DE LA RECHERCHE À L'INDUSTRIE

Non-linear MHD Modelling of Rotating Plasma Response to Resonant Magnetic Perturbations.

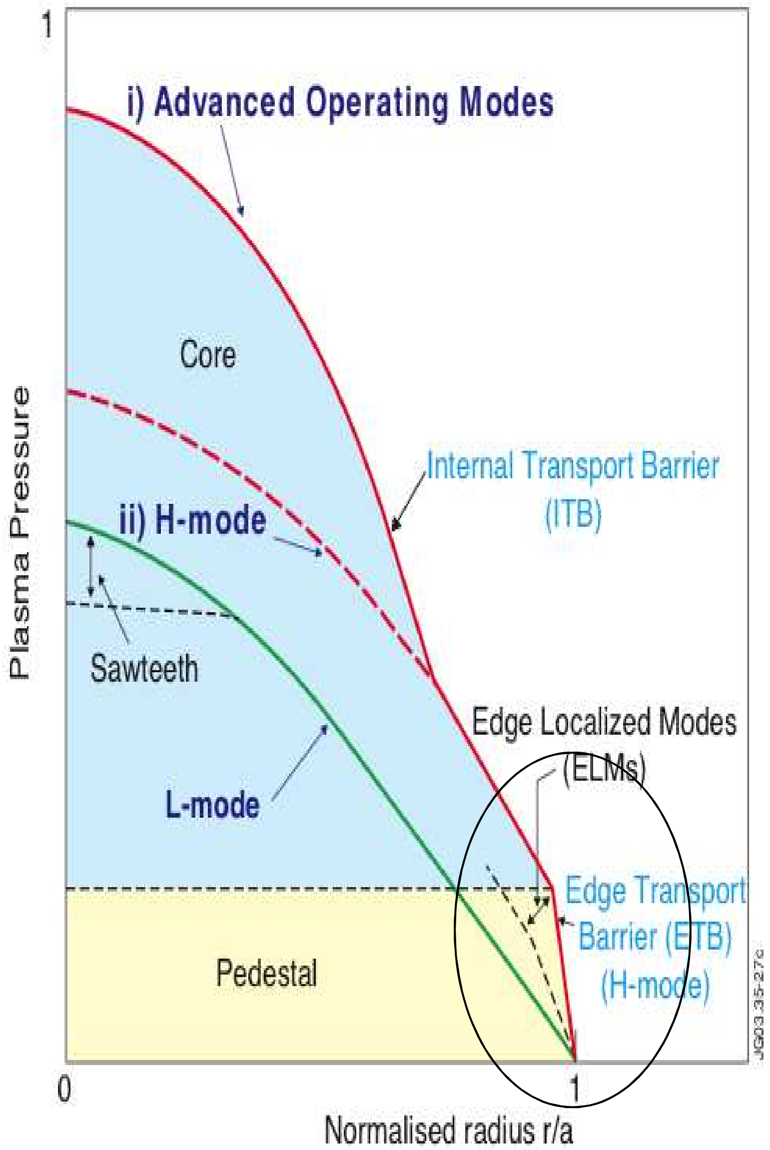
M. Becoulet[1], F. Orain[1], G.T.A. Huijsmans[2], G. Dif-Pradalier[1], G. Latu[1], C. Passeron[1], E. Nardon[1], V. Grandgirard[1], A. Ratnani[1], S. Pamela[3], I. Chapman [3], A. Thornton[3], A. Kirk[3]

[1]*Association Euratom-CEA, CEA/DSM/IRFM, Centre de Cadarache, 13108, Saint-Paul-lez-Durance, France.*
[2] *ITER Organization, Route de Vinon,13115 Saint-Paul-lez-Durance, France*
[3]JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK

*This work has benefitted from financial support from the National French Research Program (ANR): **ANEMOS**(2011).*
*Supercomputers used: **HPC-FF**(Julich, Germany), **JADE**(CINES, France), **Mésocentre** (Marseille, France)*

www.cea.fr

Motivation: H-mode pedestal height (=> global confinement) is limited by MHD instabilities=> ELM crash . Quasi-periodic f_{ELM}~1-150 Hz , Δt_{ELM} ~250μs. Large heat&particle loads on divertor



ELM in JET

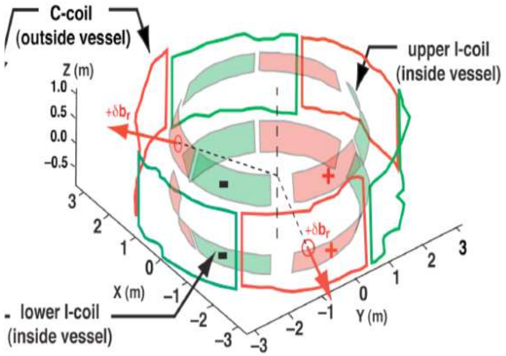
Safe ELMs for divertor W_{ELM}<1MJ, but predictions for ITER : $W_{ELM,ITER}$~20MJ => Droplets, melting of tungsten ITER divertor.

Tungsten sample after ELM–like power load (produced by electron gun).

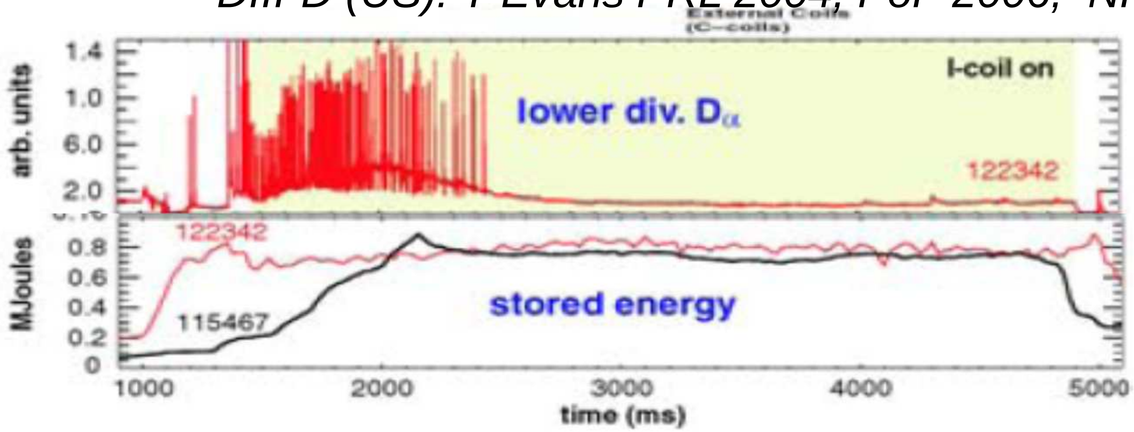
J Linke et al Proc. 13th Int Conf on Fusion Materials, Nice, Dec. 10-14, 2007.

Total ELM suppression by Resonant Magnetic Perturbations (RMPs) : DIII-D(US)-first experiments , ASDEX Upgrade(Germany), KSTAR (Korea).

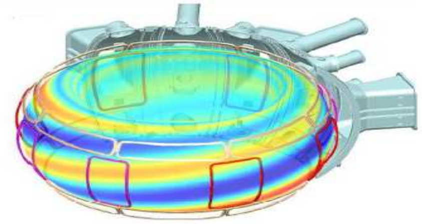
DIII-D (US): T Evans PRL 2004, PoP 2006, NF2008, n=3



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

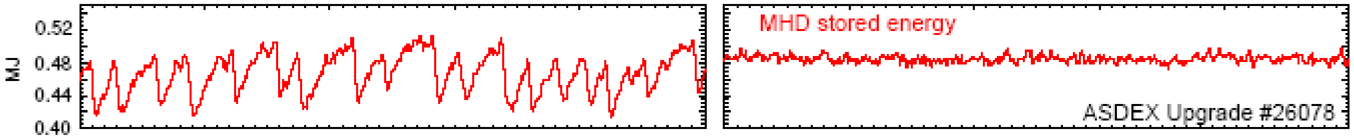


ASDEX Upgrade

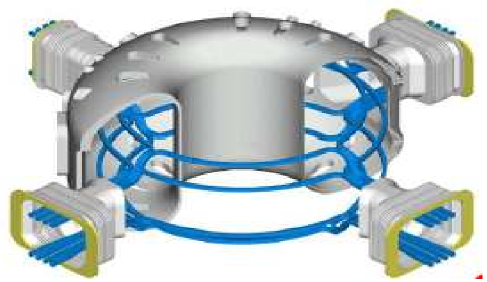


Full in-vessel coil set:
3 rows à 8 saddle coils

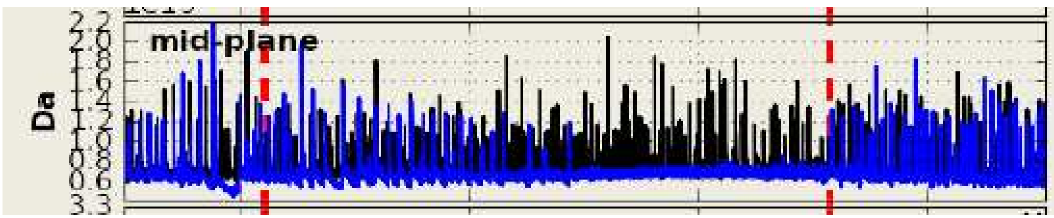
AUG (Germany) : W. Suttrop PRL2011,IAEA 2012, n=1,2



KSTAR



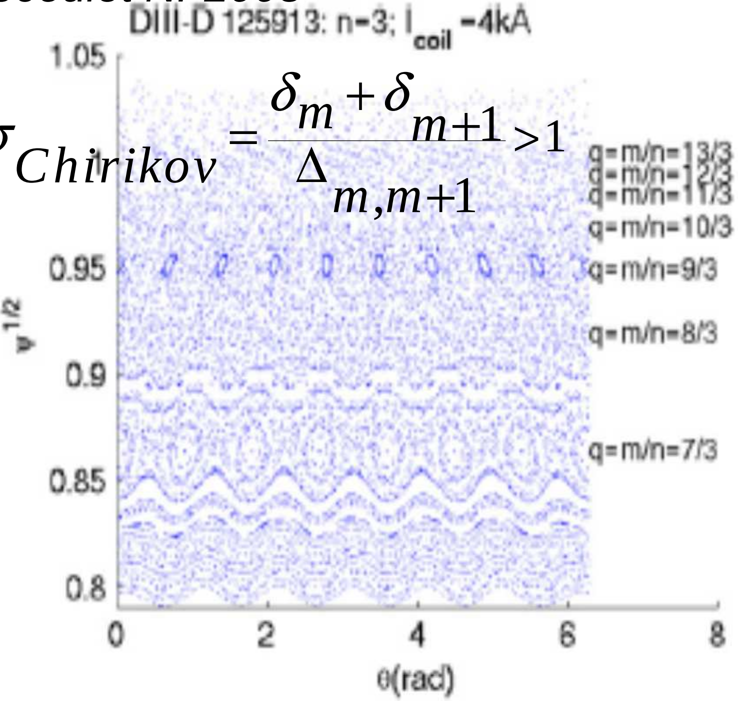
KSTAR (Korea) : Si-Woo-Yoon, IAEA 2012, n=1

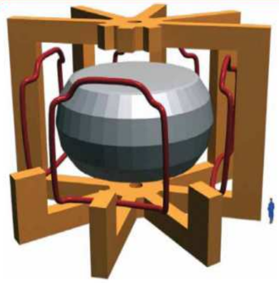


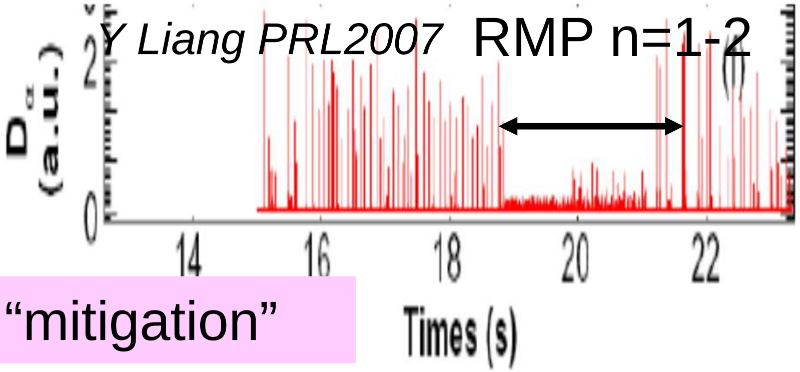
Idea: "ergodisation" increases edge transport ($\sigma_{Chir}>1$ for $\psi>0.8$) => $gradP<gradP_{crit}$ => no ELMs? But very different response on RMPs! In ITER?

Becoulet NF2008

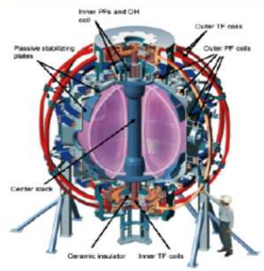
$$\sigma_{Chirikov} = \frac{\delta_m + \delta_{m+1}}{\Delta_{m,m+1}} > 1$$

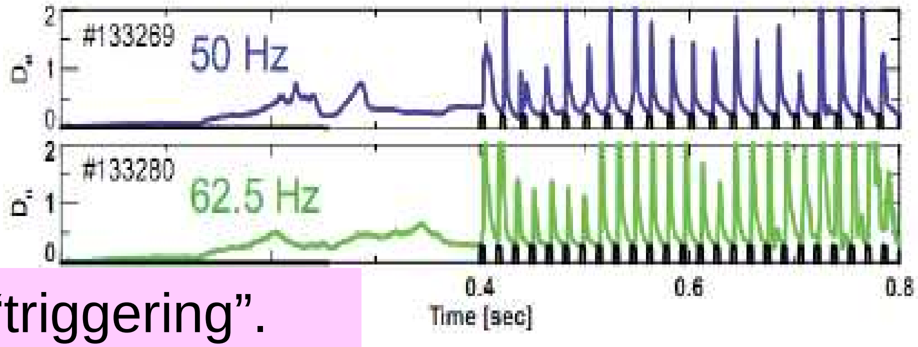




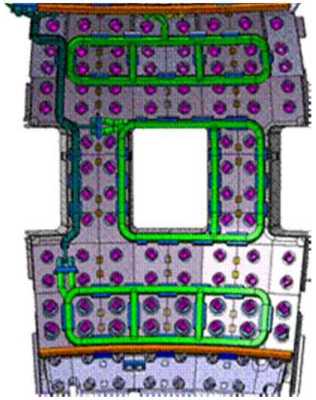


JET : ELM "mitigation"



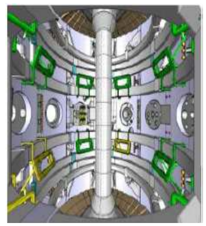


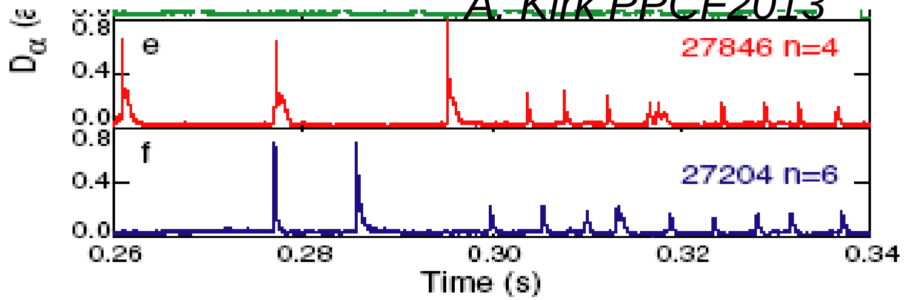
NSTX: ELM "triggering".



RMPs are foreseen in ITER (90kAt,n=4,3) will it work???

A. Kirk PPCF2013





MAST : small mitigated ELMs (n=3,4,6)

Many open questions in physics of ELMs+RMPs still remain. Aim: progress in understanding of RMPs, give reliable predictions for ITER.

- Idea: RMP coils=> magnetic perturbation =>edge ergodic region=> control of edge transport, MHD. However, at the same edge ergodisation in "vacuum" => **different reaction of ELMs to RMPs in experiment: suppression, mitigation, triggering?**

- **RMPs are different from "vacuum" RMPs in plasma! Rotating plasma response : current perturbations on q=m/n => screening of RMPs.** *[Fitzpatrick PoP 1998], [Waelbroeck NF2012], [Izzo NF 2008] , [Becoulet NF 2009, 2012], [Strauss NF 2009], [Orain EPS2012], [Ferraro APS 2011] etc…*

- **RMPs /ELMs at high ν*? (**Type II ELMs- like events, density, magnetic field fluctuations, no changes in profiles)

- Density pump-out (at low ν*) ? (here not addressed yet)

- Rotation braking/acceleration? (here not addressed yet)

- Why ELMs are suppressed? (not addressed yet)

Outline:

- **RMPs and flows in non-linear resistive MHD code JOREK (model development) :**
  - ✓ *RMPs at the computational boundary (SOL, X-point, divertor geometry)*
  - ✓
  - ✓ *2 fluid diamagnetic effects (large in pedestal!),*
  - ✓ *neoclassical poloidal viscosity (* $V_\theta \sim V_\theta^{neo}$ *in pedestal),*
  - ✓ $V_{||}$ *: toroidal rotation source, SOL flows.*
  - ✓ *equilibrium radial electric field (large* ***ExB*** *in pedestal!).*
- **RMPs in JET-like case. (n=2).**
  Three regimes depending on resistivity and rotation.
- **RMPs in MAST (n=3)**
- **RMPs in ITER.(n=3).**

Non-linear reduced resistive MHD in torus (X-point, divertor, SOL) with 2 fluid diamagnetic and neoclassical effects (important in large pedestal gradients region!). JOREK. *[Huysmans PPCF2009]*

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

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

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

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

If this term is ~zero at q=m/n => $V_{e,\theta}=V_{E,\theta}+V_{e,\theta}^{dia}\approx 0$ => no RMP screening

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

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

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

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]*

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

Ion poloidal velocity => neoclassical

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

JET-like case. Equilibrium flows (w/o RMPs) : parallel velocity (central source, SOL-sheath conditions on divertor targets). Poloidal velocity => neoclassical in the pedestal.

Parallel flow.

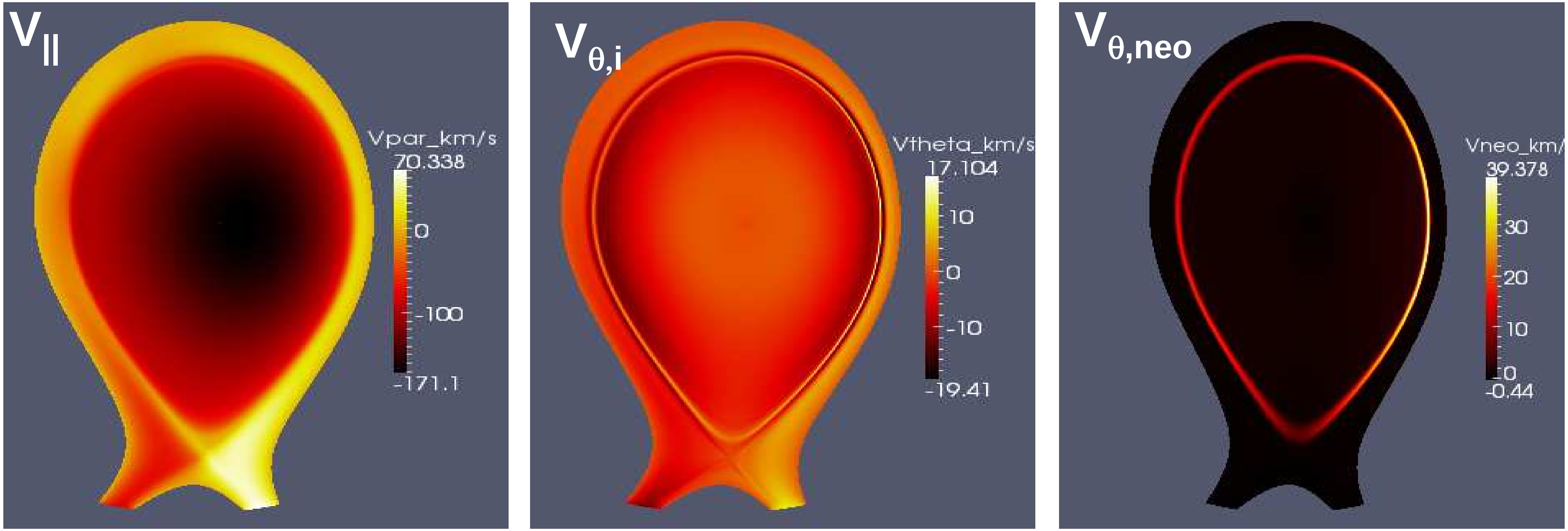
- **Central plasma**: toroidal rotation source keeps initial $V_{\|}$ profile: $S_{V\,\|} = -\nu_{\|} \Delta V_{\|, t=0}$
- **SOL**: sheath conditions on targets: $V_{\|, div} = \pm C_s$

Poloidal flow.

$$V_{\theta,i} = \left[-(\nabla_{\perp}\psi, \nabla_{\perp}u) - \tau_{IC}(\nabla_{\perp}\psi, \nabla_{\perp}p)/\rho + V_{\|}B_{\theta}^{2} \right] / B_{\theta}$$

$$V_{\theta,e} = \left[-(\nabla_{\perp}\psi, \nabla_{\perp}u) + \tau_{IC}(\nabla_{\perp}\psi, \nabla_{\perp}p)/\rho \right] / B_{\theta}$$

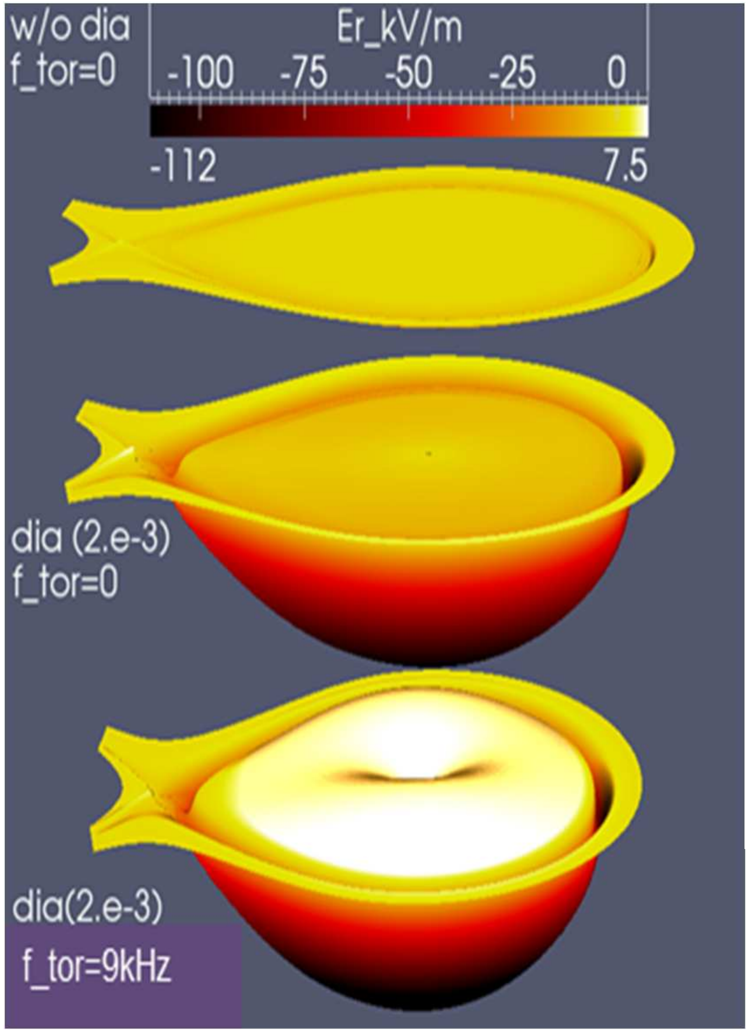
- **Pedestal**: $V_{\theta,i} \rightarrow V_{\theta,neo} \propto \nabla_{\perp} T_i$
- **SOL:** $V_{\theta,i} \approx V_{\|} B_{\theta}$

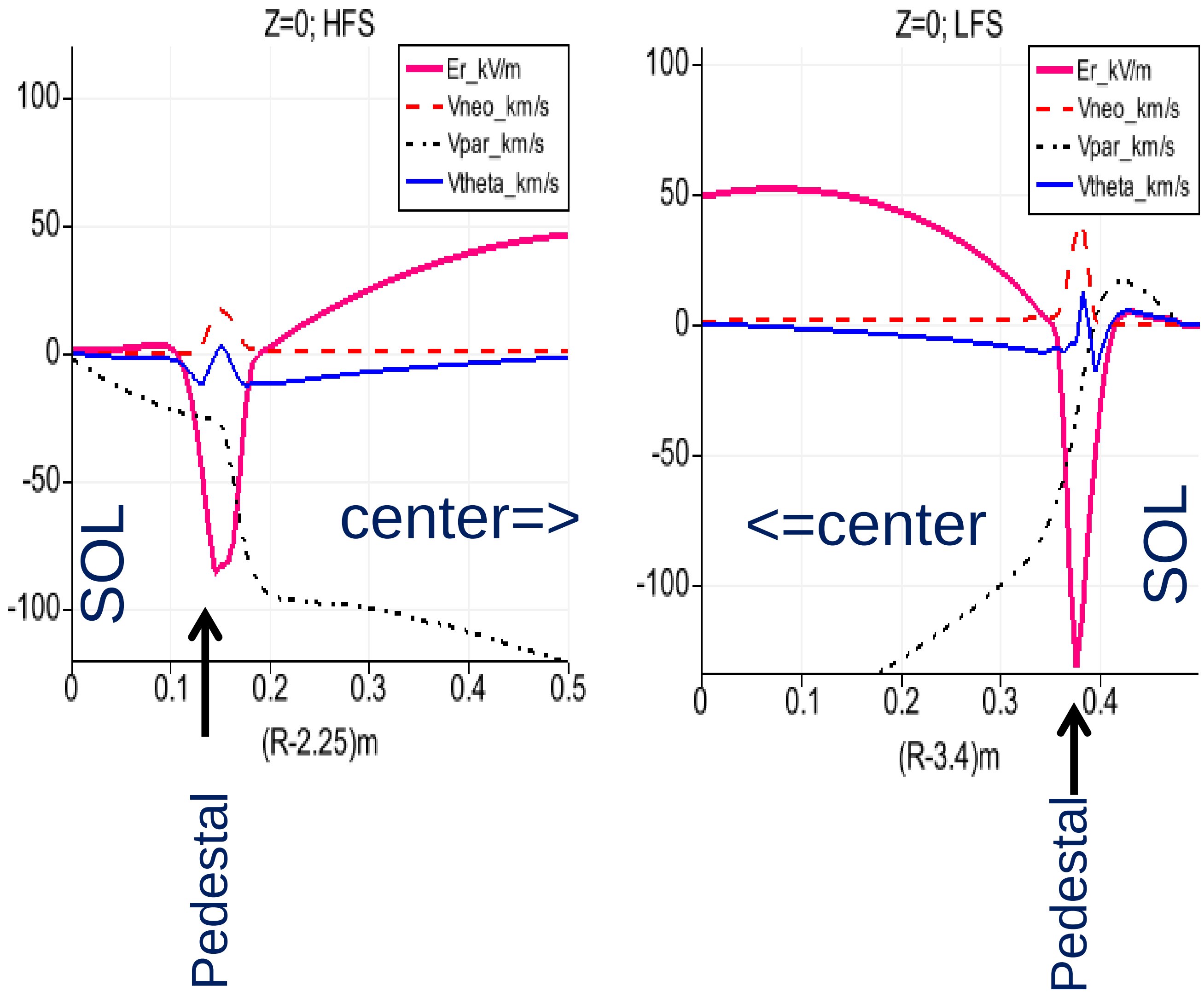


JET-like:R=3m, a=1m, q_{95}*=3,* T_0*=5keV,* n_e*=6 10*^{19}*m*$^{-3}$*,* f_0*=9kHz.* $\tau_{IC} \sim 2.10^{-3}; \mu_{i,neo} \sim 10^{-5}; k_{i,neo} = 1.; \eta = 5.10^{-8}$

JET-like case. Radial electric field “well” in the pedestal=> large ExB rotation=>likely to screen RMPs.

$$E^r \equiv -(\nabla_\perp u, \nabla_\perp \psi)/|\nabla_\perp \psi|$$



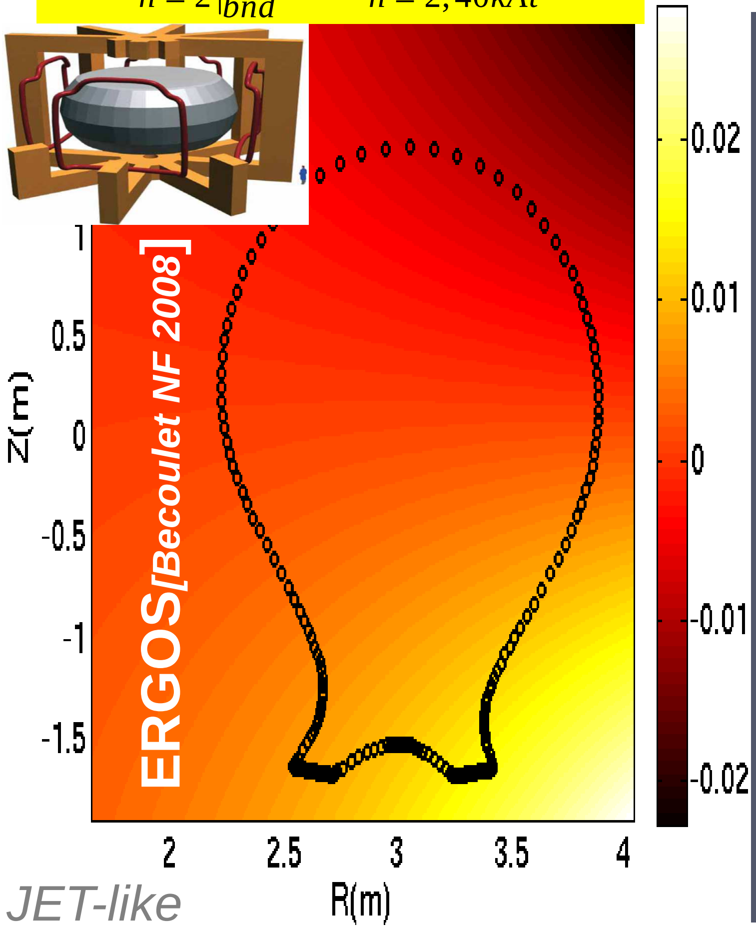


JET-like parameters.

JET-like case. Static RMPs + rotating plasma => response currents on the resonant surfaces=> RMP screening.

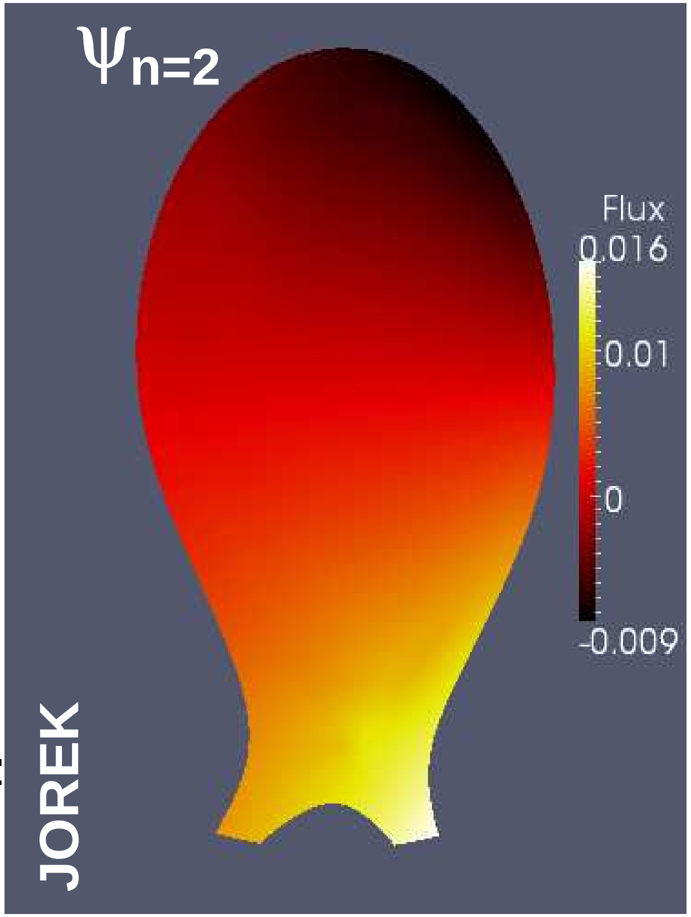
Vacuum RMP (***EFCC, n=2,*** ***I_{coil}=40kAt)*** are increased in time at JOREK boundary.

$$\psi(t)_{n=2}\big|_{bnd} = \psi^{vacuum}_{n=2,40kAt}\, f(t)$$

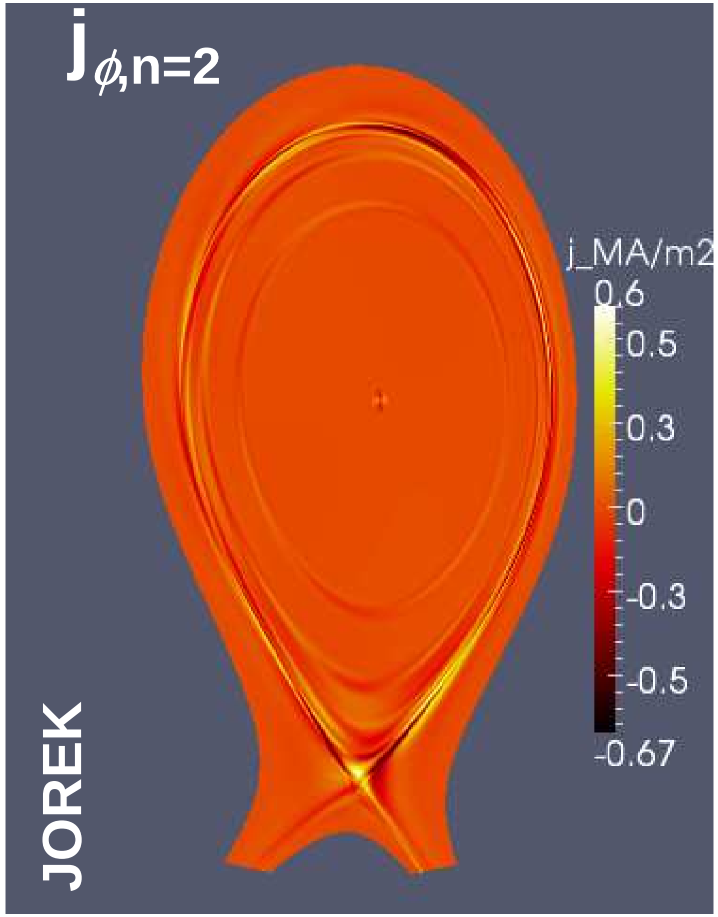


JET-like

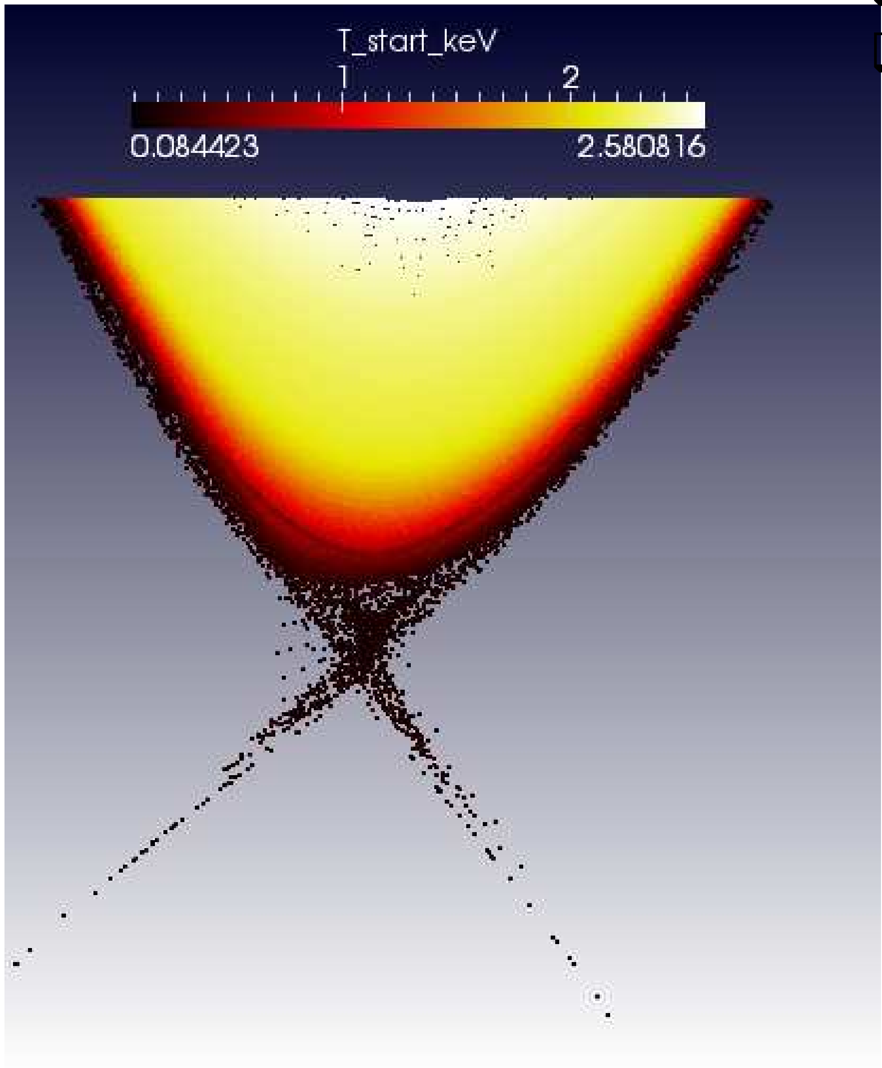
Poloidal magnetic flux perturbation (max) with RMPs in plasma with flows.

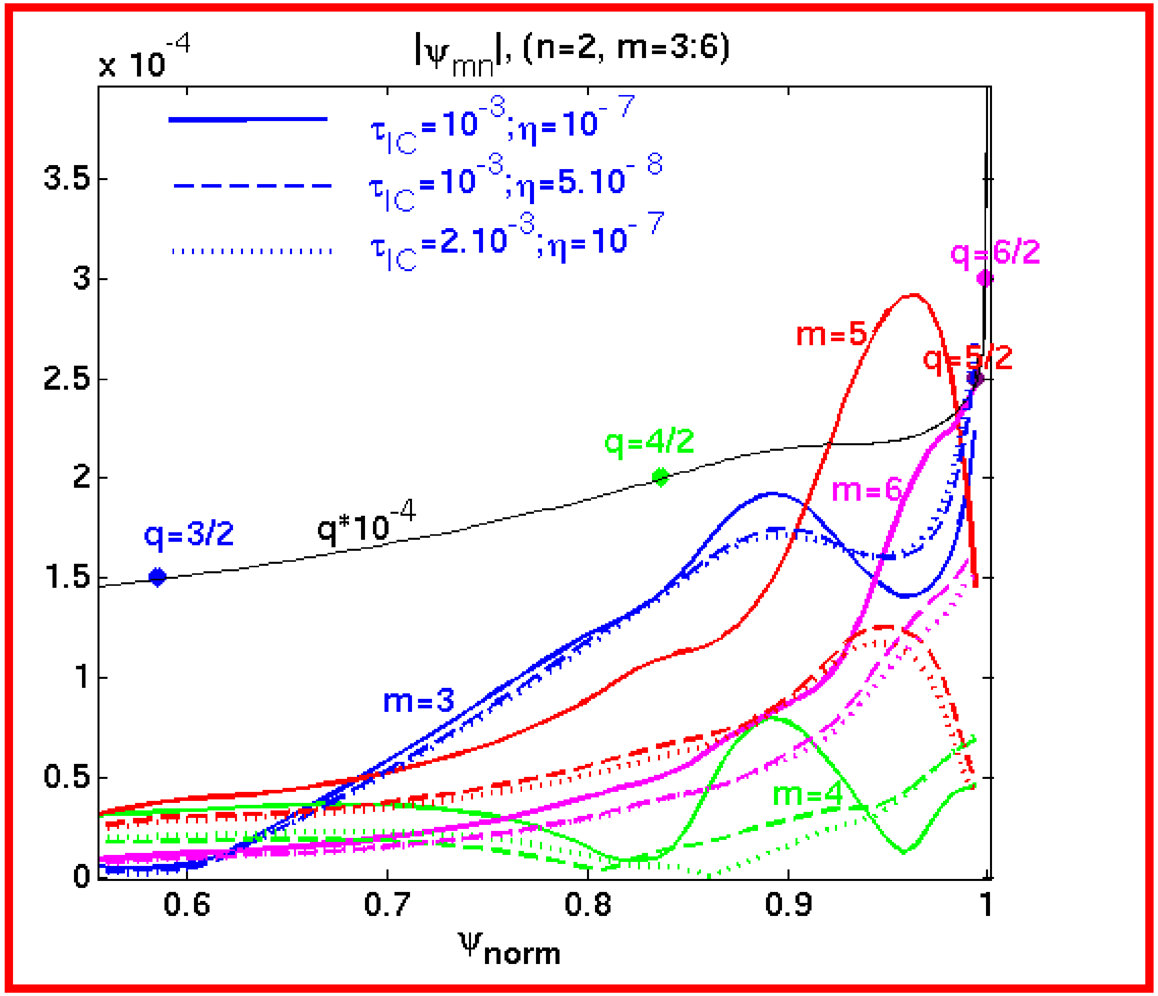


Toroidal current perturbations on the rational surfaces (q=m/2; m=3,4,5,6) with RMPs.



- Central islands are screened: *(m/n)=3/2; 4/2*.
- Edge ergodic region: *(5/2,6/2)* penetrate ($\eta \sim T^{-3/2}$)



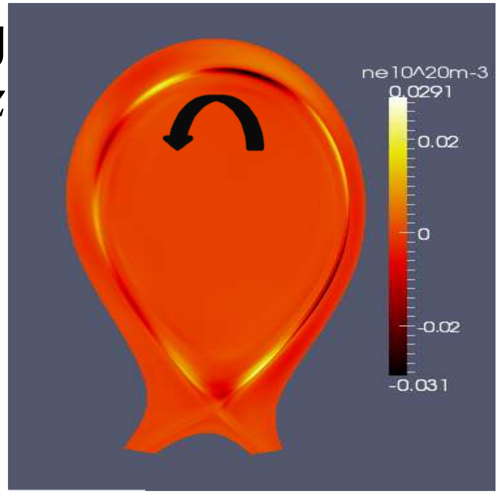


JET-like

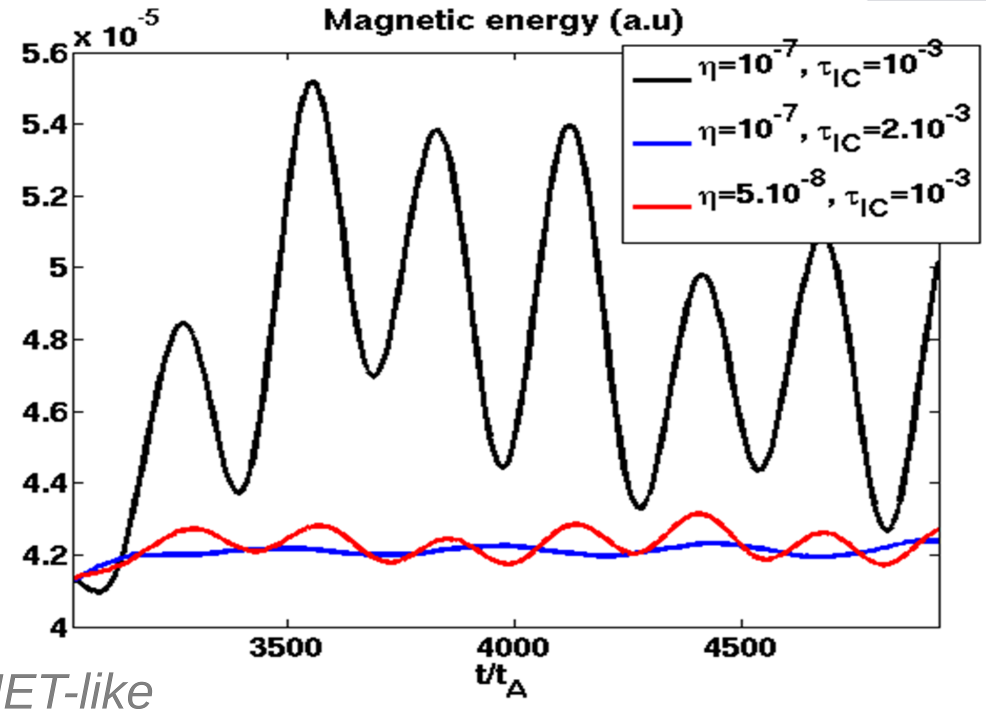
Similar results in cylinder [Becoulet NF 2012]

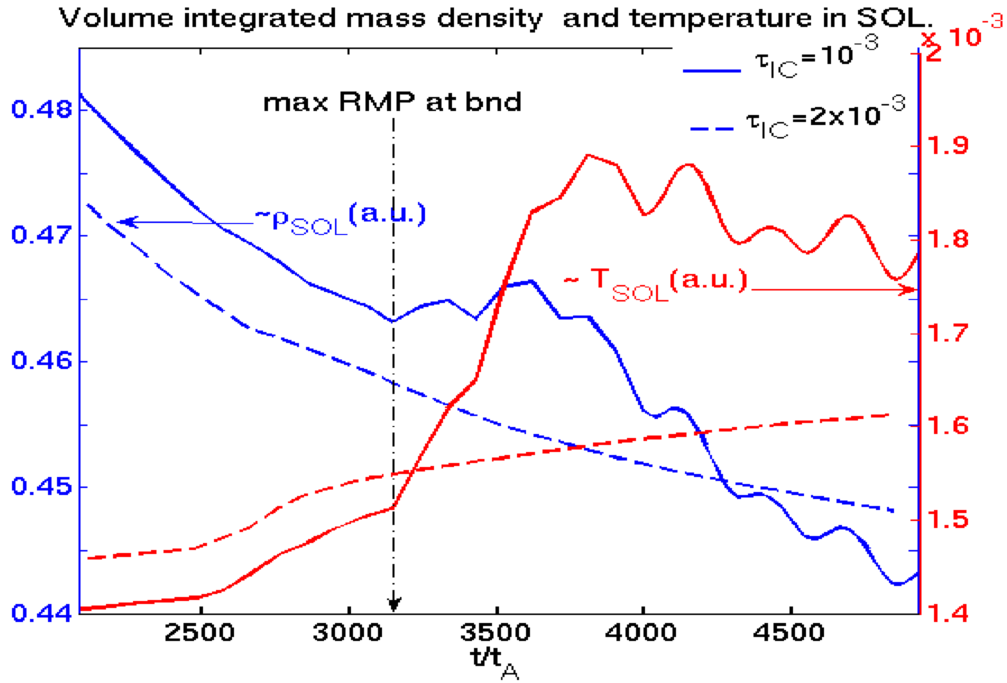
JET-like case. Three regimes depending on rotation & resistivity.

- high η, low τ_{IC}: rotating oscillating islands $f^* \approx mV_\theta/(2\pi r_{res}) \sim 6kHz$
- high τ_{IC}: static islands, more screening of RMPs.
- low η, low τ_{IC} : intermediate-ocsillating, quasi-static islands



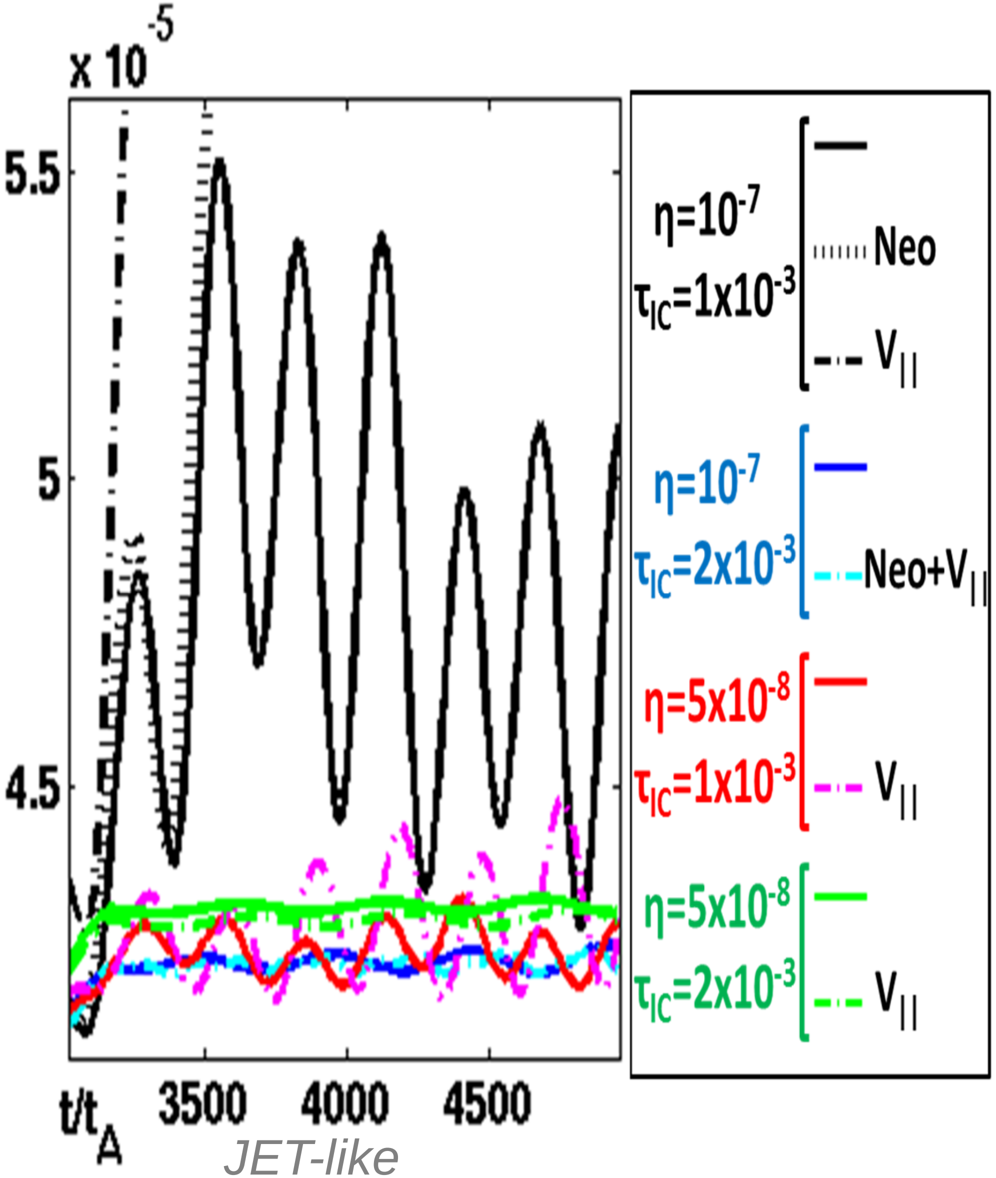
=>fluctuations of magnetic field, density and temperature no significant transport *(Possibly related to RMPs suppression at high ν*? Rutherford regime ? [Fitzpatrick PoP 1998], [IzzoNF2008])*



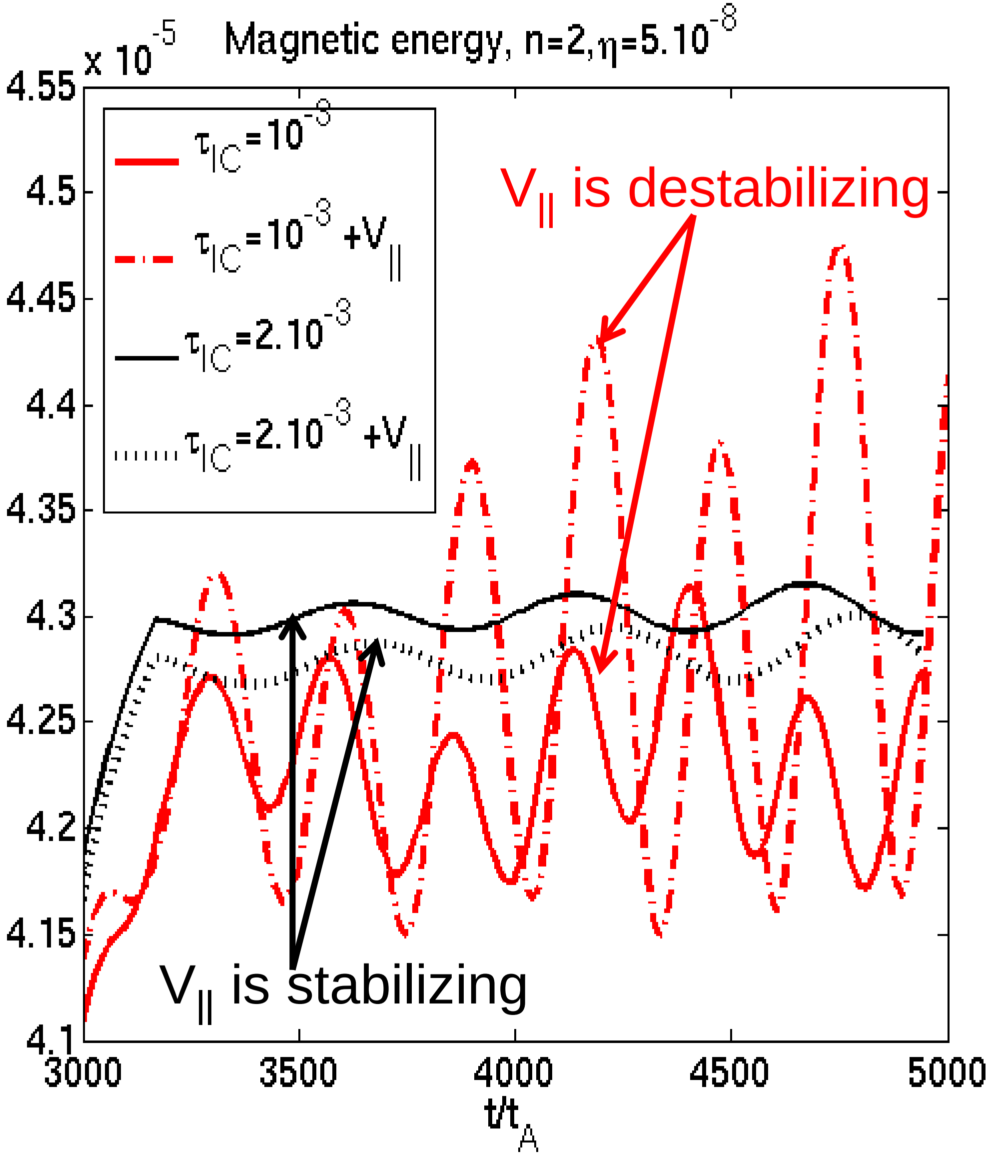


JET-like

JET-like case. $V_{||}$ can be stabilising and destabilising. Mechanism? Change in radial electric field (ExB part in poloidal rotation) ? => under investigation



JET-like

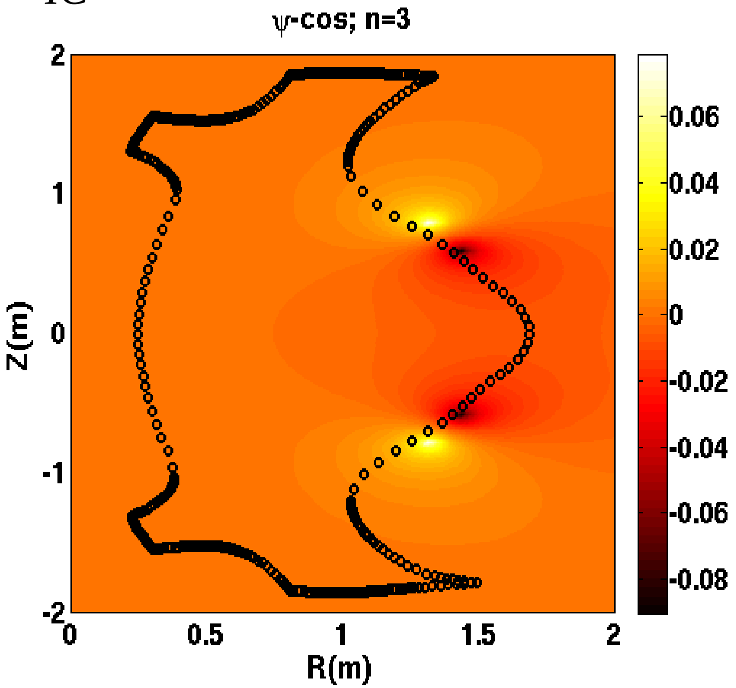


MAST case. Penetration of n=3 RMP in MAST. Small amplification with diamagnetism included.

RMPs generated by coils in 90L configuration. Limits (numerical stability):

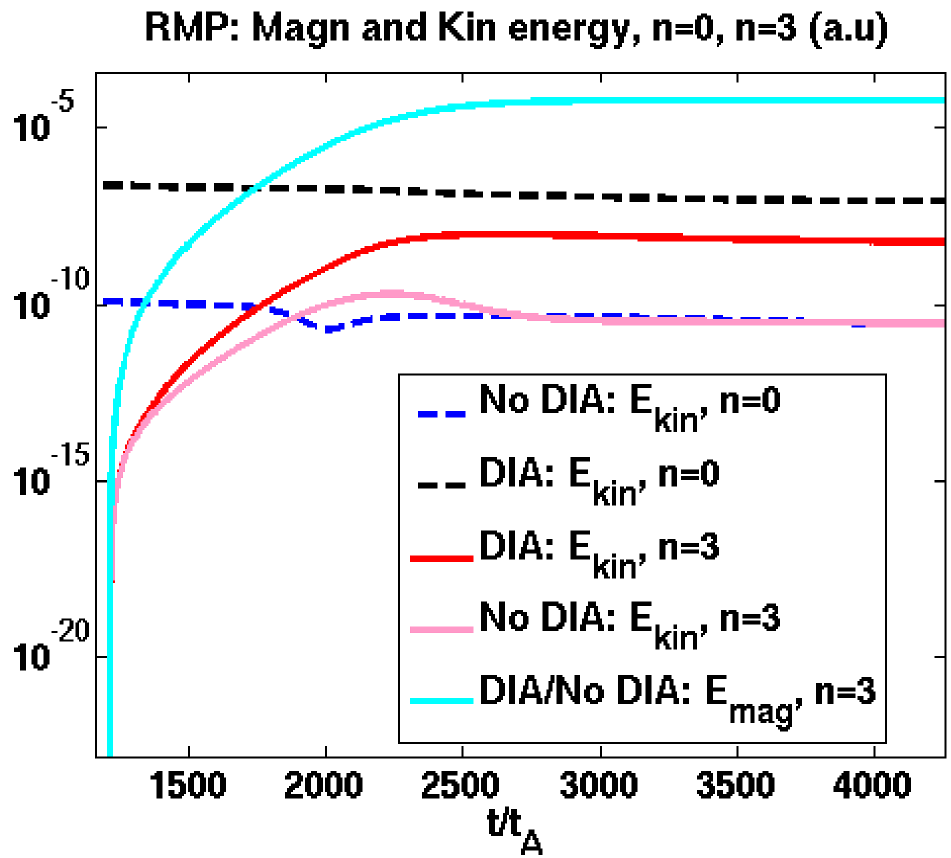
$I_{coil,simulation} = I_{coil,experiment}/10$

$\tau_{IC} = 10^{-2}$ *(realistic one:* 5×10^{-2} *)*



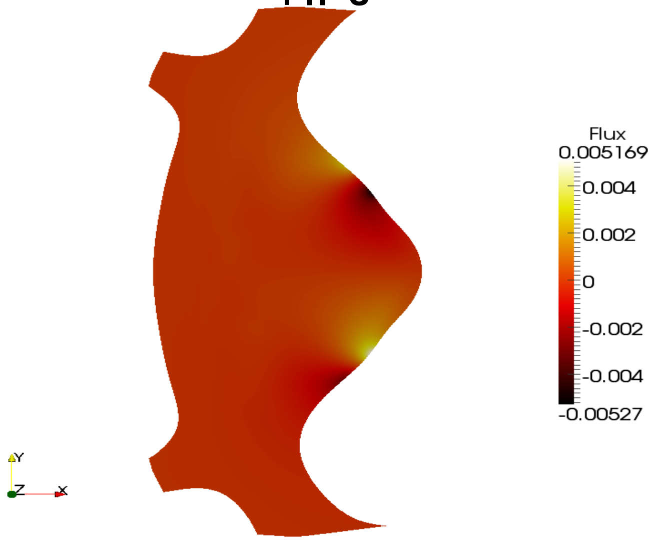
n=3 Fourier component of the magnetic perturbation

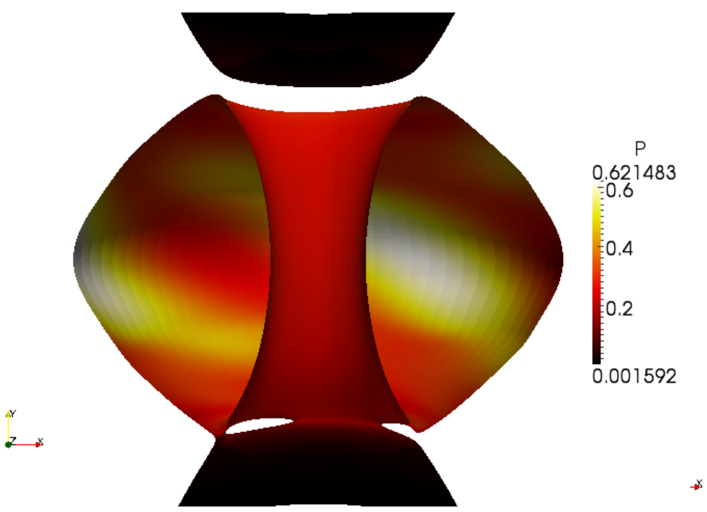
With RMPs: n=3 grows, driven by RMPs

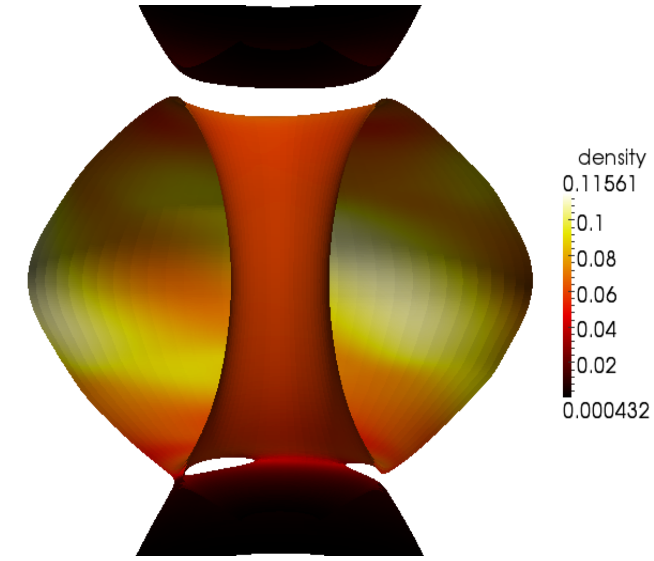


MAST case. Current response on resonance surfaces. Density, temperature, toroidal current are not uniforme on flux surfaces (here presented surface close to separatrix)

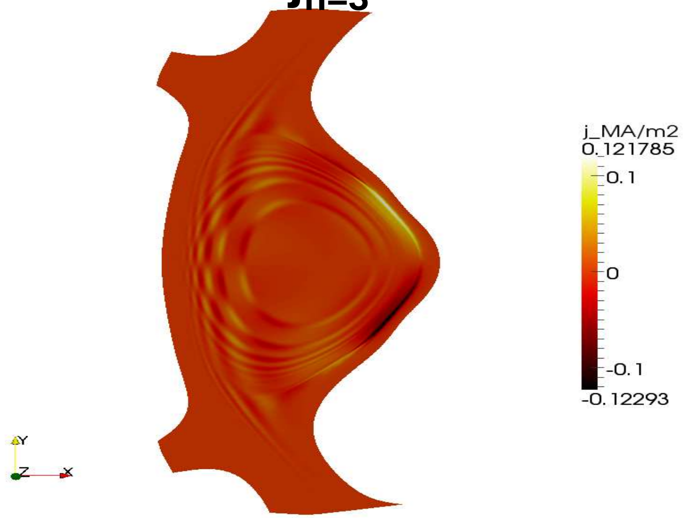
Flux $\psi_{n=3}$

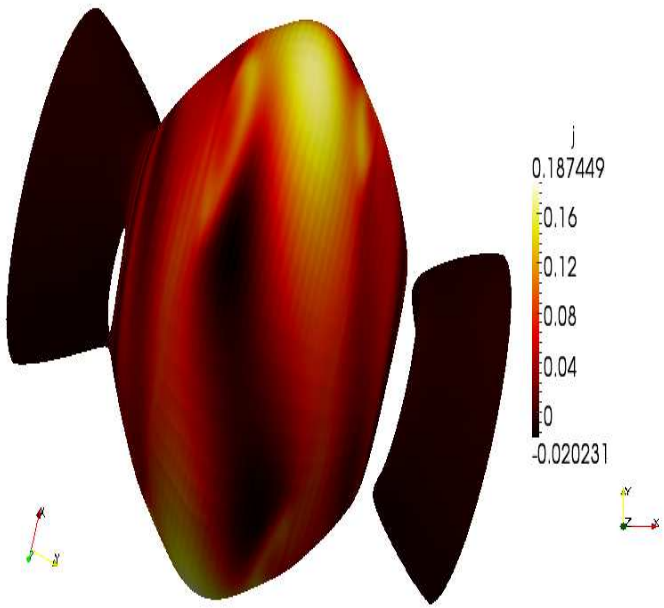


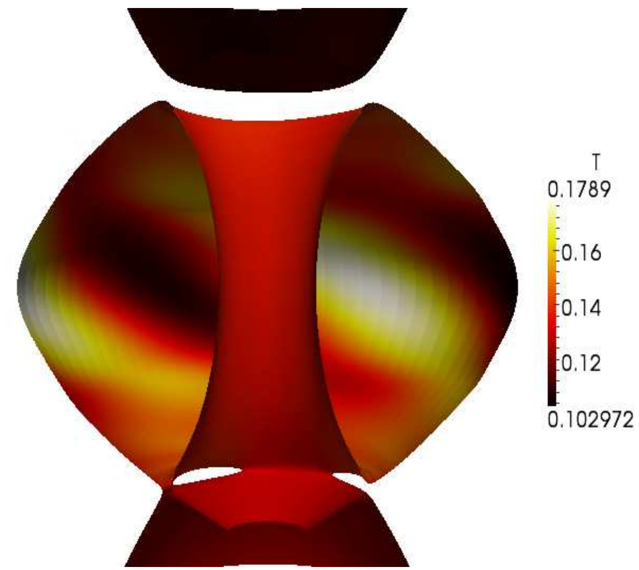




Current $j_{n=3}$

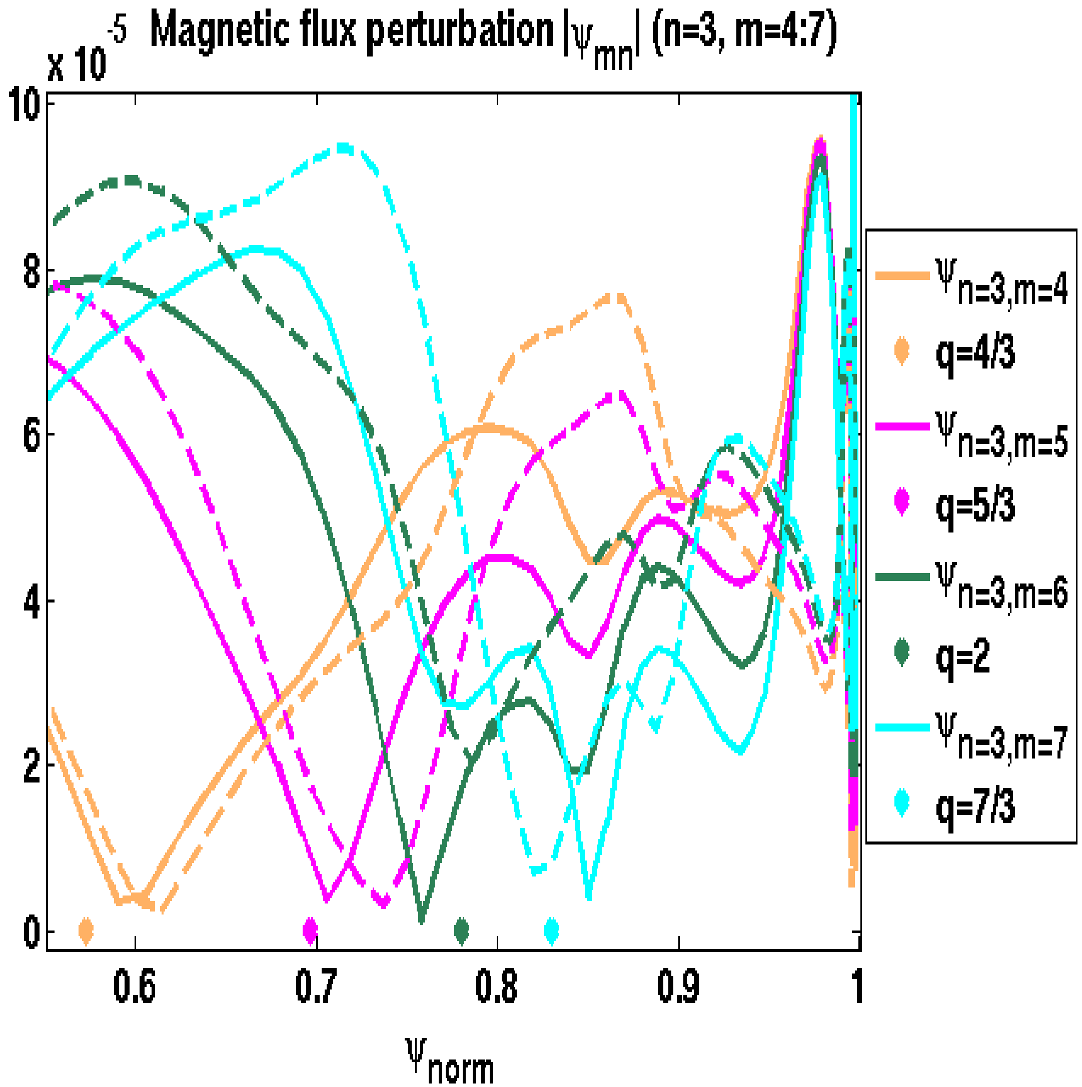


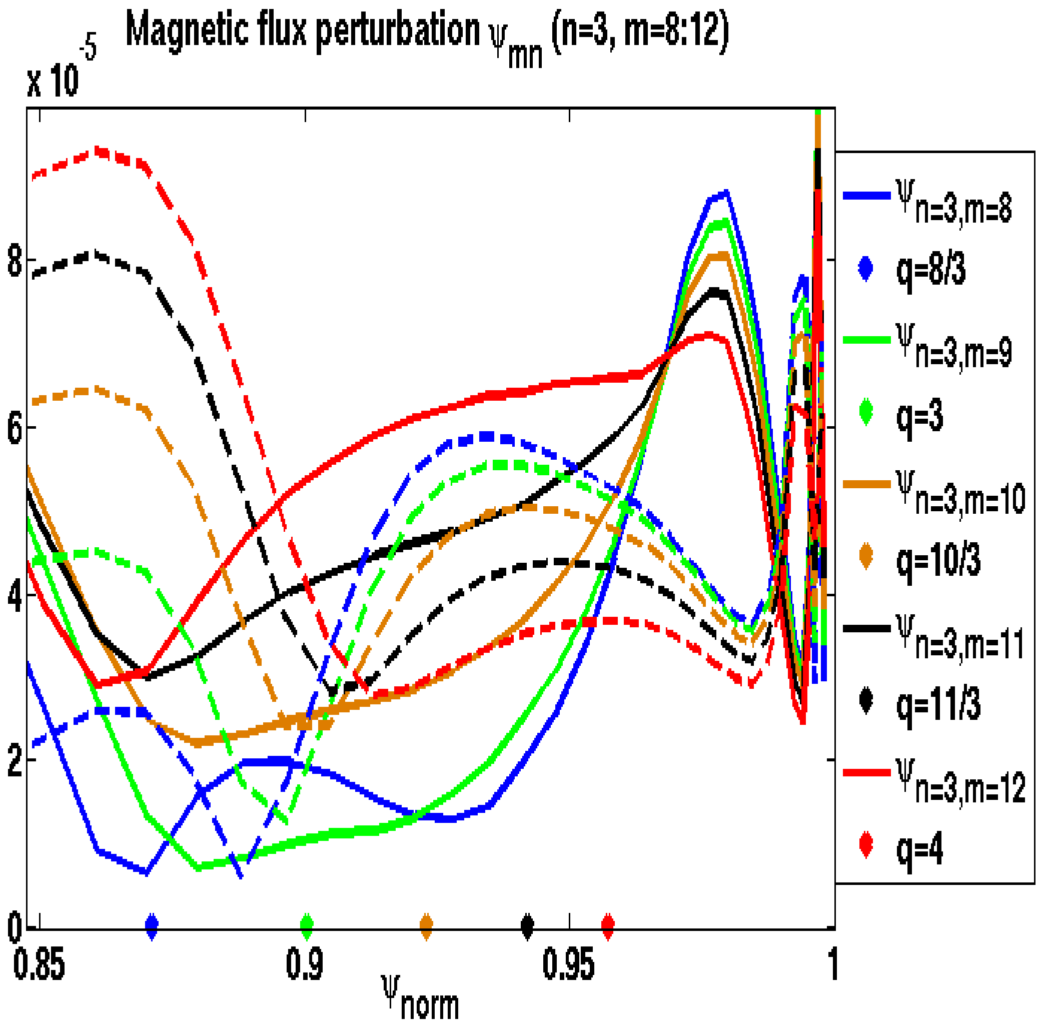




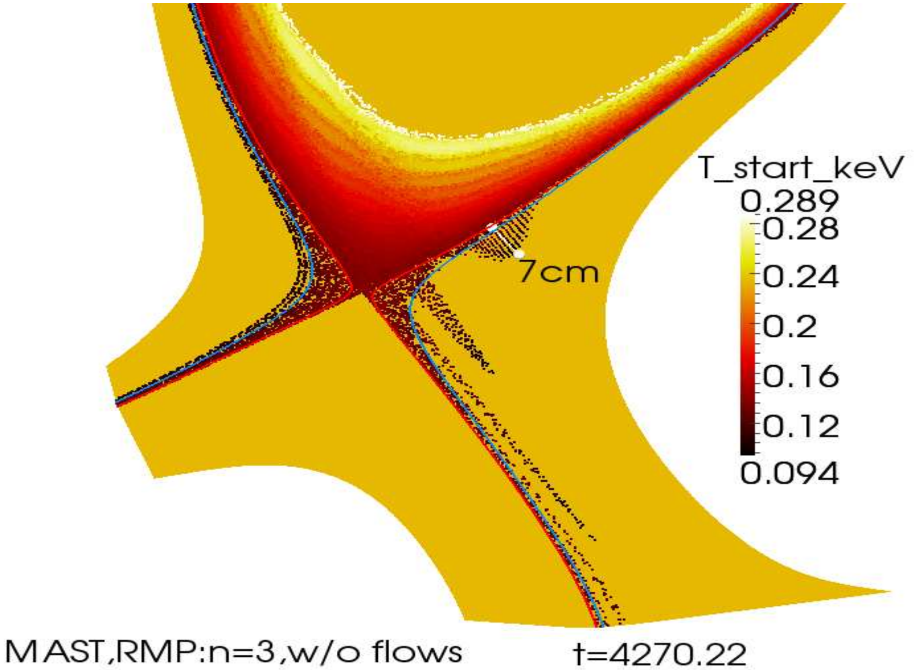
MAST case. In both cases (w/wo dia): screening of the central harmonics (m=4-9), penetration/amplification (with dia) at the edge (m>10)

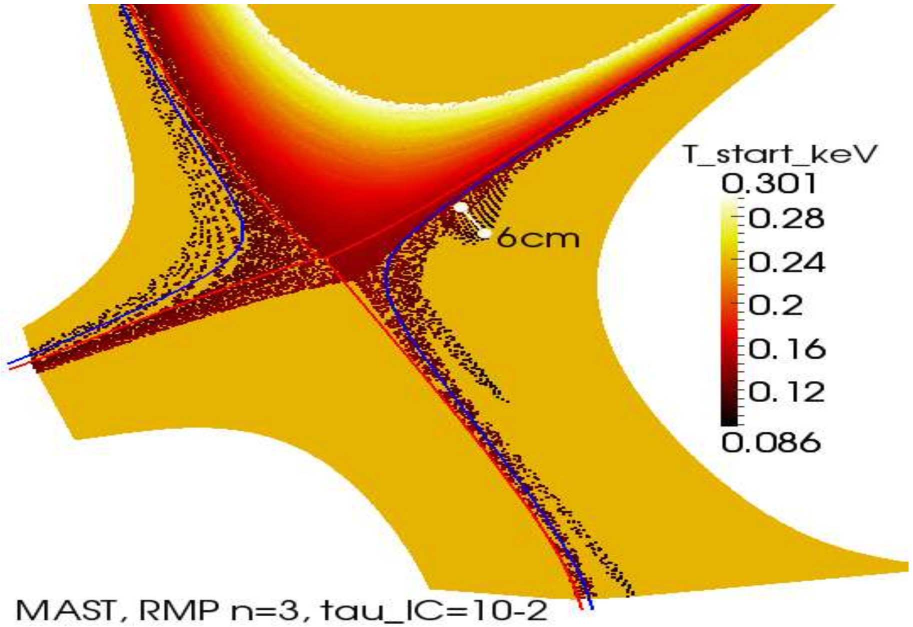
Dashed: without diamagnetic. **Full line: with diamagnetic effects.**

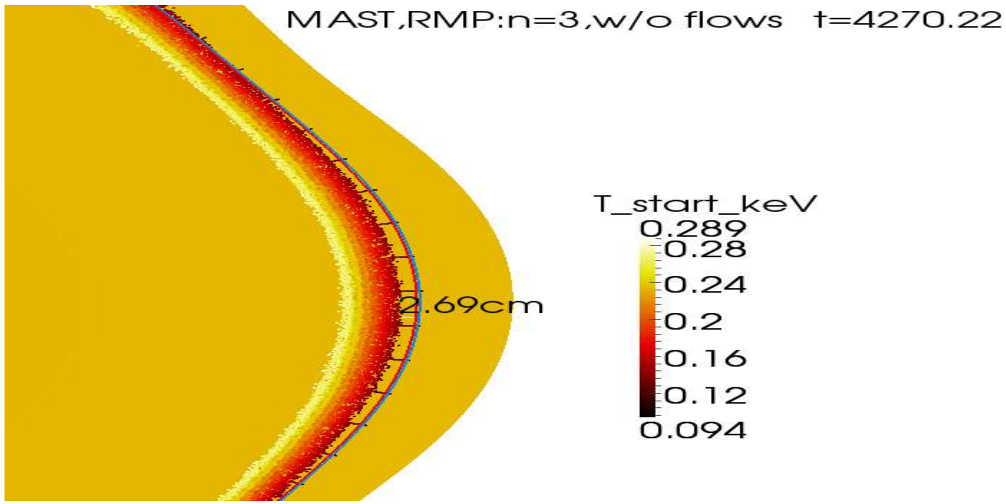


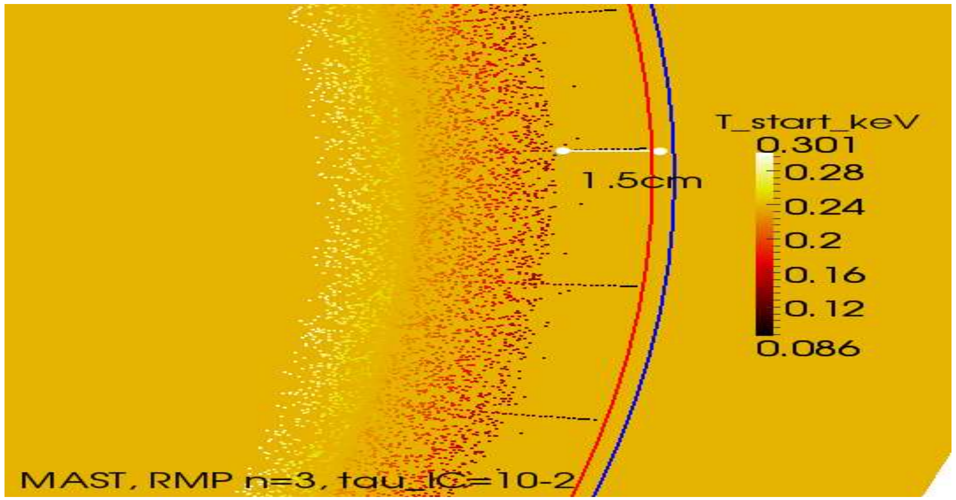


Boundary deformation in MAST. Lobes induced by RMPs: in DND configuration, only located in the LFS.



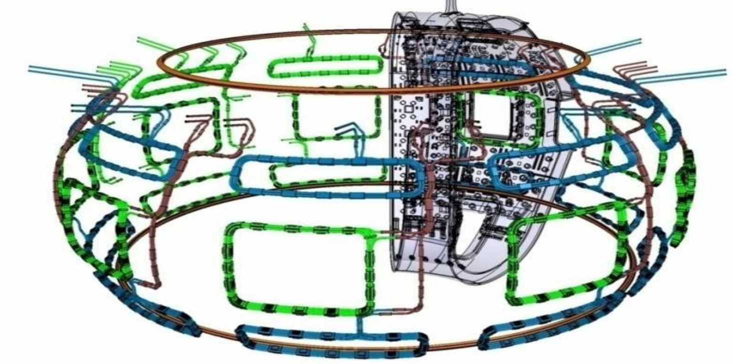




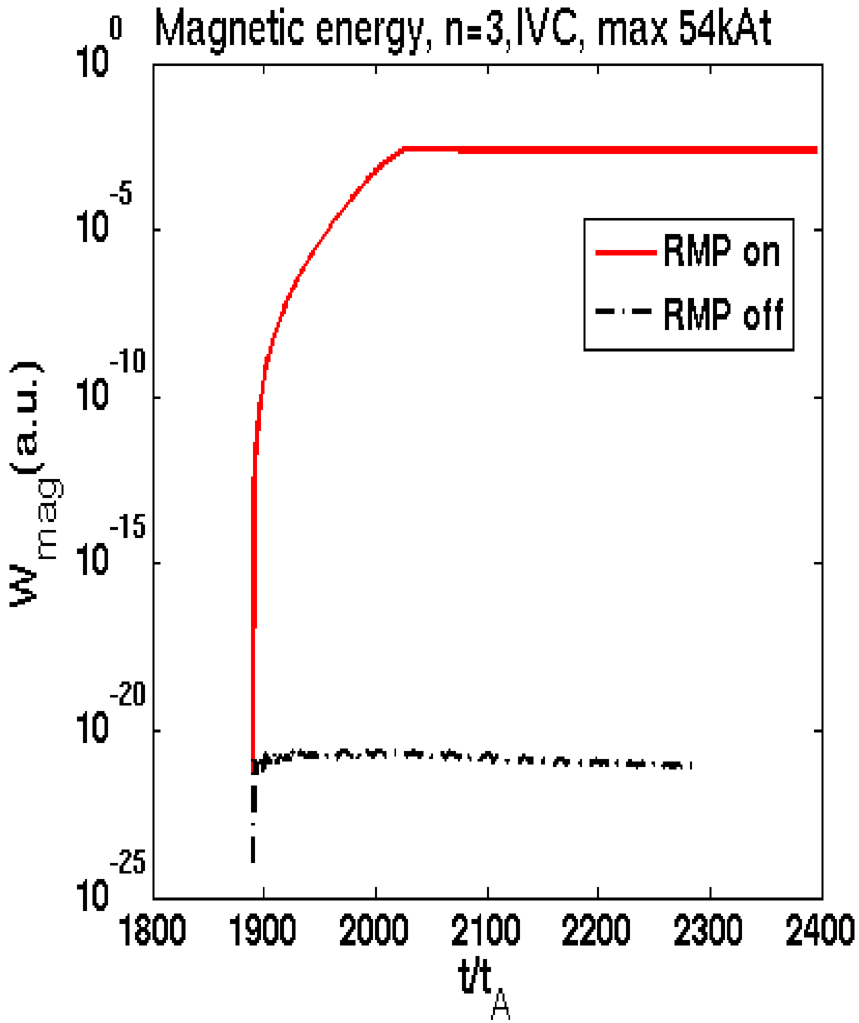


RMPs in ITER. W/o RMPs n=3 is stable. With RMPs =>n=3 static perturbations at the edge.

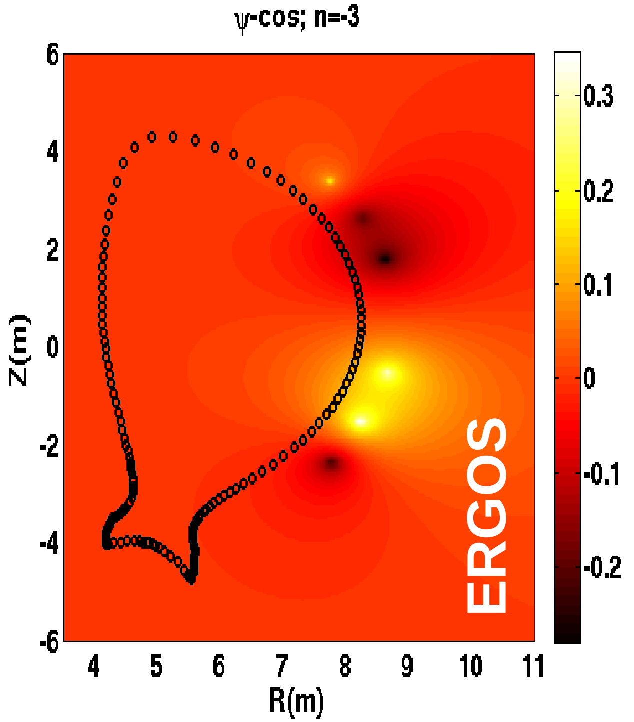
Courtesy to E.Day, M.Schaffer

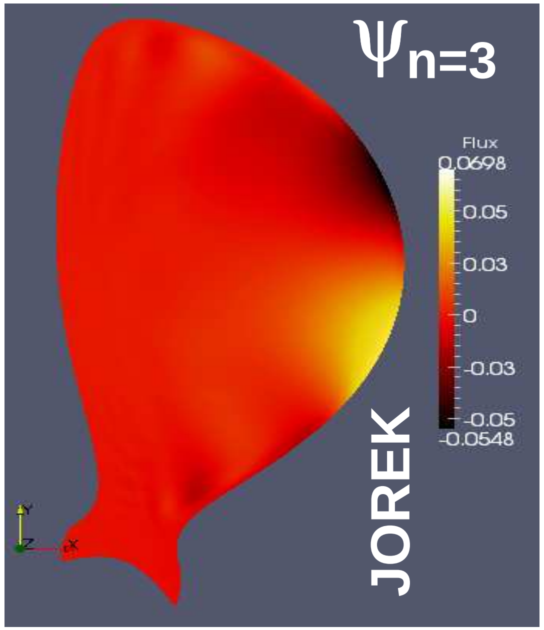


ITER, IVC, max:
I_{coil}=90kAt, n=2,3,4.
Used here n=3, 54kAt.



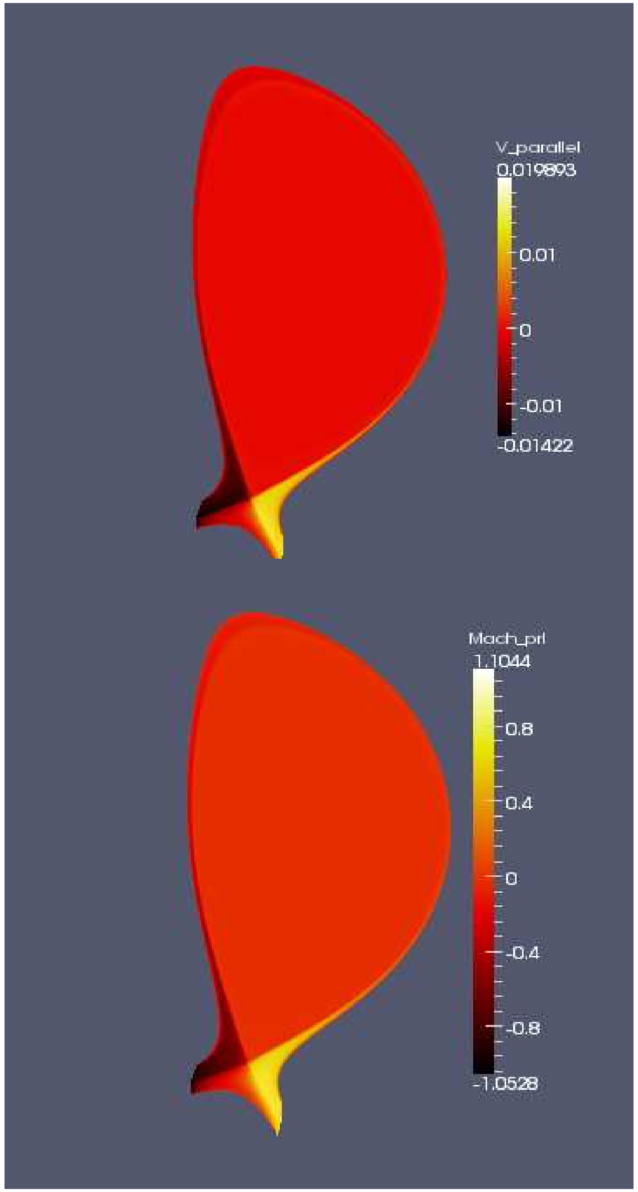
ERGOS (vacuum) =>JOREK boundary

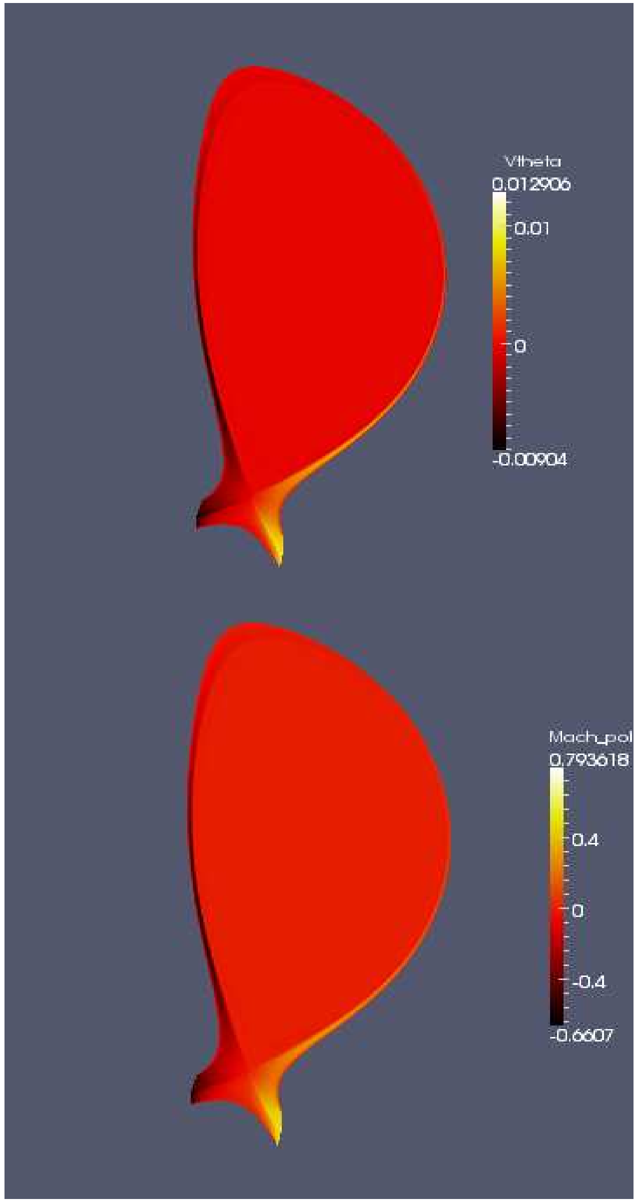


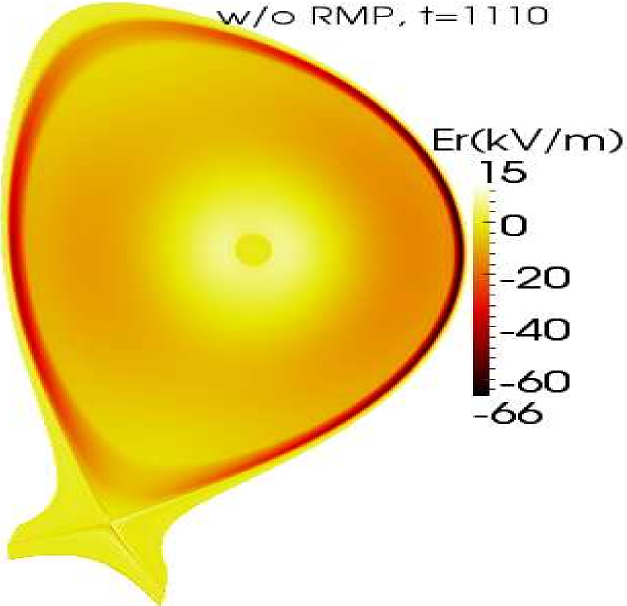


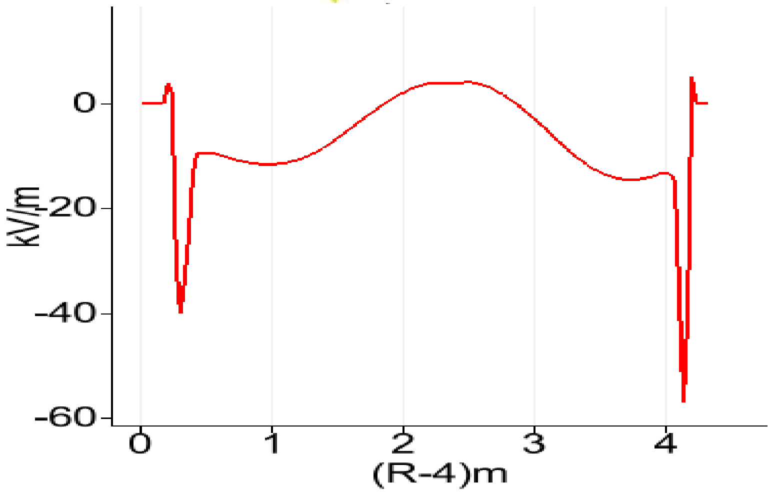
Equilibrium flows and radial electric field in ITER (w/o RMPs)

ITER: H-mode,15MA/5.3T, R=6.2m, a=2m,q_{95}=3,T_0=27.8keV,n_e=$8\,10^{19} m^{-3}$,f_0=1kHz



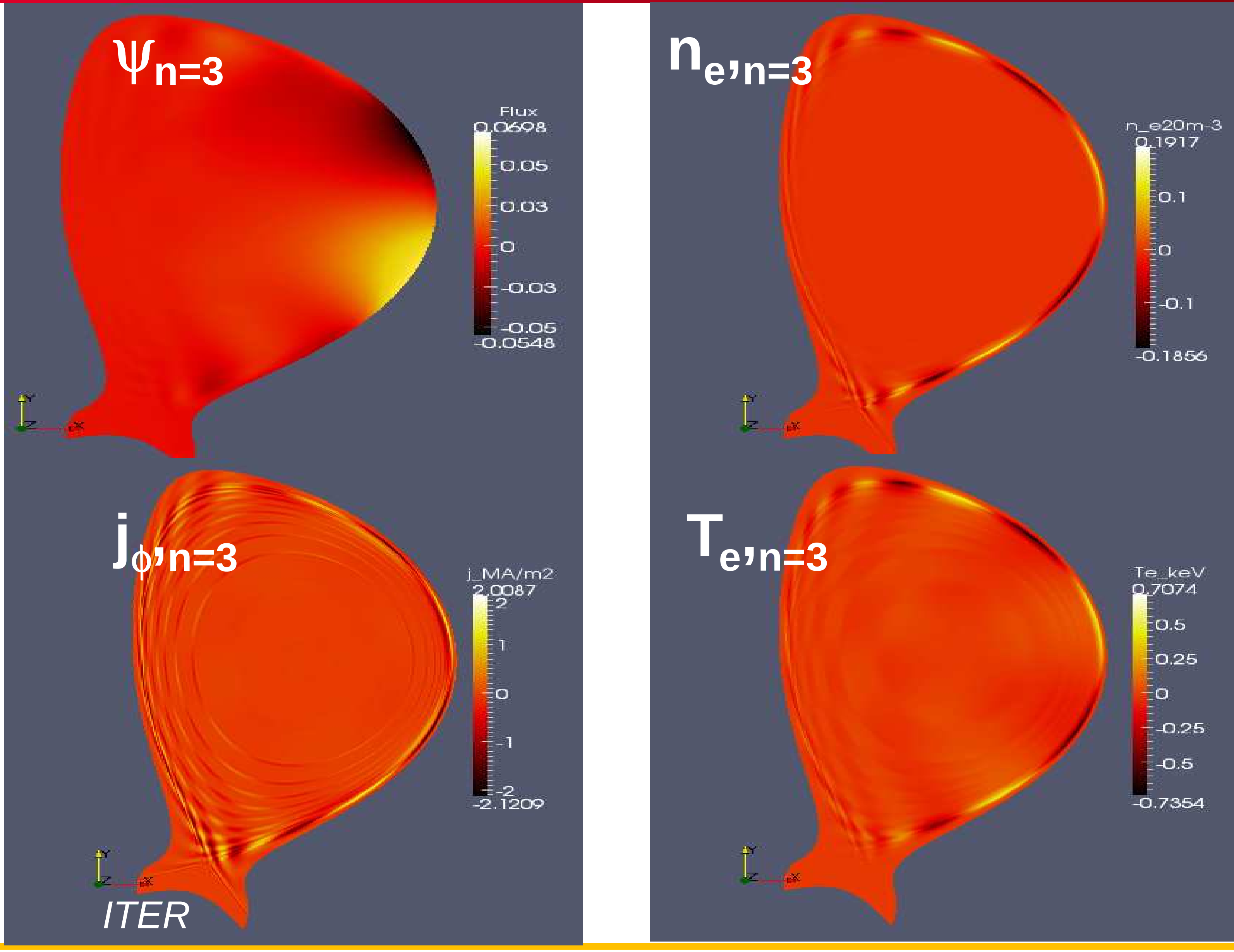






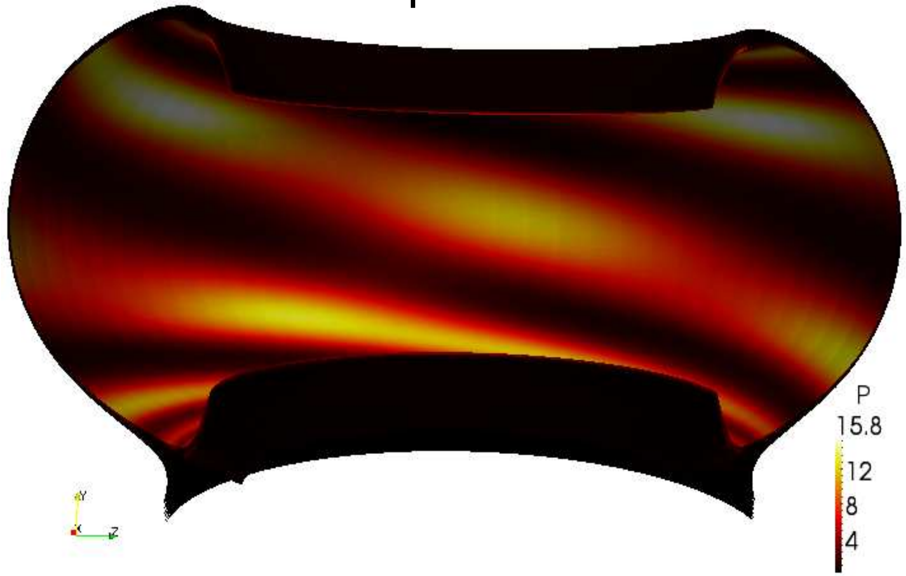
$$\tau_{IC} \sim 5.10^{-4}; \mu_{i,neo} \sim 10^{-5}; k_{i,neo} = 1; \eta = 10^{-8}$$

RMPs in ITER. With RMPs =>n=3 static perturbations at the edge.

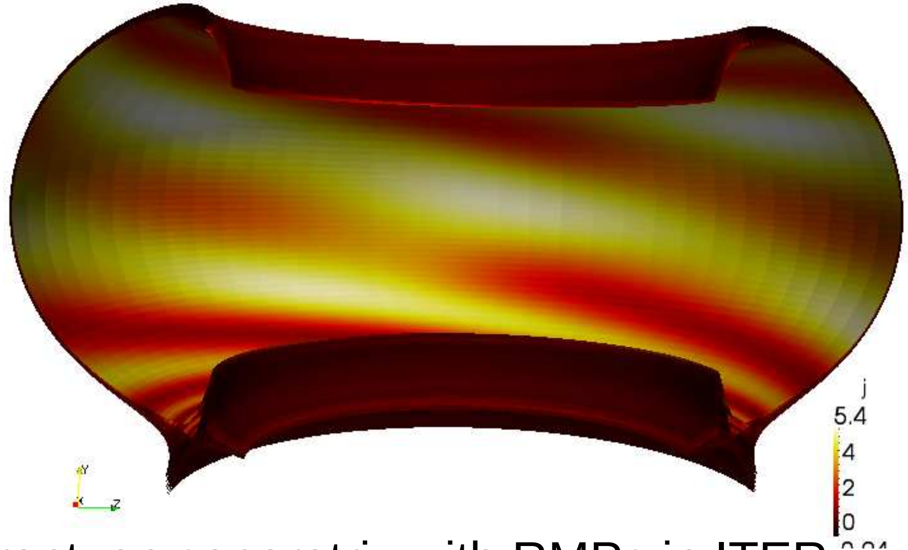


With RMPs: (density, temperature, pressure, current have stationary 3D structures at the edge . They are not constant at flux surfaces as in equilibrium. Future: 3D MHD stability to study…

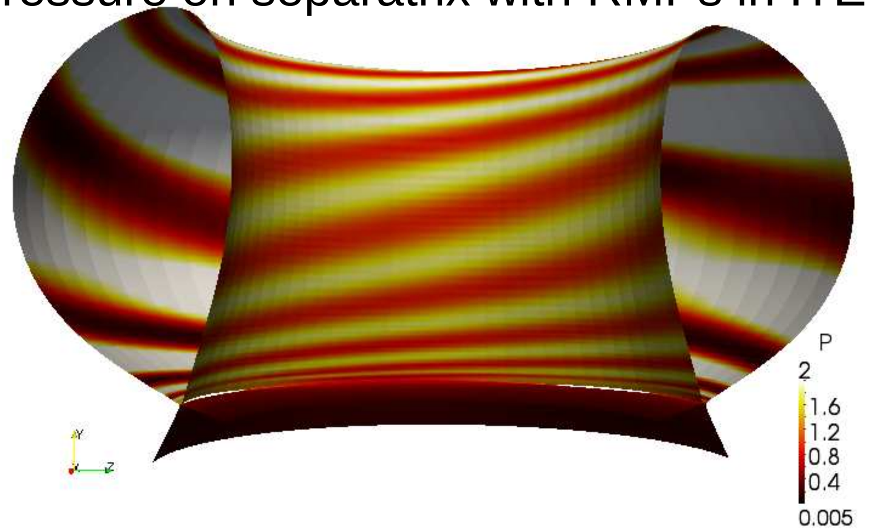
Pressure inside separatrix with RMPs in ITER.



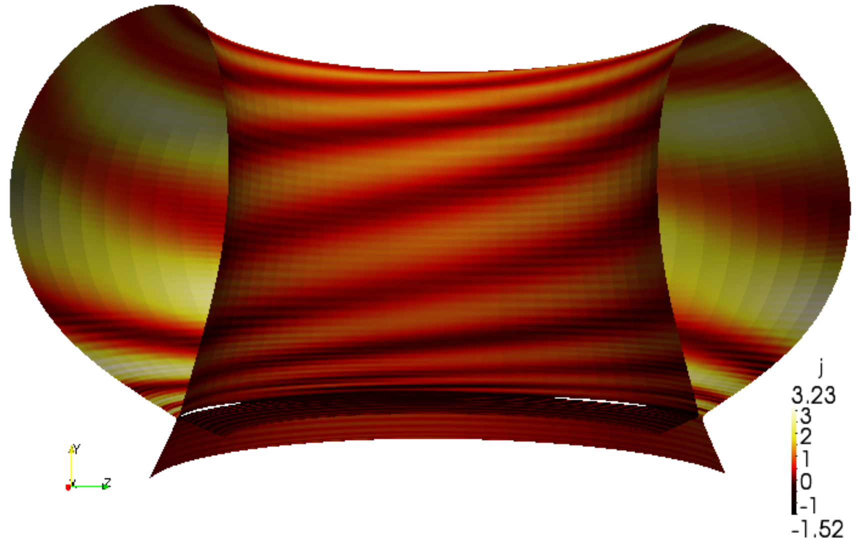
Current inside separatrix with RMPs in ITER



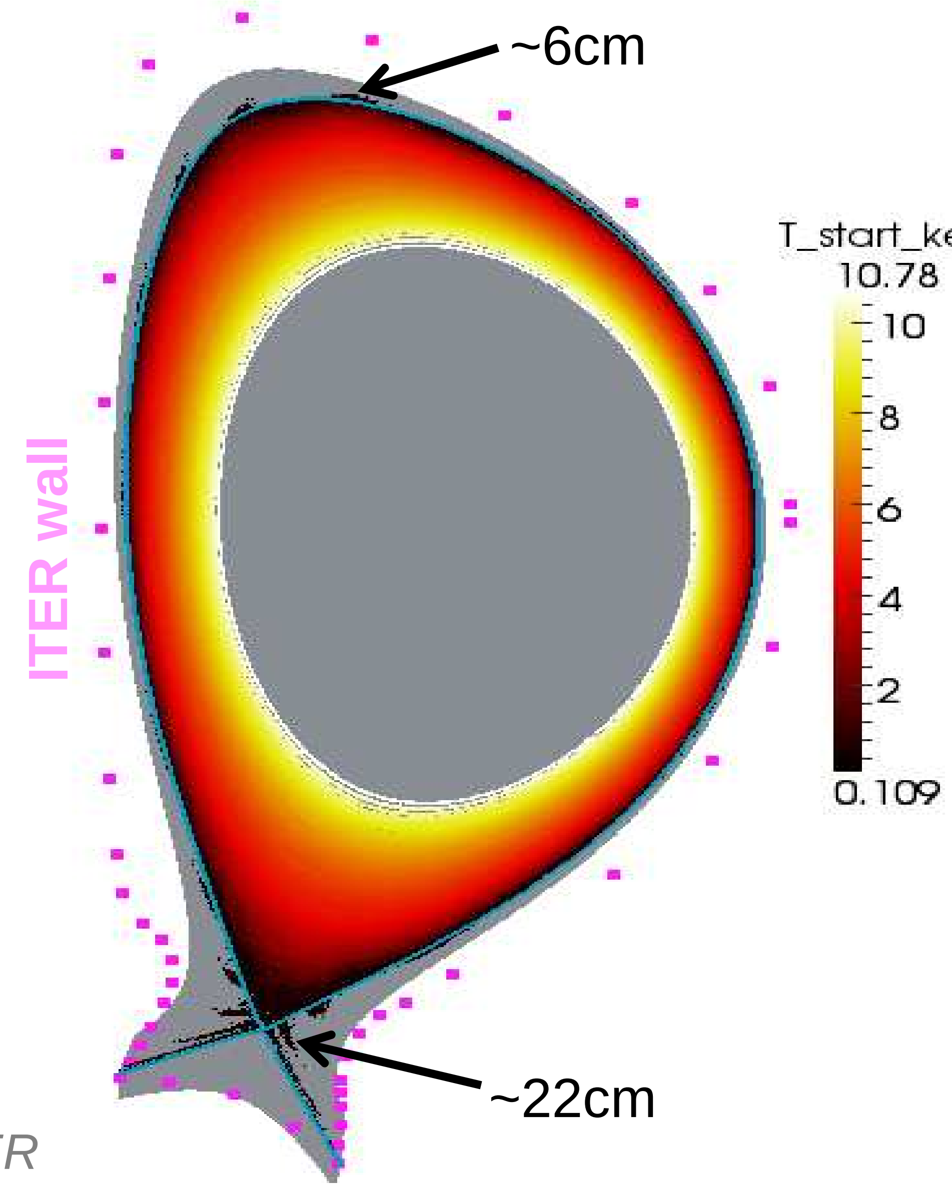
Pressure on separatrix with RMPs in ITER.



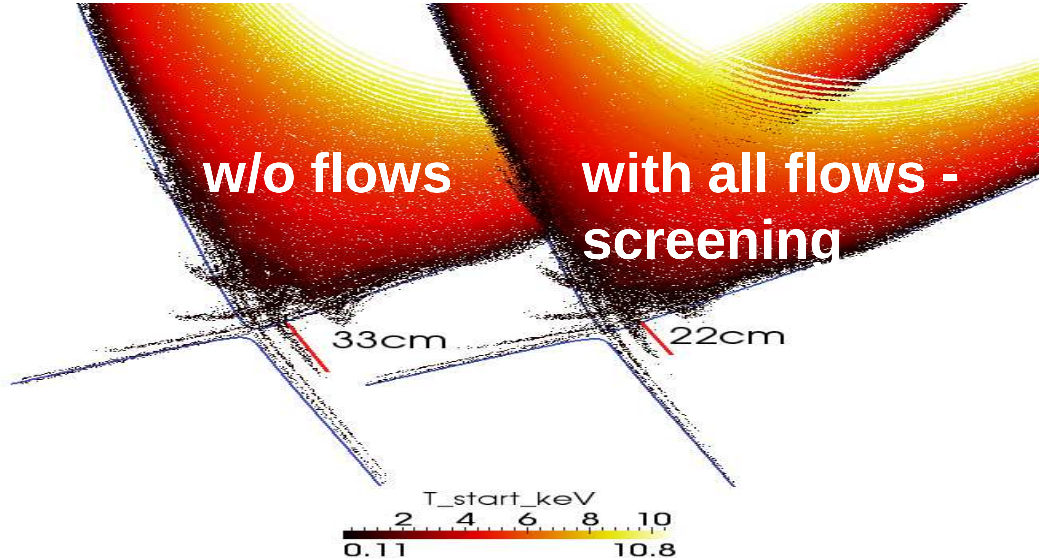
Current on separatrix with RMPs in ITER.

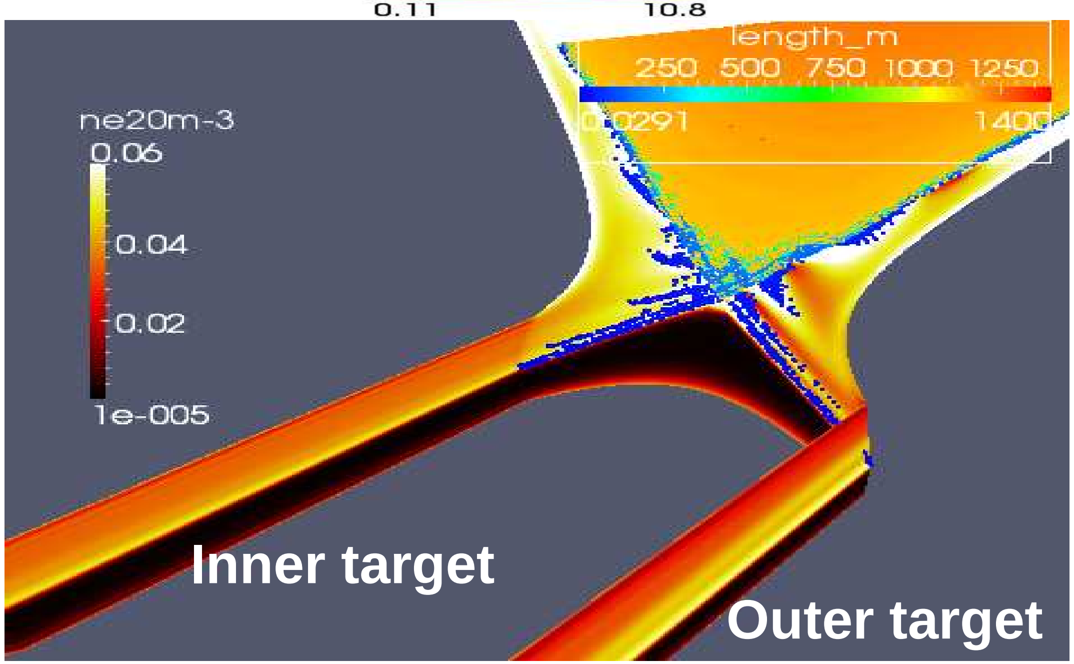


Boundary deformation. Lobes near X-point (smaller with rotation). Splitting of strike points (> on outer target)

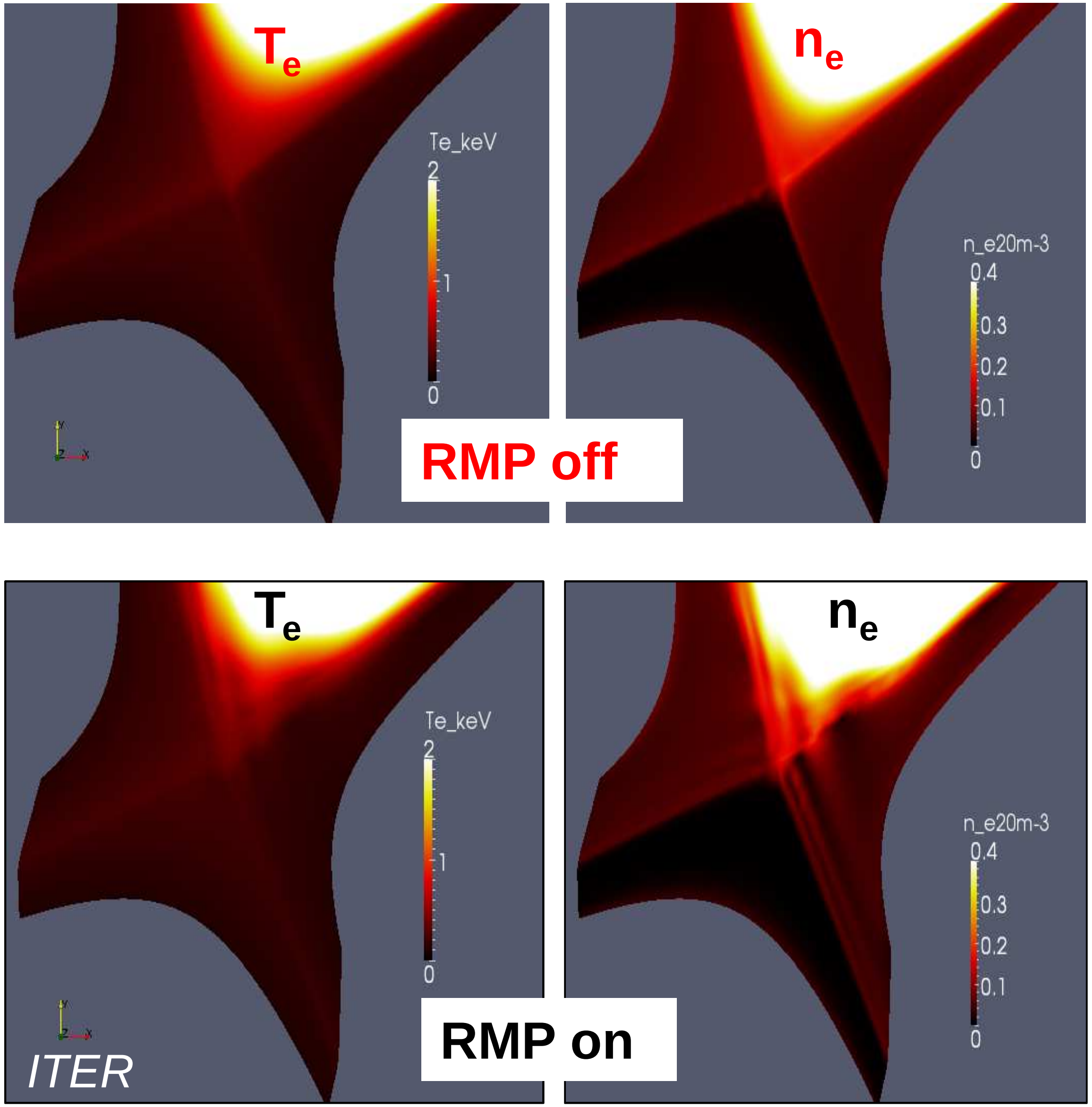


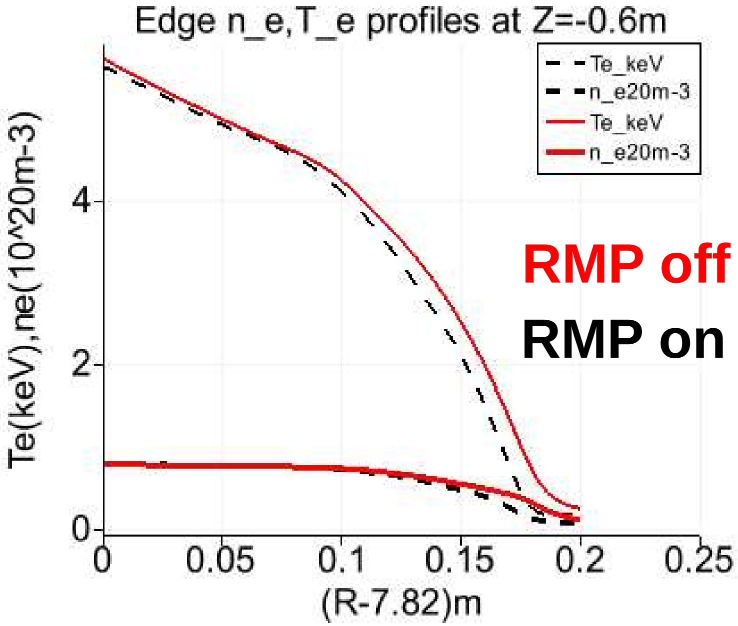
ITER

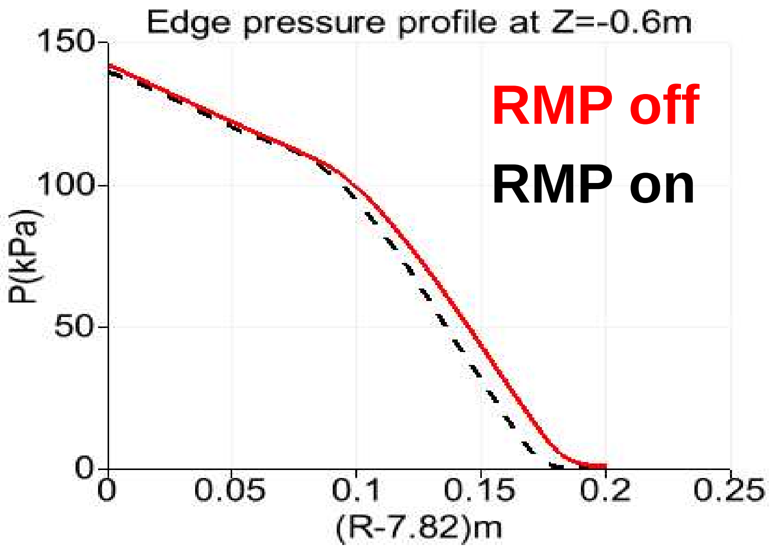




Small changes in edge T_e, n_e profiles. Modulations of T_e,n_e: max ~near X-point.







Discussion and conclusions.

- **Non-linear resistive MHD code JOREK development for RMPs with flows:** RMPs - at the boundary, 2 fluid diamagnetic effects, neoclassical poloidal viscosity, toroidal rotation source, SOL flows.

- **JET-like(n=2).Three regimes:**

✓ high η, small (poloidal) rotation (high ν*?) => oscillating and rotating islands, fluctuations δn_e, δT_e, $\delta\psi$ (t) (~kHz).

✓ low η, higher rotation => static islands, more screening of RMPs.

✓ Intermediate => oscillating, quasi-static islands.

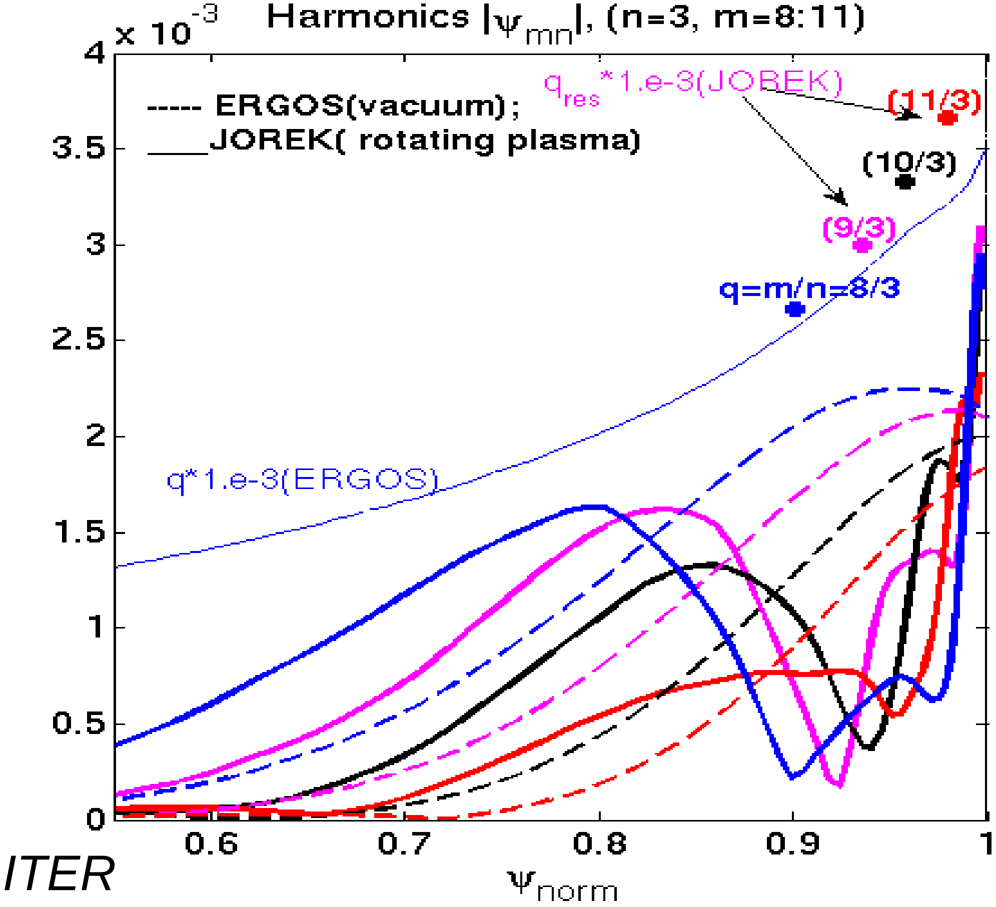
- **MAST case** (still limited in coil current amplitude /10 ,dia parameter /5) : RMP penetration, screening/amplification with dia. 3D boundary deformation.

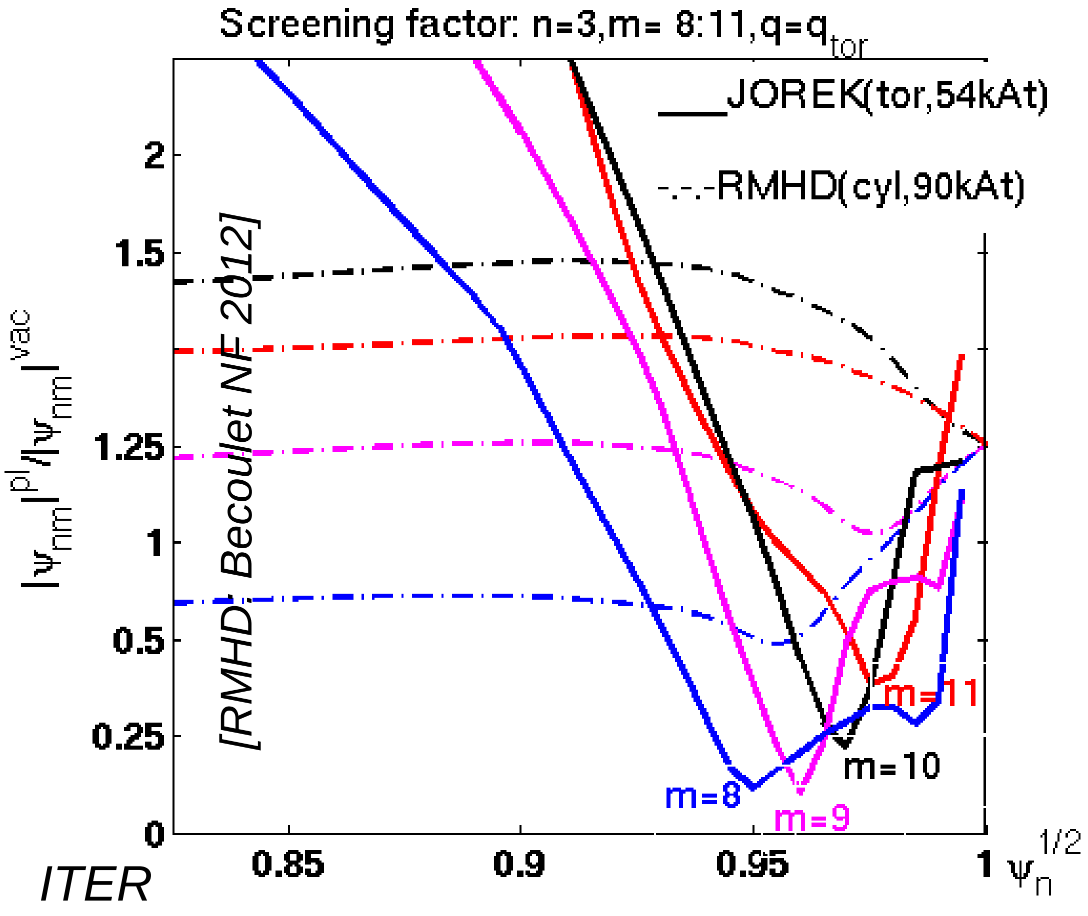
- **RMPs (n=3) in ITER.** Screening of central islands, static screened edge islands, ergodic edge, splitting of strike points (>outer), flattening of averaged ne,Te profiles, 3D edge temperature, density, current structures, boundary deformation: lobes near X-point.

- **Future:** RMPs interaction with ELMs (milti-harmonics modelling). Modelling of realistic shots MAST, JET, AUG. Continue ITER RMPs with ELMs.

Comparison JOREK&ERGOS(vacuum)&RMHD(cylinder). JOREK (torus, rotating plasma) : RMPs screening on q=m/n (stronger for central islands). Amplification $r<r_{res}$ in JOREK.

- Compared to vacuum (ERGOS). **RMPs screening by rotating plasma (JOREK)**, smaller screening for edge RMP harmonics *($\eta \sim T^{-3/2}$).*
- Compared to cylinder (RMHD, $q=q_{tor}$): **Stronger RMPs screening in JOREK. Amplification for $r<r_{res}$.**





Island is not screened if at q~(m/n) electron poloidal velocity => zero. For ITER parameters: $V_{e,\theta} \neq 0$

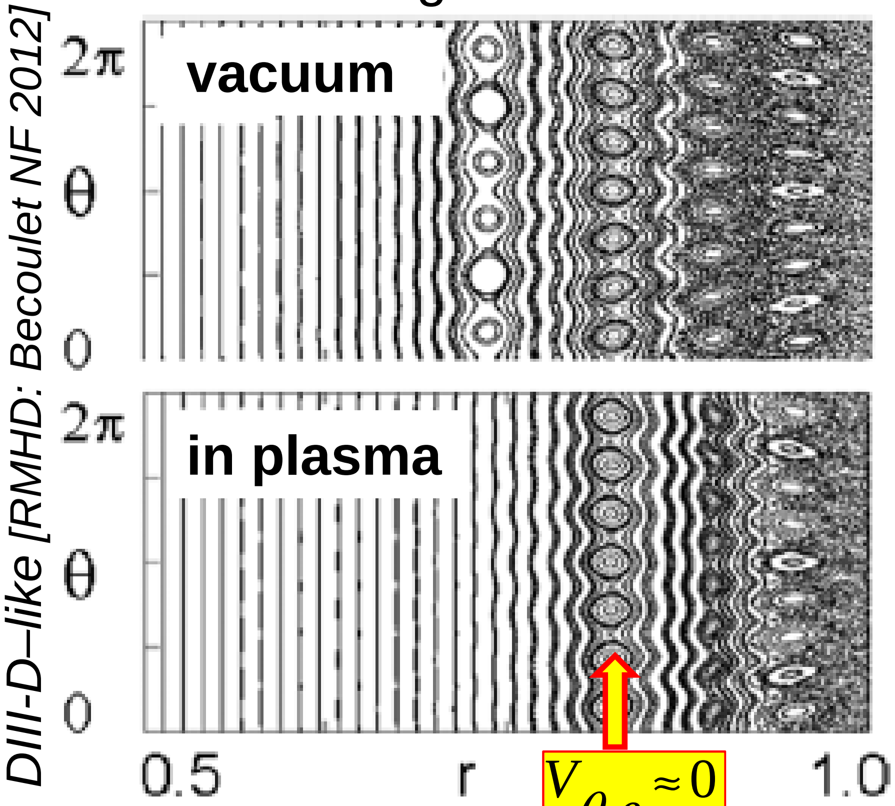
Ohm's law=>if electron poloidal velocity=>zero: $V_{e,\theta}\big|_{q\sim m/n} = V_{E,\theta} + V^{dia}_{e,\theta} \approx 0$

current perturbation $J_{\varphi,mn}\big|_{q\sim m/n} => 0$

no RMP screening **=> vacuum-like island.**

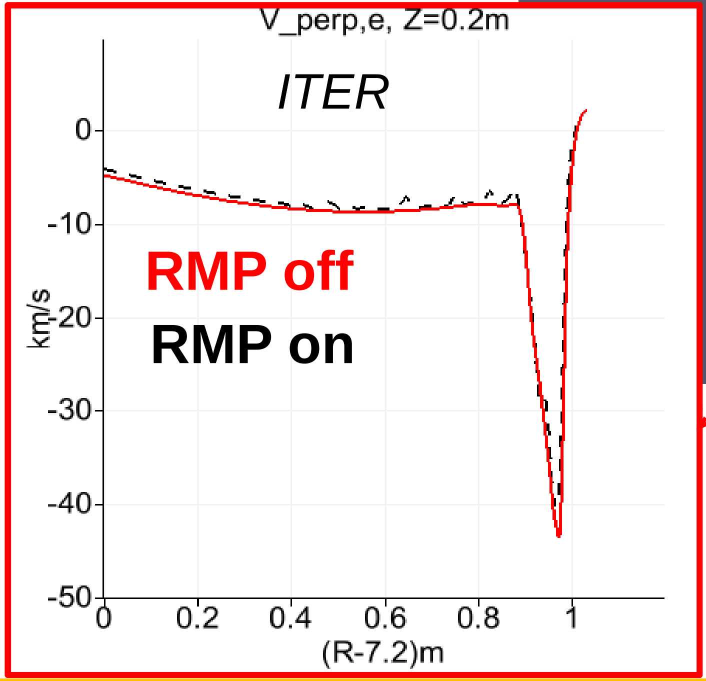
$V_{\theta,e} = \left[-(\nabla_\perp \psi, \nabla_\perp u) + \tau_{IC}(\nabla_\perp \psi, \nabla_\perp p)/\rho\right]/B_\theta$

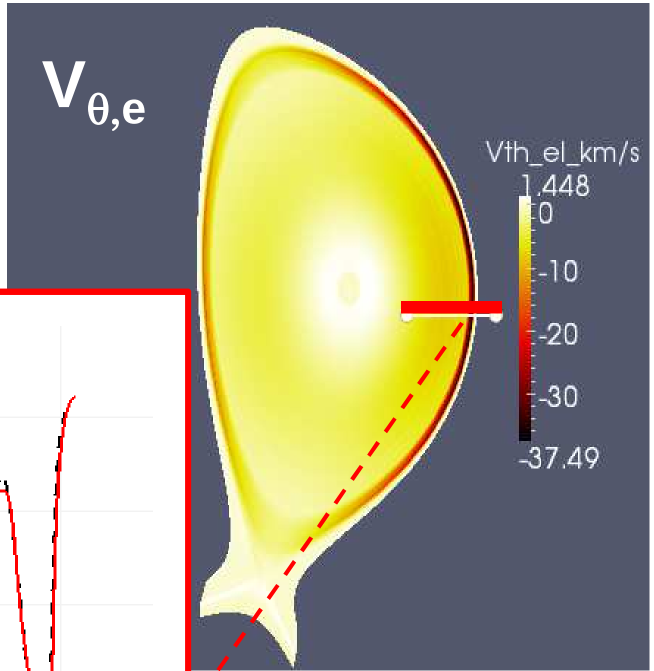
For ITER parameters used here electron poloidal velocity is not zero: **=>screening**



$V_{\theta,e} \approx 0$

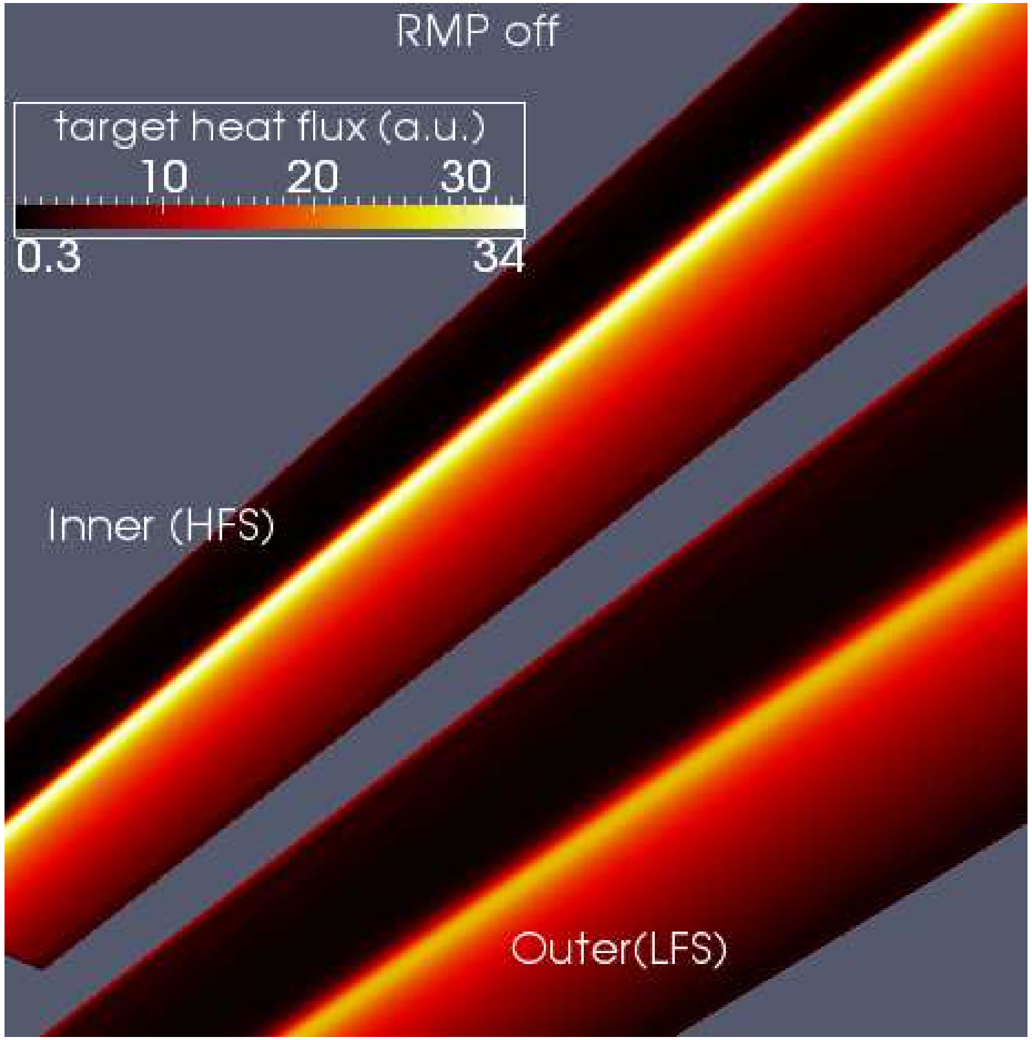
$V_{e,\theta} = V_{E,\theta} + V_e^{dia} \neq 0$

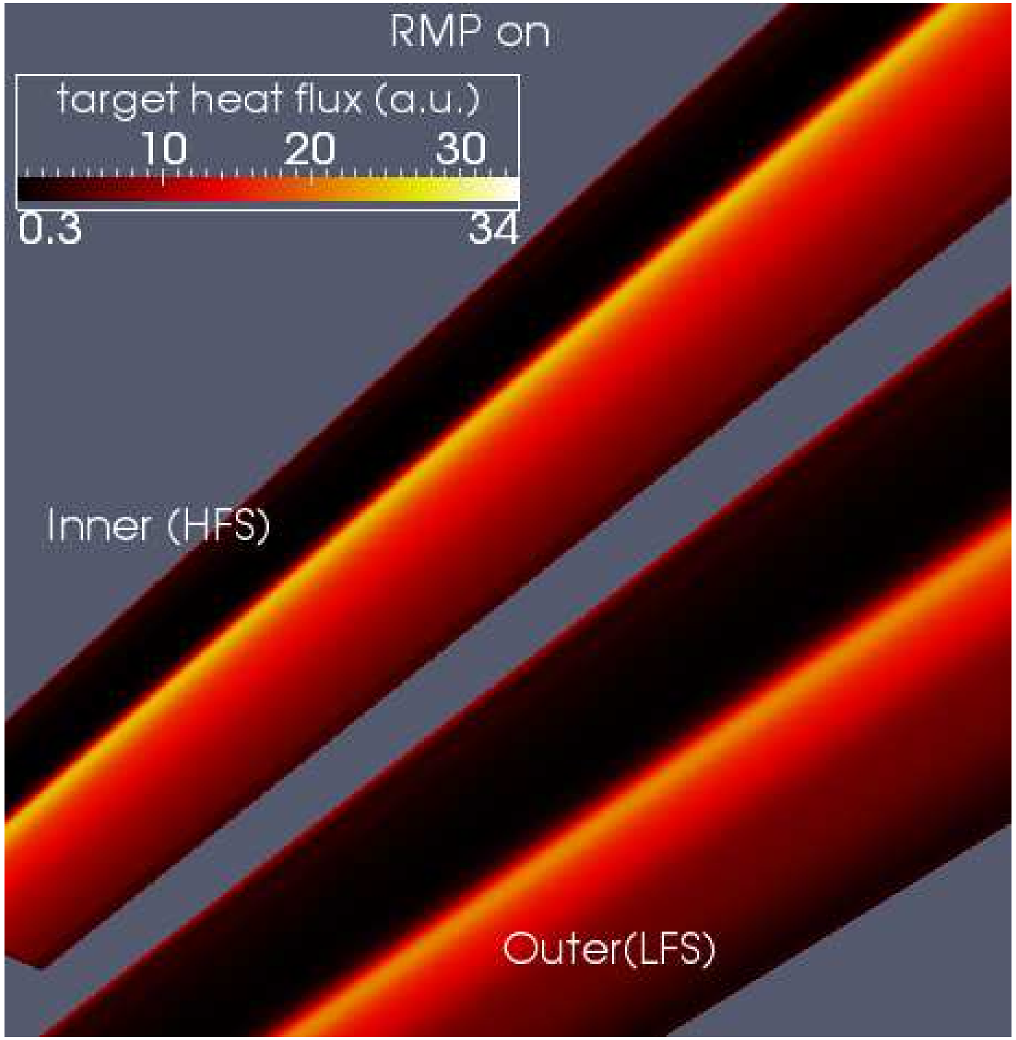




Peak heat fluxes on divertor targets are ~25% reduced (spreading due to ergodisation) with RMPs on.

Heat flux on inner and outer divertor targets.





NB! No divertor physics (radiation, ionisation, sources, detachment….) in the model

Pressure gradient is 3D, locally could be even steeper with RMP.