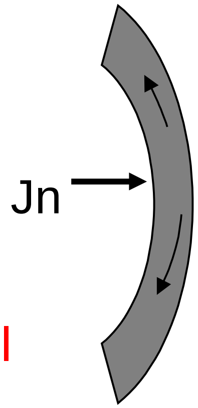


$$[n \times \vec{B}] = \mu_0 \vec{K}$$

If Jn $\neq$ 0

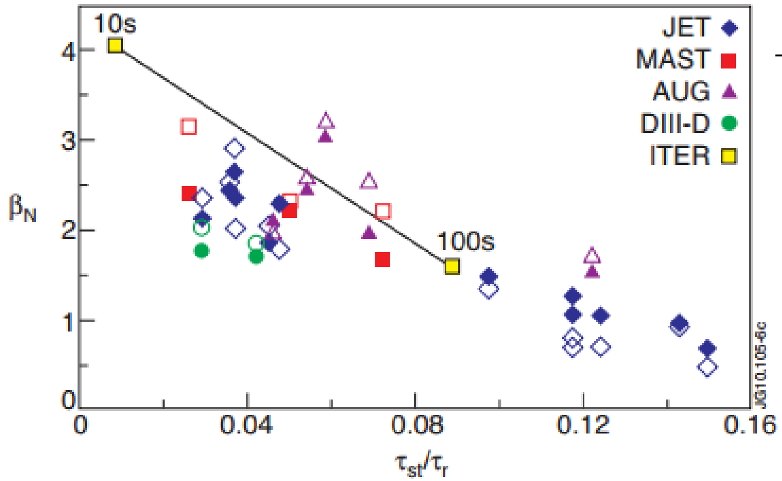
extra

currents circulate in the wall since $\nabla \cdot J = 0$



ITER vs Simulations: (1)

Chapman et.al., NF (2010)
Neocl.tearing threshold



$\tau_{wall}^{iter} \approx 200$ ms

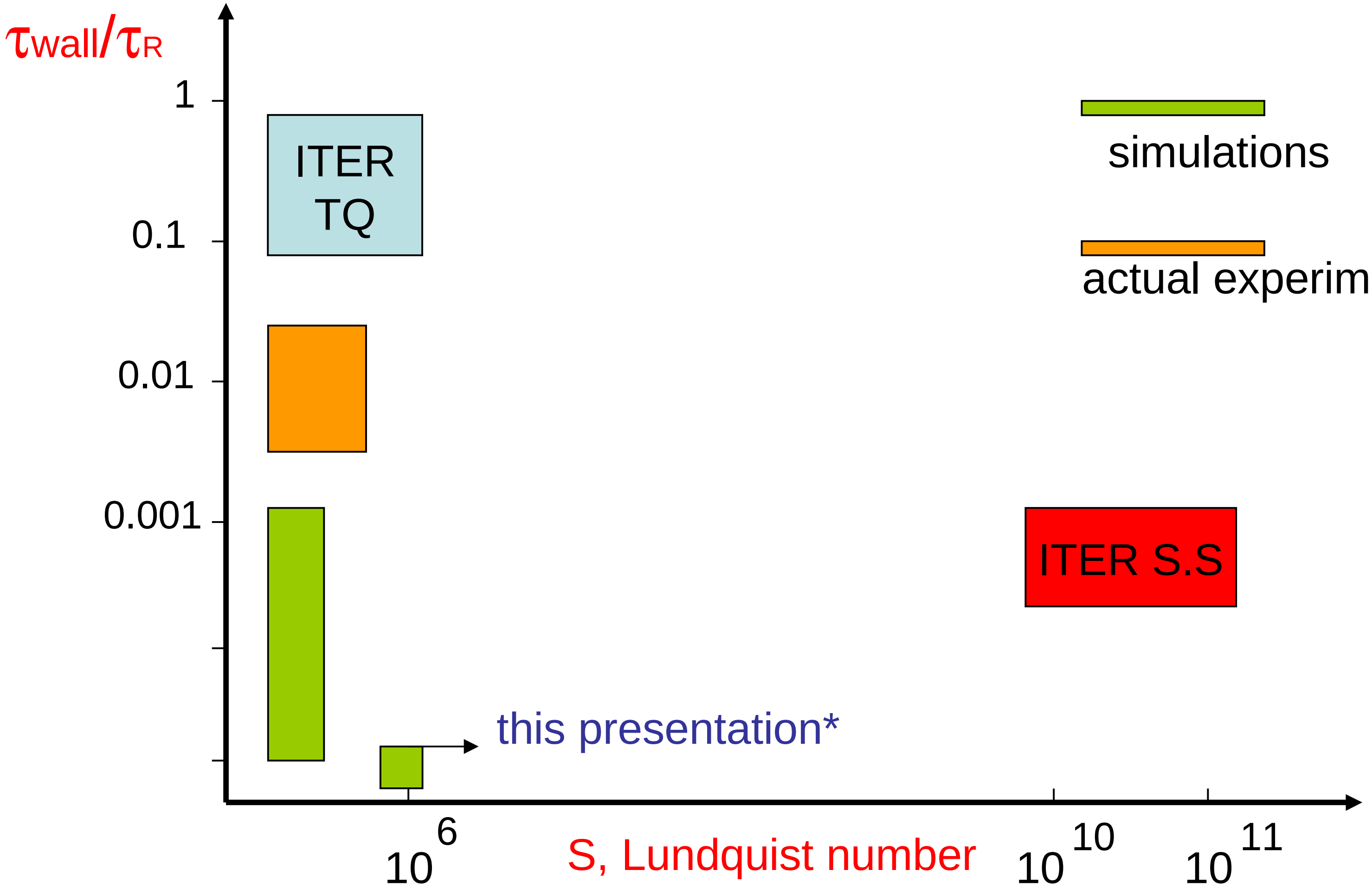
$\tau_R = 1000$ sec

$\tau_{Wall} / \tau_R = 10^{-4} - 10^{-3}$

However after thermal quench with T → 100-10 eV range :

$\tau_{Wall} / \tau_R = 0.1 - 1$

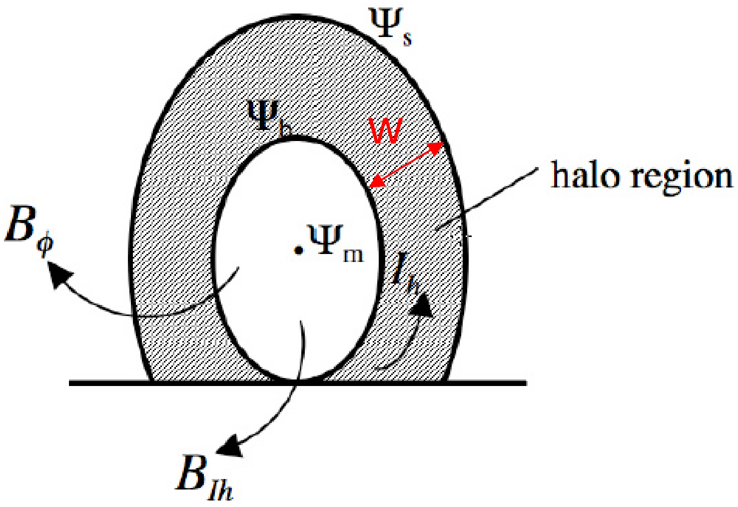
ITER vs Simulations: (2)



* At high S it is very time consuming having long wall time constants

Halo region effects:
which halo in ITER?

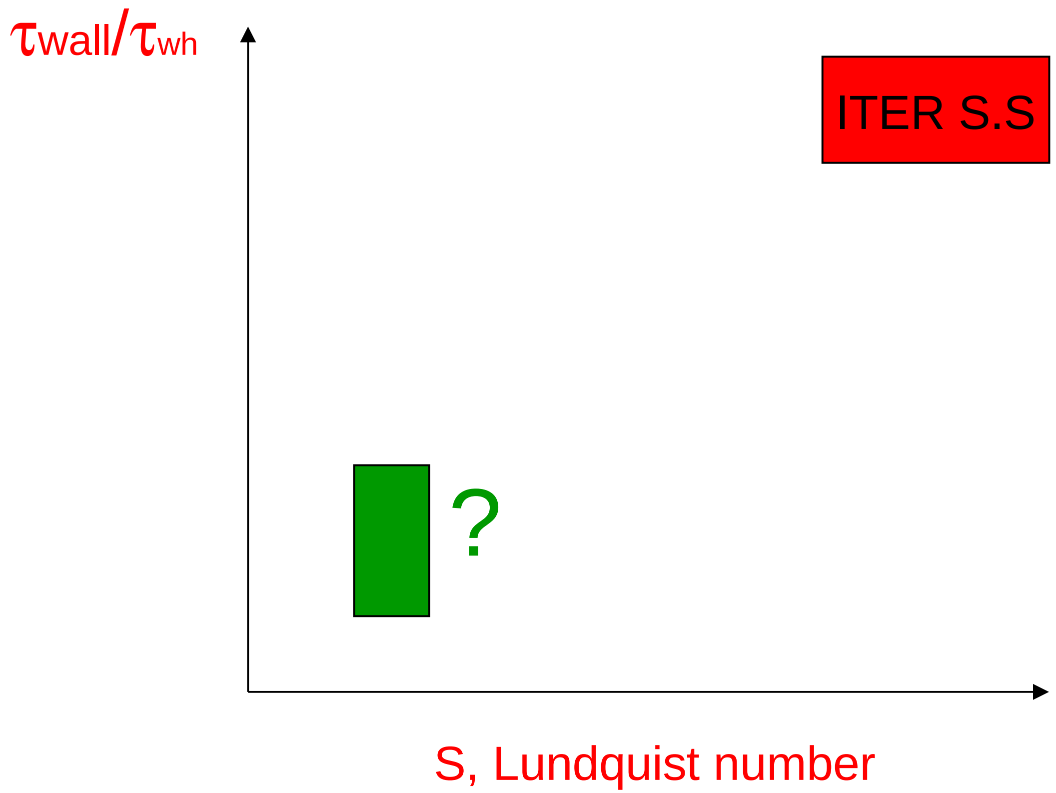
2D codes empirical scheme:



$$\gamma(t,w) = \frac{S_0}{S(t,w)}\left[C + \left(\frac{I_p(t,w)}{I_{p0}}\right)\right]\frac{1}{C+1} = 1$$

w= halo region width
S= total flux (core+halo)
So = initial flux
for C >>1 as plasma shrinks w increases
for C=0 w is narrow and shrinks with current

DINA code



$\tau_{wh} \approx \; w\, a\, /\, \eta_h$

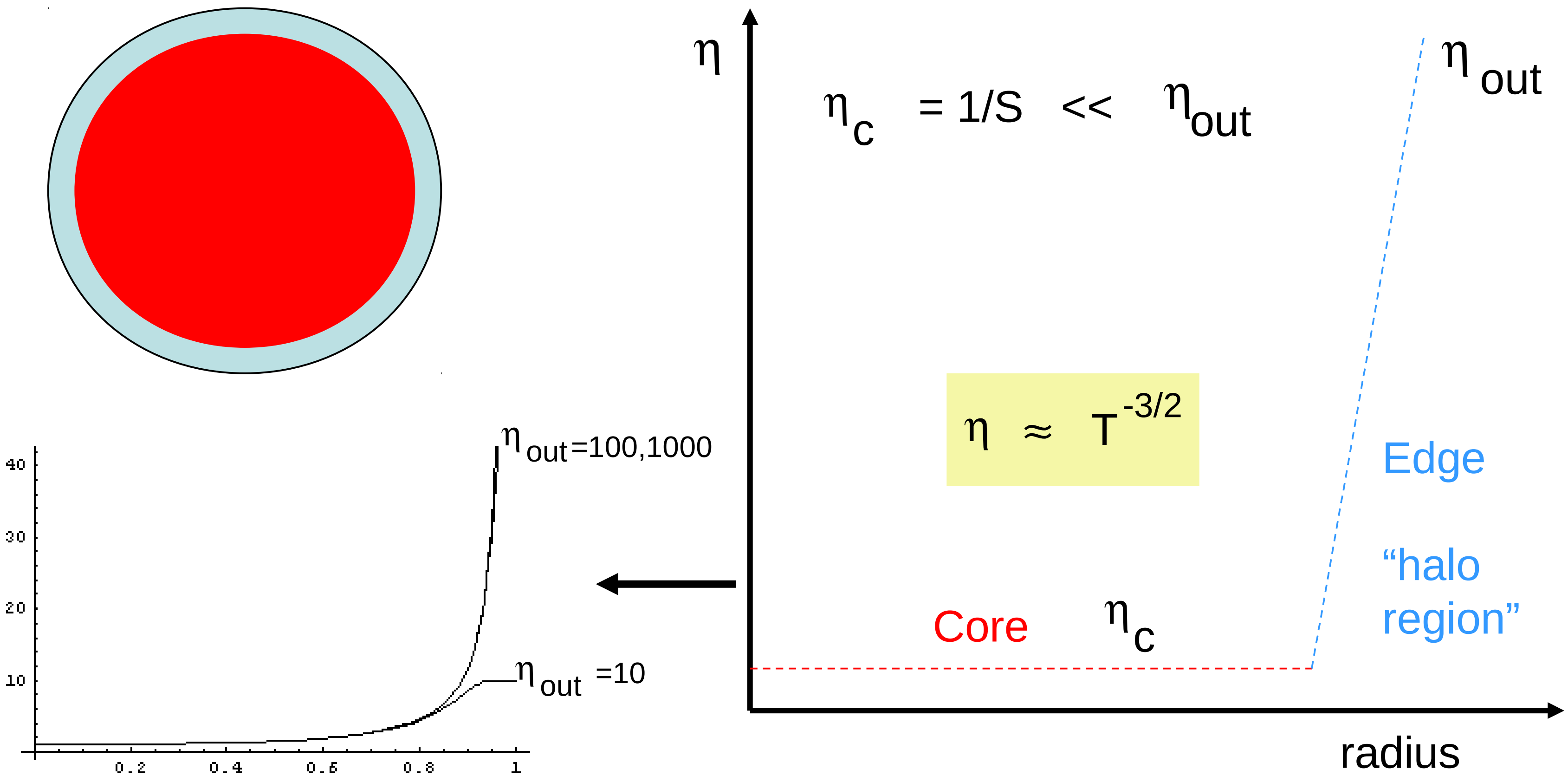
M3D Critical parameters:

Plasma physical state :
- S (Lundquist), P (Prandtl i.e. viscosity)
- η resistivity => Spitzer & two regions with high (100-1000x) edge η
- density => constant
- perpendicular thermal conduction => constant
- coeff. to describe waves propag. in parallel direction

Wall parameters:
- wall proximity (from eqdsk)
- τ_wall (not too long to speed up VDEs)

Code numerical parameters:
- mesh resolution in the poloidal planes
- number of poloidal planes in toroidal direction

M3D 2 resistivity regions:



Apart the arbitrariness of η_{out} the halo region is self-consistently determined by the time evolution of temperature

Simulations features:

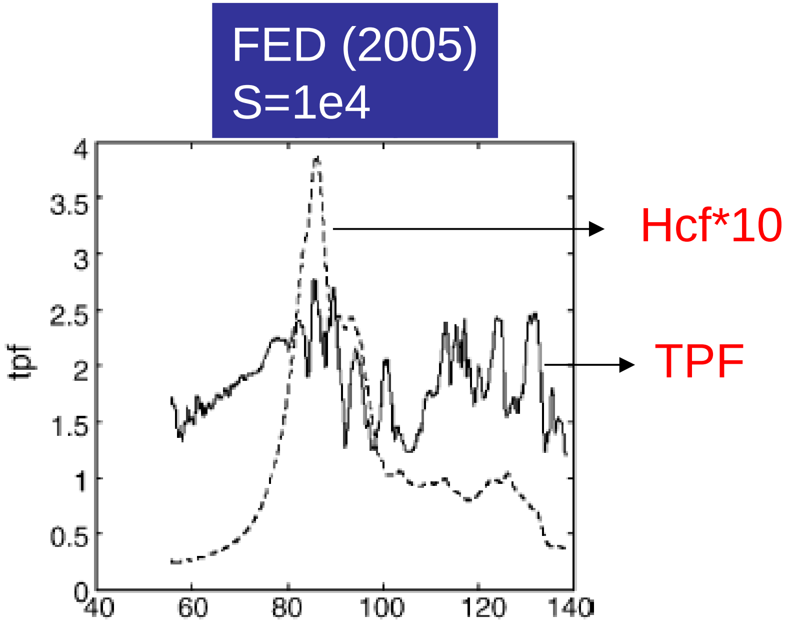
- Toroidal Geometry, Full single fluid compressible MHD Equations, Resistive Wall Boundary (2D thin shell)
  Initial equilibria from EQDSK's

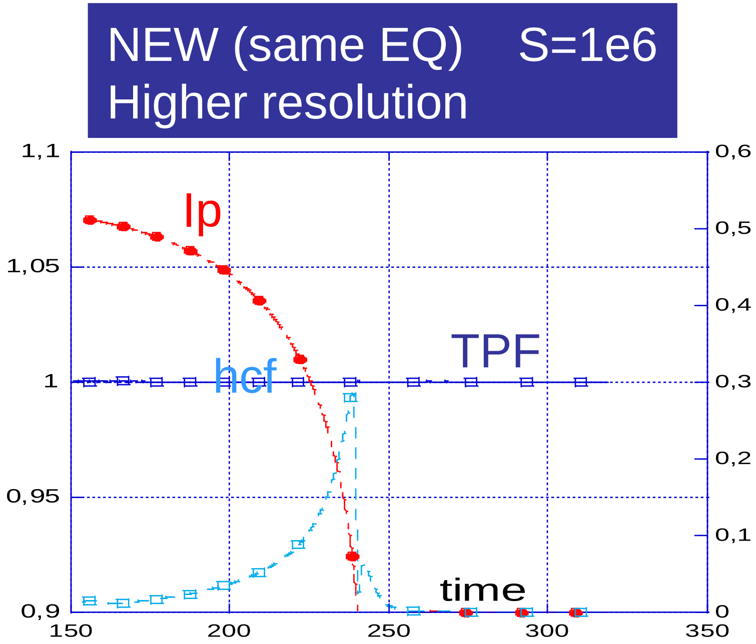
- Simulations are done at higher Lundquist S >= 1e6 (10-100 times higher in comparison with previous cases), Prandtl P ranges from 100 to 500 (at lower P convergence is difficult)

- MPI M3D code has been used (fully parallel)
  700 khours CPU time on hopper @ NERSC have been used

- mesh elements range from 3e4 vertices x poloidal plane (AUG) to 2e5 (ITER) with 16 toroidal planes

Omp vs. MPI results:





- the two codes (omp and MPI versions) differ
- @ high S non axi-symmetry seems not be present

SOME GENERAL OBSERVATONS

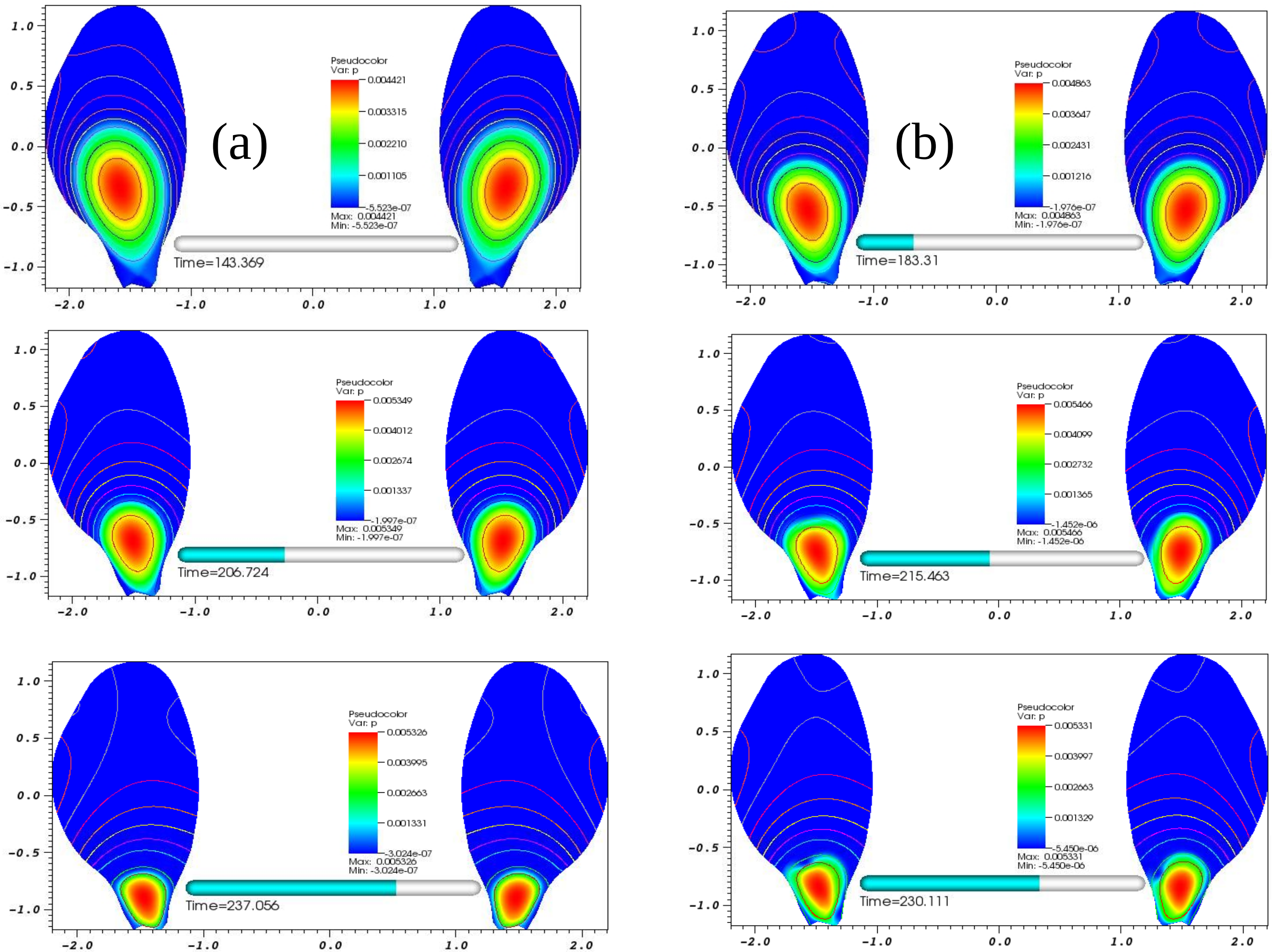
- Other AUG cases have confirmed the observation done for the FED case i.e. higher resolution and higher S, contribute to produce more symmetric VDE's.

(2D VDE overtakes 3D effects -> due to unrealistically low τ_{wall} and S mode scaling)

- non axi-symmetry can be obtained by enhancing the amplitude of an arbitrary initial perturbation to the plasma (at time t=0) .

- Enhancing the plasma viscosity for a given resistivity (or S) (i.e. enhancing the Prandtl number) has also the effect to smooth out non axi-symmetric modes, and to produce more symmetric VDE's.

- there is a clear competition in the system between the VDE time scale (mainly determined by the wall time constant), the current and temperature evolution in the plasma (determined by the transport and by the Lundquist number) and the evolution of the resistive modes, which determine the final TPF and halo fraction.



TPF = 1

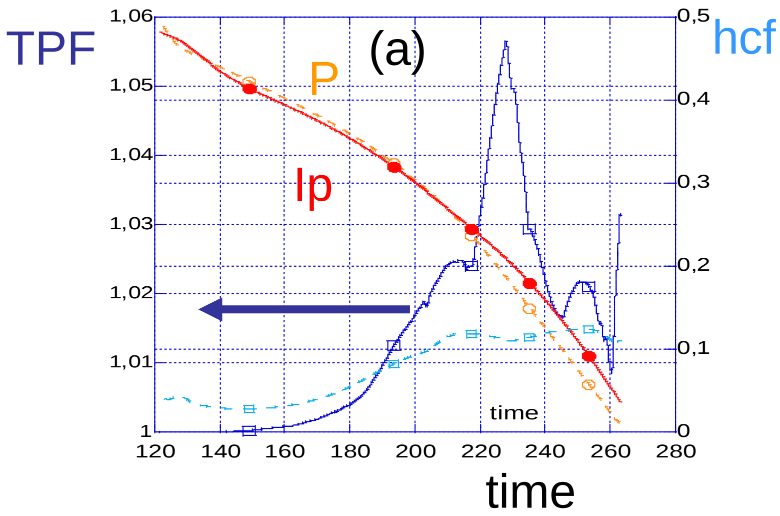
S=5e6

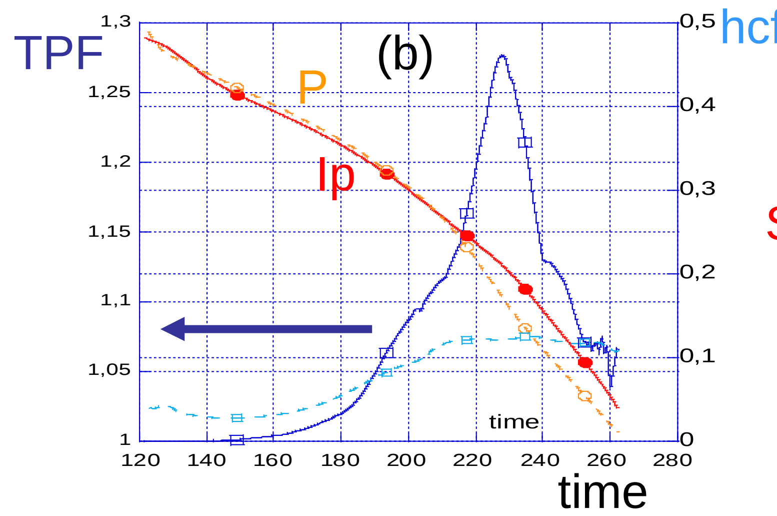
TPF = 1.3

(no applied initial perturbation)

(with initial perturbation)

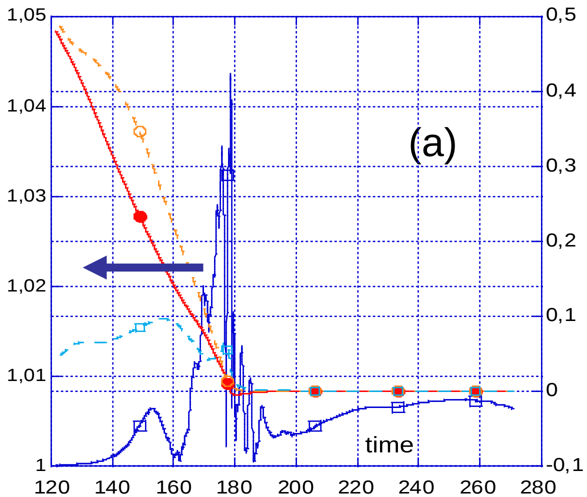
- Current and pressure decay on the same time scale
- low and high S have different timing

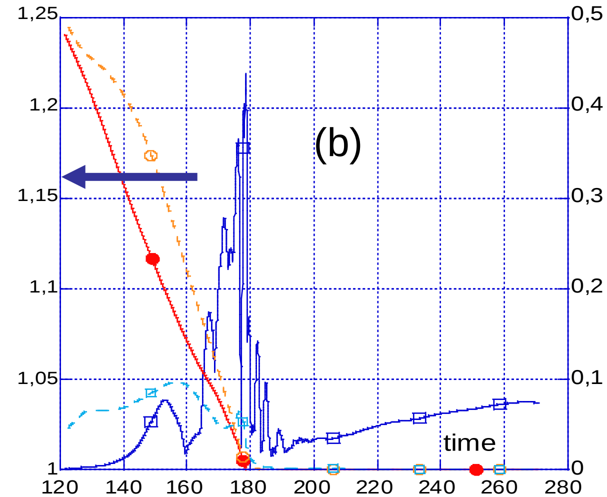




S=5e6

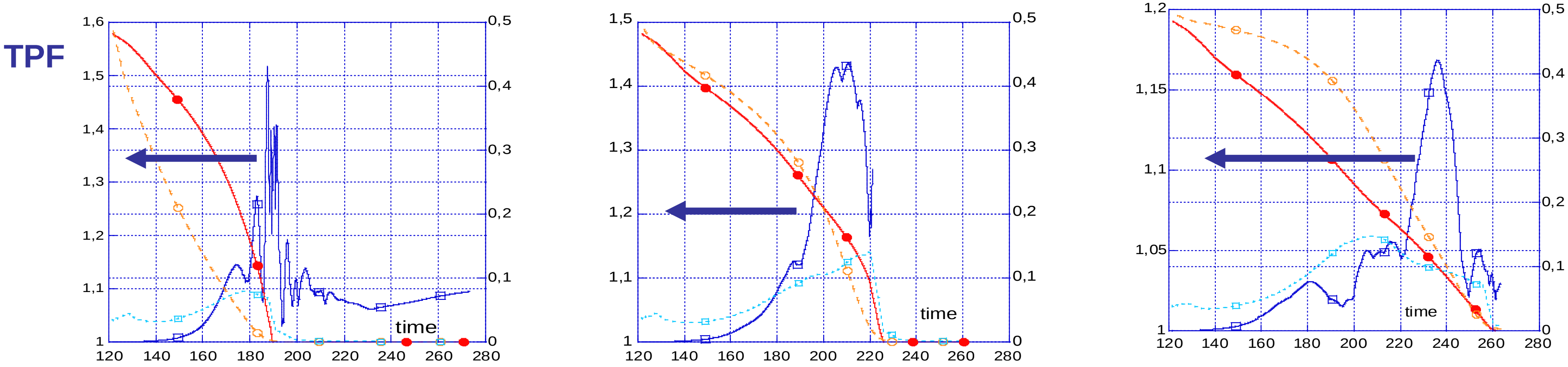
P=pressure *250





S=1e5

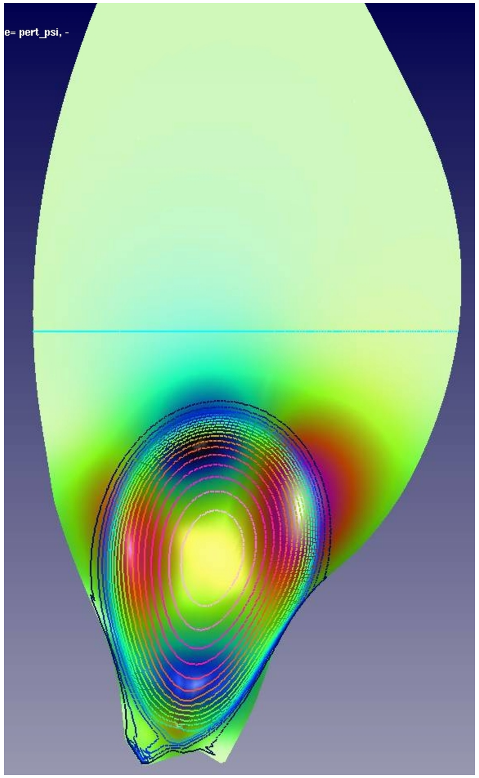
χ^1_{perp} > χ^2_{perp} > χ^3_{perp}



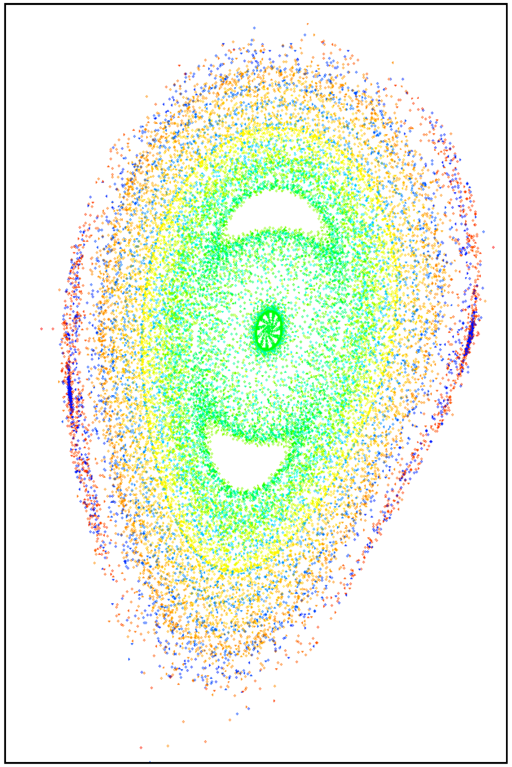
S=1e6

χ_{perp} **Influences pressure decay but also timing and TPF magnitude**

(in this case perpendicular transport is independent of T)

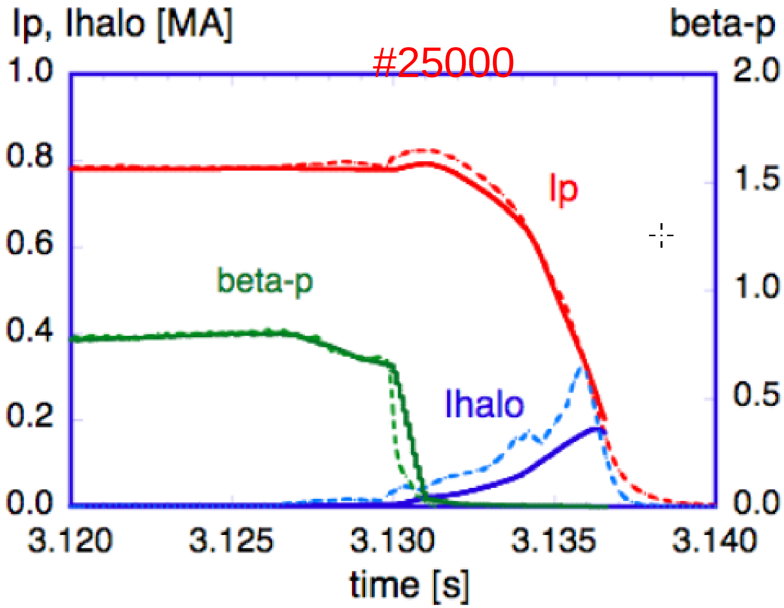


Perturbed poloidal flux and pressure contours



Poincarè puncture plot

a 2/1 resistive mode is dominant in these simulations



Several discrepancies with the experiment

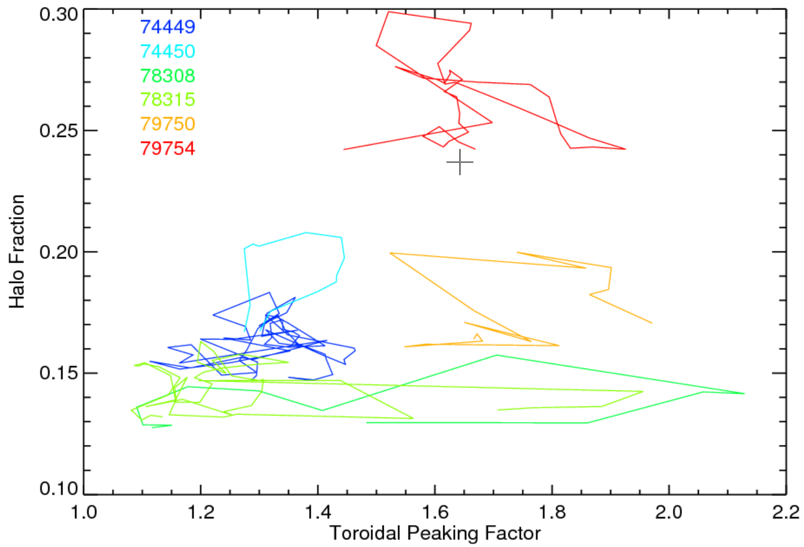
- **the thermal quench is well before the current quench**
(instead similar rate in simulation)

- **high perpendicular transport, can reproduce a faster pressure decay:**
in this case however TPF and hcf can become unrealistic

- **a 2/1 resistive kink responsible for asymmetry in simulations**
Experimentally unclear (role of pure ideal modes?)

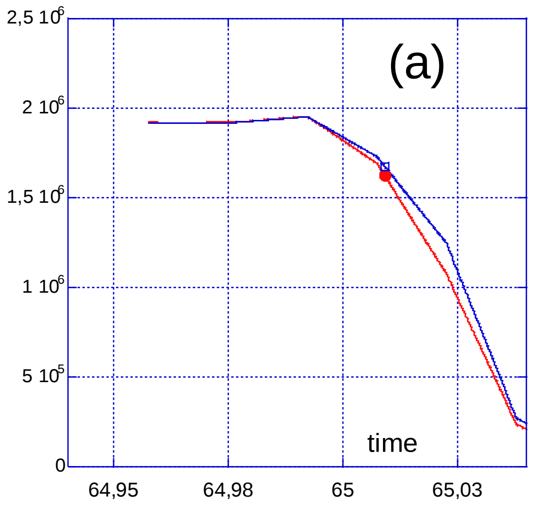
- **high resolution simulations resilient to asymmetry (init. pert. needed)**
What happens in experiments?

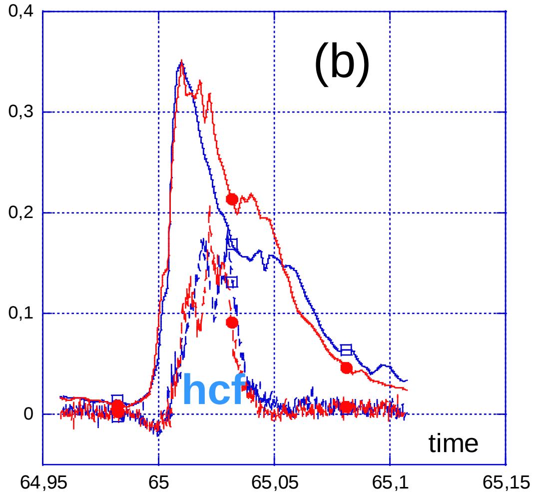
JET CASES:



Typical TPF & hcf

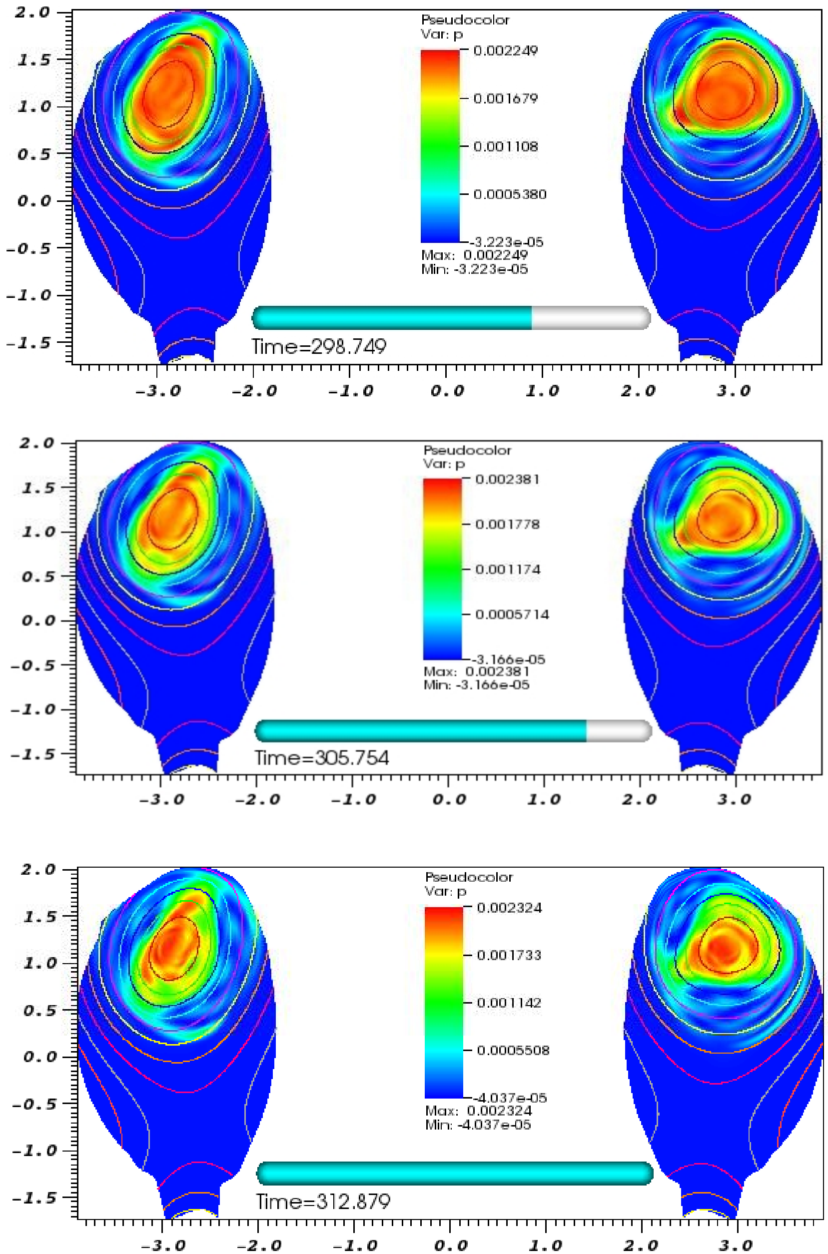
Current decay &hcf & odd modes vs. Time #74449,74450

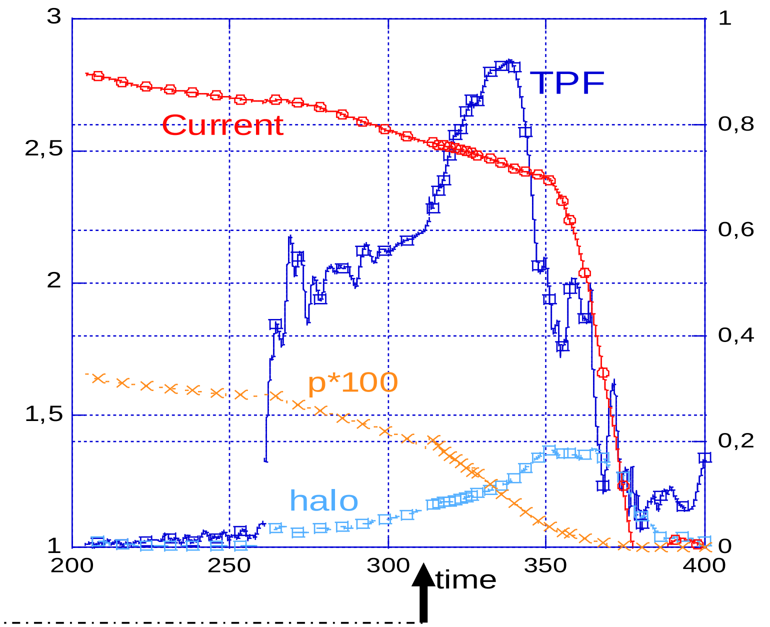




Simulation #78338 (S=1e6, P=1e2)

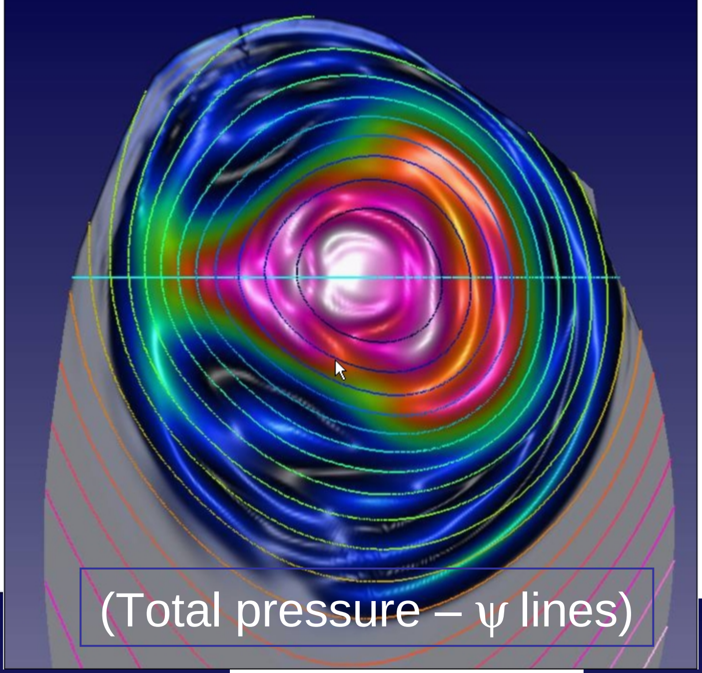
(with an initially applied perturbation)



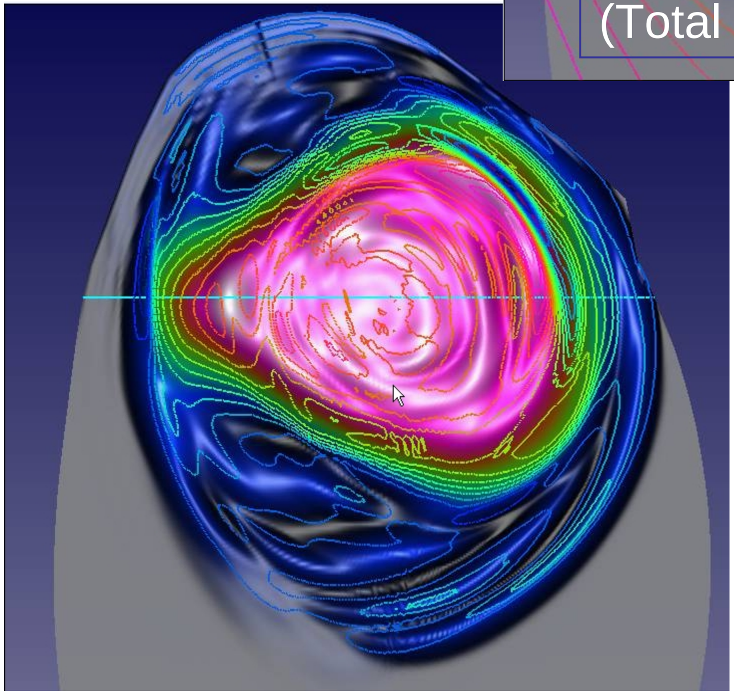


Poloidal flux (contours), pressure

#78338
@time = 313

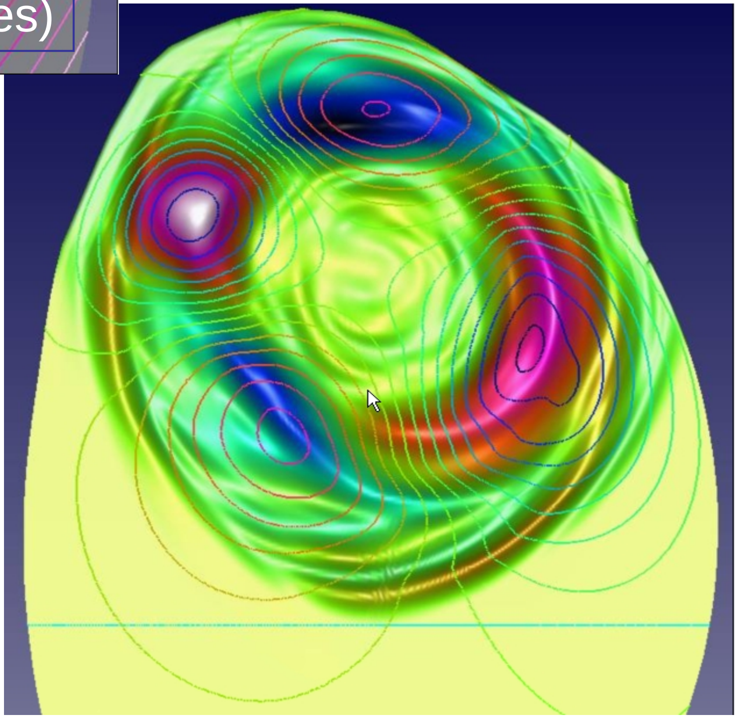


(Total pressure – ψ lines)



(pressure colors – tor. current lines)

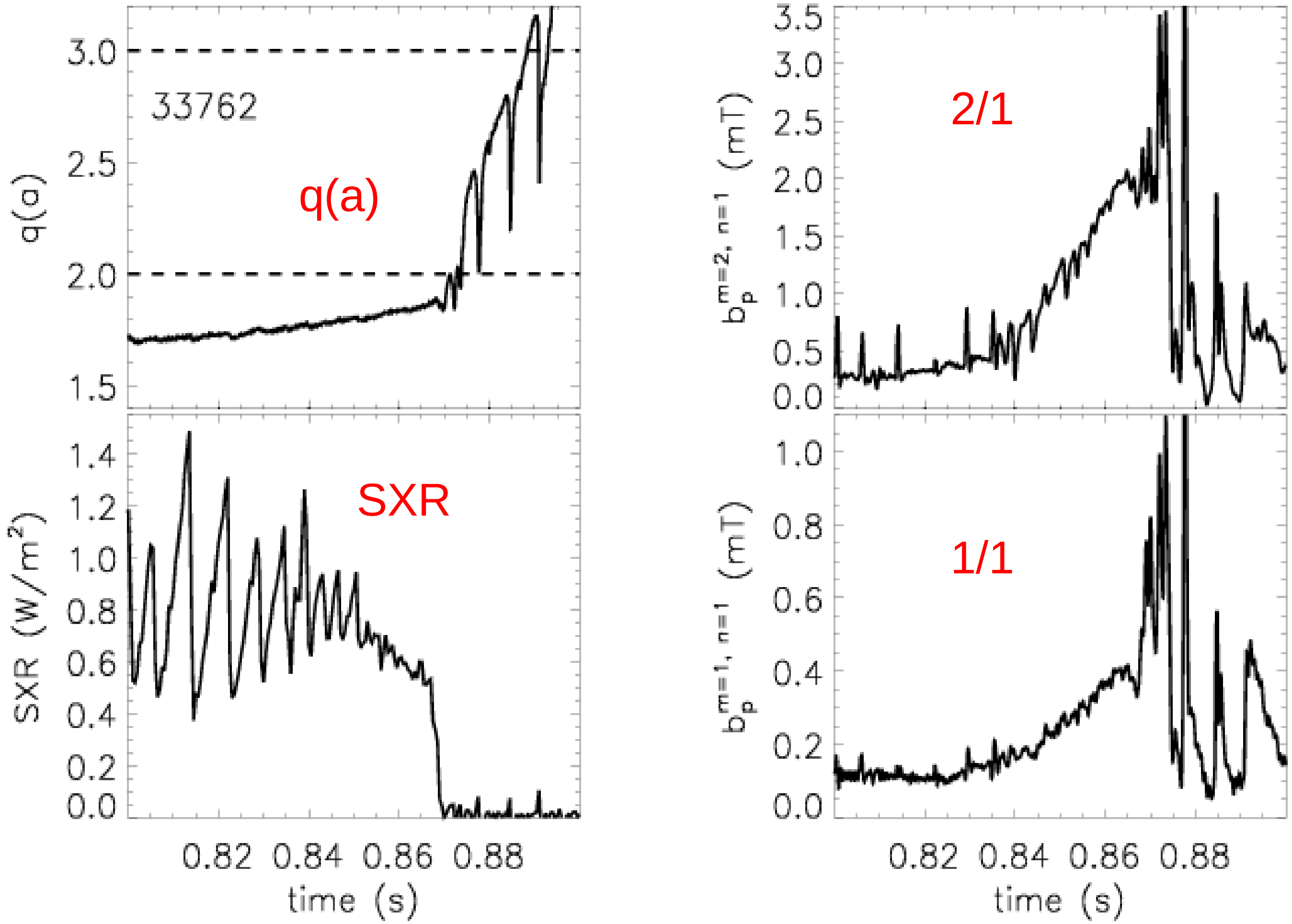
1/1 in the core



(pert. pressure – pert. ψ)

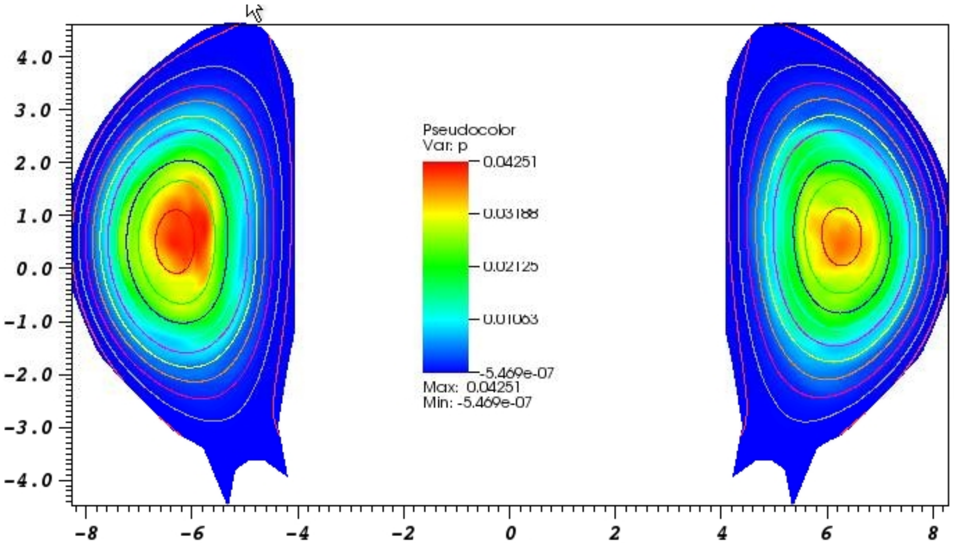
2/1 outside

RFX (RECENT) CASES:



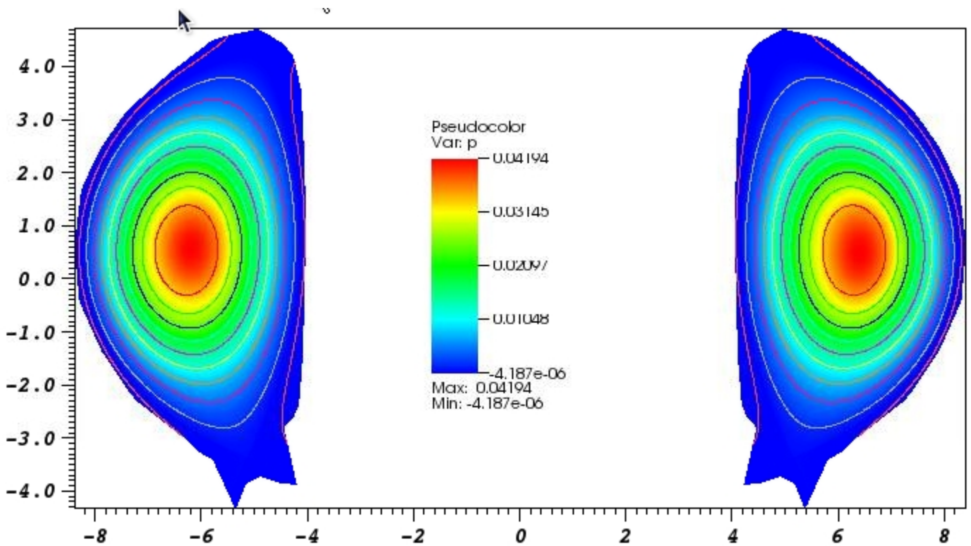
(by courtesy of Lidia Piron)

ITER CASES:



Very high resolution

SOF case q(0) < 1
After 80 tau_A TPF=1.3
No VDE



F4E case q(0) around 1
After 120 tau_A TPF=1.
No VDE

..These runs need to be continued..

Conclusions (1)

- Progress in 3D disruptions simulations/validation have been acchieved
- Thermal quench (TQ) remains a big issue (simulation possible?)
- plasma conditions after TQ crucial in determining evolution
- role of transport and transport scaling after TQ also crucial
- resistive instabilities seem to play the main role in simulations
(2/1 mode and in some case 1/1 also)
- more data on relevant modes probably needed from experiments
- ITER simulations need to be completed at high resolution
- force calculations can be refined by using 3D electromag. wall codes

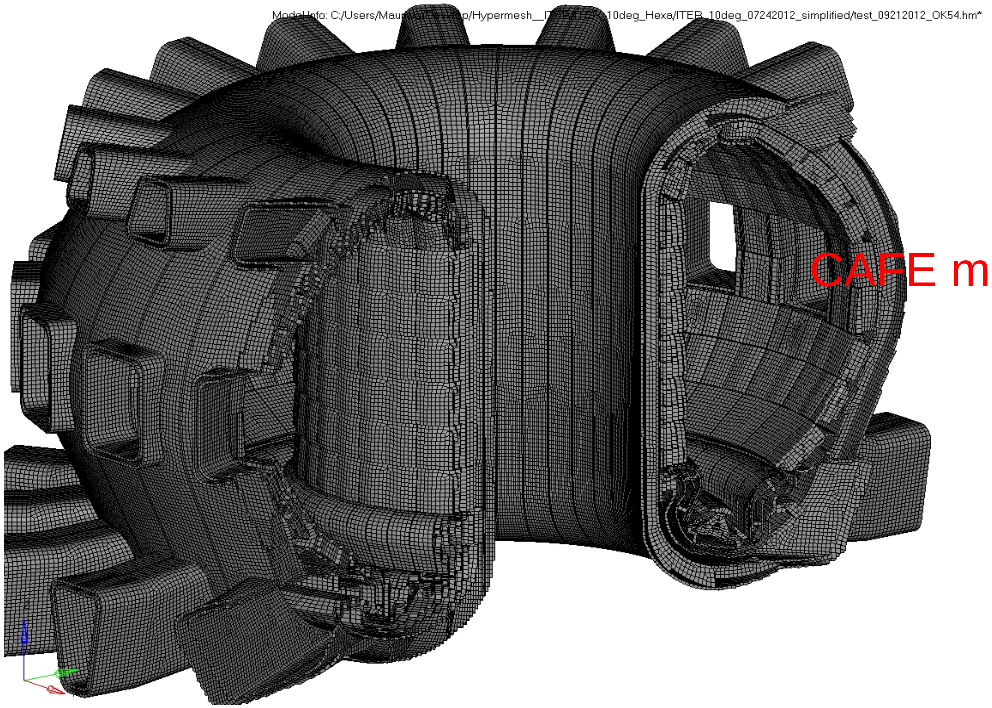
Conclusions (2)

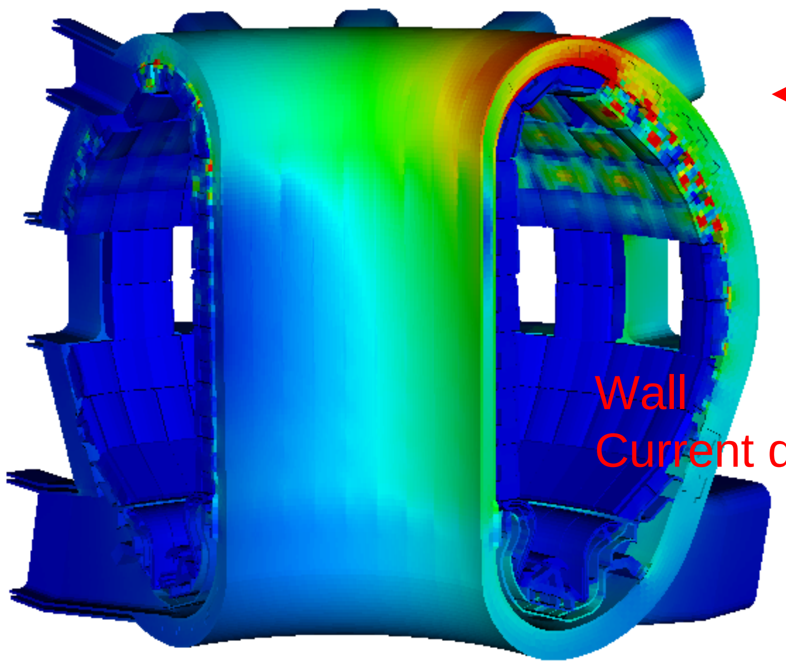
- DISRUPTIONS represent a **very serious** problem
- Their comprehension & avoidance is mandatory !
- Basic physics issues are still unresolved and theory+ simulations are urgently needed, for example:
- 1/1 vs 2/1 mode , Ideal vs. Tearing, scaling to ITER
- hiro vs. Halo, 2 Fluid effects, role of radiation
- mode rotation ? (..and possible resonances with structures)

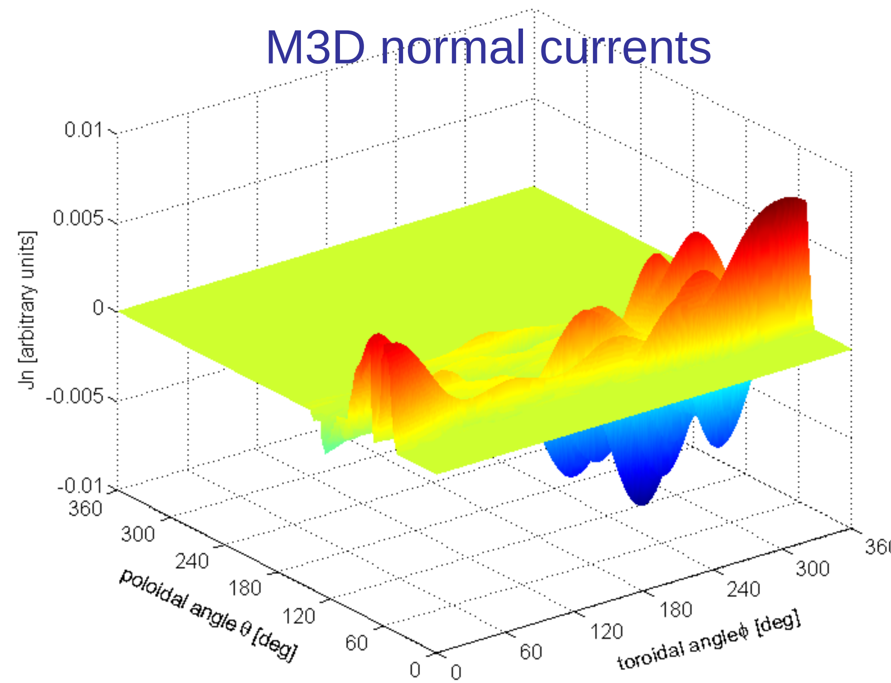
- Promises about 20xx FUSION ON THE MARKET are meaningless without a reliable disruption avoidance strategy

Forces calculations:

- M3D runs to calculate the normal currents flowing from the plasma to the resistive wall
- Development of a detailed 3D model of the ITER structures
- Identification of the mesh elements (about 80,000) facing the plasma, where the input currents are prescribed
- Evaluation of the resistive distribution of the currents inside the 3D structures by means of a 3D electromagnetic code (CAFE)
- Evaluation of the Lorentz force (**f**=**J**x**B**) for each element of the mesh. **(J** is the current density in the 3D structures)
- Evaluation of the total force and tilting moment on specific components.


CAFE mesh


Wall
Current distribution


M3D normal currents
Jn [arbitrary units]
0.01
0.005
0
-0.005
-0.01
poloidal angle θ [deg]
360
300
240
180
120
60
0
toroidal angleϕ [deg]
0
60
120
180
240
300
360