Non-linear MHD modelling of ELMs dynamics and their control by RMPs.

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DE LA RECHERCHE À L'INDUSTRIE

international collaboration "JOREK team" : http://jorek.eu/

CEA/IRFM (France)
INRIA Nice & Bordeaux (France)
Barcelona Supercomputing Center (Spain)
ITER
IPP Prague (Czech Rep)
IPP Garching (Germany)
CCFE, JET,Abingdon (UK)
DIFFER (Netherland)
KSTAR(Korea) –new in 2016
Thailand (PhD student)-new in 2016

ANR-s (ASTER, ANEMOS , E2T2) contracts F4E(2012-2013), EUROFUSION – 2014, ER-2015-2018.

HPC resources:

GENCI, MESO CENTRE Aix-Marseille Université, PRACE, IFERC

OUTLINE:

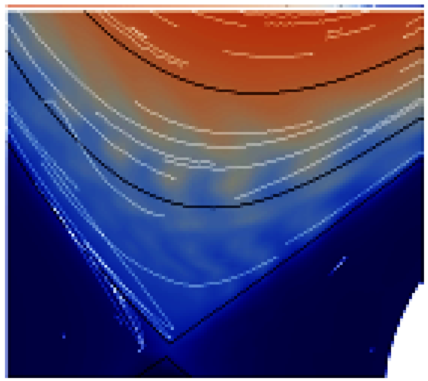
1. Motivation: MHD (ELMs, disruptions) control in ITER.
2. JOREK code.
3. ELM dynamics with flows: multi-harmonics, multi cycles simulations. (example KSTAR)
4. RMPs with plasma response, divertor fluxes with RMPs in ITER
5. Conclusions and perspectives.

Motivation=ITER! Our aim is to understand physics of MHD instabilities in fusion plasmas and propose & optimize methods of active MHD control in present devices and ITER.

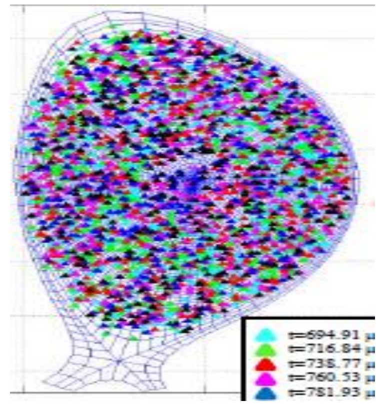
JOREK code was designed to study & understand MHD instabilities in fusion plasma and propose & optimize methods of active MHD control . Strong link with experiment, predictions for ITER.

ELMs, divertor loads

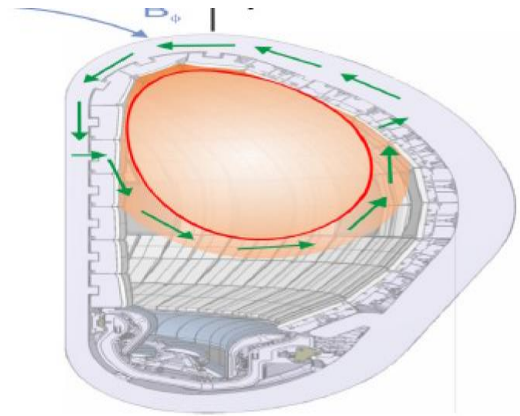
Tungsten transporti n ELMs (JOREK+PIC)



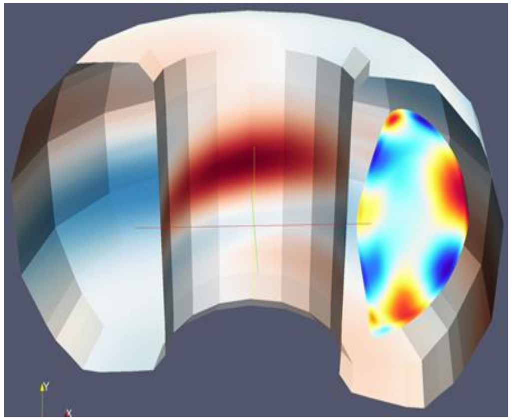
Disruptions, runaways (JOREK+PIC)



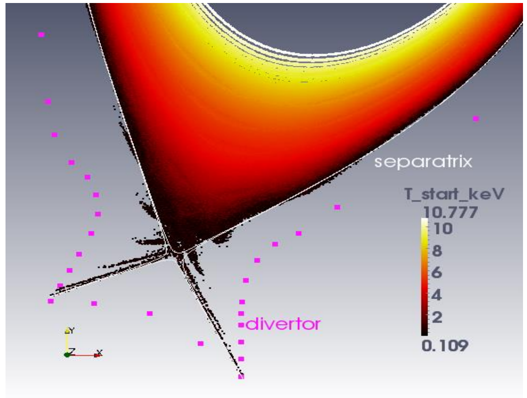
Global vertical displacement event (VDE)



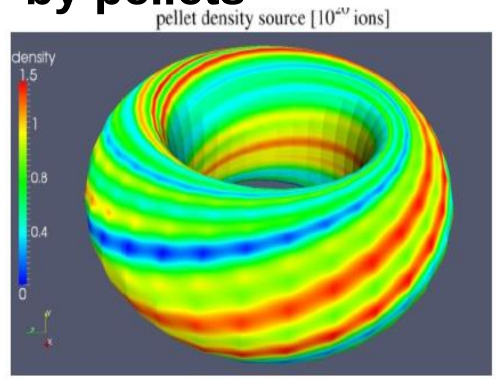
QH-mode-no ELMs regime



ELMs control by ergodic fields (RMPs)

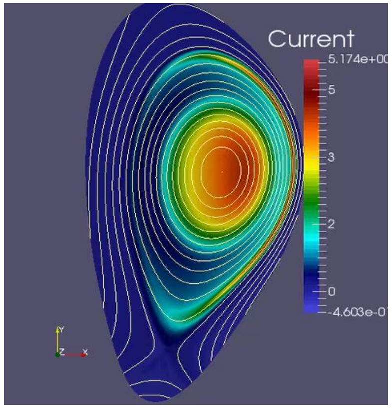


ELMs triggering by pellets



Contours of pressure perturbation during pellet triggered ELM in ITER plasma.

ELM triggering by vertical kicks



JOREK. Non-linear resistive MHD (full and reduced models) in realistic tokamak geometry, wall, coils. High space resolution (mm to m), time scales (Alfven 10-7 s to sec). Kpar/Kperp~1.e10, Lindquist : S~1.e10

[Huysmans NF 2007, PoP 2015, Orain PoP 2013, PRL2015,Becoulet PRL 2014] –reduced MHD

$\vec{B} = F_0 \nabla \varphi + \nabla \psi \times \nabla \varphi$

Magnetic field

$$\vec{V}_i = \underbrace{-R^2 \nabla u \times \nabla \varphi}_{\vec{E}\times\vec{B}} \underbrace{- \tau_{IC} \frac{R^2}{\rho} \nabla p \times \nabla \varphi}_{diamagnetic} + V_{\|} \vec{B}$$

$\tau_{IC} = m_i / (2 \cdot e \cdot F_0 \sqrt{\mu_0 \rho_0})$

diamagnetic parameter

Total pressure (here $T_i=T_e=T/2$) $p = \rho T$

Poloidal flux:

$$\frac{1}{R^2}\frac{\partial \psi}{\partial t} = \eta \nabla \cdot \left(\frac{1}{R^2} \nabla_\perp \psi \right) - \frac{1}{R}[u,\psi] - \frac{F_0}{R^2}\partial_\varphi u + \frac{\tau_{IC}}{2\rho B^2}\frac{F_0}{R^2}\left(\frac{F_0}{R^2}\partial_\varphi p + \frac{1}{R}[p,\psi] \right)$$

Parallel momentum:

$$\vec{B} \cdot \left(\rho \frac{\partial \vec{V}}{\partial t} = -\rho \left(\vec{V} \cdot \nabla \right) \vec{V} - \nabla(\rho T) + \vec{J} \times \vec{B} + \vec{S}_V - \vec{V} S_\rho + \nu_{\|} (\nabla\nabla) \vec{V} - \nabla \cdot \Pi_i^{neo} \right)$$

Poloidal momentum:

$$\vec{\nabla} \varphi \cdot \nabla \times \left(\rho \frac{\partial \vec{V}}{\partial t} = -\rho \left(\vec{V} \cdot \nabla \right) \vec{V} - \nabla(\rho T) + \vec{J} \times \vec{B} + \vec{S}_V - \vec{V} S_\rho + \nu_{\|} (\nabla\nabla) \vec{V} - \nabla \cdot \Pi_i^{neo} \right)$$

Temperature:

$$\frac{\partial (\rho T)}{\partial t} = -\vec{V} \cdot \nabla(\rho T) - \gamma \rho T \nabla \cdot \vec{V} + \nabla \cdot \left(K_\perp \nabla_\perp T + K_{\|} \nabla_{\|} T \right) + (1-\gamma) S_T + \frac{1}{2} V^2 S_\rho$$

Mass density:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \left(\rho \vec{V} \right) + \nabla \cdot (D_\perp \nabla_\perp \rho) + S_\rho$$

Temperature dependent viscosity, resistivity: $\eta \sim \eta_0 (T/T_0)^{-3/2}$

Neoclassical poloidal viscosity *[Gianakon PoP2002]*

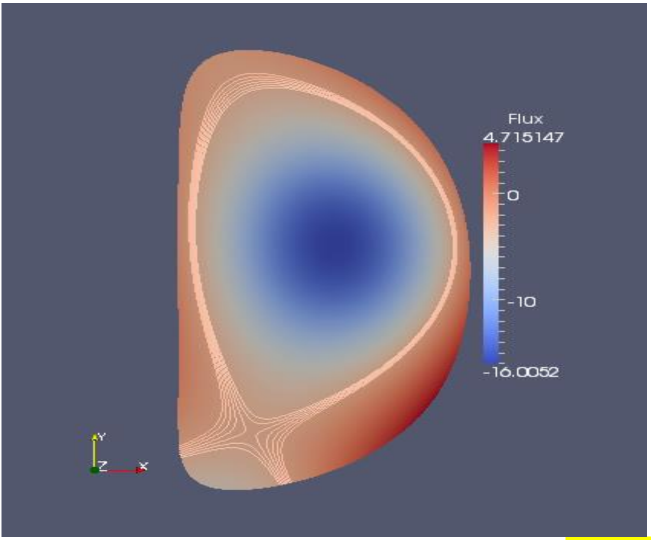
$$\nabla \cdot \Pi_i^{neo} \approx \mu_{i,neo} \rho (B^2 / B_\theta^2)(V_{\theta,i} - V_{\theta,neo}) \vec{e}_\theta \qquad \vec{e}_\theta = (R / |\nabla \psi|) \nabla \psi \times \nabla \varphi$$

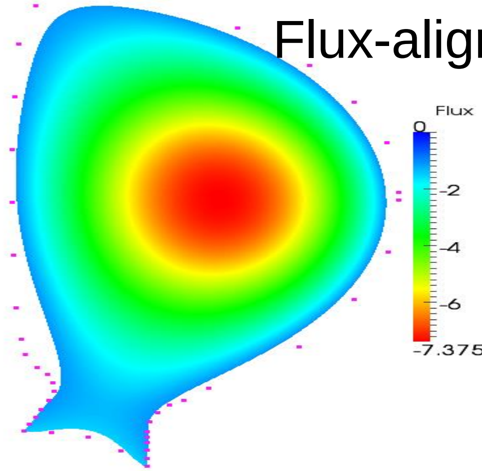
Ion poloidal velocity => neoclassical

$$V_{\theta,i} \rightarrow V_{\theta,neo} = -k_{i,neo} \tau_{IC} (\nabla_\perp \psi \cdot \nabla_\perp T) / B_\theta \qquad B_\theta = |\nabla \psi| / R$$

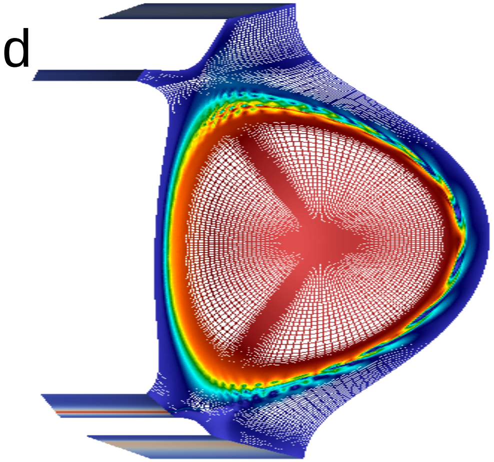
Magnetic field aligned grid (R,Z,ϕ) , X-points, open field lines SOL, realistic divertor geometry, free boundary: resistive wall, coils.

Fixed boundary with ideal wall, divertor geometry, no coils (commonly used)





Flux-aligned grid

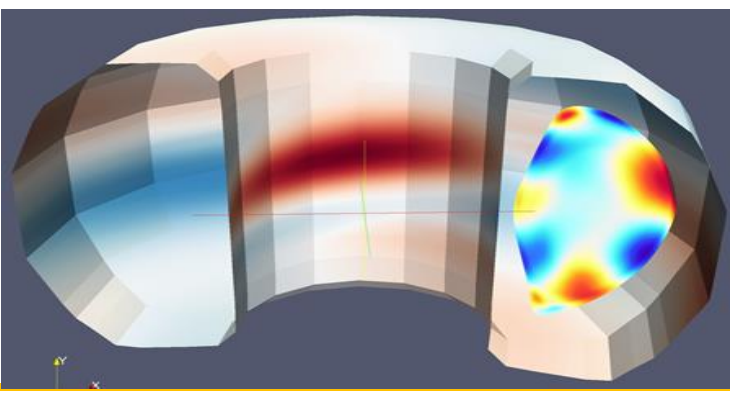


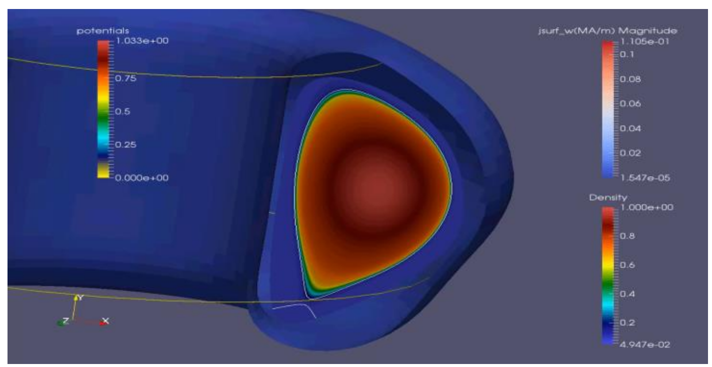
one X-point (here ITER)

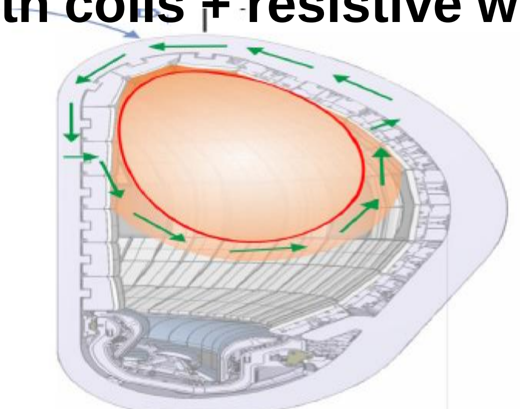
two X-points (here KSTAR)

Free boundary (JOREK+ STARWALL)

equilibrium fixed+ resistive wall **equilibrium calculated with coils + resistive wall**







JOREK code: 2D cubic Bezier elements (C1) in poloidal plane, Fourier in toroidal. Non-linear, fully implicit, large sparse matrix. Full and reduced MHD. New developments- coupled with PIC (W and ruaways)

Weak form of equations.
Finite elements in poloidal plane: 2D cubic Bezier (16 control points), C1
Toroidal direction: Fourier decomposition.
Fully implicit Crank-Nicholson or Gears scheme
Large sparse matrix solver (PastiX) using iterative method (GMRES).
HPC: MPI/OpenMP, typical run: 50.000-200.000 cpuh >20Mcpuh/year
New in 2016: coupling with PIC codes (2 models: for W transport and runaway electrons)

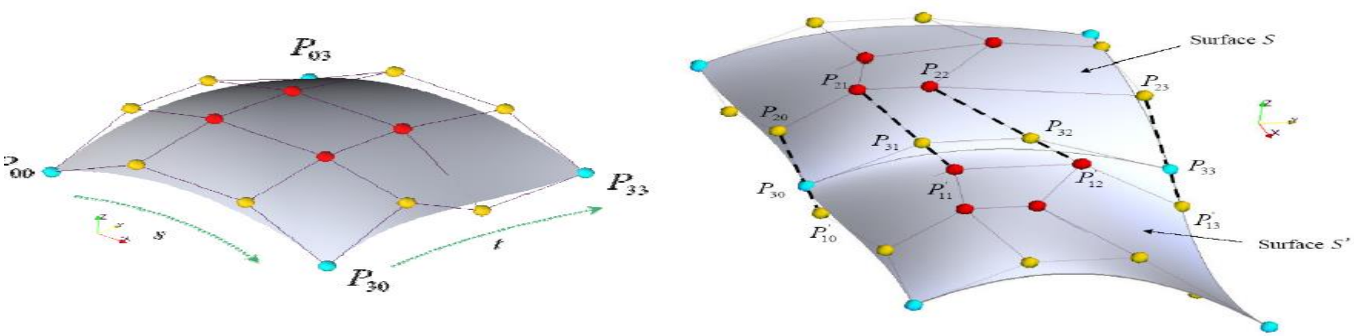
2D Bezier patches

O. Czarny, JCP 2008

- 2D cubic Bezier patch defined by 16 control points

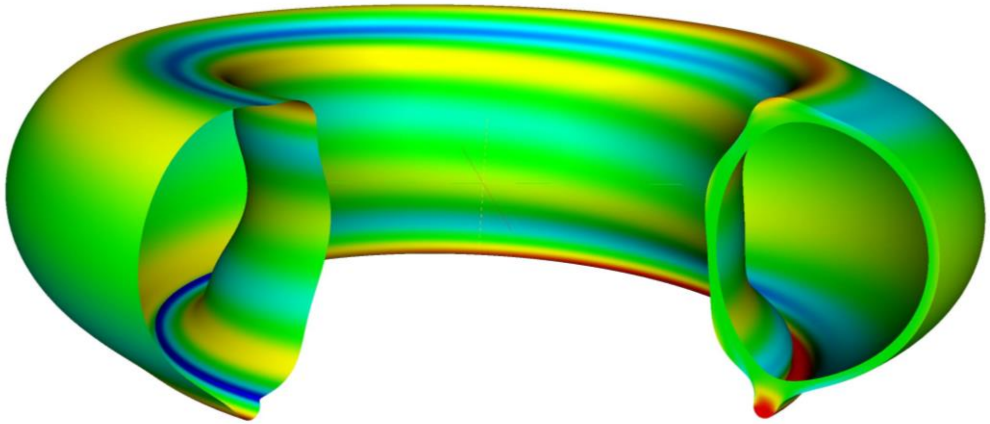
$$\vec{B}(s,t) = \sum_{k,m=0}^{N_1 N_2} \vec{p}_{km} \frac{N!}{k!(N-k)!} s^k (1-s)^{N-k} \frac{N!}{m!(N-m)!} t^m (1-t)^{N-m}$$

- C1 continuity between patches requires that the 4 boundary control points lie on a line with their neighbouring control points

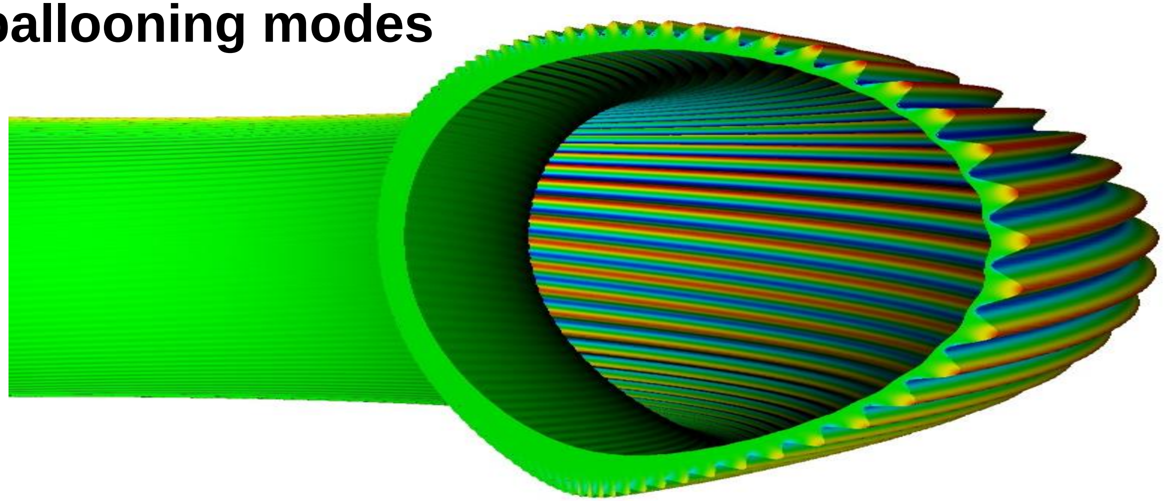


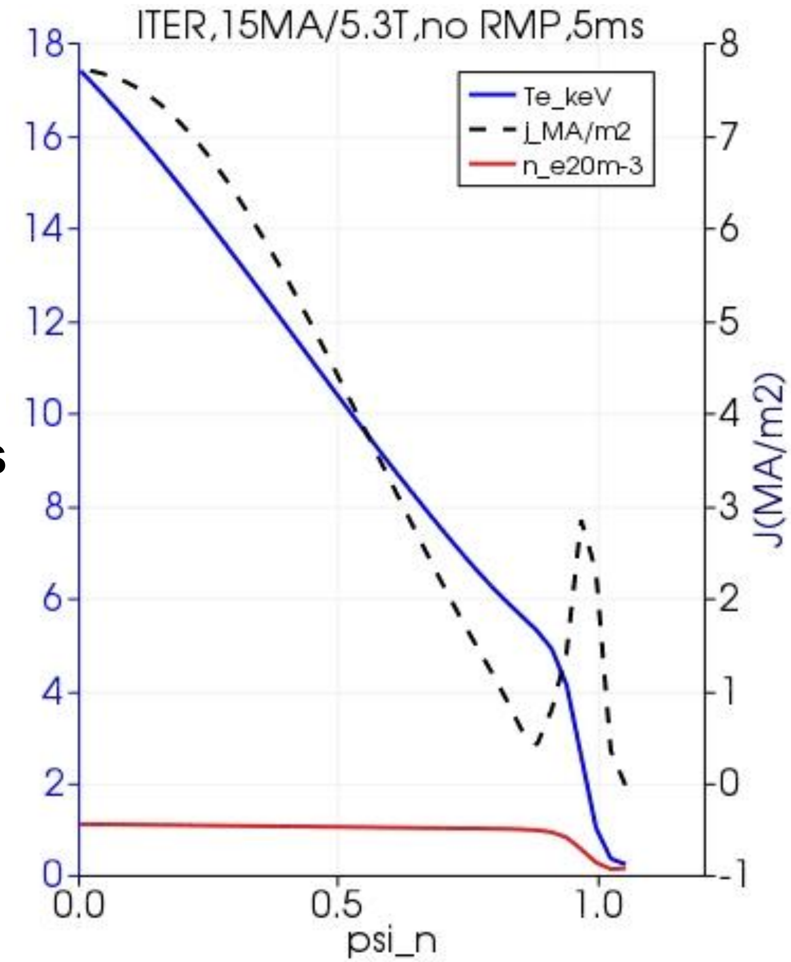
Large edge current (bootstrap): drives peeling/kink modes

[Huysmans PPCF 2005]



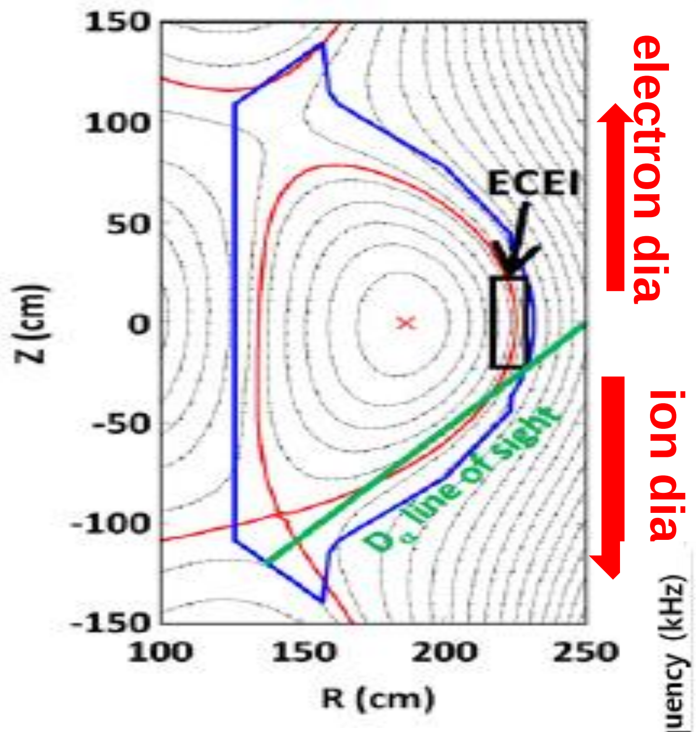
Large edge pressure gradient in H-mode drives ballooning modes





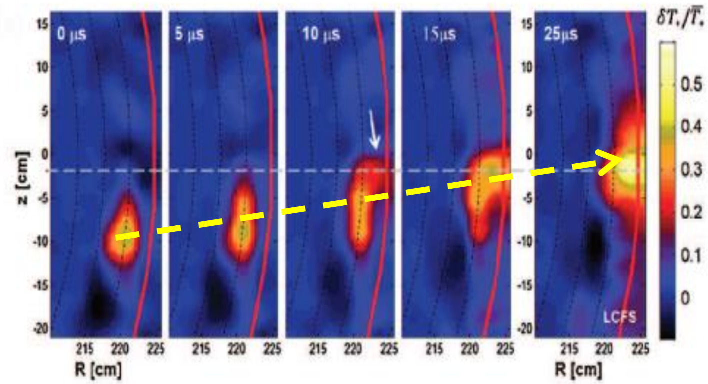
Development towards direct comparison with experiment. Collaboration with KSTAR (Korea)=> Non-linear multi harmonics, multi-cycles ELM dynamics with flows *[Becoulet IAEA2016]*

$$\vec{V}_{p,s} = -\frac{\nabla p_s \times \vec{B}}{e_s n_s B^2}$$

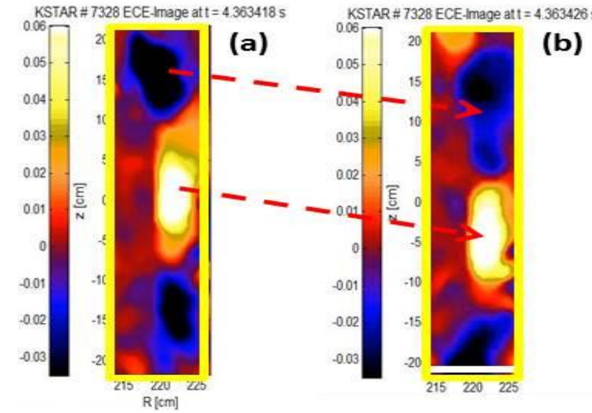


KSTAR: M. Kim , NF2014

Typically rotation of modes before ELM crash in anti-clockwise (electron dia) direction. MAST, AUG, NSTX, KSTAR, sometimes in in clockwise (ion dia) on KSTAR. Why?

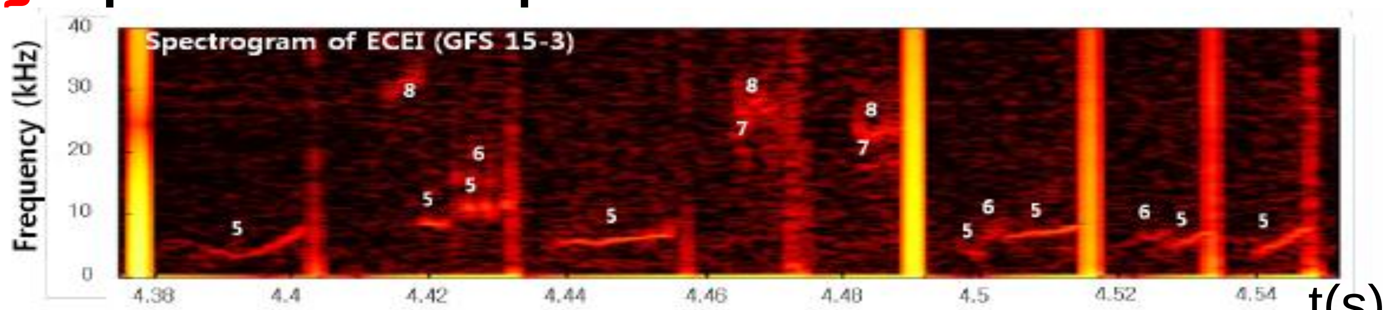


***KSTAR**: Yun et al., PRL, 2011*



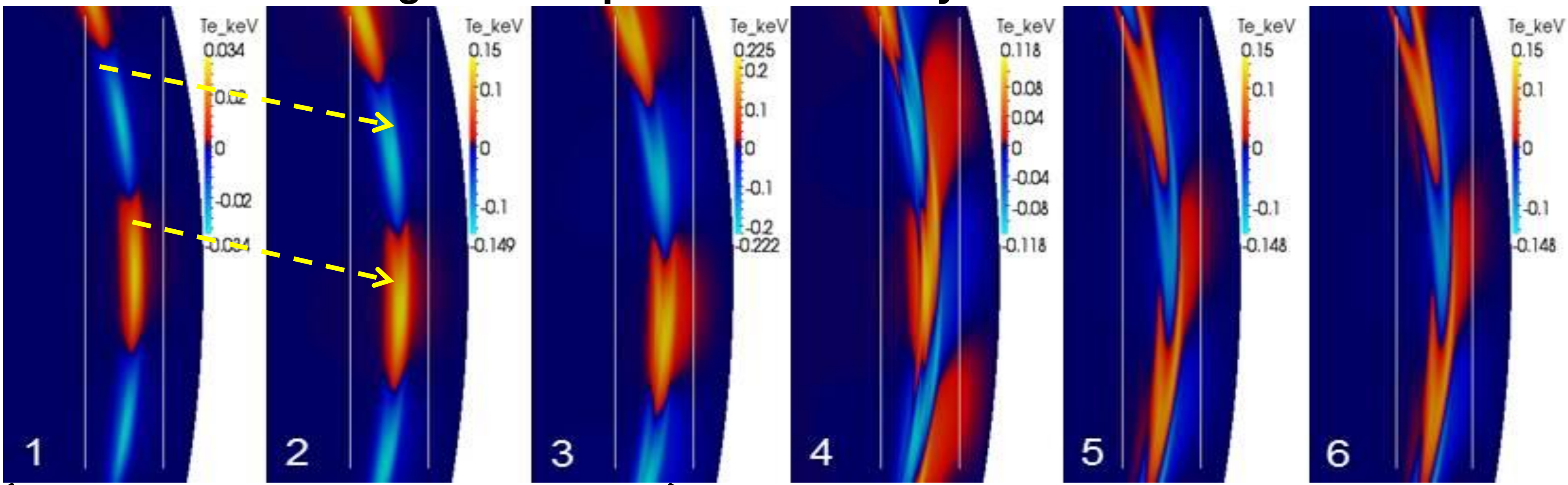
***KSTAR**: Becoulet IAEA2016*

Rotating modes (*n=5-8,5-30kHz*) in inter-ELM period and ELM precursors: *0.2- few ms.*



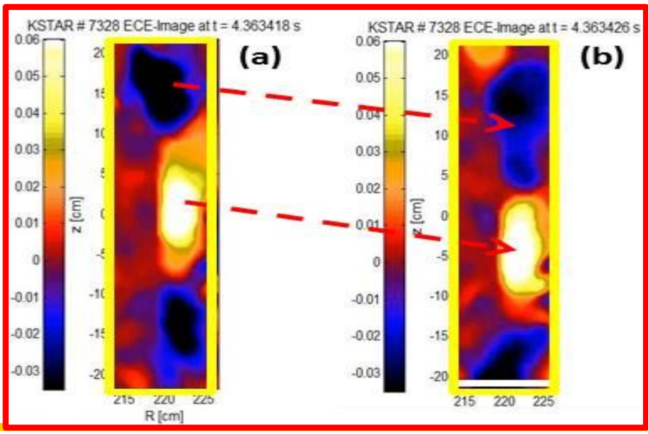
Snapshots of temperature fluctuations in the mid-plane on LFS before and during ELM crash in JOREK modelling correspond well to the experimental observations.

Images are separated in time by ~0.0166ms



Before ELM crash

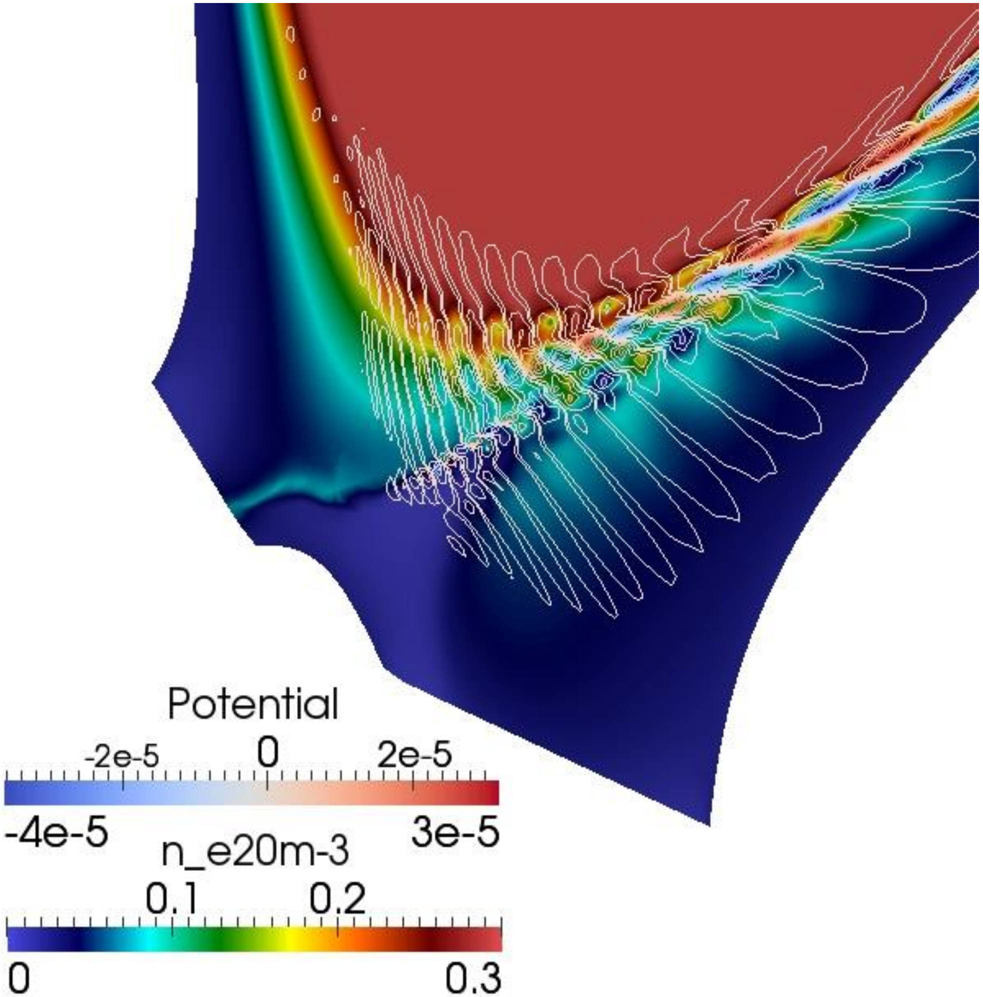
ELM crash



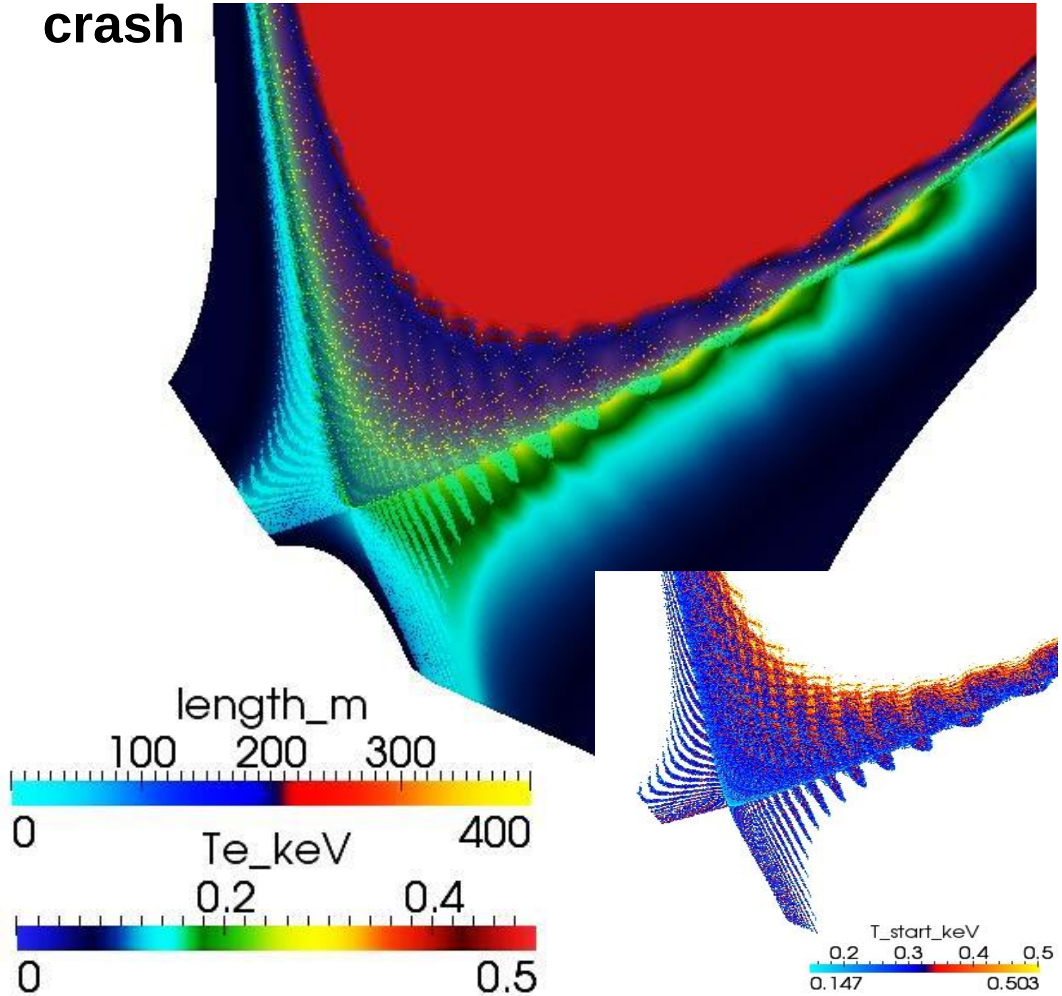
Before ELM crash: ballooning mode n=8 rotates poloidaly in ion diamagnetic direction Vpol~5km/s in modelling (~5.4km/s in experiment)

Transport mechanisms during non-linear phase (ELM crash) .
Density transport: convective (ExB) cells.
Energy: conduction along perturbed magnetic field lines.

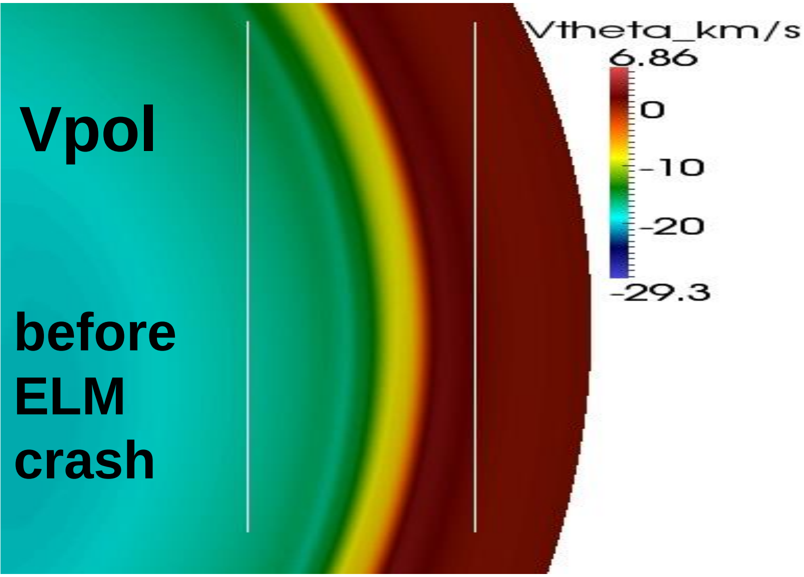
Density and electro- static potential perturbation contours

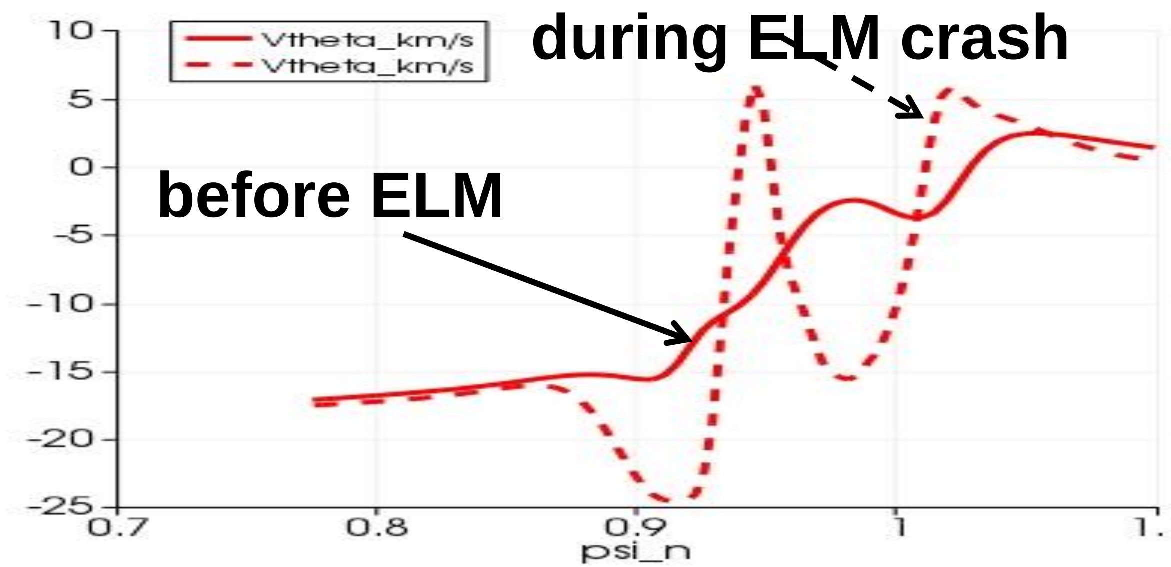


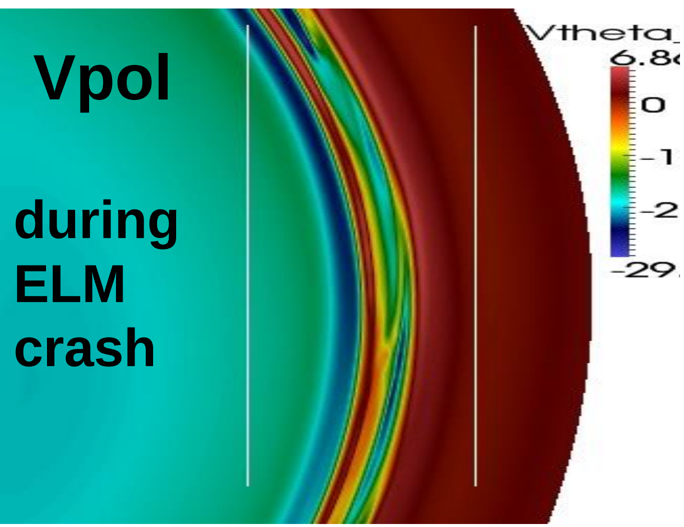
Temperature and edge magnetic topology (ergodisation) during ELM crash

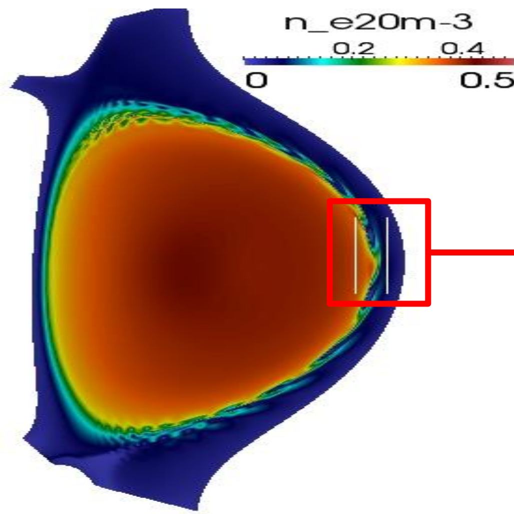


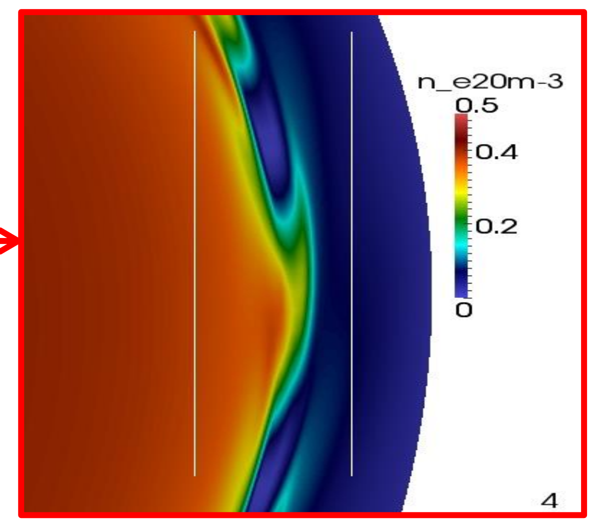
Strongly sheared mean (n=0,m=0) poloidal flow is generated due to the non-linear mode coupling via Maxwell stress tensor *[HuysmansNF2007, MoralesPoP2016].*



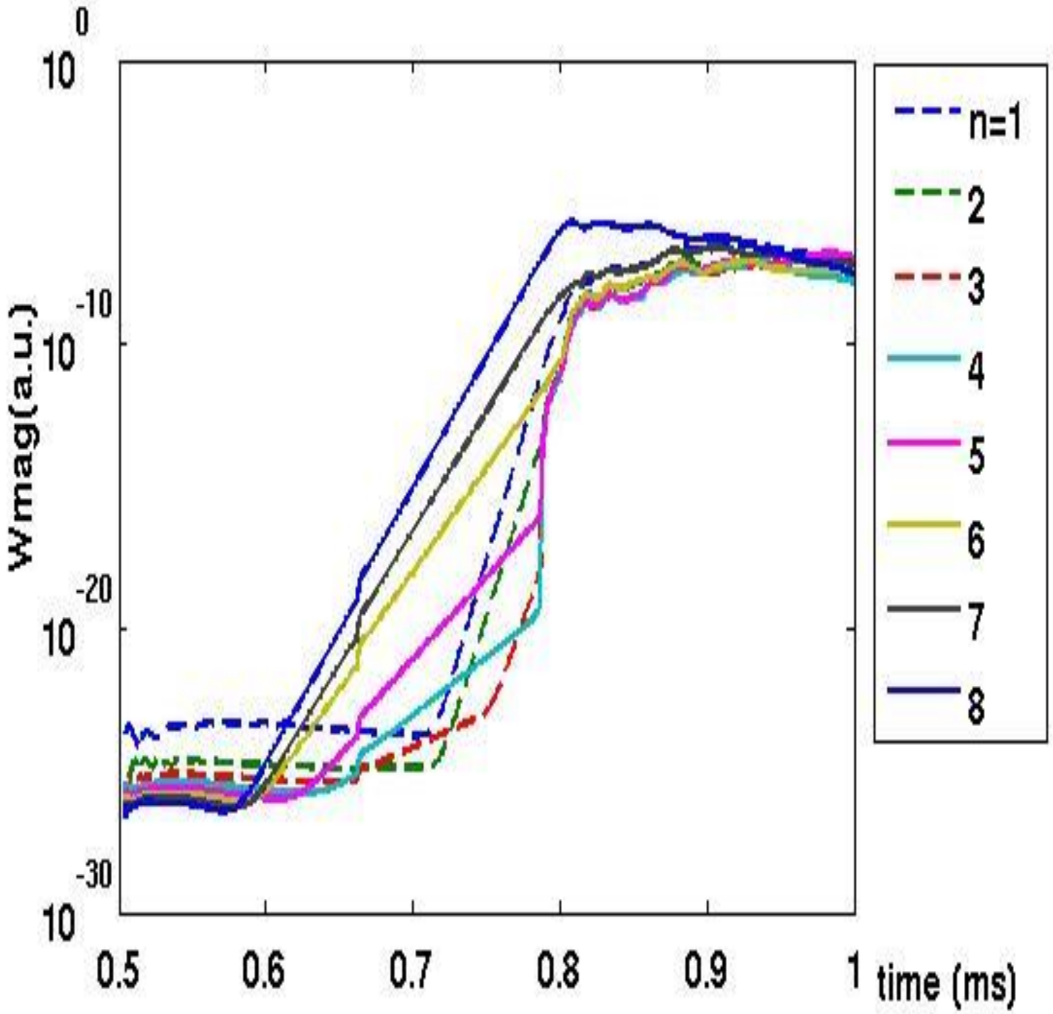




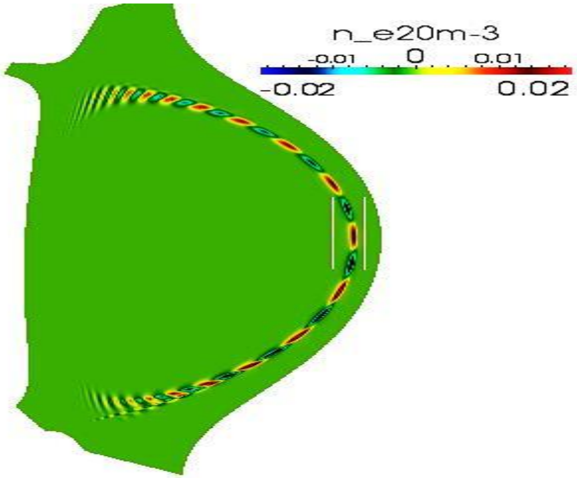




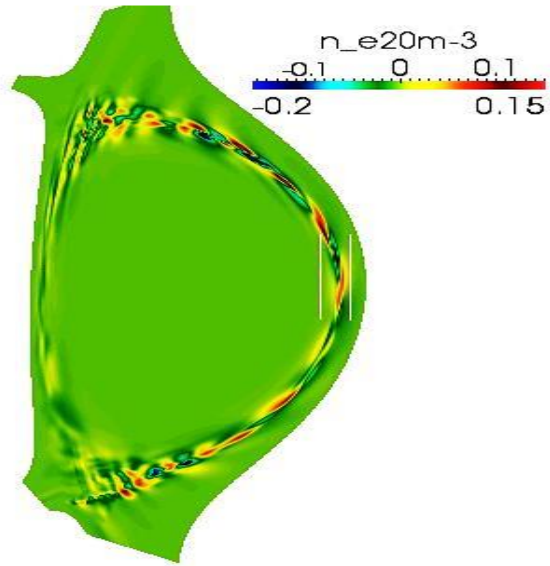
Multi-modes (n=1-8) ELM : destabilization of the previously linearly stable or weakly unstable modes while approaching the ELM crash due to the non-linear coupling.



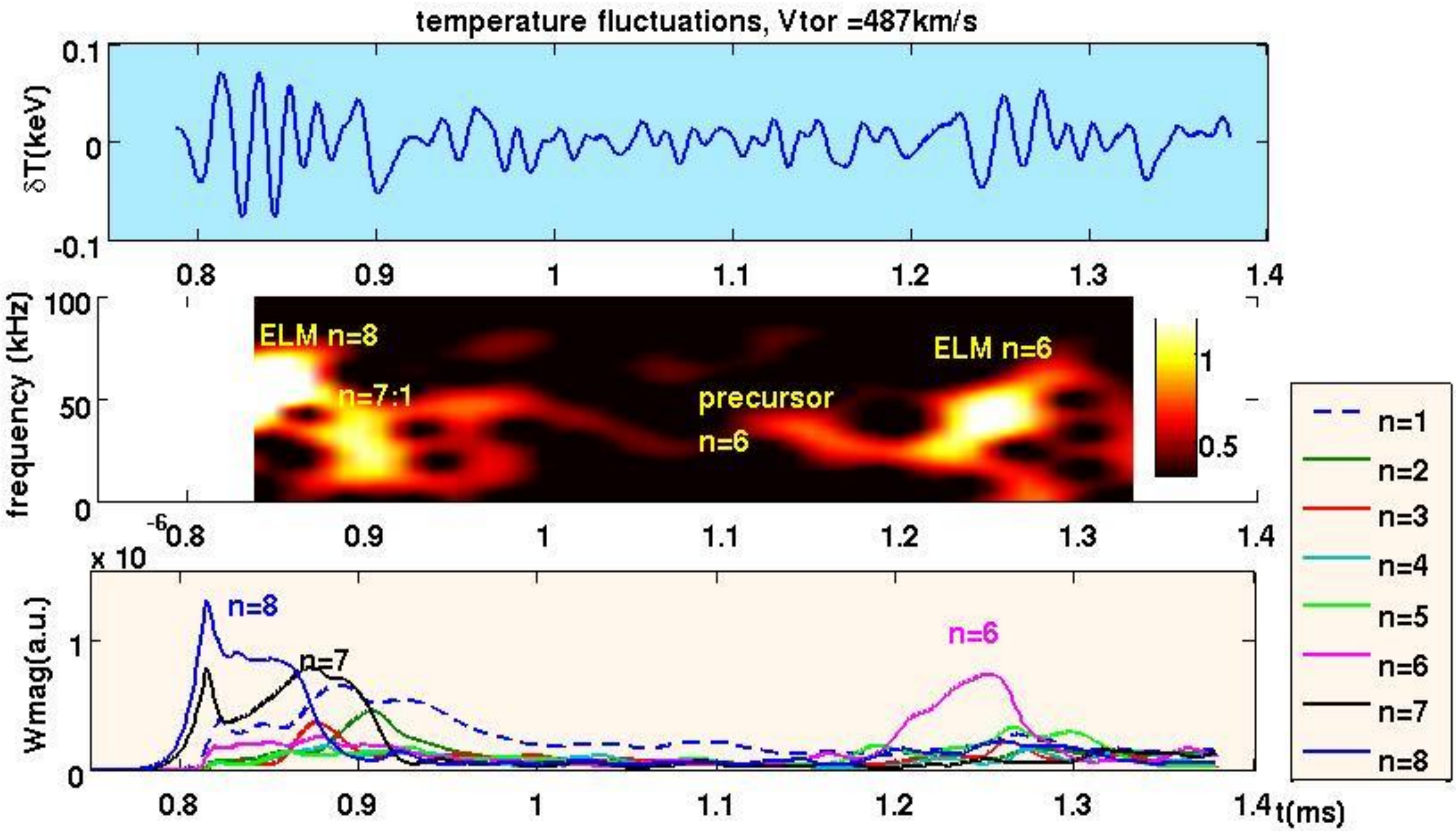
Linear phase: main unstable harmonic n=8



Non-linear coupling of modes n=1-8 during ELM crash



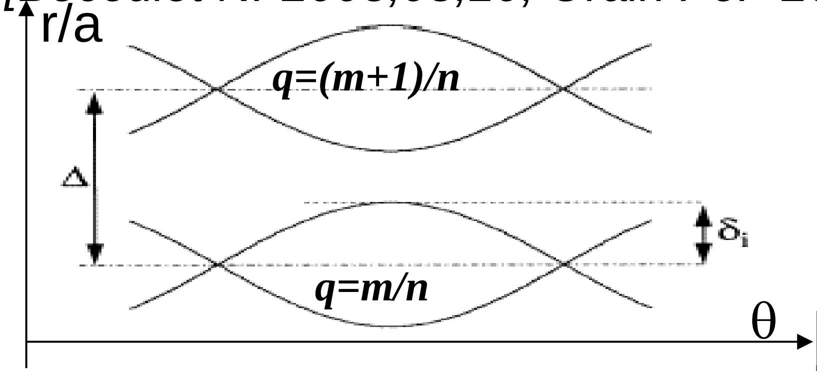
ELM cycling with multi harmonics n=1-8. Precursor n=6 in inter-ELM period (0.15ms) after ELM crash on the most unstable n=8. Second ELM is due the most unstable n=6.

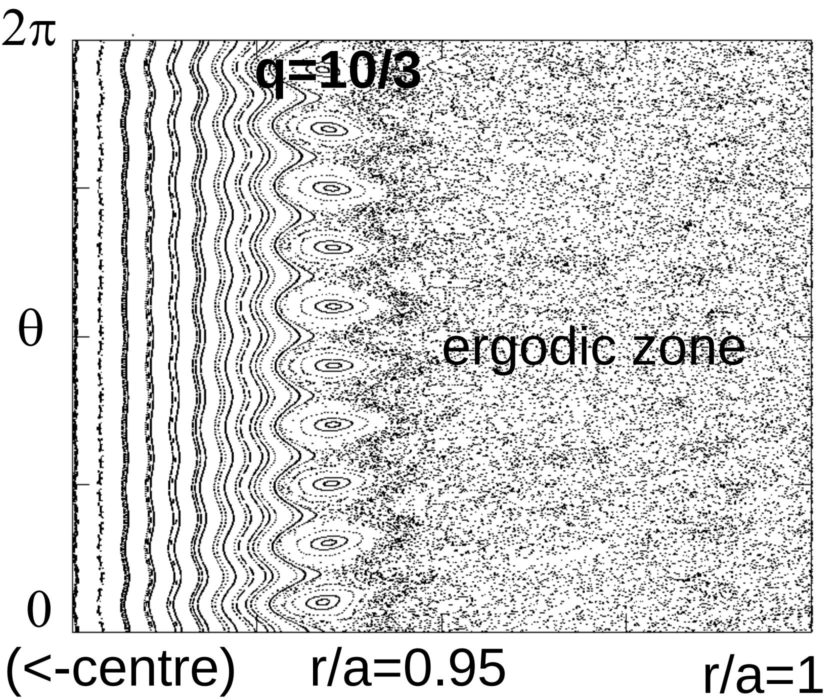


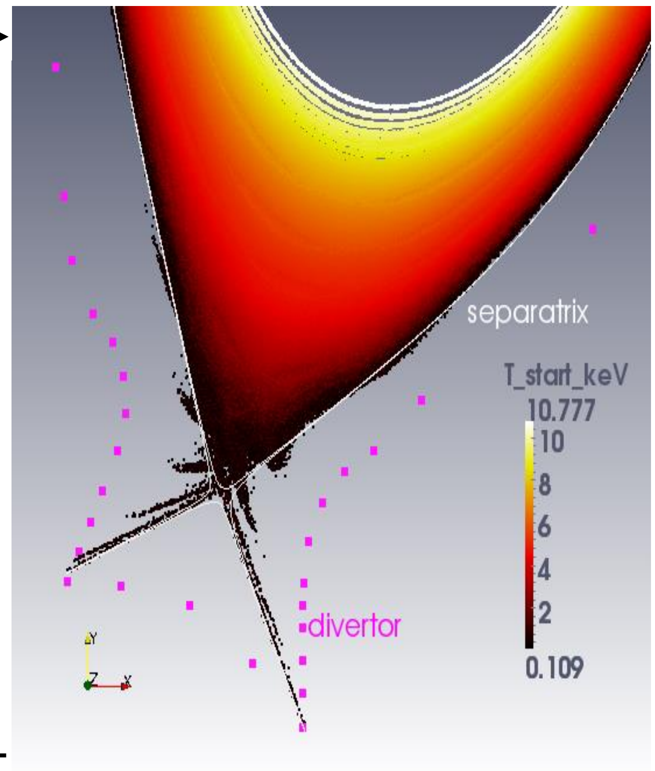
ELM control by Resonant Magnetic Perturbations (RMPs)

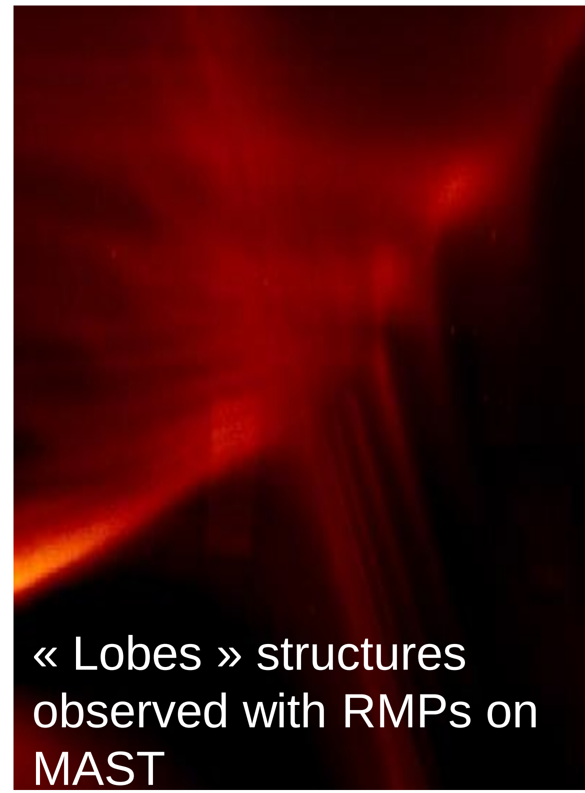
[Becoulet NF2005,08,10, Orain PoP 2013]

Idea of ELM contron by RMPs: small radial magnetic field $\delta B^r \sim 10^{-4}$, islands on resonant surfaces q=m/n, ergodic edge, increase transport→ decrease ∇P below ELM triggering threshold. Does it work like that?



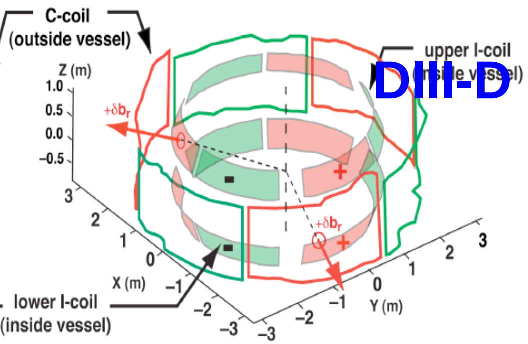




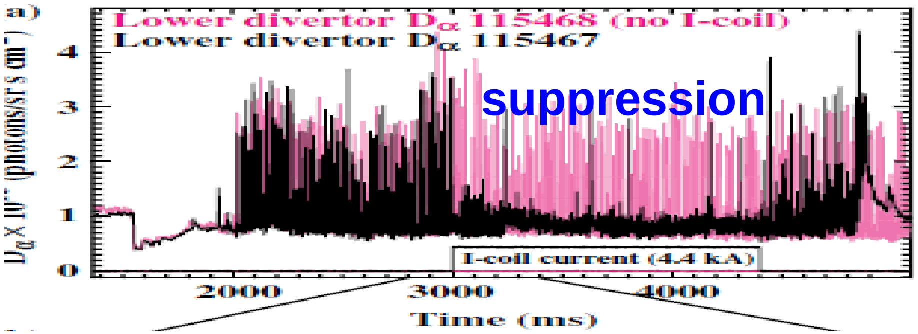


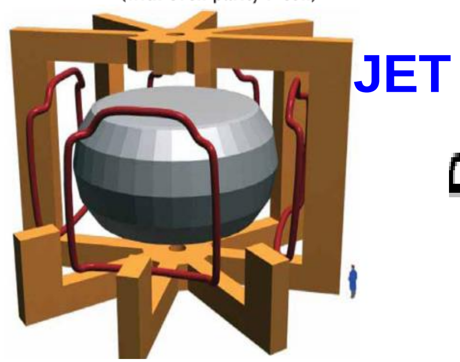
ELM suppression/mitigation by RMPs is observed on many tokamaks. RMPs will be used in ITER. Why it works, how plasma responds? Will it work in ITER? Still many open questions remain.

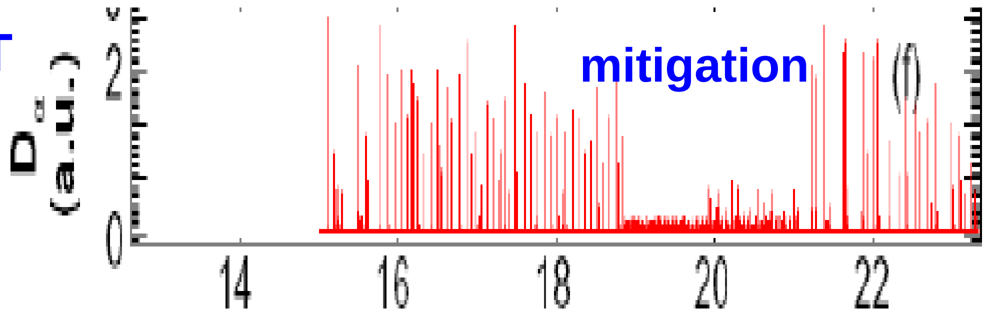
[DIII-D Evans NF2005, JET Liang PRL 2007, AUG Suttrop PRL2011, MAST Kirk PPCF2013]

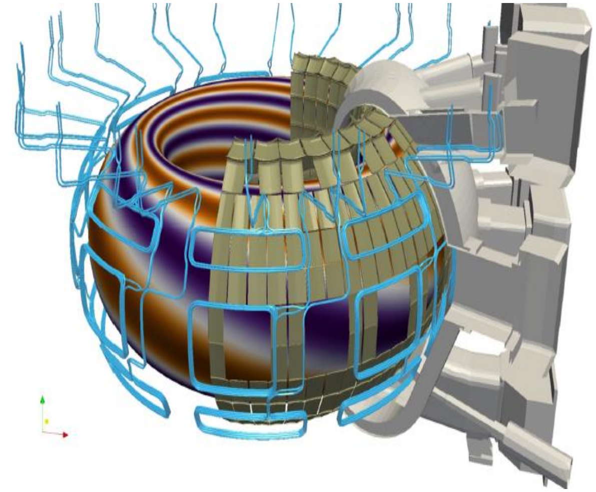


n=3 I-coil and C-coil configuration
(with even parity I-coil)

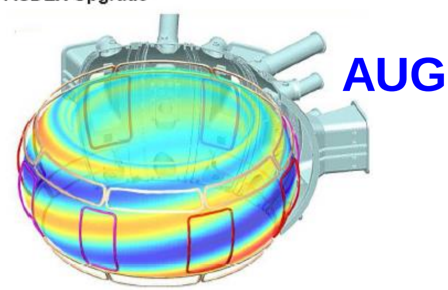




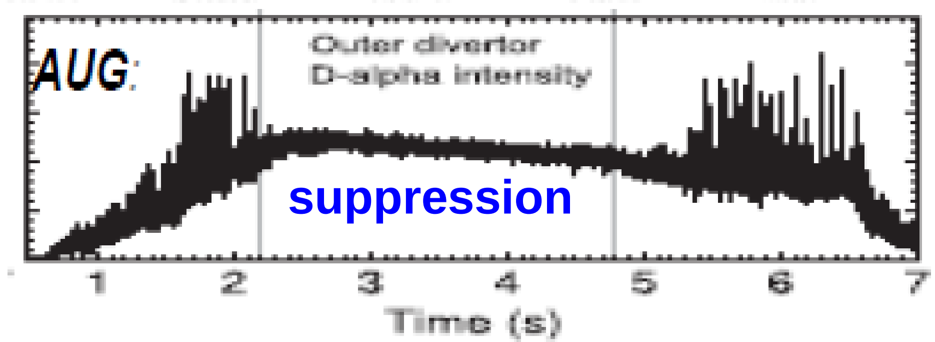




ASDEX Upgrade



Full in-vessel coil set:
3 rows à 8 saddle coils



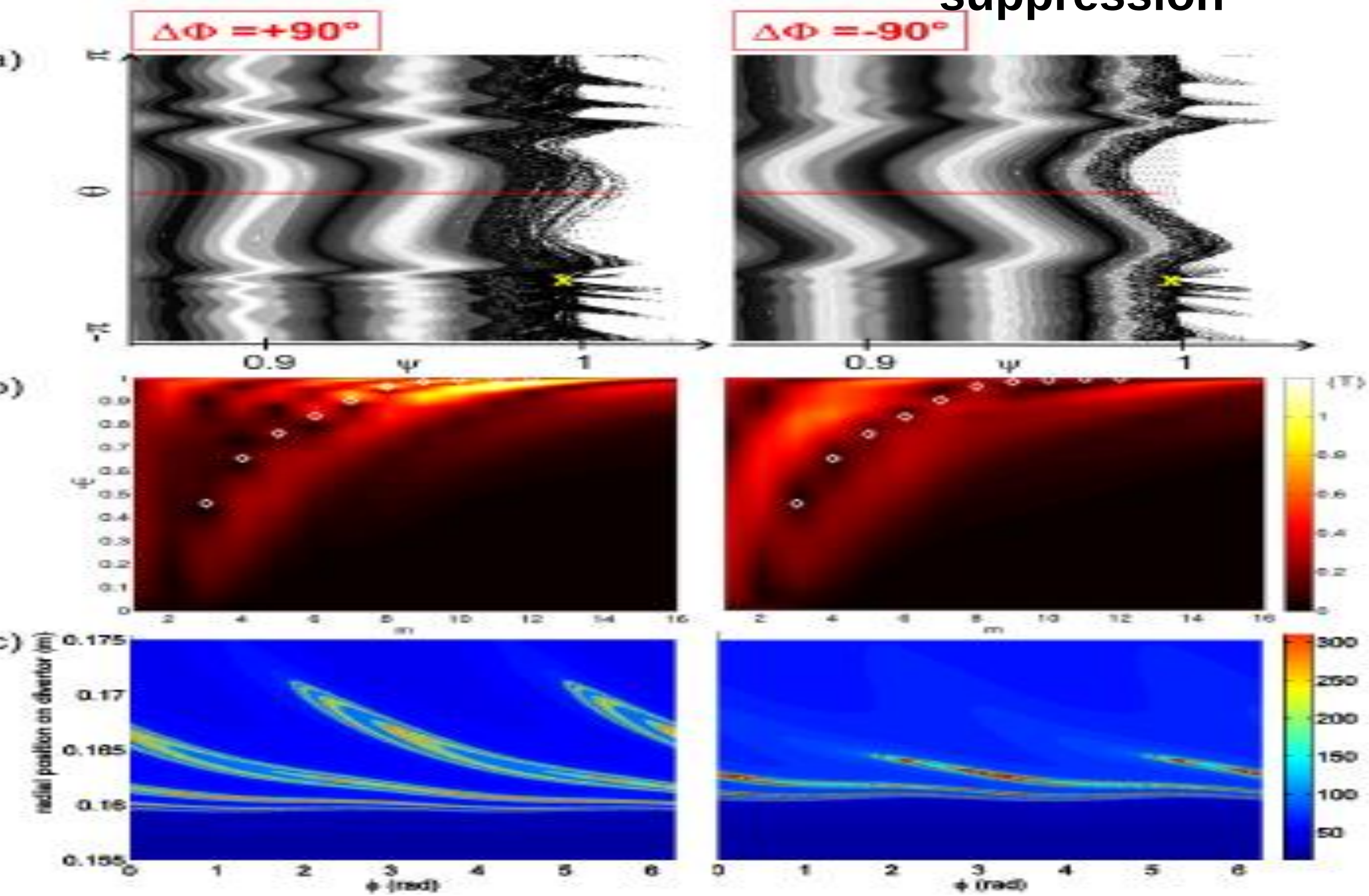
ITER RMP In-Vessel Coils :
3 rows of 9 RMP coils are planned

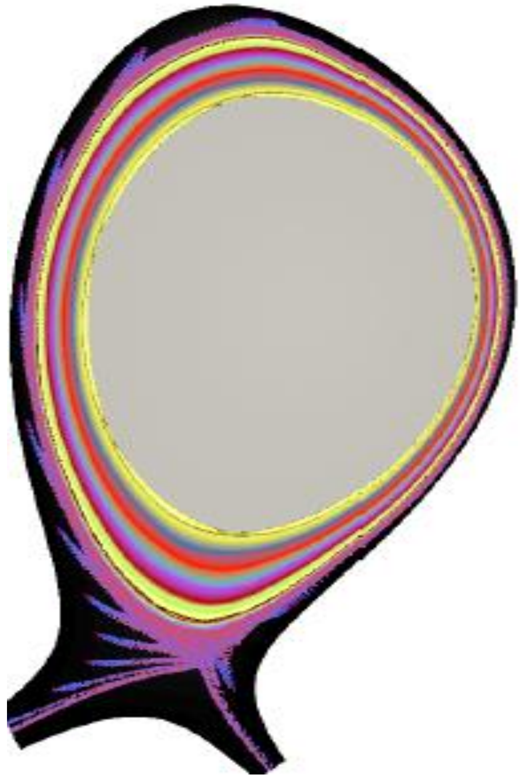
Experiment+modelling suggest that when ELMs are suppressed when plasma amplifies RMPs by external kink-tearing mode . Depends on q profile and specific phasing in RMP coils.

AUG, JOREK [Orain NF 2016, IAEA2016]

ELMs suppression

No ELMs suppression





3D edge with RMPs=>Non-axisymmetric footprints ("hot spots") in divertor. Divertor fluxes with RMPs in ITER ? *[Becoulet ITPA2016]*

O. Schmitz NF(2016)

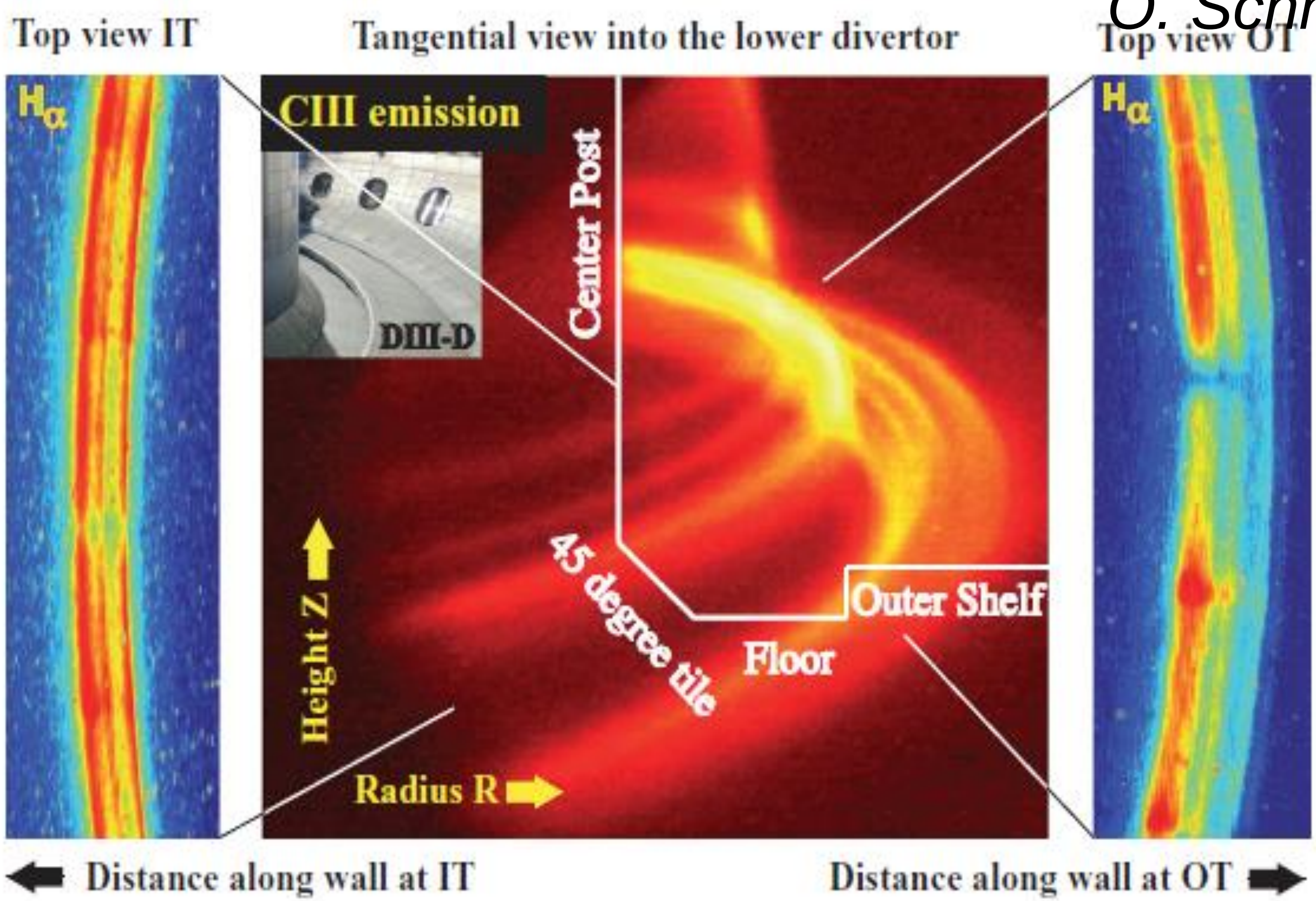
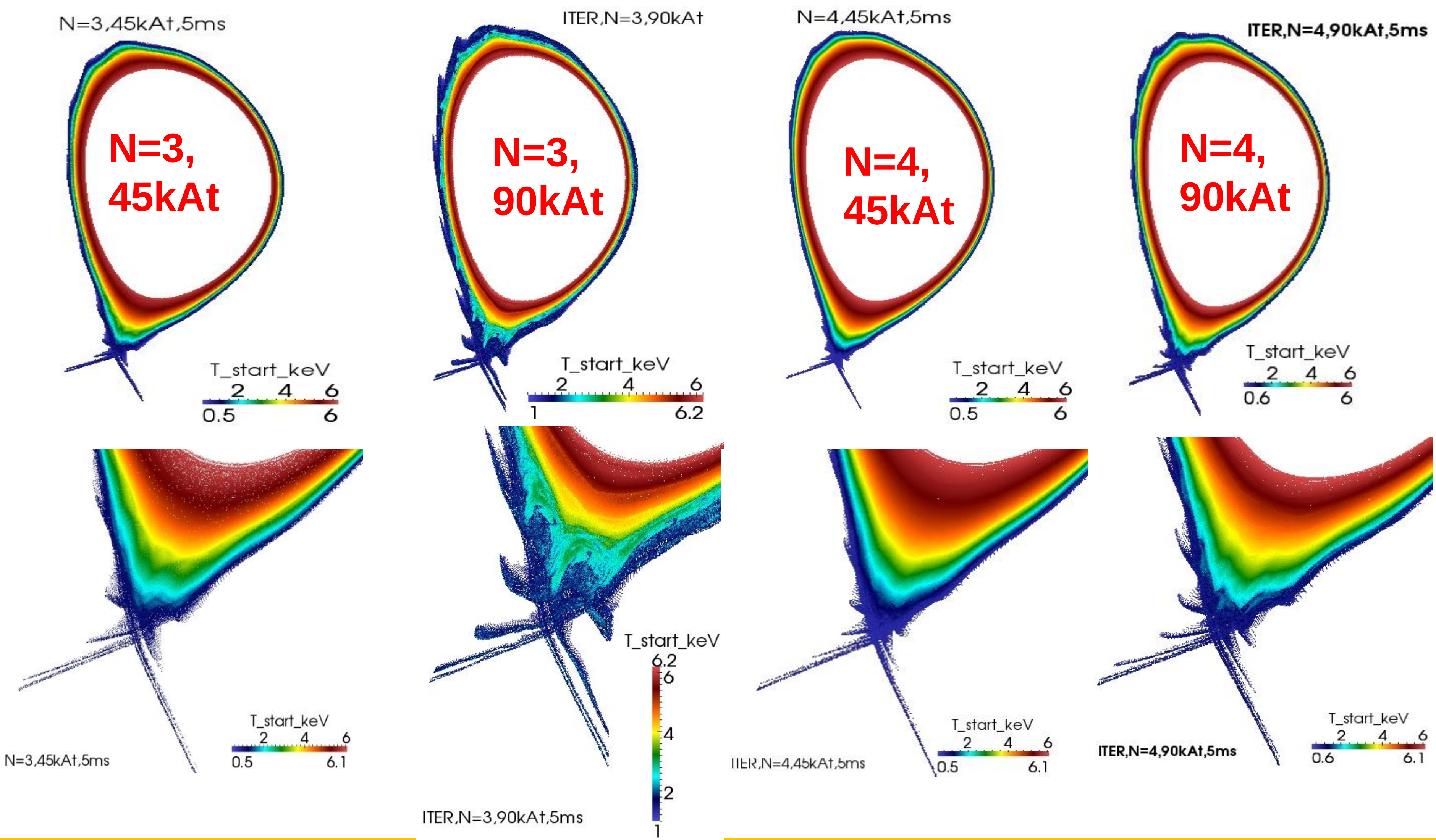
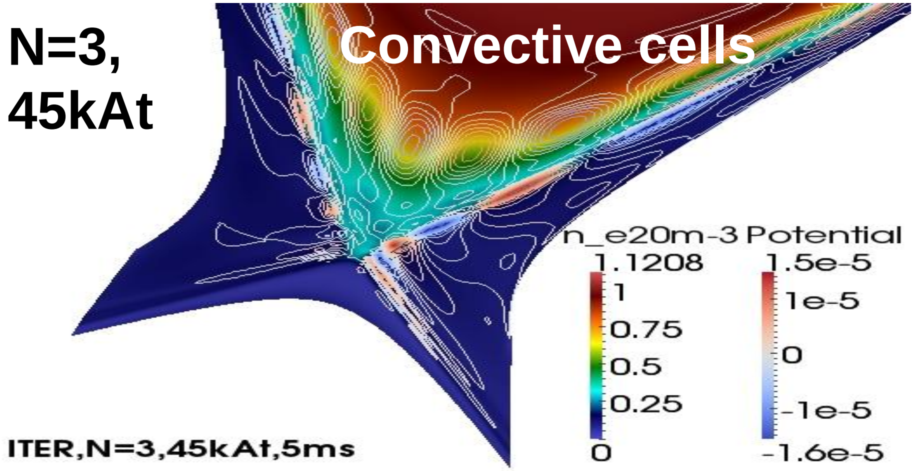


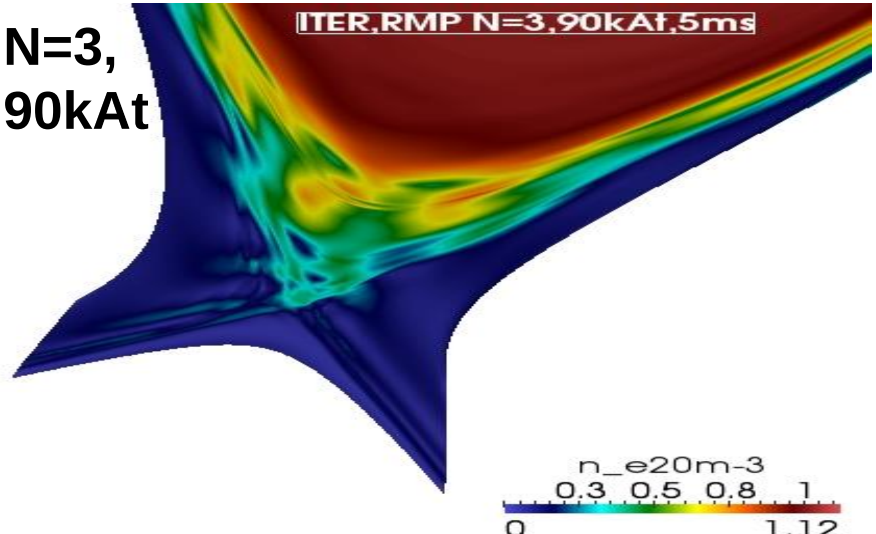
Figure 1. Divertor light emission patterns showing the formation of a 3D plasma boundary during suppression of ELMs by RMP fields at DIII-D. A tangential view in the light of double-ionized carbon is shown in the middle figure. The left and right figures show the Balmer-α emission of deuterium at the inner (IT, left side) and the outer (OT, right side) divertor target.

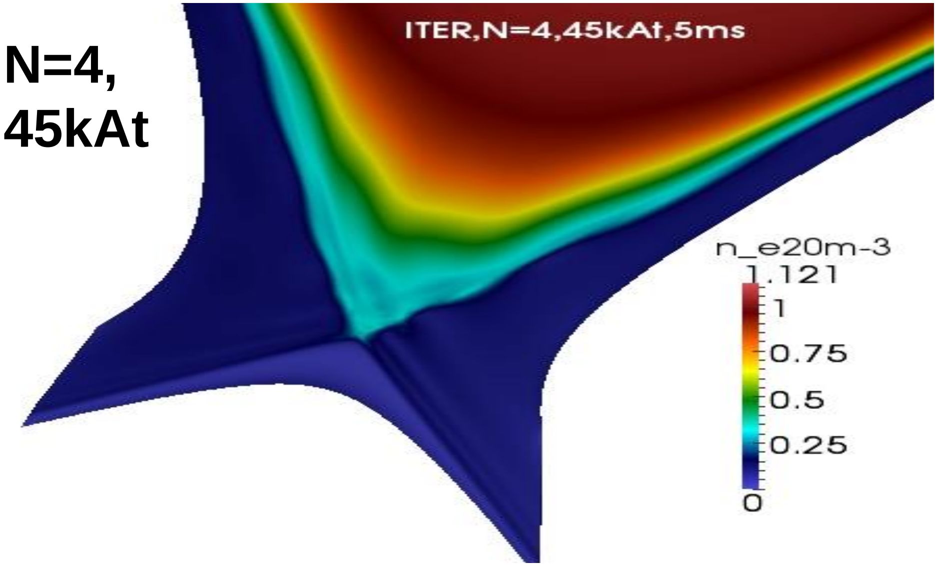
Edge ergodisation increases with RMP coils current and decreases with RMP main toroidal harmonic number (larger for N=3 compared to N=4 at the same coil current). Largest

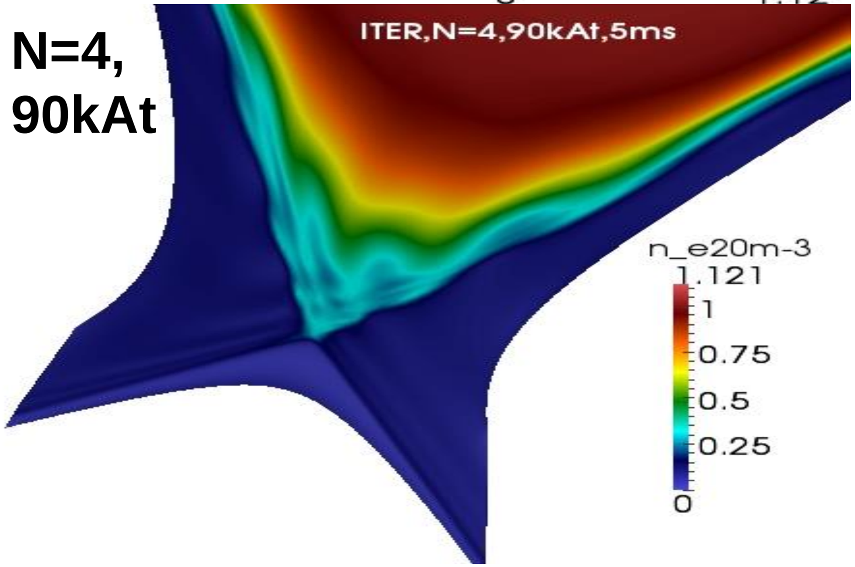


Convective (ExB) density transport due to RMP is similar to ELMs but continues in time.

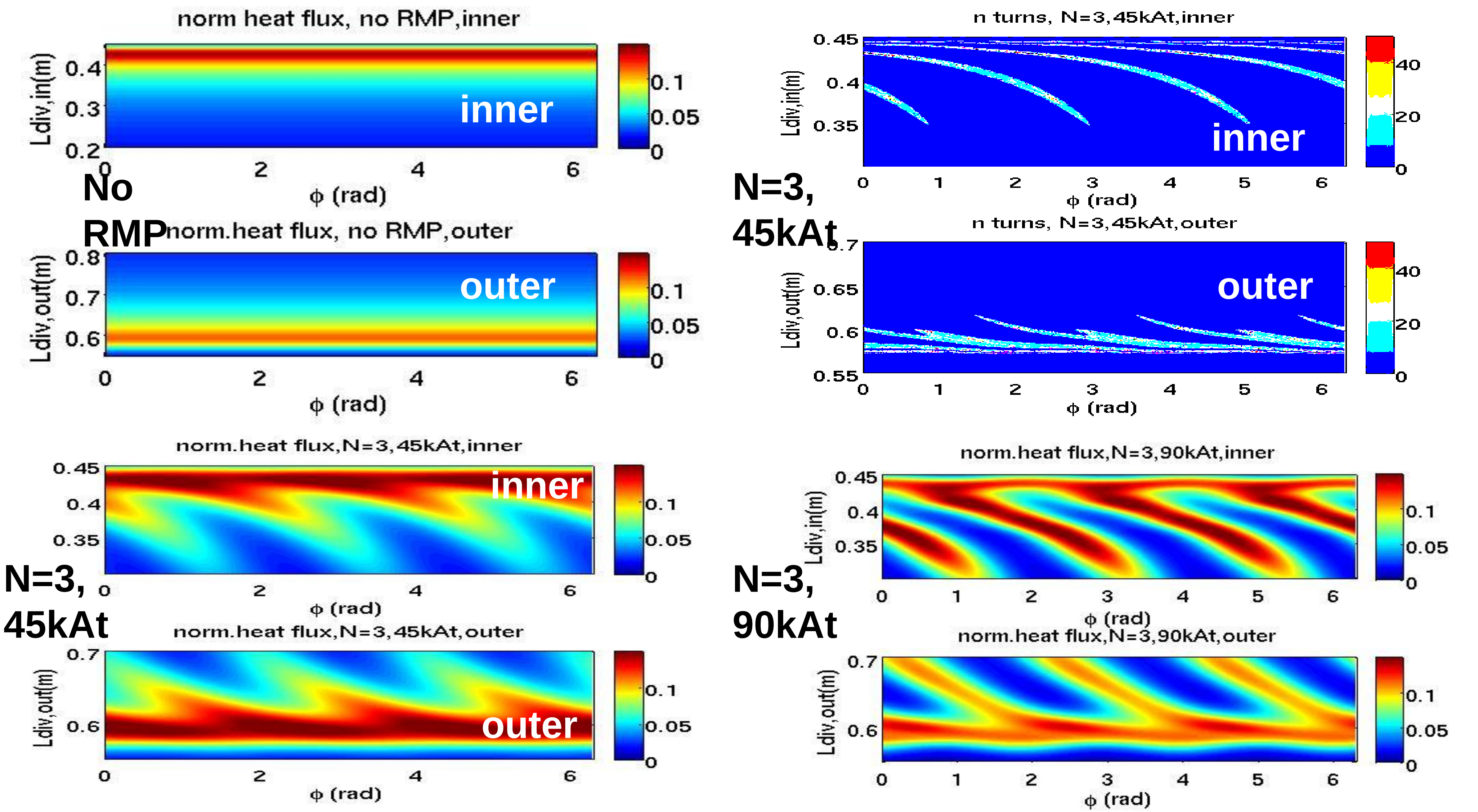








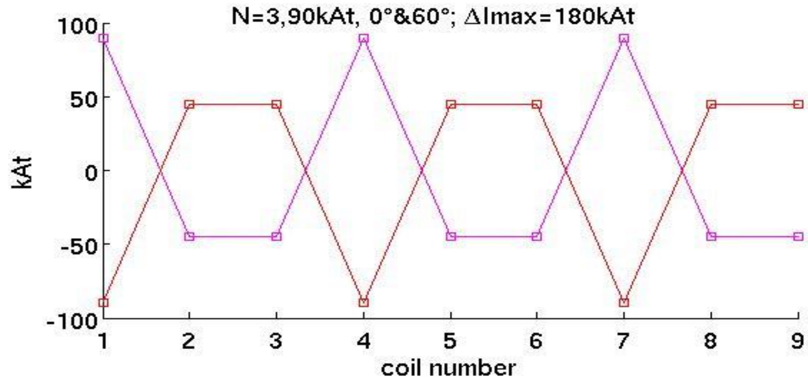
Divertor heat flux $\gamma_{sh} T n_e (\vec{V}\cdot\vec{n}) / P_{tot,div}$ is not uniform over magnetic footprints. Larger splitting for larger RMP.

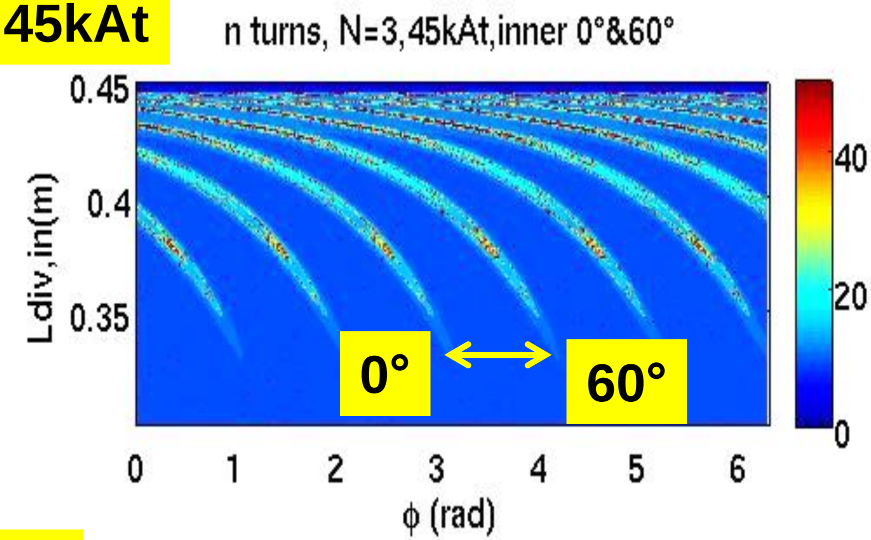


Full rigid rotation $\Delta\phi_j=\pi/N$ => almost axisymmetric heat flux in average, BUT full stress on RMP coils: $\Delta I_{max}=2 \cdot I_{max}$ (180kAt for Imax=90kAt !)

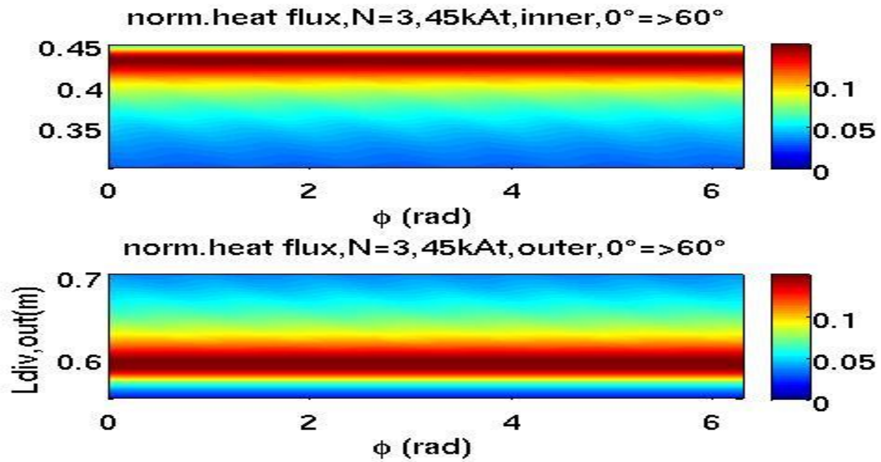
$I_{ij}=I_{max}\cdot\cos(N(\phi_i-\Delta\phi_j))$;

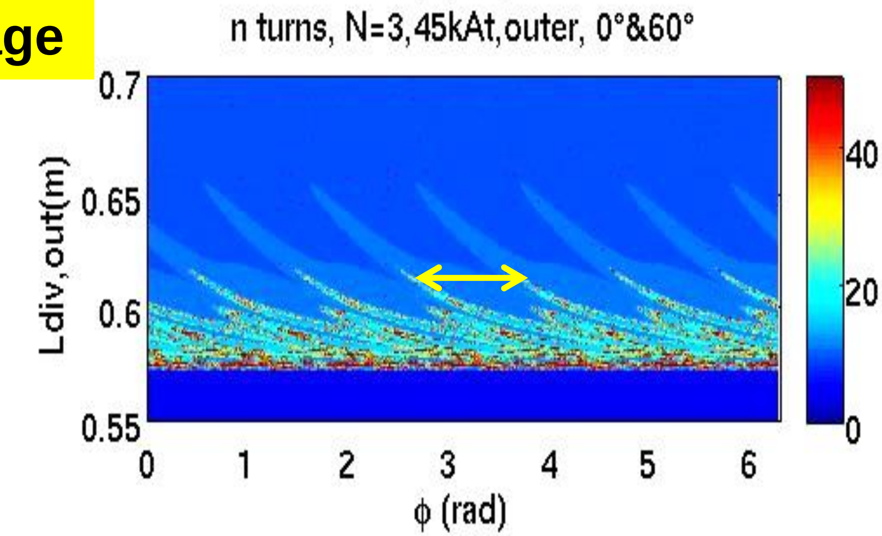
N=3,45kAt





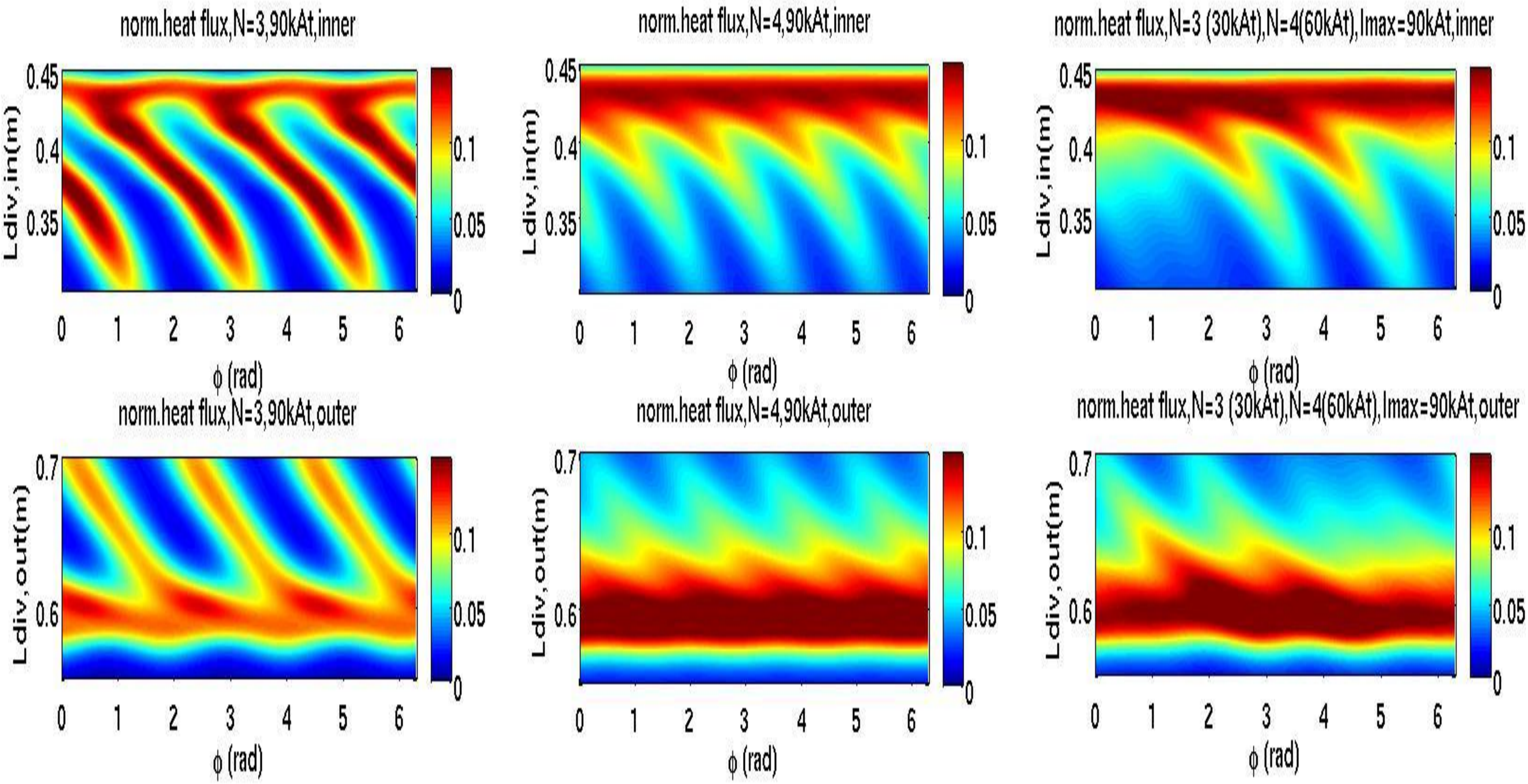
$\Delta\phi_j=\pi/N=60°$=> **uniform flux in average**





New development in JOREK (spectre of several RMP harmonics) one possible solution was proposed: use of mixture N=3&N=4 to reduce non-axisymmetry of flux . No rotation (=no stress) of RMP?

single N=3 **single N=4** **Mixture N=3&N=4**



Conclusions:

Code JOREK is resistive non-linear fluid MHD code especially designed for modelling of transient MHD events and their active control in realistic tokamak geometry. Resistive wall, all flows, open and closed field lines, coils, divertor geometry etc…Reduced MHD (most developed), full MHD (good progress in stability). 2D finite elements (cubic 2D Bezier) C1+toroidal harmonics. 3D finite elements in progress.

- Disruptions & control by massive gas injection, **runaway electrons(PIC);**
- ELMs dynamics ,heat/particle fluxes in divertor**. Multi-harmonics, multi-cycles.**
- **W transport (PIC) during ELMs.**
- ELMs control by RMPs. **External kink response=>ELM suppression?. Divertor fluxes in ITER (ITPA task).**
- ELMs control by pellets.
- QH mode (naturally small ELMs regime)
- **Recycling in divertor**
- **VDEs, ELMs control by vertical kicks**

Future: ITG turbulence, L/H, ELMs+ITG, RMP+ITG etc.

Numerical improvements needed: mesh with complicated wall geometry, memory for larger matrix inversion (multi-harmonics), stability with flows (when large diamagnetic, full MHD), better convergence on non-linear phase of large ELMs….

METHOD & MODEL

The method is based on the implementation of a Guiding-Center [2] and full orbit relativistic particle tracker within the JOREK code [3], [4], which is being used for simulating plasma disruptions [5]. The main features are:

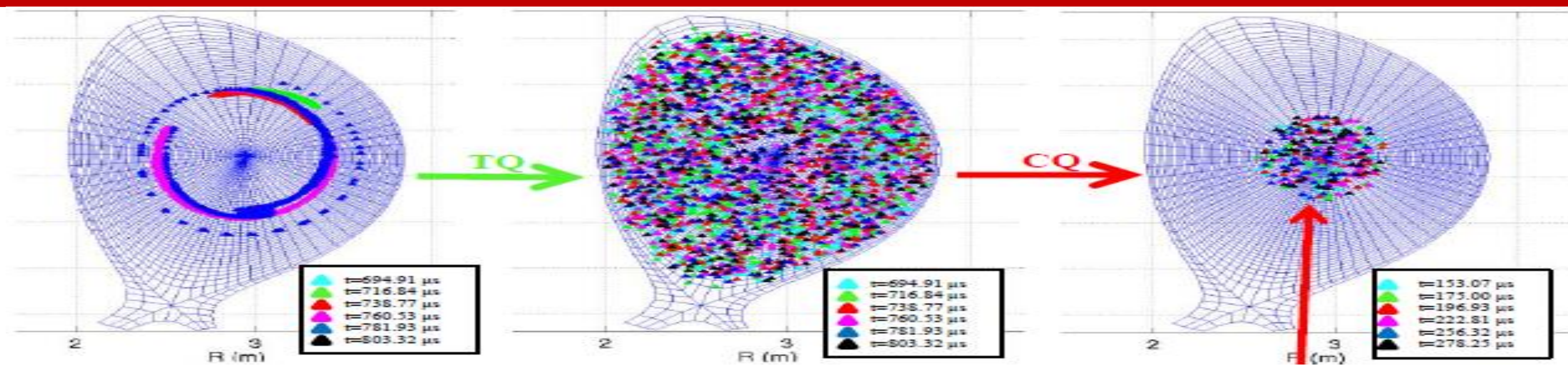
- Full interpolation in 3D physical space and time (global C^1 field description)
- Particle Tracking in 2D flux-aligned non structured grid
- Guiding Center orbit integration via Runge-Kutta (Cash-Karp) method

$$\frac{d\vec{R}}{dt} = \frac{1}{\hat{b}\cdot\vec{B}^*}\left(q\vec{E}\times\hat{b} - p_{/\!/}\frac{\partial\hat{b}}{\partial t}\times\hat{b} + \frac{\mu\hat{b}\times\nabla B}{\gamma} + \frac{p_{/\!/}\vec{B}^*}{m\gamma}\right)$$

$$\frac{dp_{/\!/}}{dt} = \frac{\vec{B}^*}{\hat{b}\cdot\vec{B}^*}\cdot\left(q\vec{E} - p_{/\!/}\frac{\partial\hat{b}}{\partial t} - \frac{\mu\nabla B}{\gamma}\right)$$

$$\vec{B}^* \equiv p_{/\!/}\nabla\times\hat{b} + q\vec{B} \quad \text{and} \quad \gamma \equiv \sqrt{1 + \left(\frac{p_{/\!/}}{mc}\right)^2 + \frac{2\mu B}{mc^2}}$$

- Full orbit integration via Volume Preserving Algorithm [6]



BORIS method is implemented in PIC code for tungsten transport.

- Equations:

$$m\frac{d\vec{v}}{dt} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$$

$$\frac{d\vec{x}}{dt} = \vec{v}$$

- Boris method:

$$\vec{x}^{t+\frac{1}{2}\delta t} - \vec{x}^{t-\frac{1}{2}\delta t} = \delta t\vec{v}^{t}$$

  - Implicit

$$\vec{v}^{t+\delta t} - \vec{v}^{t} = \delta t\frac{q}{m}\left(\vec{E}^{t+\frac{1}{2}\delta t} + \tfrac{1}{2}\left(\vec{v}^{t} + \vec{v}^{t+\delta t}\right)\times\vec{B}^{t+\frac{1}{2}\delta t}\right)$$

  - Split electric and magnetic field updates
    - Implicit equation can solved

$$\vec{v}_0 = \vec{v}_{t-\frac{1}{2}\delta t} + \frac{q\vec{E}}{m}\tfrac{1}{2}\delta t$$

$$\frac{\vec{v}_1 - \vec{v}_0}{\delta t} = \frac{q}{2m}\left(\vec{v}_1 + \vec{v}_0\right)\times\vec{B}$$

$$\vec{v}_{t+\frac{1}{2}\delta t} = \vec{v}^{1} + \frac{q\vec{E}}{m}\tfrac{1}{2}\delta t$$

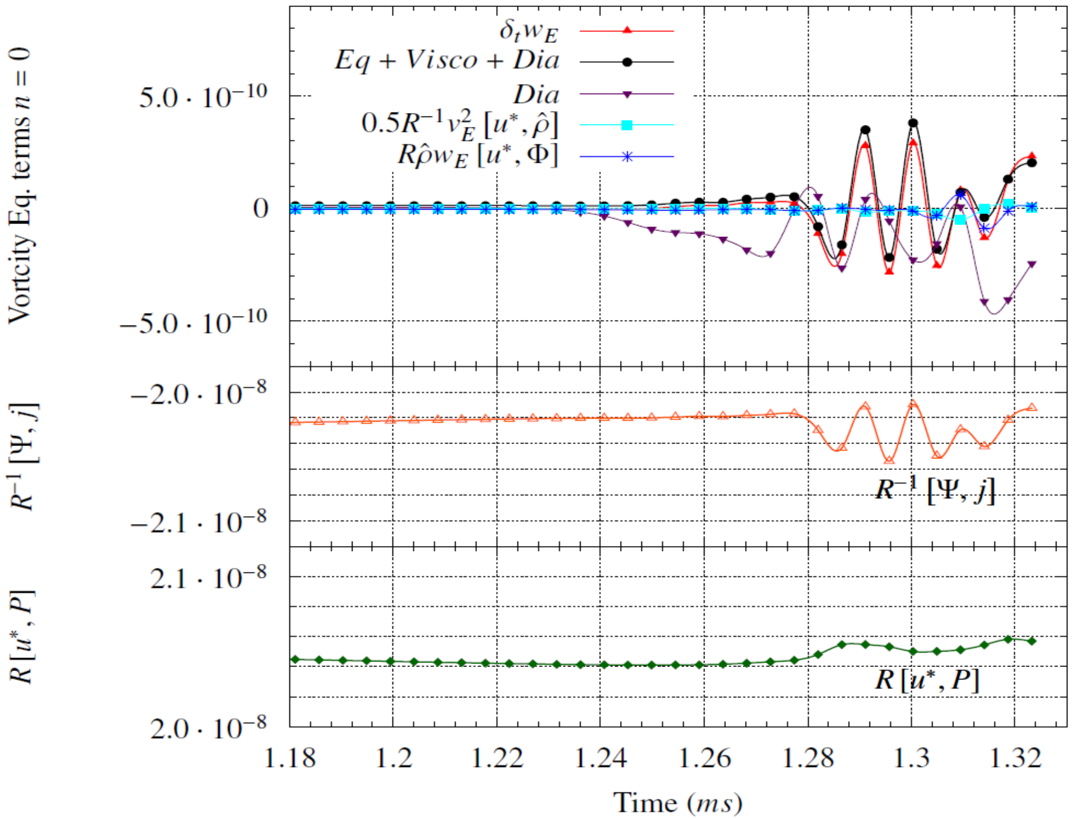
$$\vec{v}_1 - \vec{v}_0 = \left(\vec{v}_1 + \vec{v}_0\right)\times\vec{b}$$

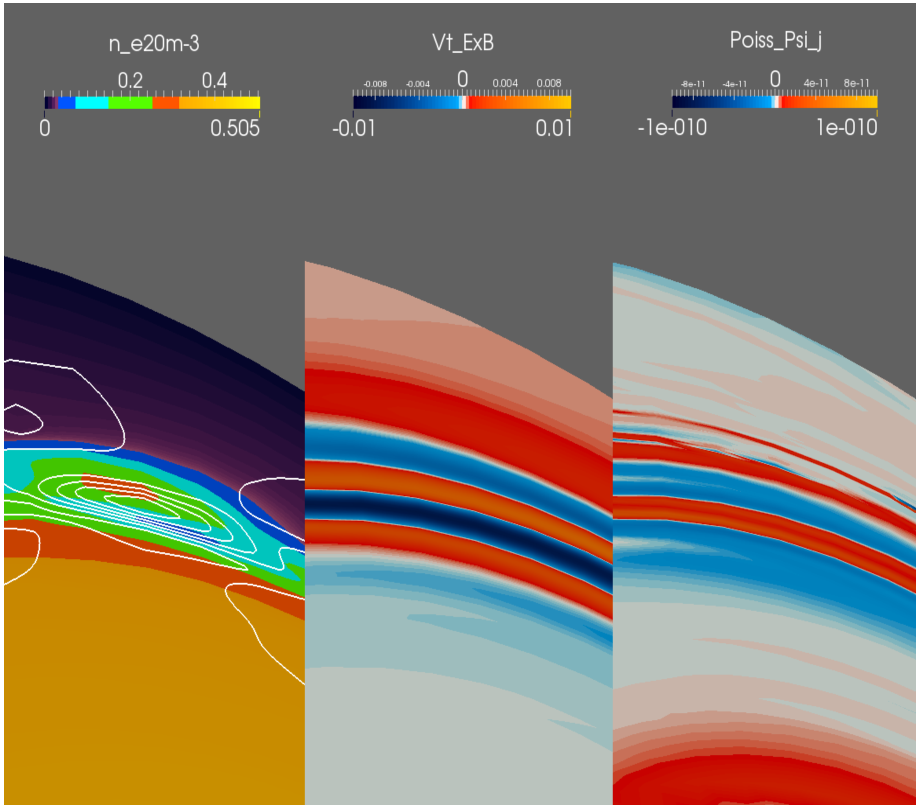
$$\vec{b} = \frac{q\delta t}{2m}\vec{B}$$

$$\vec{v}_1 - \vec{v}_0 = \frac{2}{1+b^2}\left(\vec{v}_0 + \vec{v}_0\times\vec{b}\right)\times\vec{b}$$

Non-linear phase. The mean flow generation is due to Maxwell stress *(Huysmans NF2007, Morales EPS2014, PRL sub)*

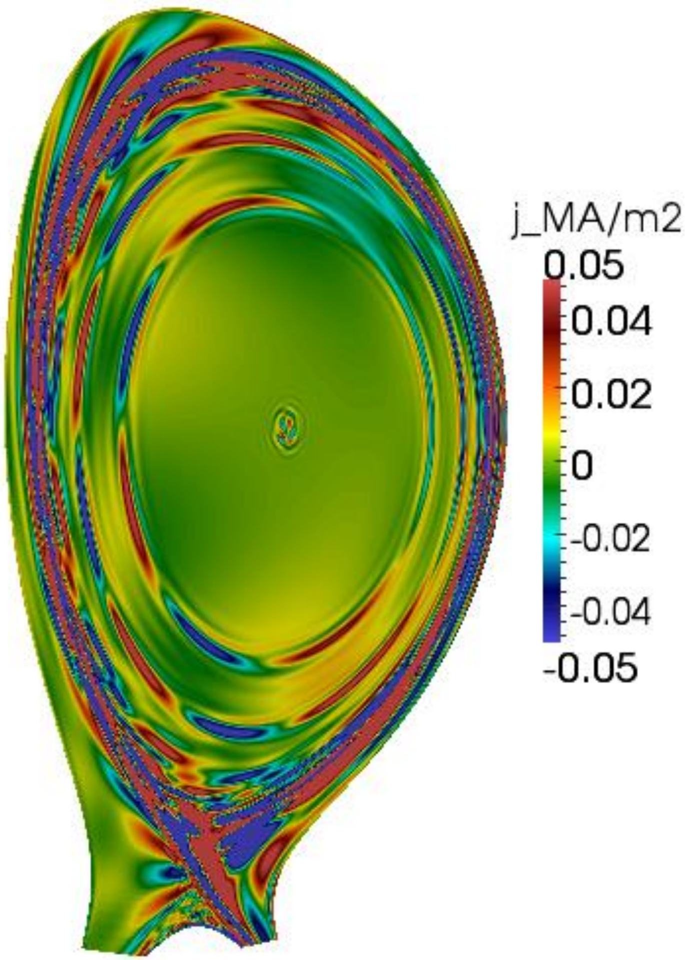
$$\delta_t w_E = -\int \hat{\rho}\nabla u^* \cdot \nabla_\perp (\delta_t \Phi)\, dV = \int \Big(-\frac{v_E^2}{2R}[u^*,\hat{\rho}] - R\hat{\rho}\, w_E\, [u^*,\Phi] + R\,[u^*,P]$$
$$- u^*\nabla\phi \cdot \nabla \times \left(R^2\rho\,(\boldsymbol{v}_i^* \cdot \nabla)\,\boldsymbol{v}_E\right) - u^*\frac{1}{R}[\Psi,j] + u^*\frac{F_0}{R^2}\partial_\phi j + u^*\nabla\phi \cdot \nabla \times \left(R^2\mu\nabla^2\boldsymbol{v}_E\right) \Big) dV$$



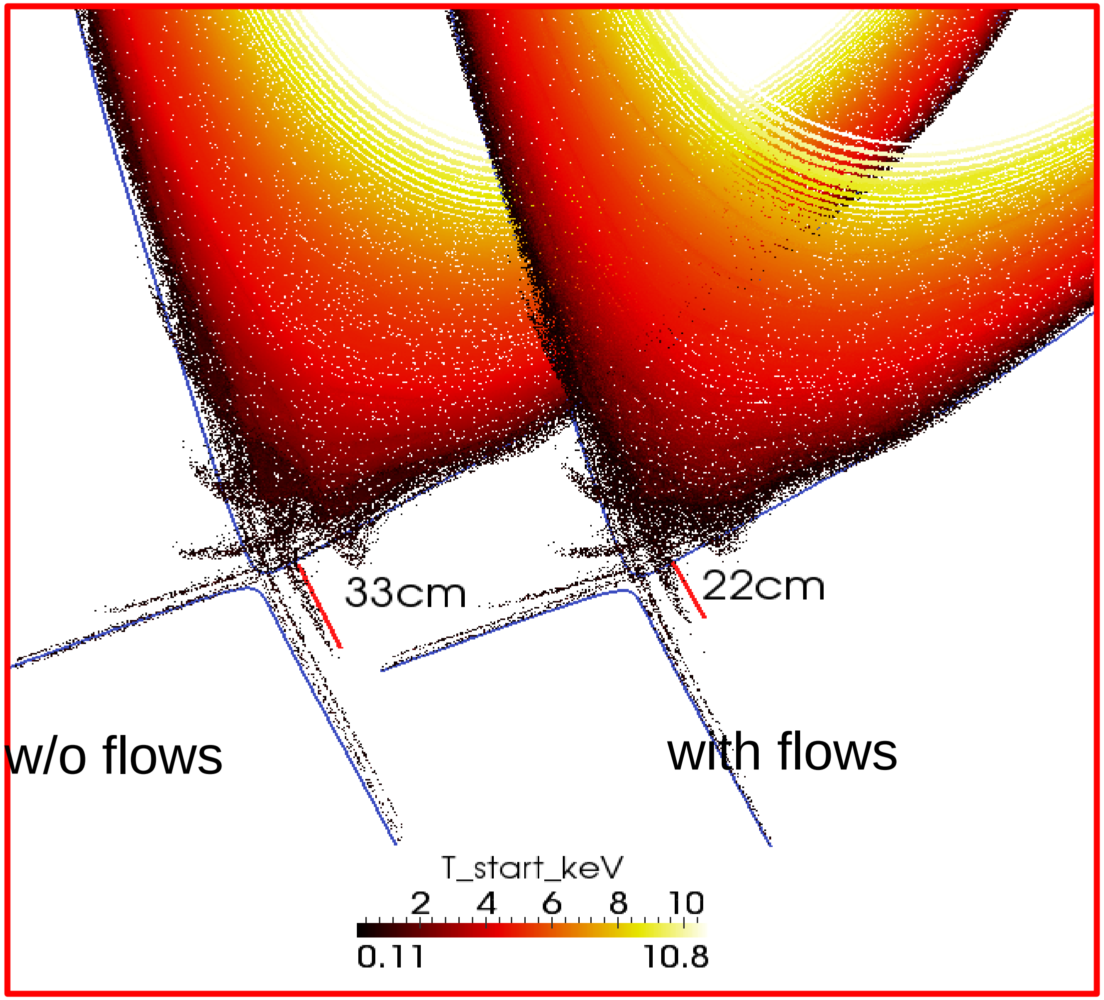


Physics of RMPs penetration. Plasma response currents on rational surfaces (q=m/n). Screening of RMPs is typical response,

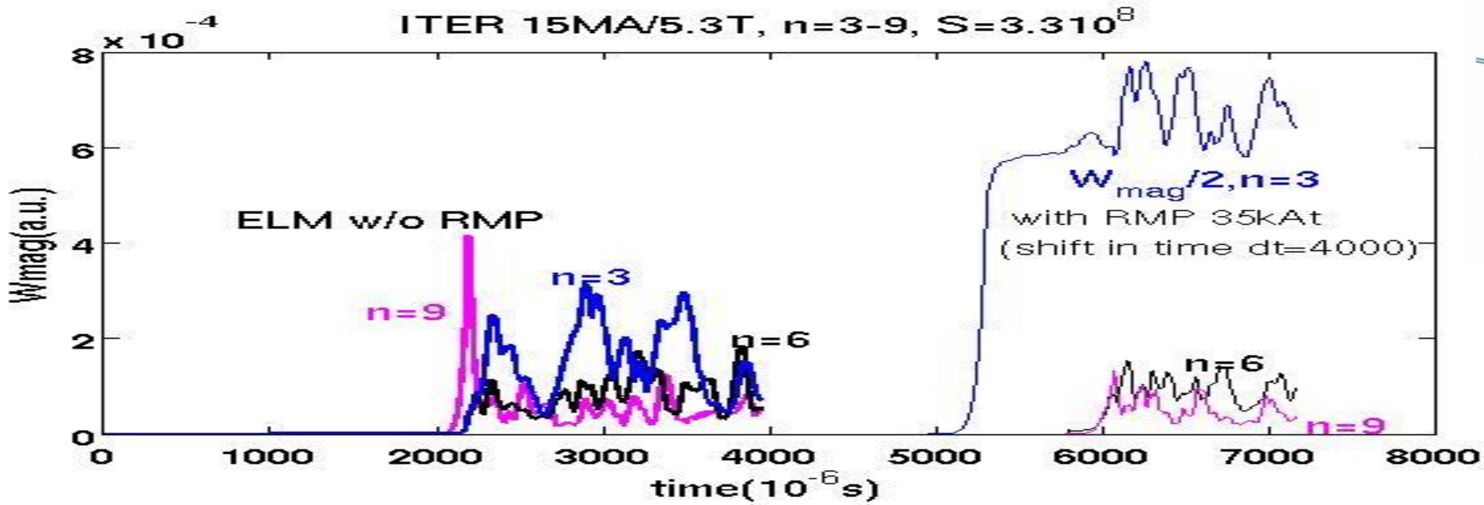
Response current on q=m/n with RMPs.

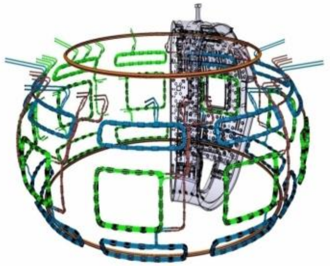


ITER. RMP screening by rotation
(Becoulet IAEA 2012)



ELM mitigation by RMPs. Mitigated ELMs= non-linear driven modes coupled to RMPs=> edge ergodisation, continued MHD turbulence prevent large ELM crash *(Becoulet PRL2014)*





RMP off: ELM (most unstable n=9)

Mitigated ELMs: continued MHD, mixture of n=3,6,9