DE LA RECHERCHE À L'INDUSTRIE

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

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TH/2-1 (poster session P4, today,14h)

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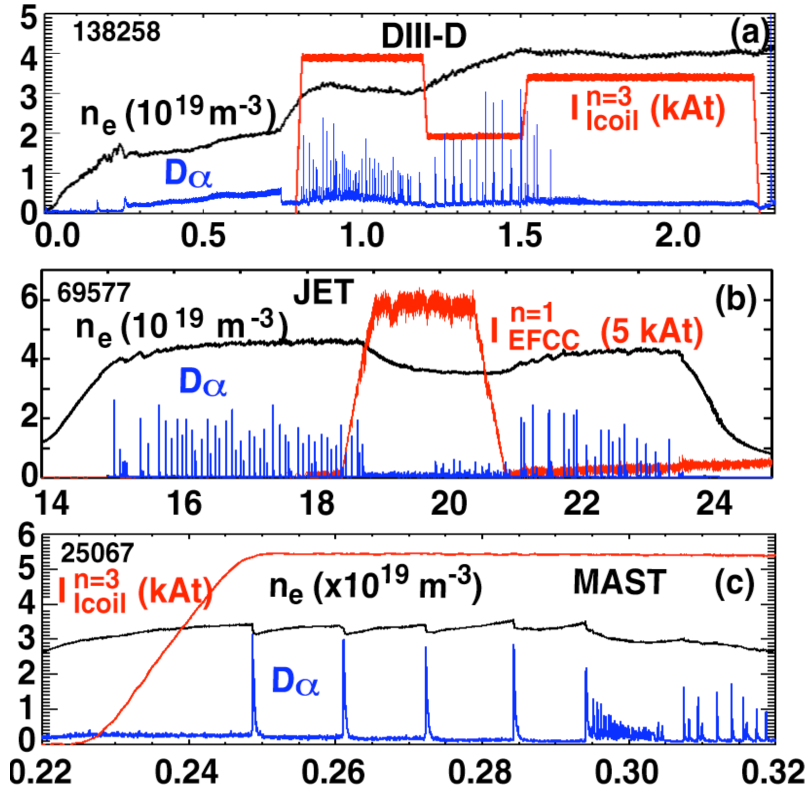
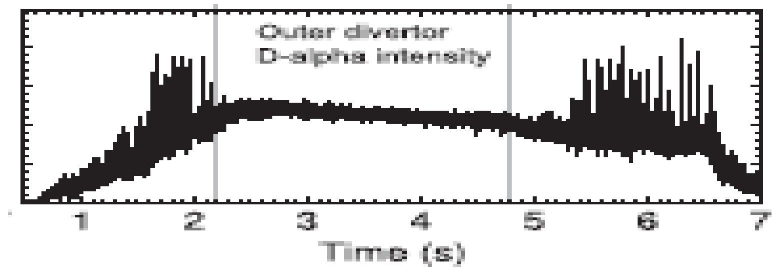
Type I ELM control by RMPs in ITER. Many open questions in physics of ELMs+RMPs still remain. Aim: progress in understanding of RMPs, give reliable predictions for ITER.

- ❑ 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*) ?
- ❑ Rotation braking/acceleration?

Fenstermacher, IAEA-2010



AUG:*Suttrop,PRL 2011*



KSTAR, Jeon, IAEA 2012 this session

[Huysmans PPCF2009]

- **RMPs and flows in non-linear resistive MHD code JOREK :**
  - ✓ *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.** *(EFCC,40kAt,n=2).* **Three regimes depending on resistivity and rotation.**
  - ✓ *Oscillating /rotating islands at high resistivity, low rotation*
  - ✓ $\delta B^r(t)$, $\delta n_e(t)$, $\delta T_e(t)$*-fluctuations (~kHz). Link with Type II ELMs with RMPs at high* ν^**?*
  - ✓ *Static islands at strong rotation, low resistivity, more screening of RMPs.*
  - ✓ *Intermediate: oscillating, quasi-static islands.*

- **RMPs in ITER***.(IVC,54kAt,n=3).*
  - ✓ *Screening of RMPs (stronger for central islands, penetration at the edge).*
  - ✓ *Boundary deformation, lobes near X-point,splitting of strike points.*
  - ✓ *No significant density/temperature transport, modulations near X-point.*

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

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

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

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

parameter

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

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

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]*

$$\nabla\cdot\Pi_i^{neo} \approx \mu_{i,neo}\rho(B^2/B_\theta^2)(V_{\theta,i} - V_{\theta,neo})\vec{e}_\theta$$

$$\vec{e}_\theta = (R/|\nabla\psi|)\nabla\psi\times\nabla\varphi$$

Ion poloidal velocity => neoclassical

$$V_{\theta,i} \to V_{\theta,neo} = -k_{i,neo}\tau_{IC}(\nabla_\perp\psi\cdot\nabla_\perp T)/B_\theta$$

$$B_\theta = |\nabla\psi|/R$$

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

Parallel flow.

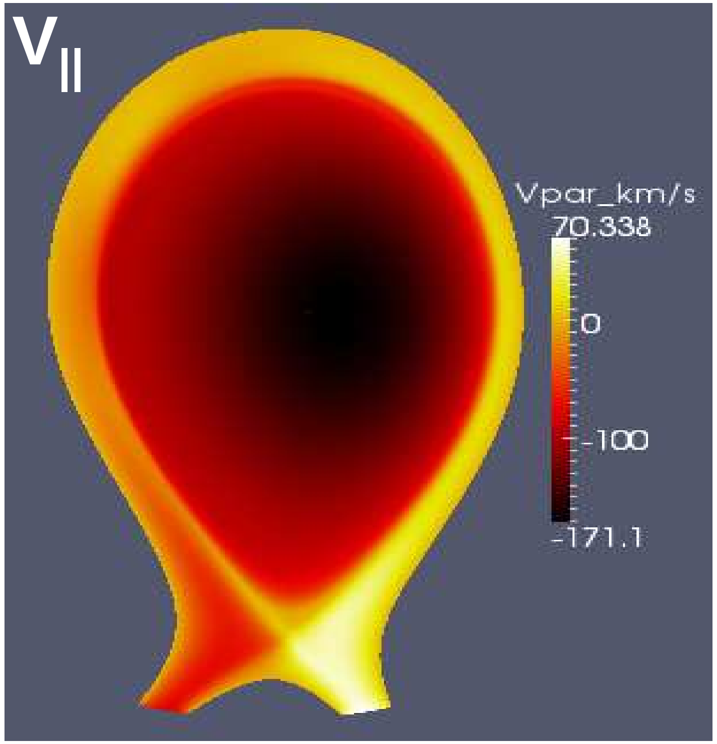
- **Central plasma**: toroidal rotation source keeps initial $V_{\|}$ profile: $S_{V\|} = -\nu_{\|} \Delta V_{\|,t=0}$
- **SOL**: sheath conditions on targets: $V_{\|,div} = \pm C_s$

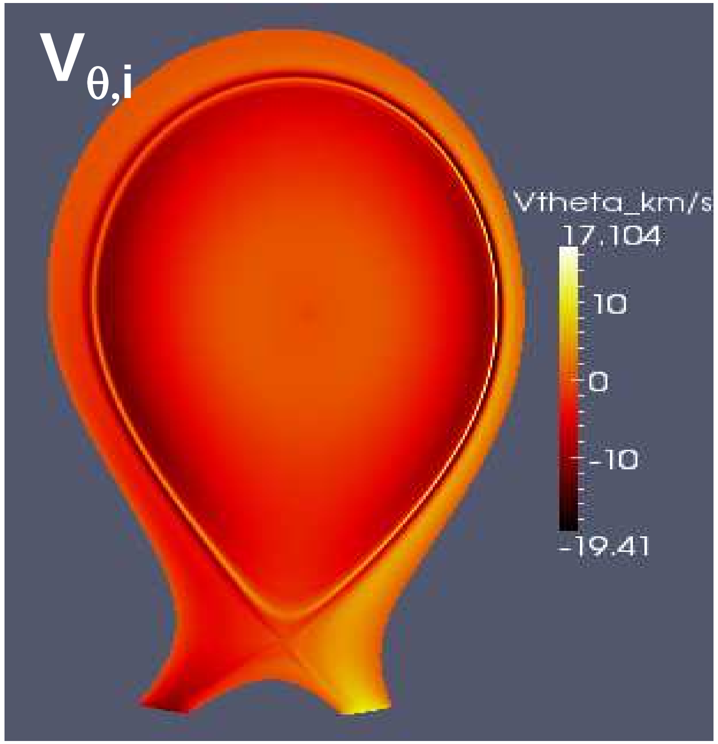
Poloidal flow.

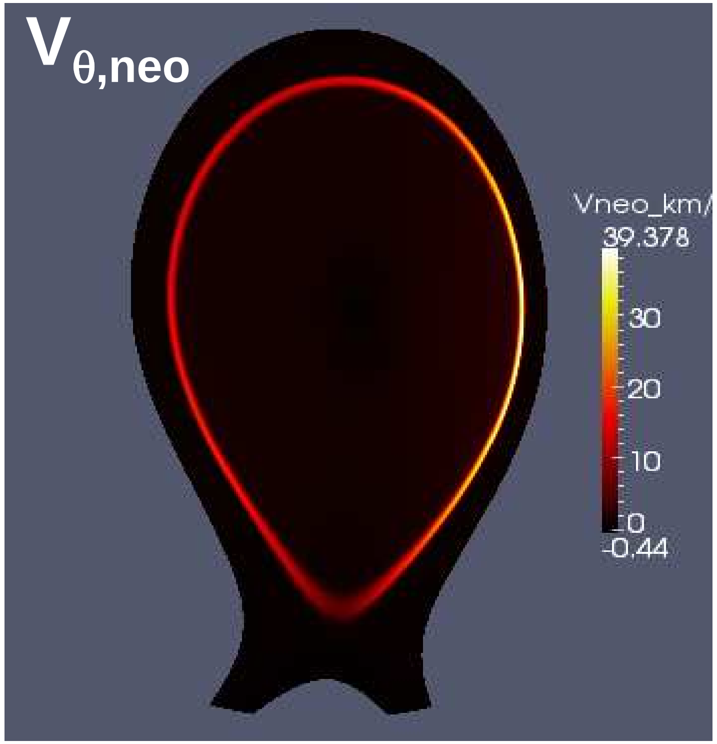
$$V_{\theta,i} = \left[-(\nabla_{\perp}\psi, \nabla_{\perp}u) - \tau_{IC}(\nabla_{\perp}\psi, \nabla_{\perp}p)/\rho + V_{\|}B_{\theta}^2 \right] / B_{\theta}$$

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

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



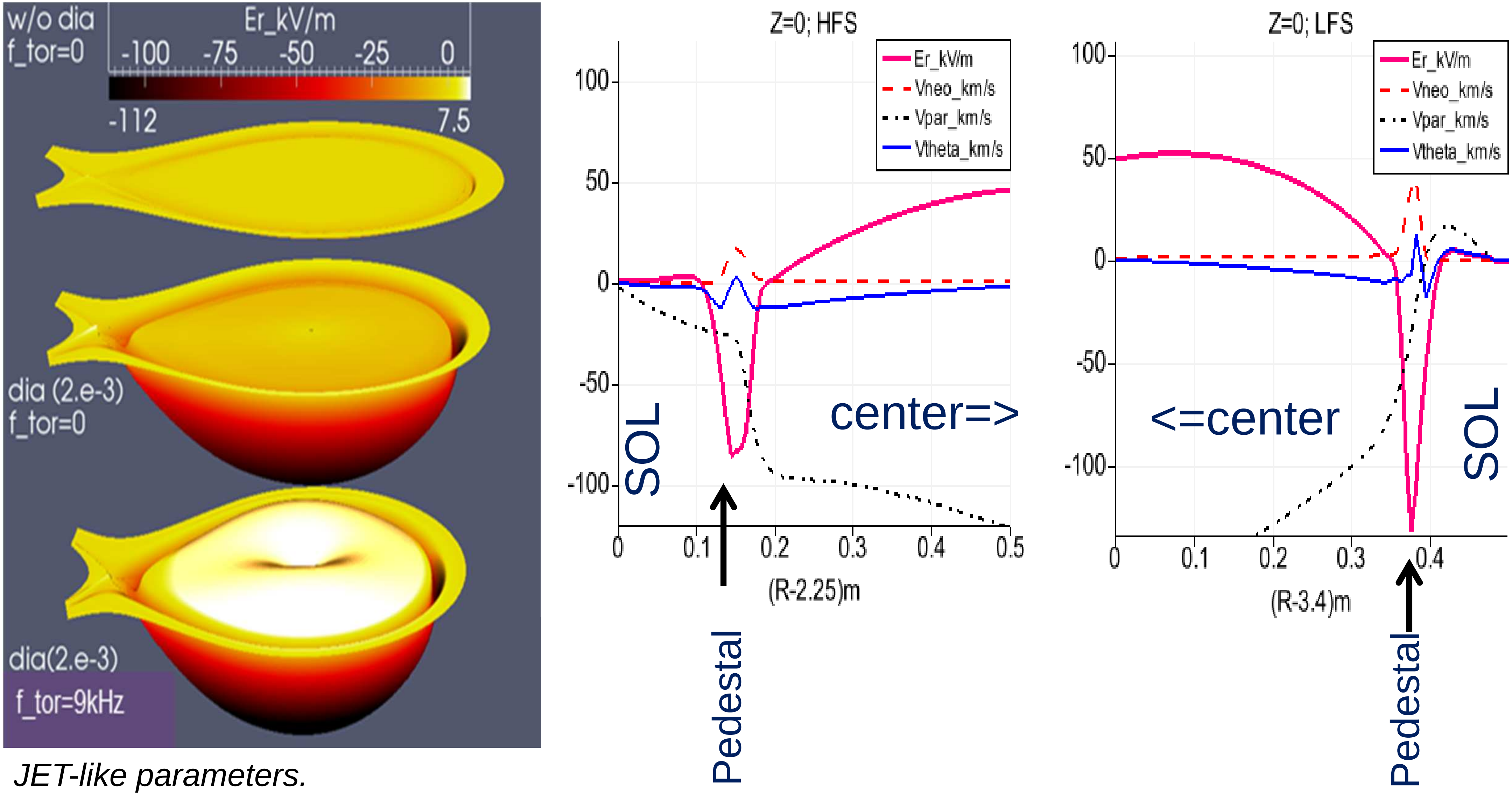




JET-like: R=3m, a=1m, q_{95}=3, T_0=5keV, n_e=6 10^{19} m^{-3}, f_0=9kHz. $\tau_{IC} \sim 2.10^{-3}; \mu_{i,neo} \sim 10^{-5}; k_{i,neo} = 1.; \eta = 5.10^{-8}$

Radial electric field "well" in the pedestal=> large ExB rotation=>likely to screen RMPs.

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

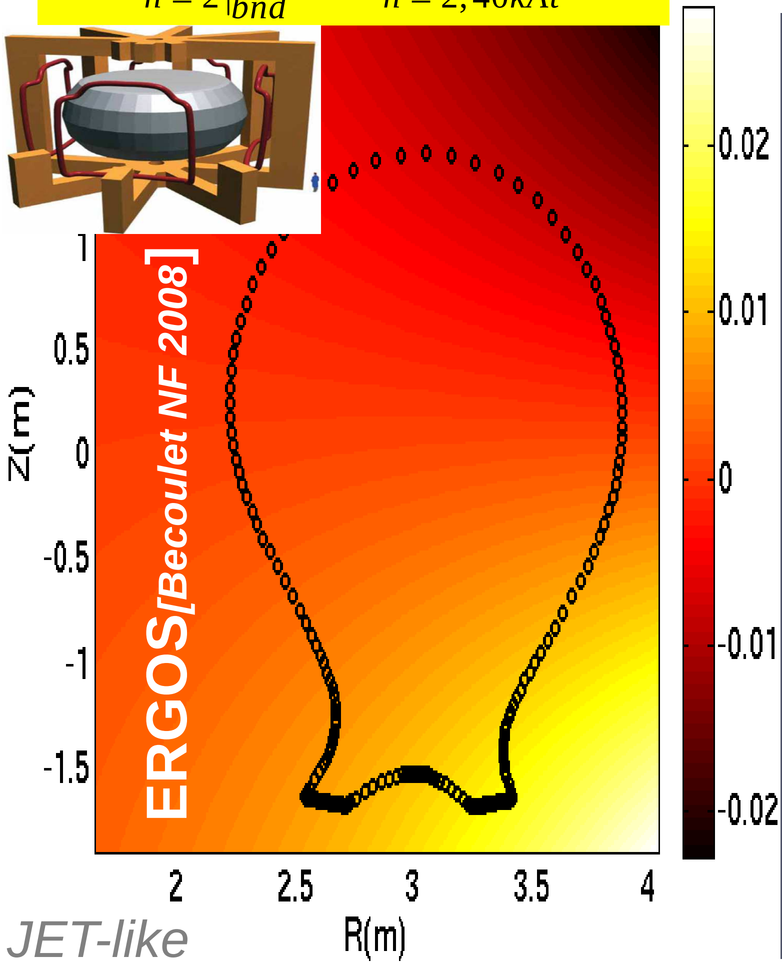


JET-like parameters.

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

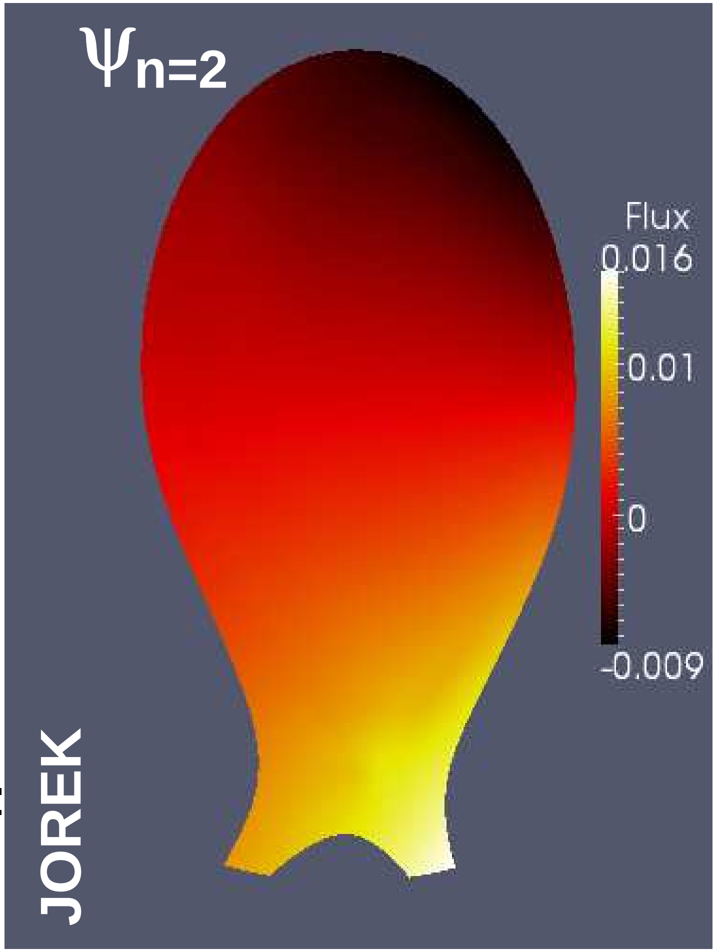
Vacuum RMP (***EFCC, n=2, I_{coil}=40kAt)*** are increased in time at JOREK boundary.

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

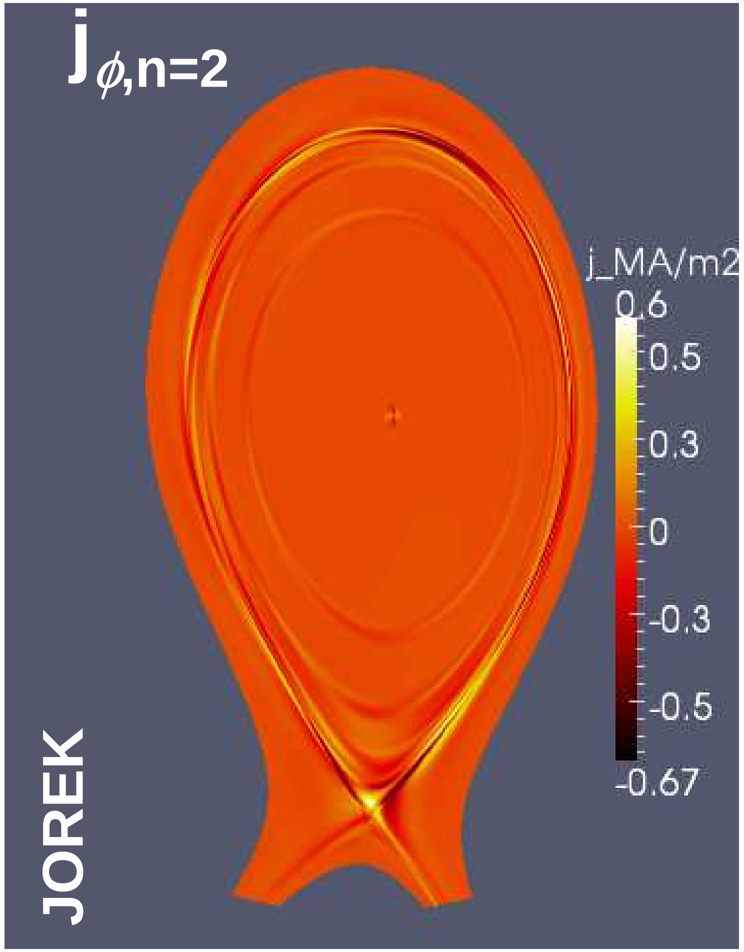


JET-like

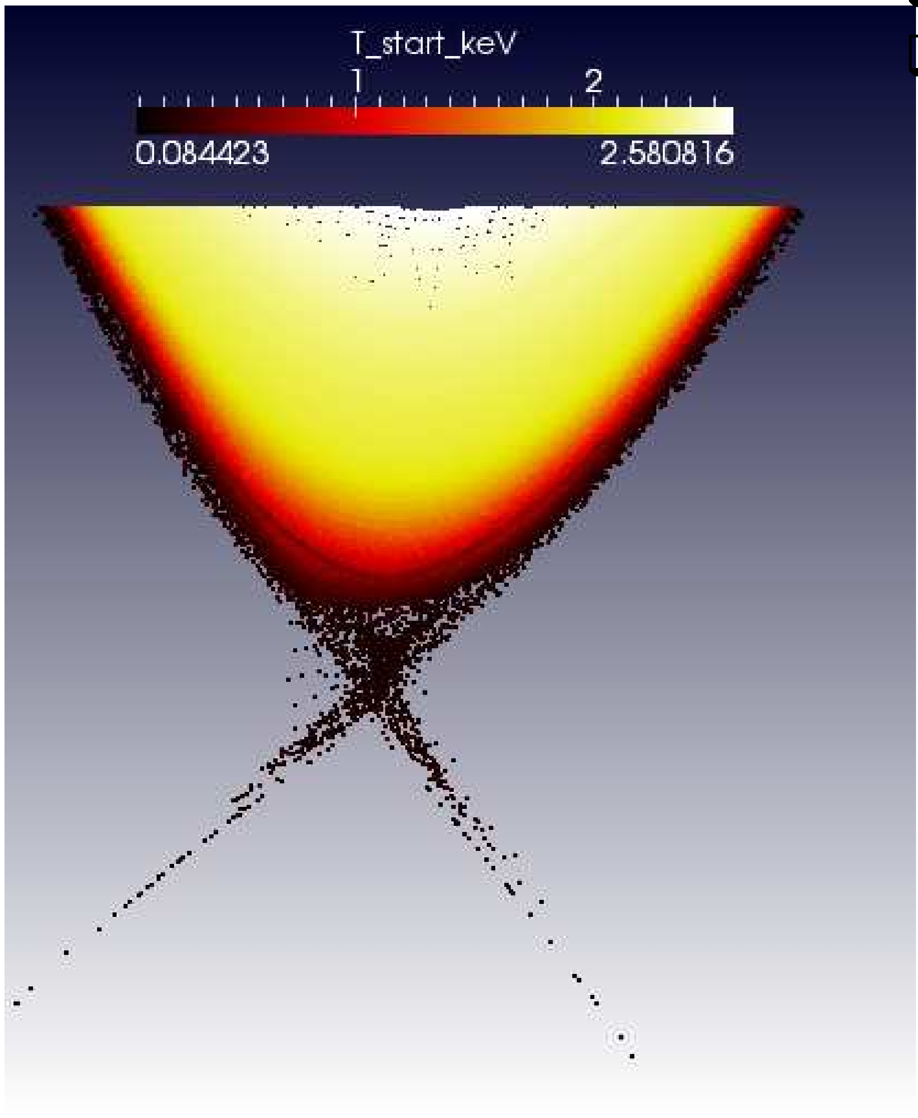
Poloidal magnetic flux perturbation (max) with RMPs in plasma with flows.



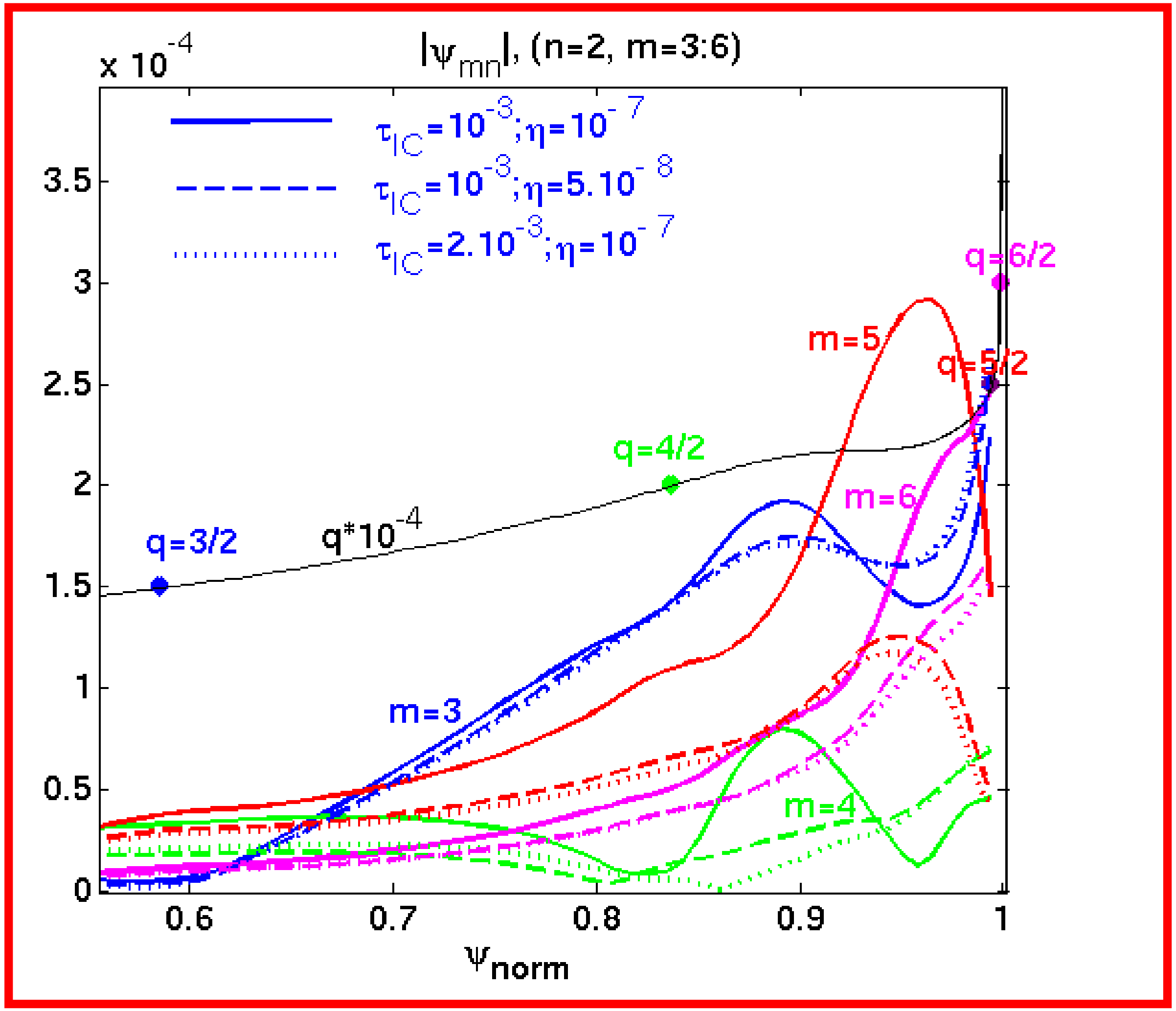
Toroidal current perturbations on the rational surfaces (q=m/2; m=3,4,5,6) with RMPs.



Stronger RMP screening for lower resistivity and larger poloidal rotation. Ergodic region at the edge.



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

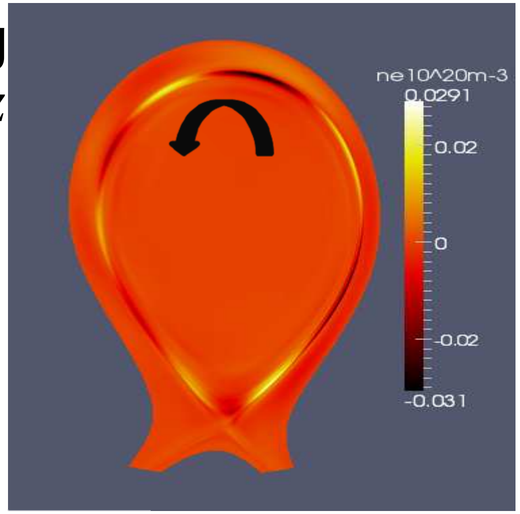


JET-like

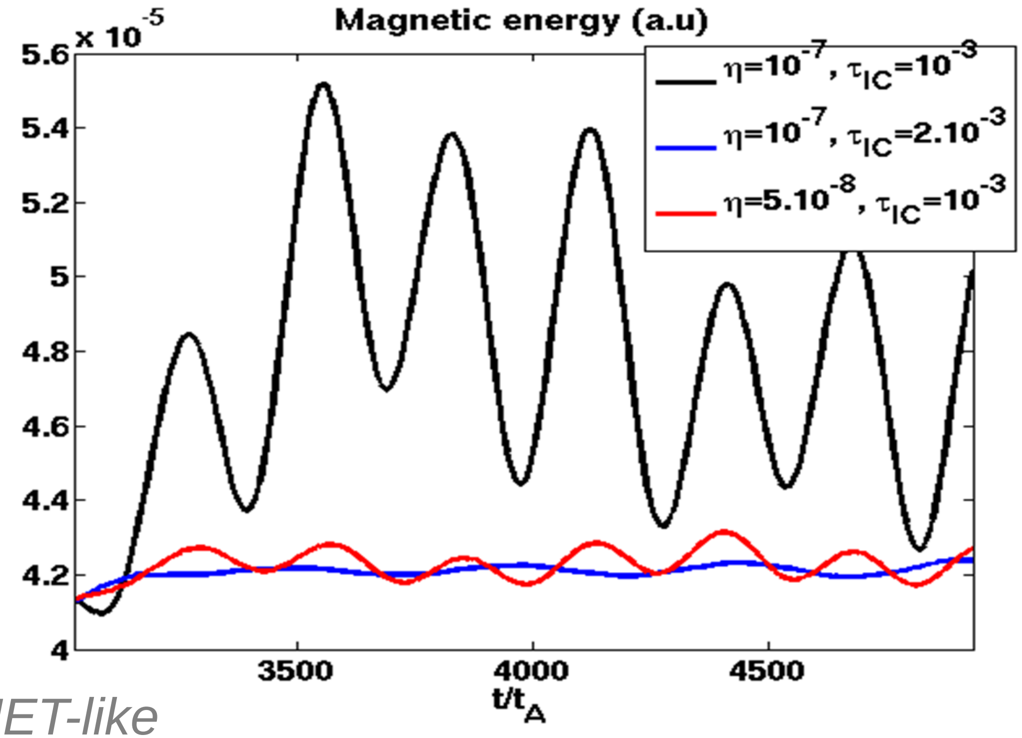
Similar results in cylinder [Becoulet NF 2012]

Three regimes depending on rotation & resistivity.

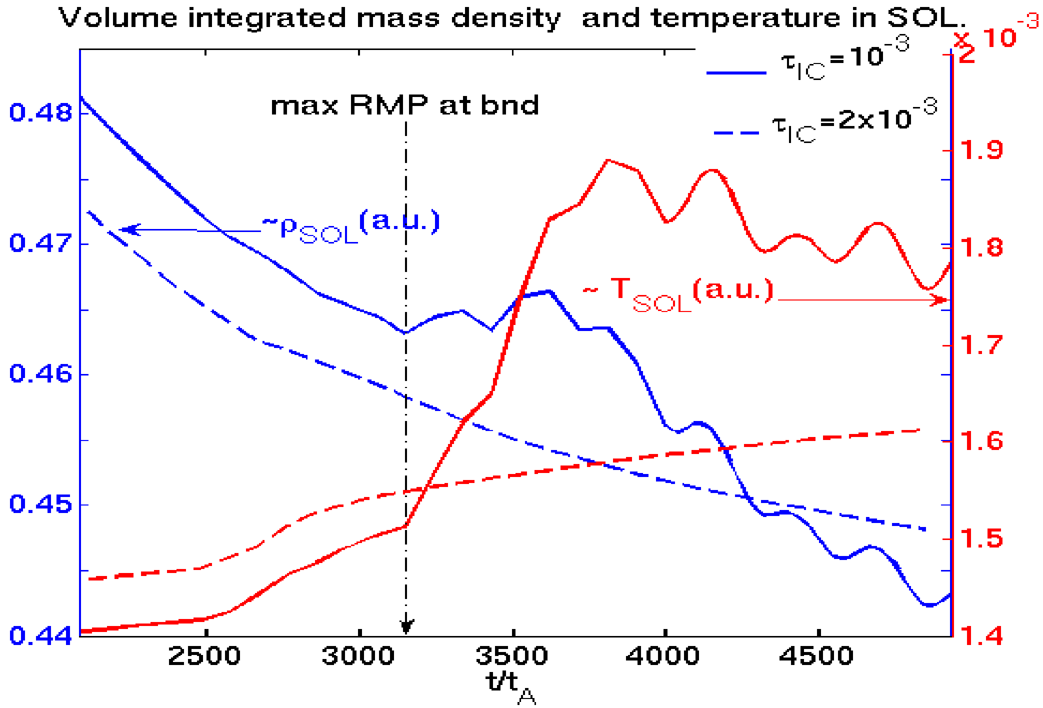
- high η, low τ_{IC}: rotating oscillating islands $f^* \approx mV_\theta/(2\pi r_{res}) \sim 6kHz$
- high τ_{IC}: static islands, more screening of RMPs.
- low η, low τ_{IC} : intermediate-ocsillating, quasi-static islands



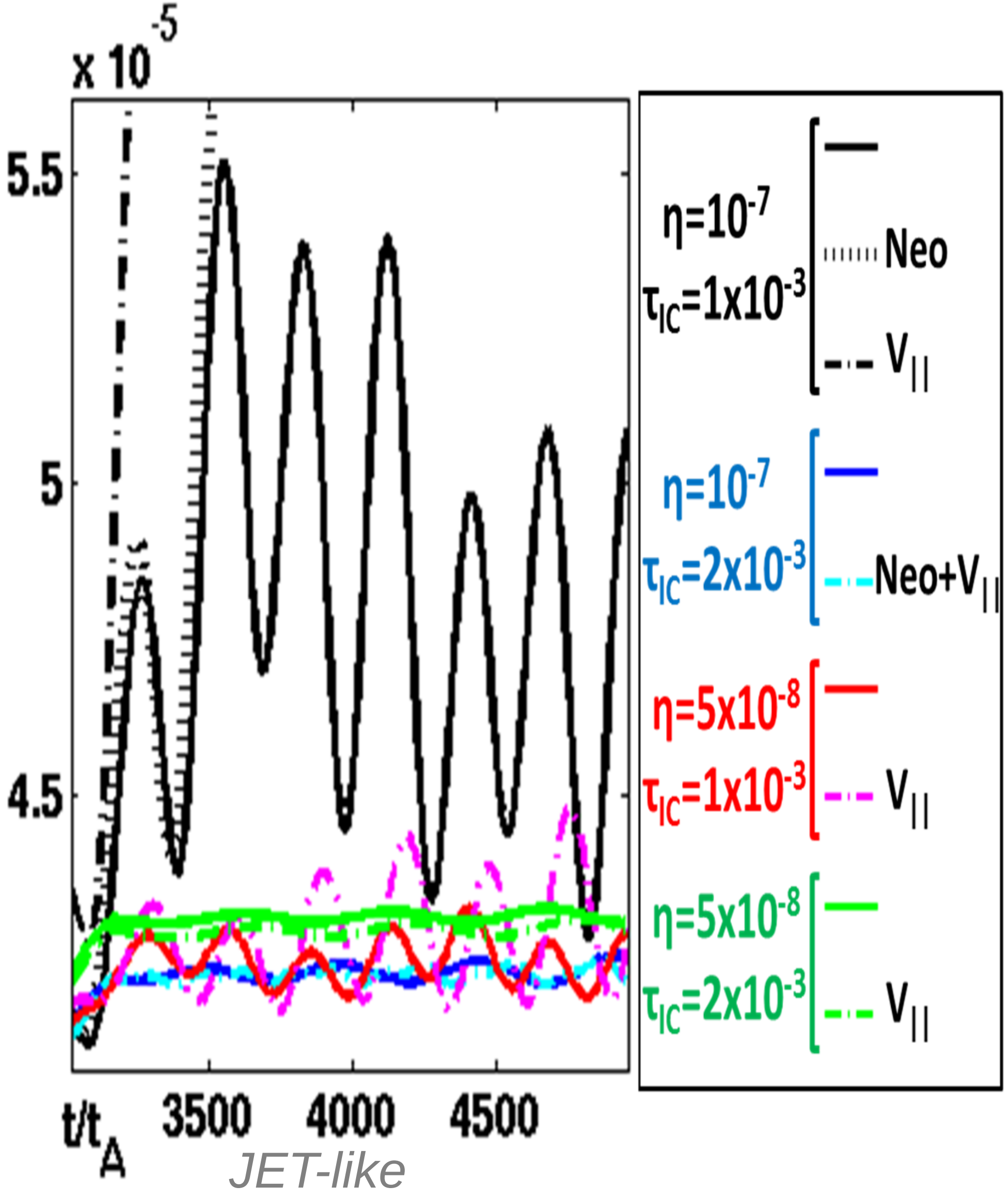
=>fluctuations of magnetic field, density and temperature no significant transport *(Possibly related to RMPs suppression at high ν*? Rutherford regime ? [Fitzpatrick PoP 1998], [IzzoNF2008])*



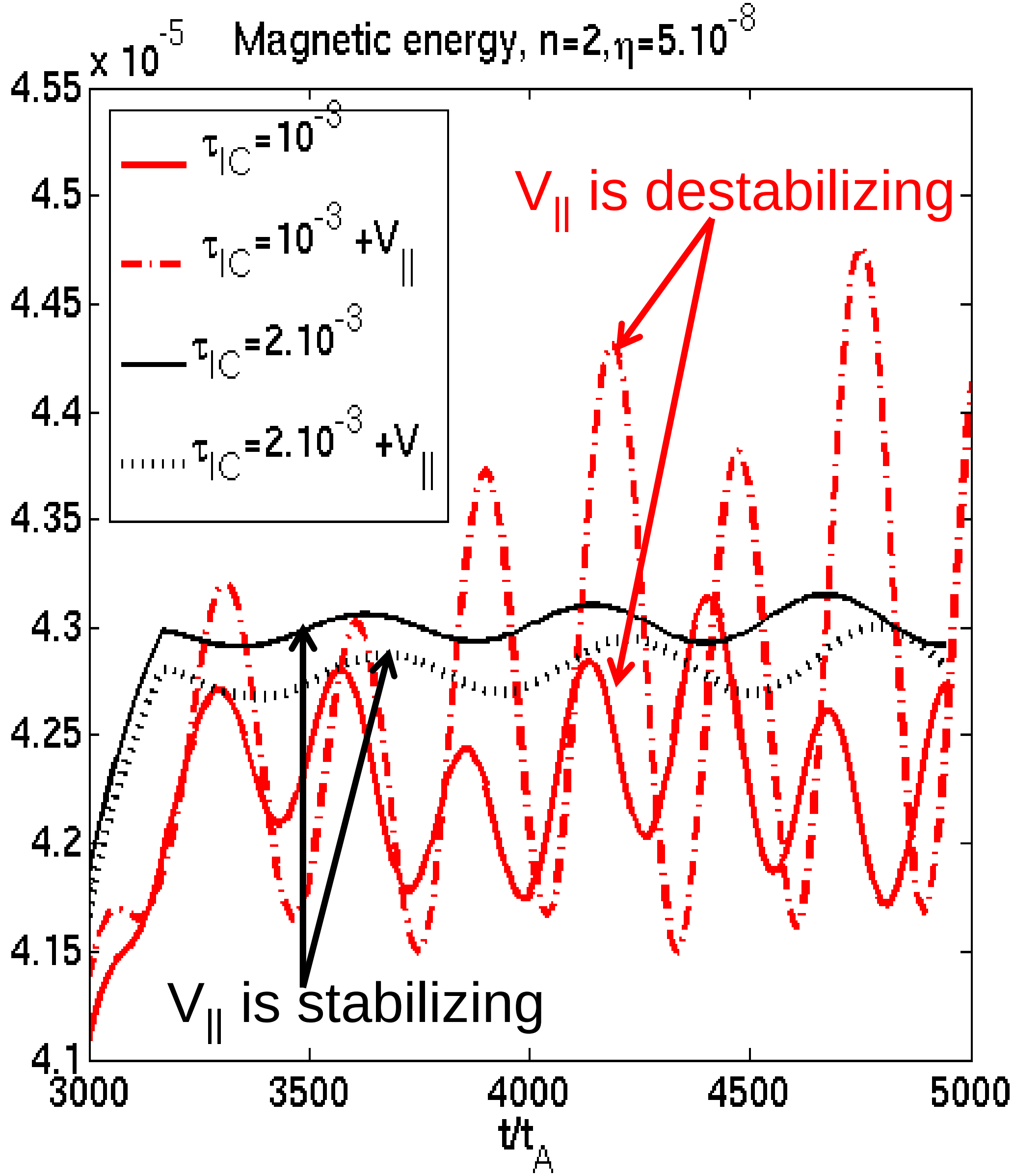
JET-like



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

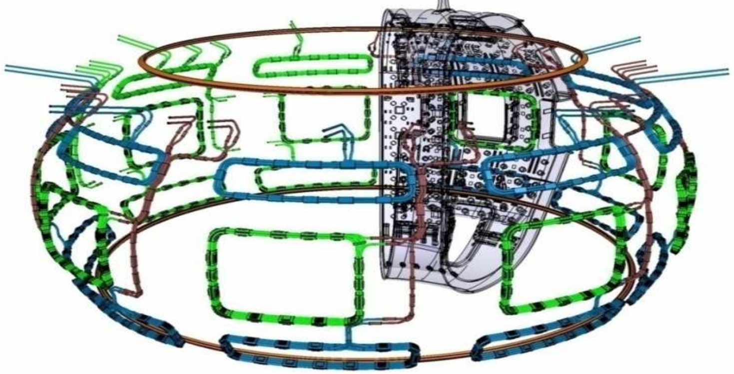


JET-like

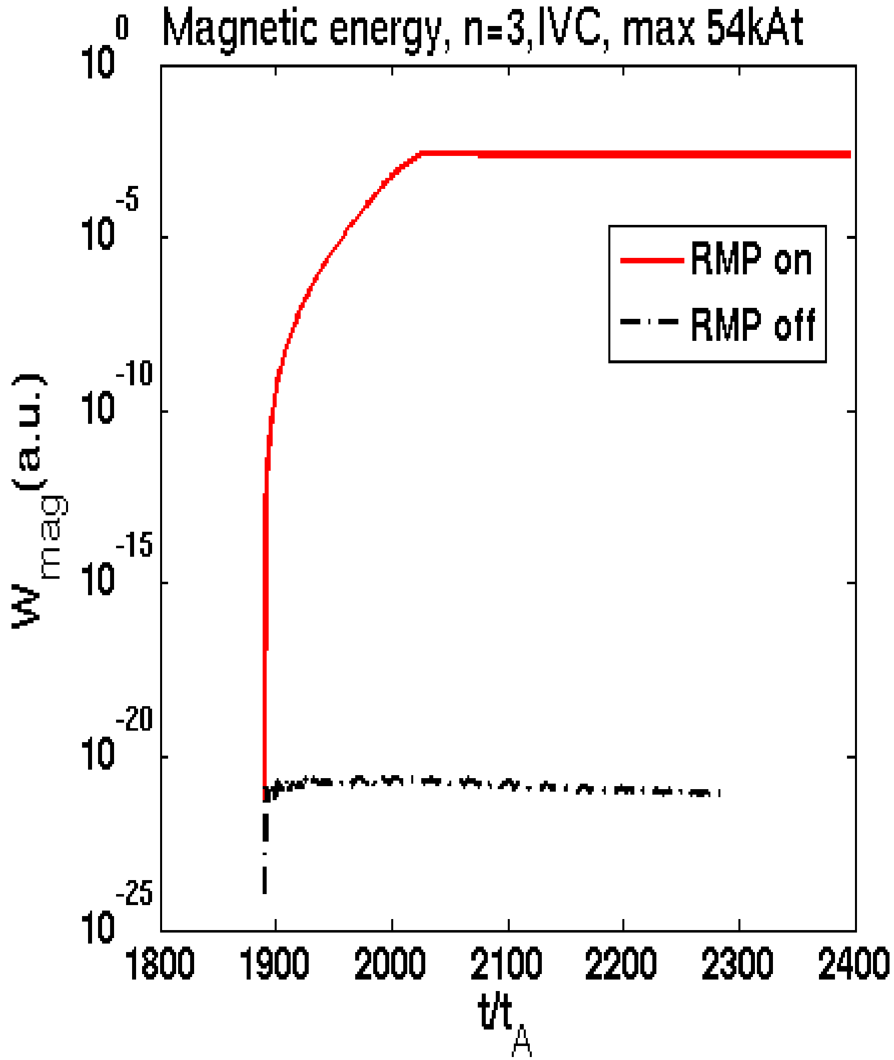


RMPs in ITER. W/o RMPs n=3 is stable. With RMPs =>n=3 static perturbations at the edge.

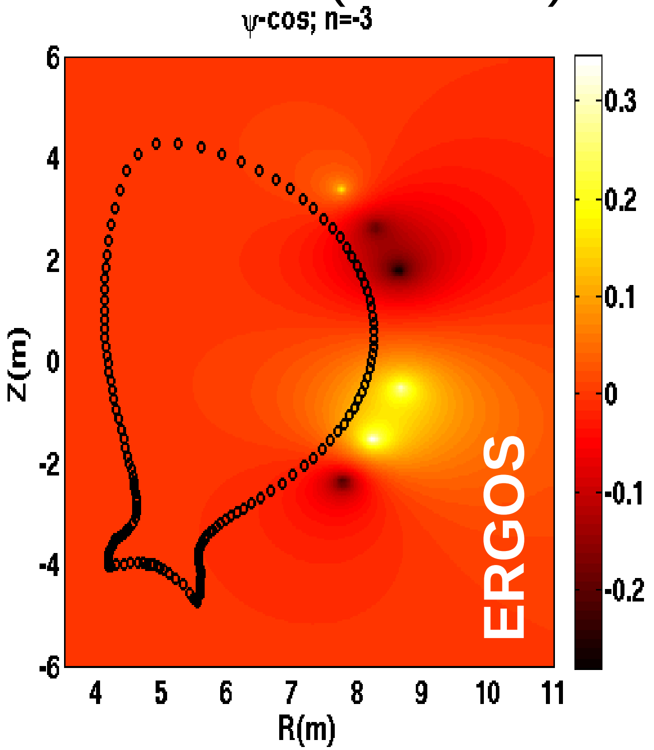
Courtesy to E.Day, M.Schaffer

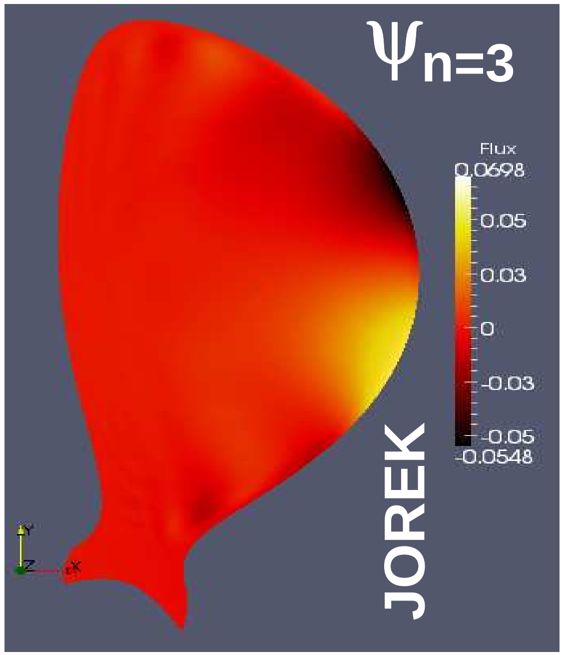


ITER, IVC, max:
I_{coil}=90kAt, n=2,3,4.
Used here n=3, 54kAt.



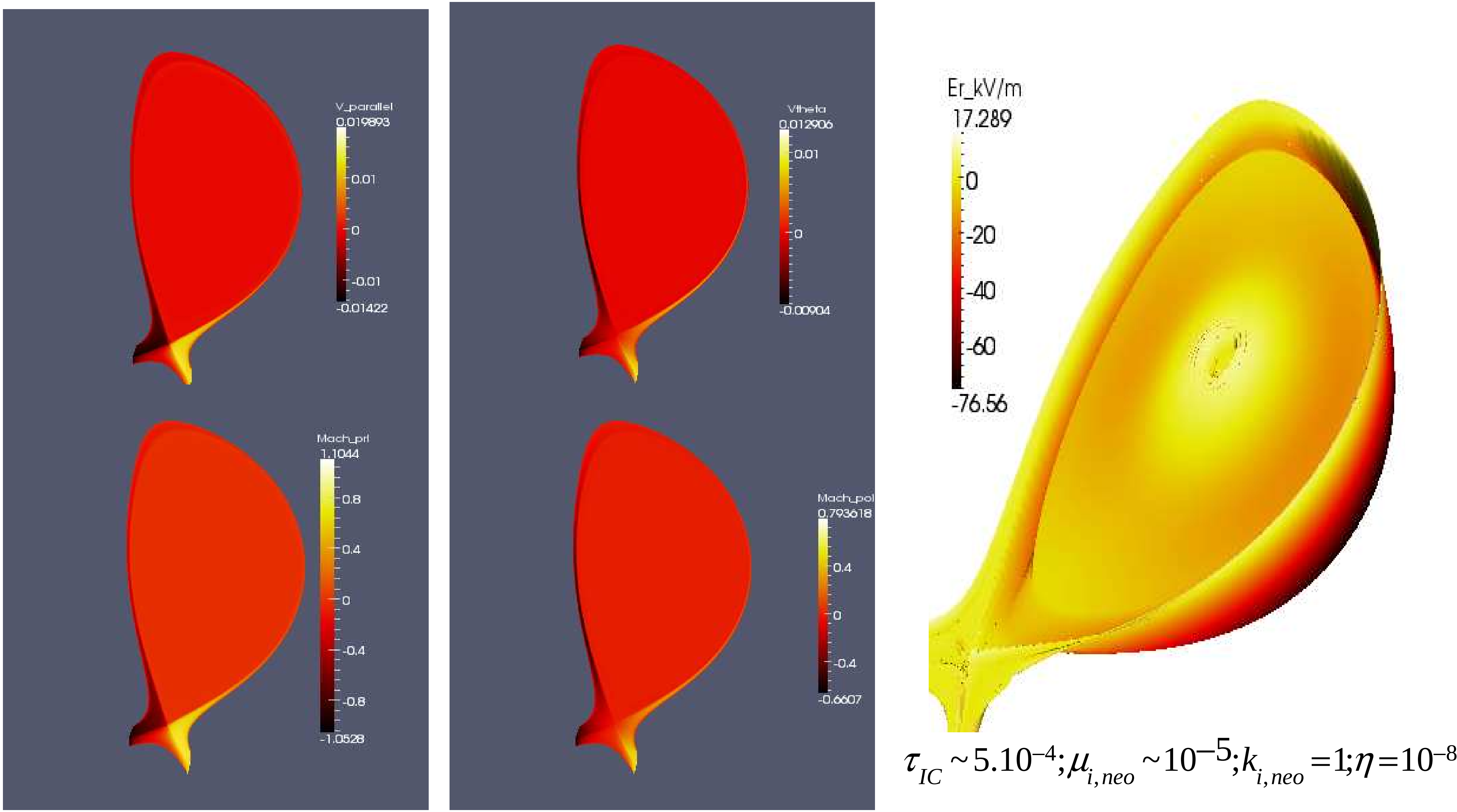
ERGOS (vacuum) =>JOREK boundary



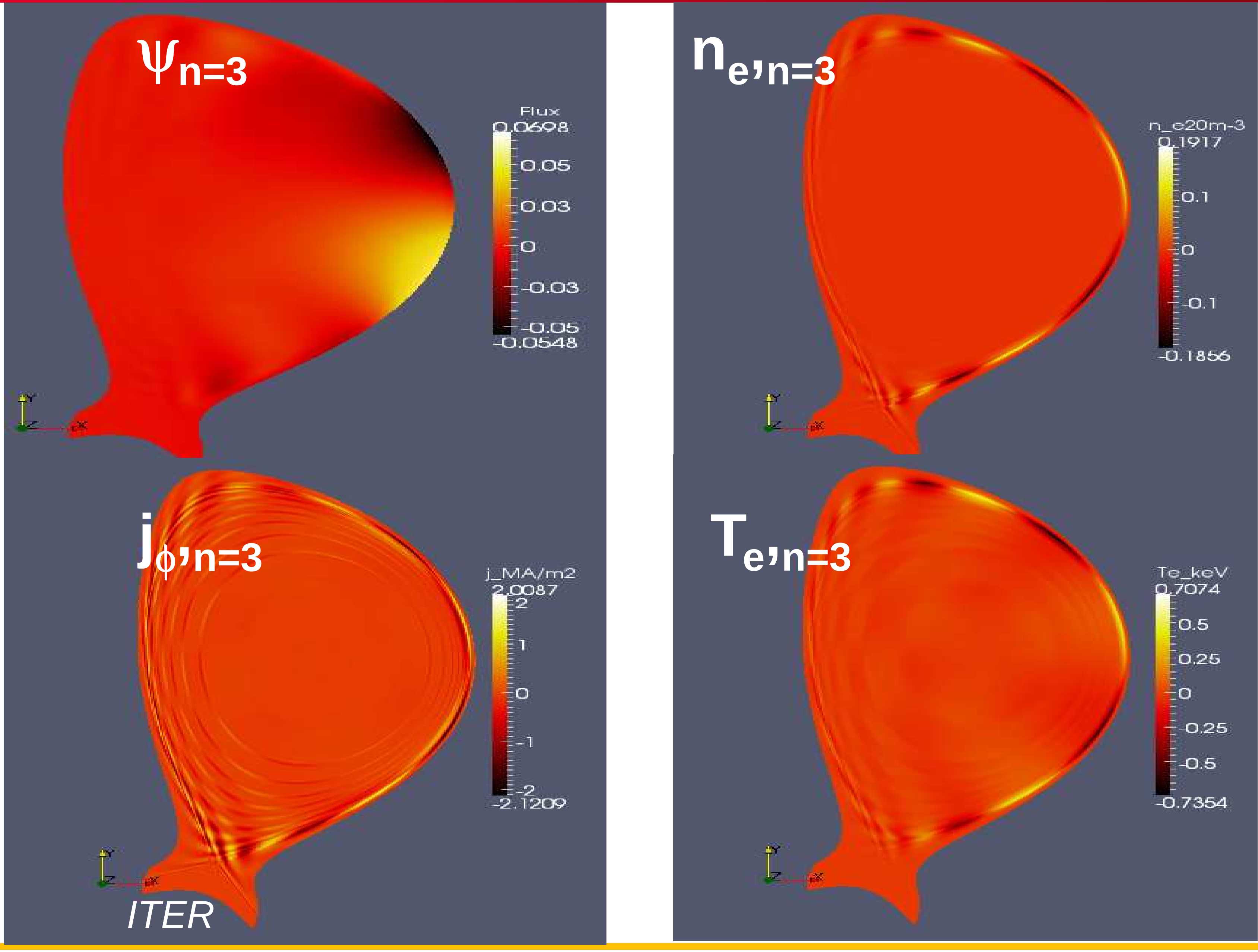


Equilibrium flows and radial electric field in ITER (w/o RMPs)

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

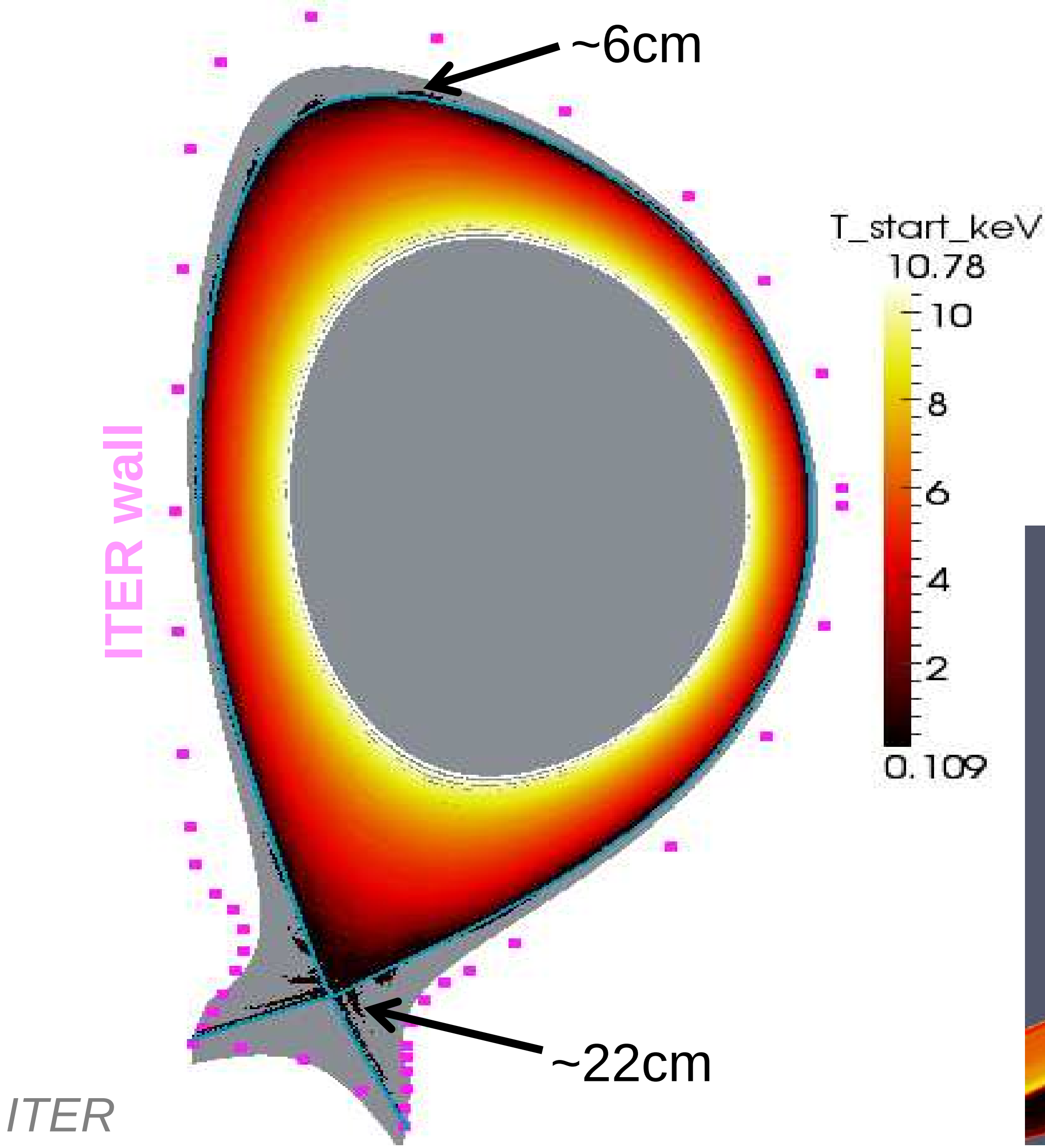


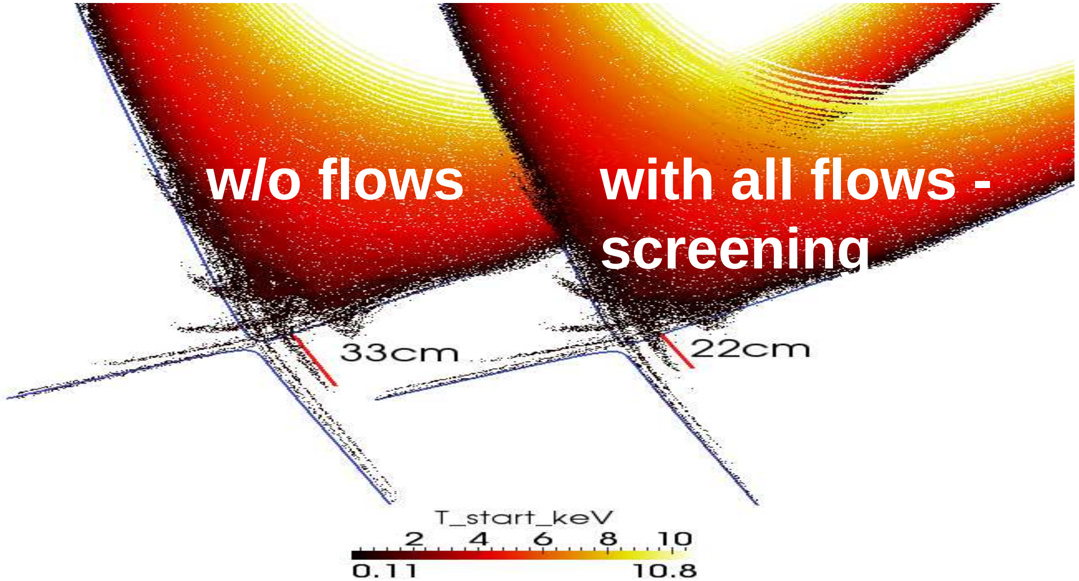
$$\tau_{IC} \sim 5.10^{-4}; \mu_{i,neo} \sim 10^{-5}; k_{i,neo} = 1; \eta = 10^{-8}$$

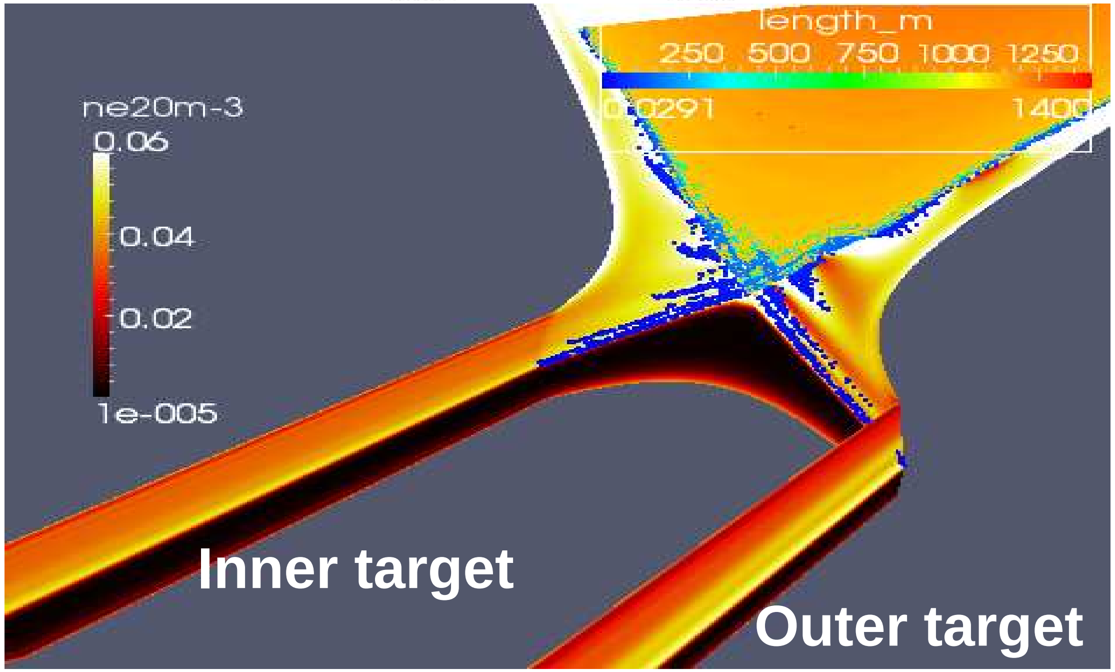


$\psi_{n=3}$
Flux
0.0698
0.05
0.03
0
-0.03
-0.05
-0.0548
$n_{e},_{n=3}$
n_e20m-3
0.1917
0.1
0
-0.1
-0.1856
$j_{\phi},_{n=3}$
j_MA/m2
2.0087
2
1
0
-1
-2
-2.1209
$T_{e},_{n=3}$
Te_keV
0.7074
0.5
0.25
0
-0.25
-0.5
-0.7354
ITER

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

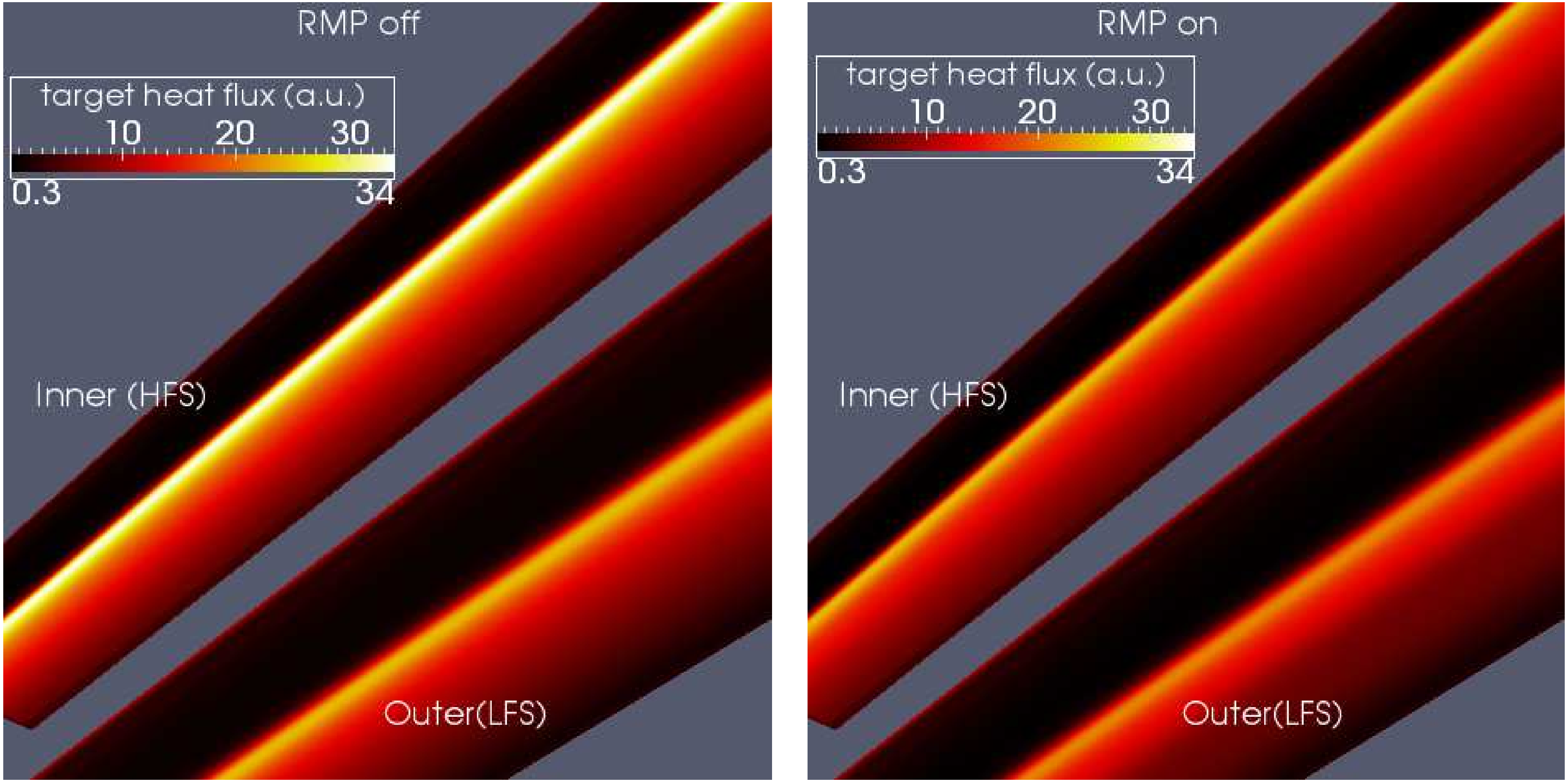






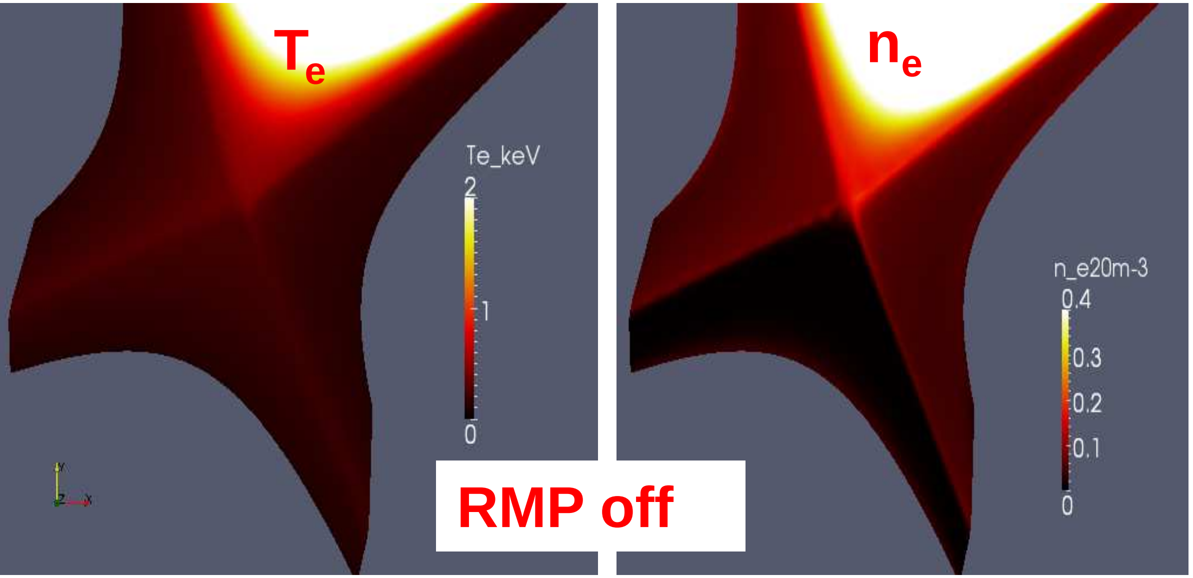
Peak heat fluxes on divertor targets are ~25% reduced (spreading due to ergodisation) with RMPs on.

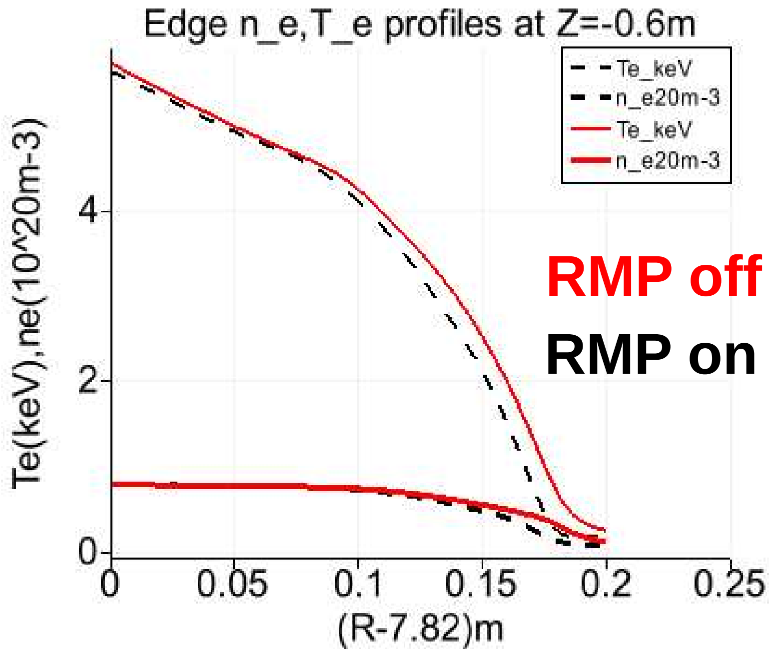
Heat flux on inner and outer divertor targets.

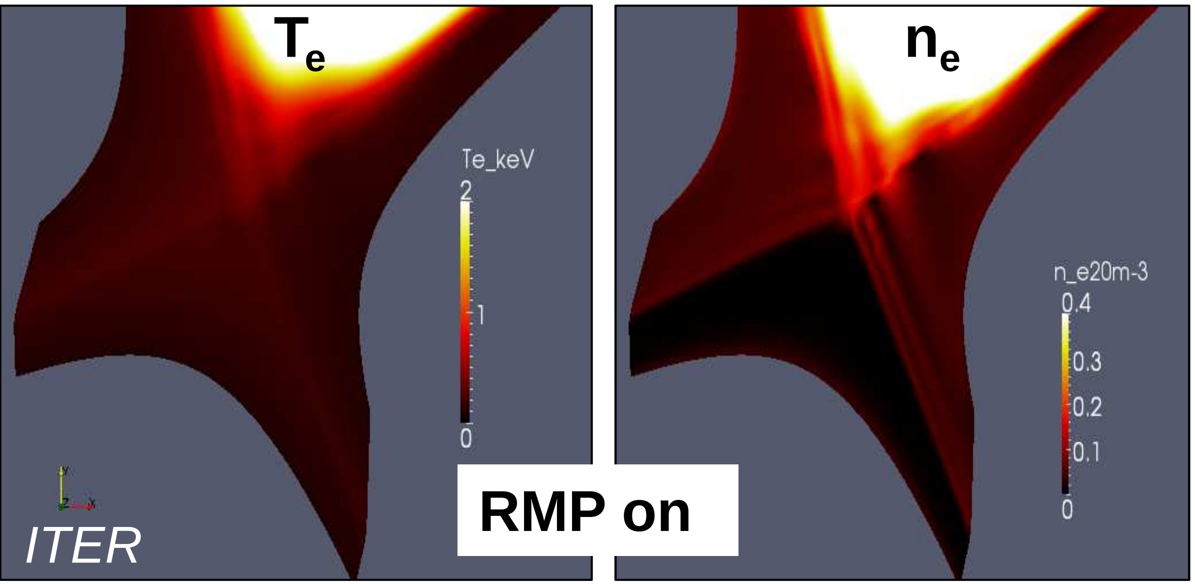


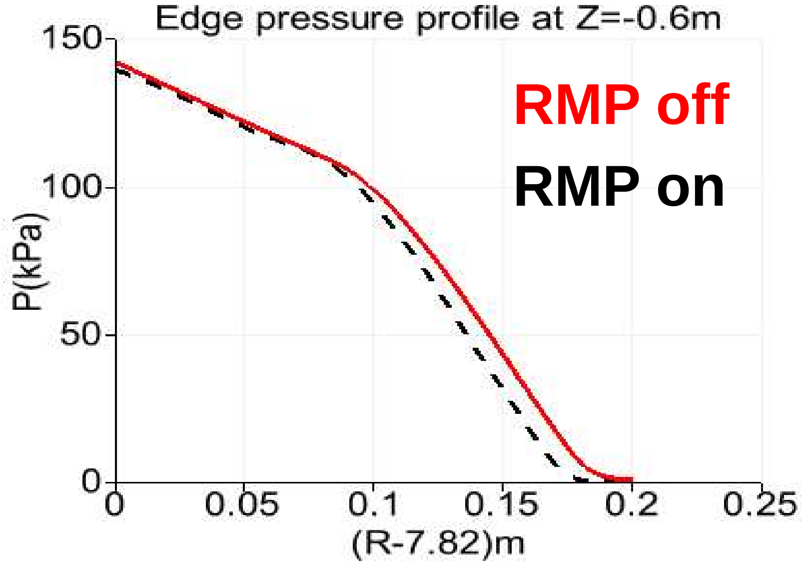
NB! No divertor physics (radiation, ionisation, sources, detachment….) in the model

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

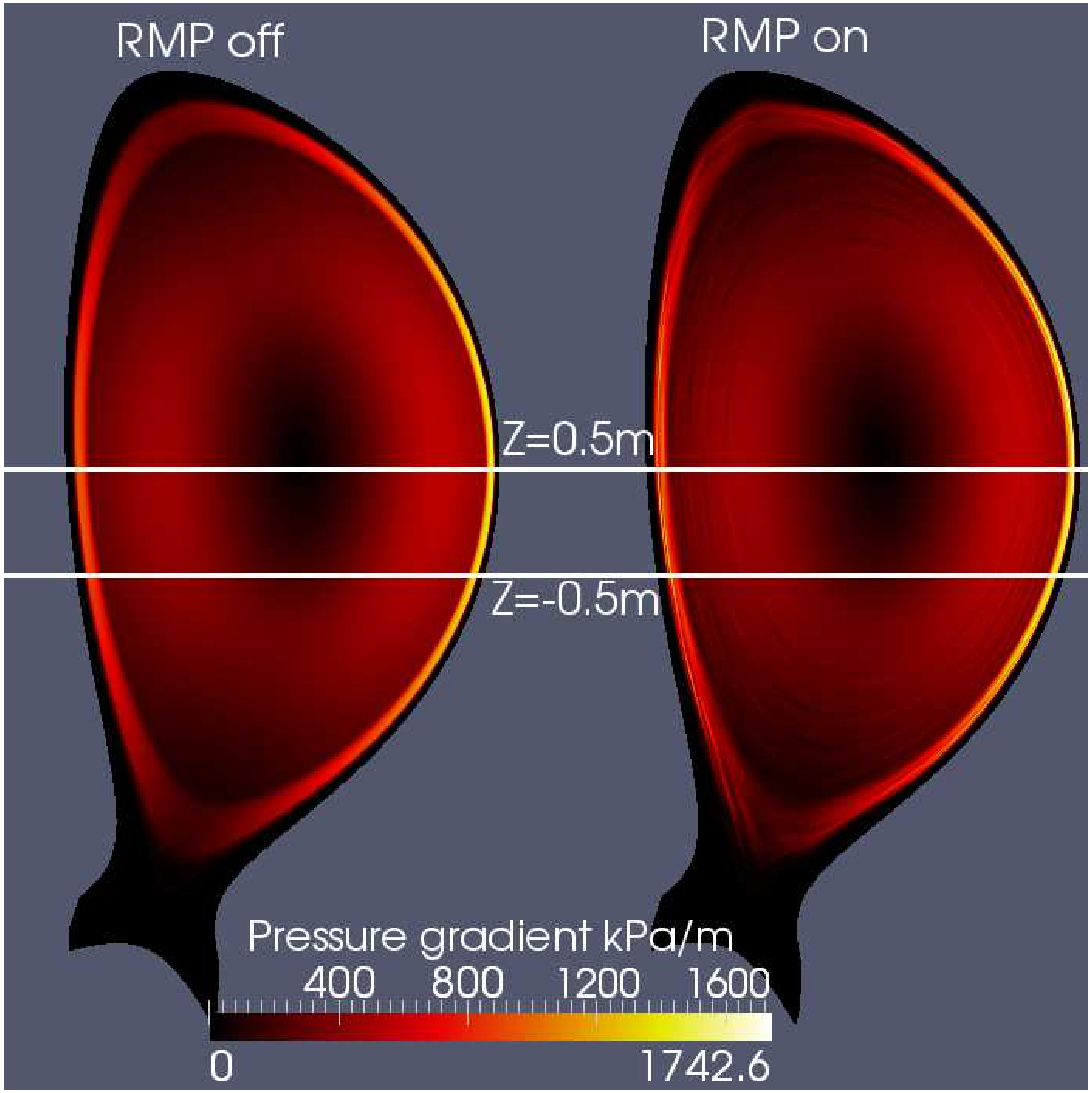


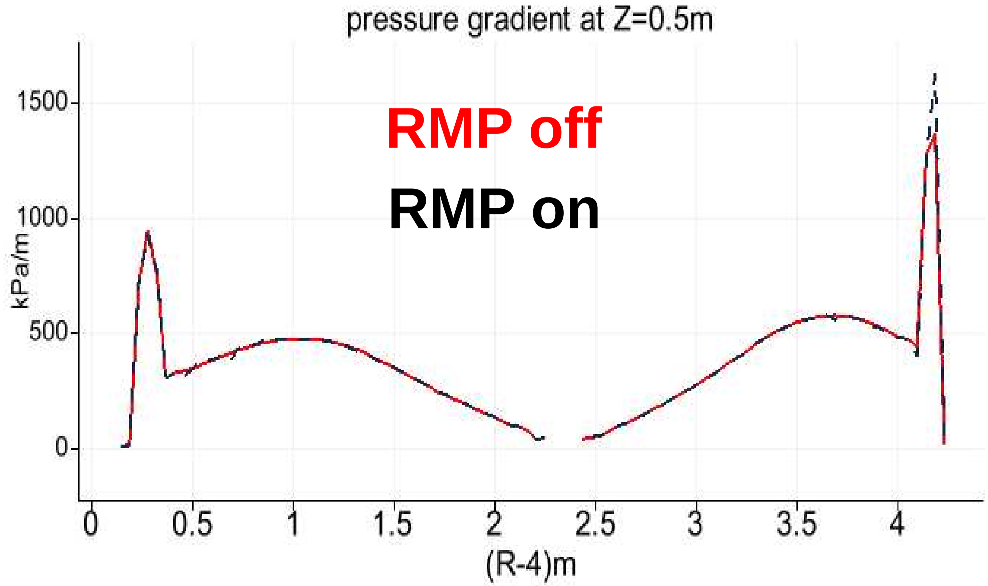


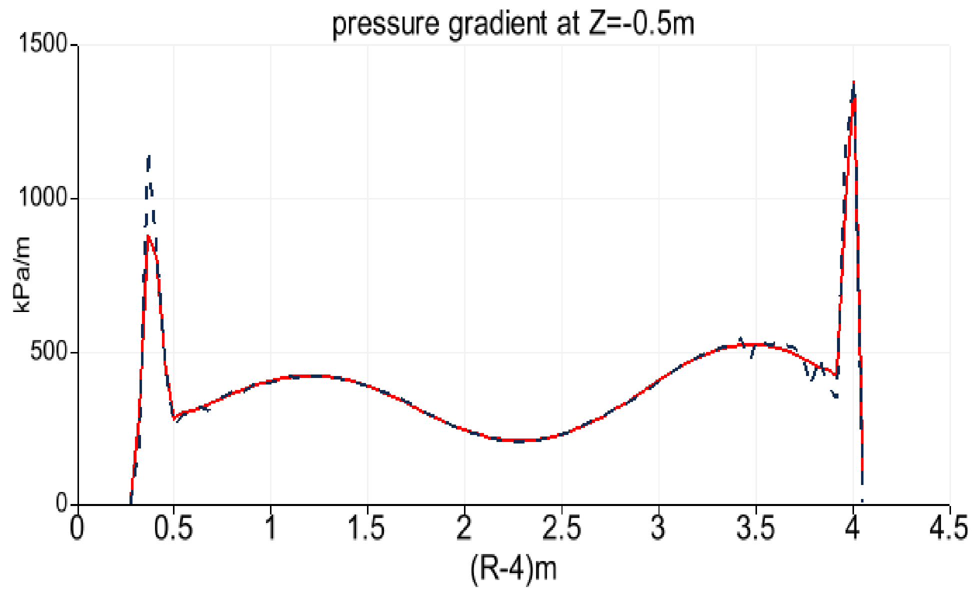




Pressure gradient is 3D, locally could be even steeper with RMP.







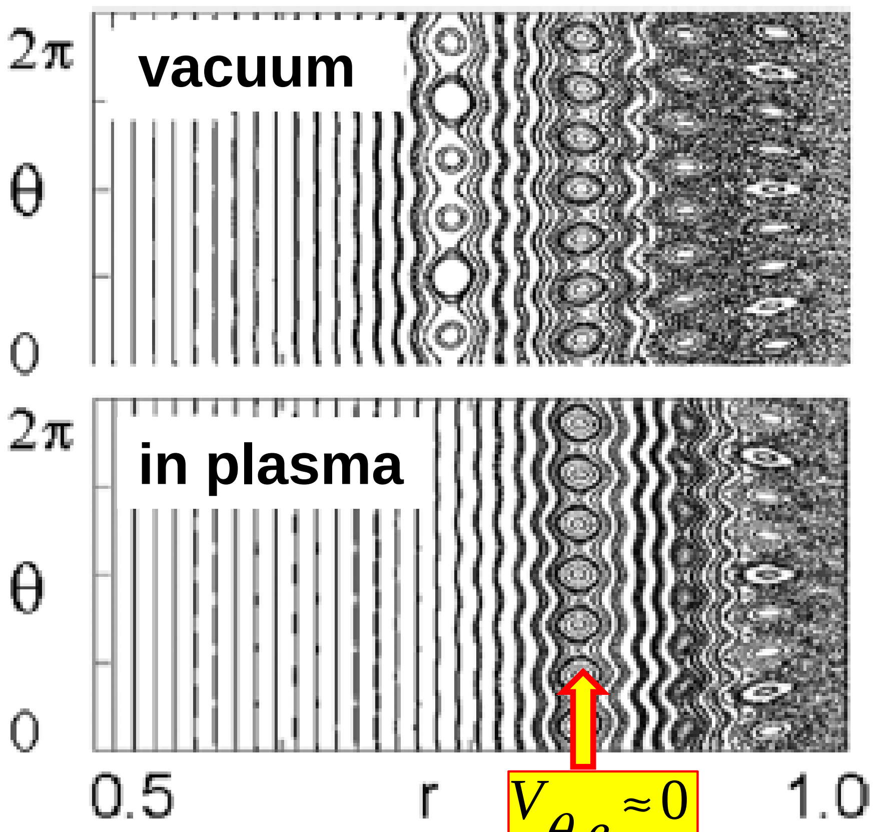
Island is not screened if at q~(m/n) electron poloidal velocity => zero. For ITER parameters: $V_{e,\theta} \neq 0$

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

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

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

DIII-D–like [RMHD: Becoulet NF 2012]

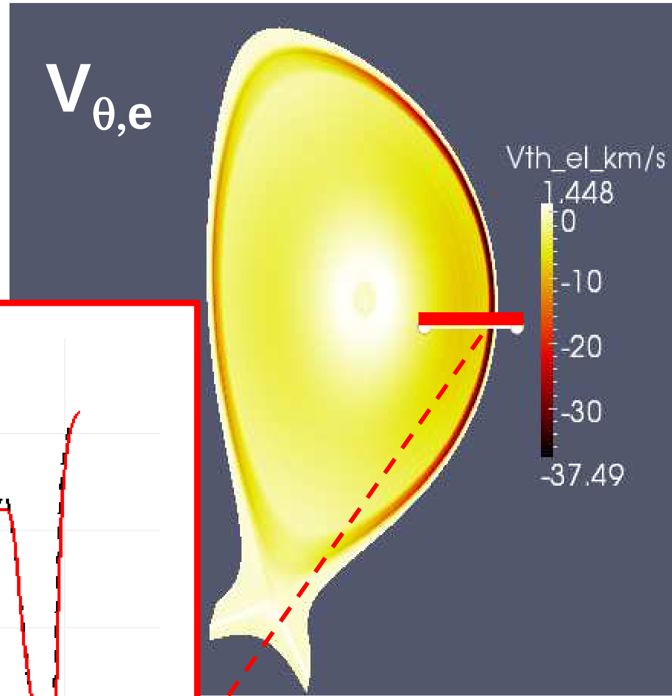


$V_{\theta,e} \approx 0$

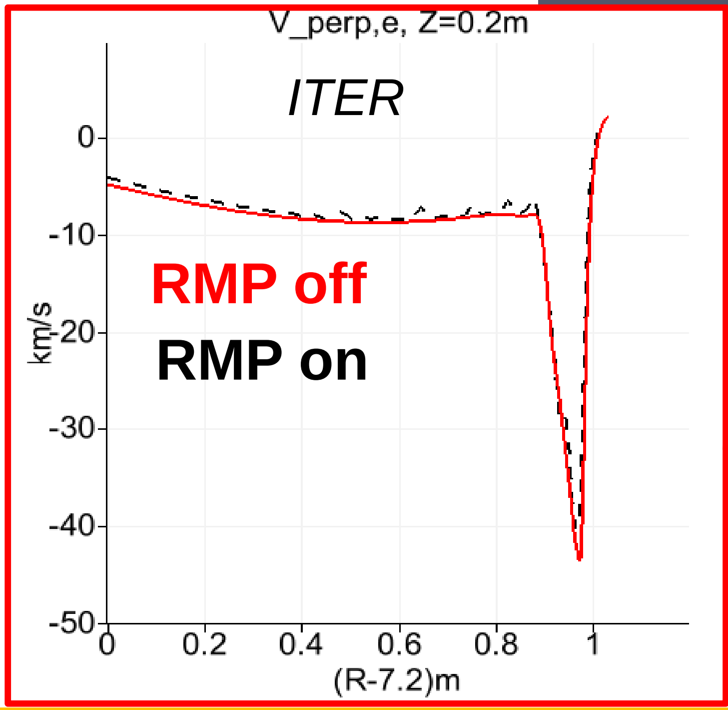
$$V_{\theta,e} = \left[-(\nabla_\perp \psi, \nabla_\perp u) + \tau_{IC}(\nabla_\perp \psi, \nabla_\perp p)/\rho\right]/B_\theta$$

For ITER parameters used here electron poloidal velocity is not zero:

=>screening

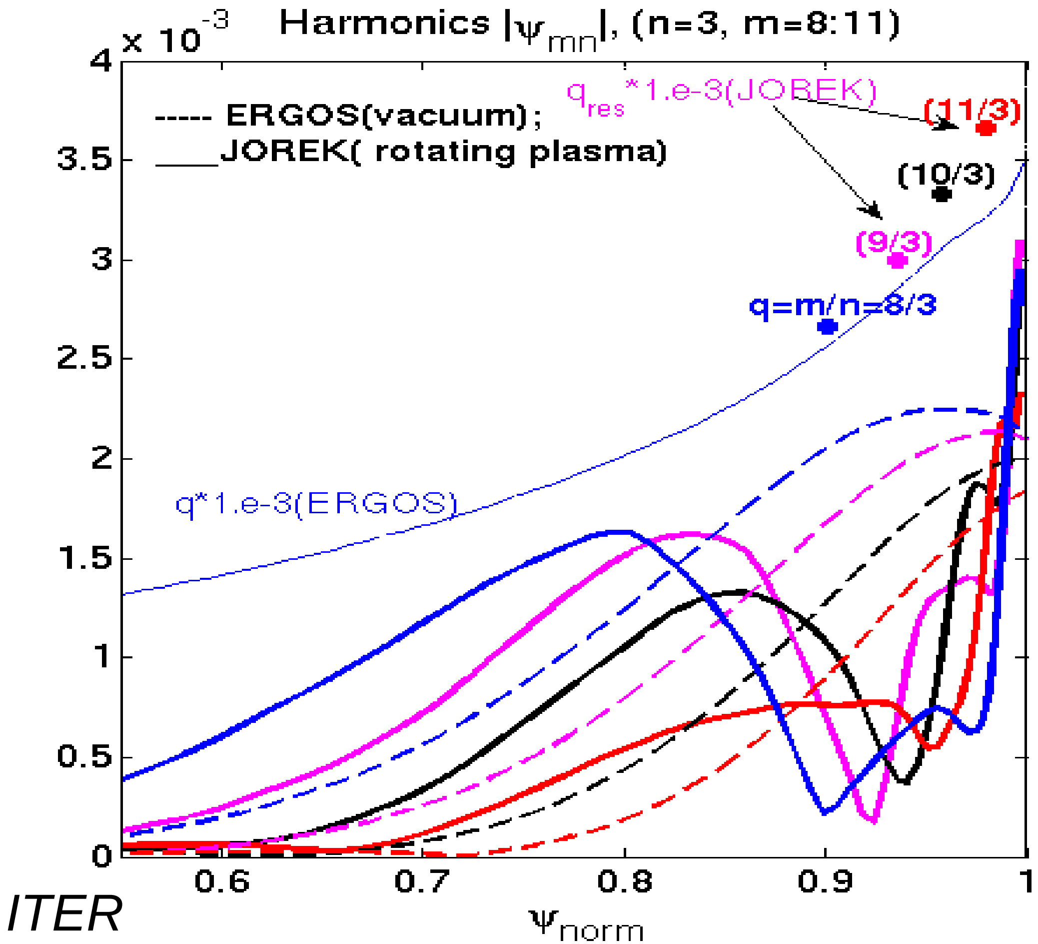


$V_{e,\theta} = V_{E,\theta} + V_e^{dia} \neq 0$

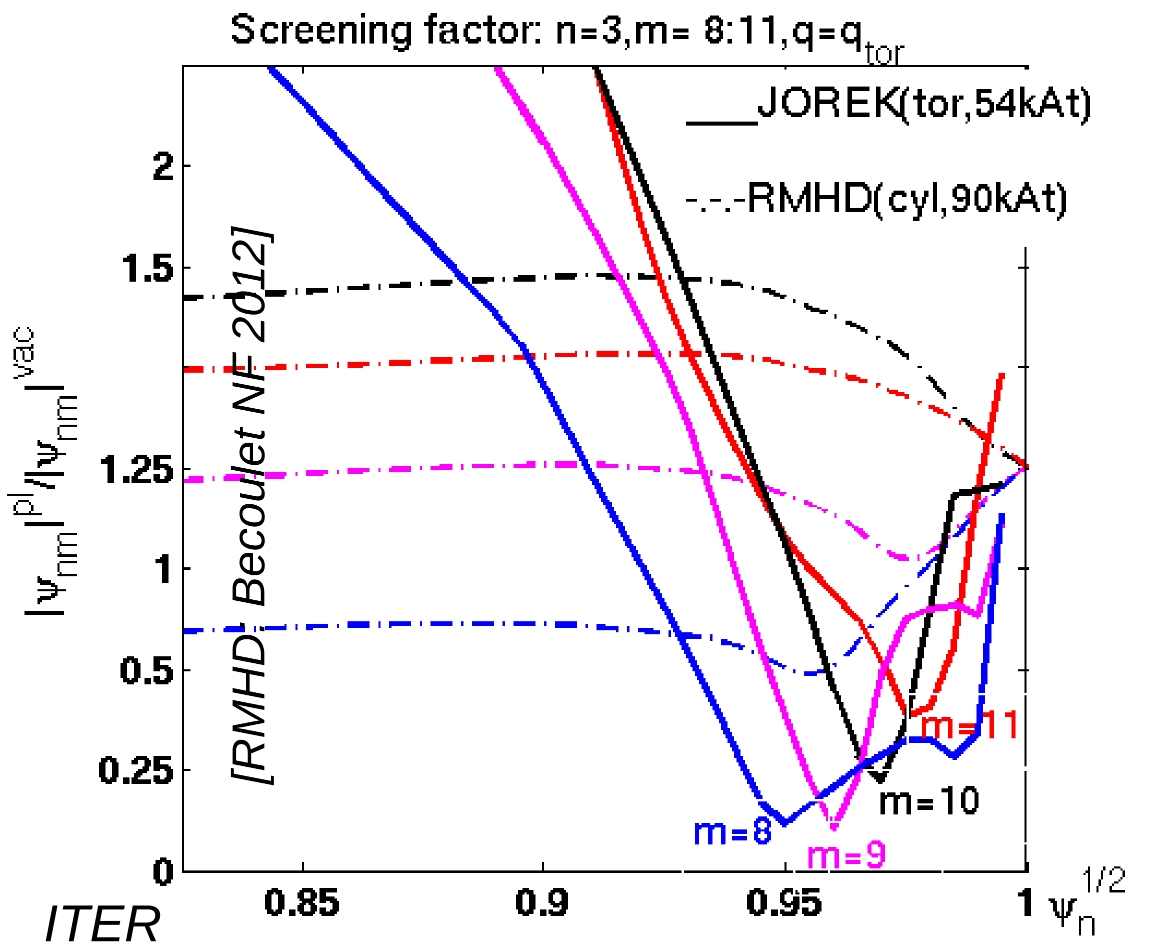


Comparison JOREK&ERGOS(vacuum)&RMHD(cylinder). JOREK (torus, rotating plasma) : RMPs screening on q=m/n (stronger for central islands). Amplification $r<r_{res}$ in JOREK.

- 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 $r<r_{res}$.**

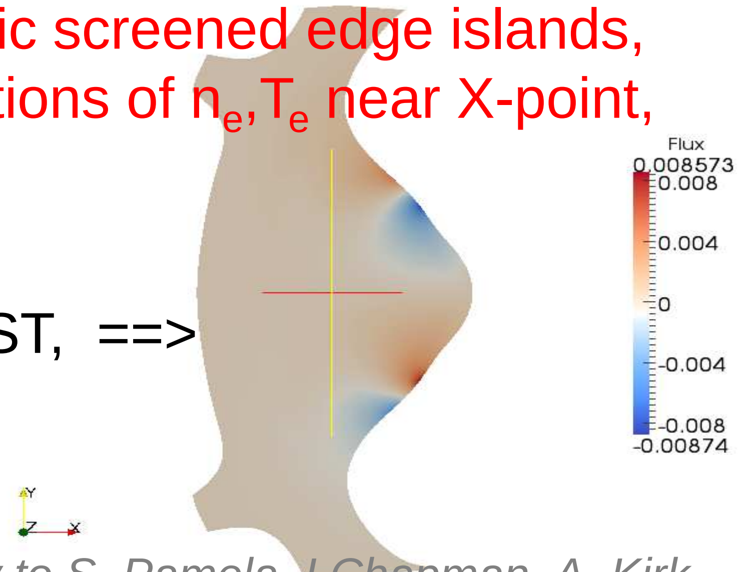


- **Non-linear resistive MHD code JOREK development for RMPs with flows:** RMPs - at the boundary, 2 fluid diamagnetic effects, neoclassical poloidal viscosity, toroidal rotation source, SOL flows.

- **JET-like(n=2).Three regimes:**
  - ✓ high η, small (poloidal) rotation (high ν*?) => oscillating and rotating islands, fluctuations δn_e, δT_e, δψ (t) (~kHz).
  - ✓ low η, higher rotation => static islands, more screening of RMPs.
  - ✓ Intermediate => oscillating, quasi-static islands.

- **RMPs (n=3) in ITER.** Screening of central islands, static screened edge islands, ergodic edge, splitting of strike points (>outer), modulations of n_e,T_e near X-point, small changes in edge profiles.

- **Future:** RMPs interaction with ELMs. Modelling of MAST, ==> JET, AUG…. RMP experiments.



Courtesy to S. Pamela, I.Chapman, A. Kirk