Modelling of RMP related physics in existing machines and predictions for ITER *: ELM suppression , divertor fluxes, fast particle losses, pellets with RMPs, NTV, turbulence*

Presented by Marina Becoulet

Atomic Energy Commission, Institute for Magnetic Fusion Research, France.

on behalf of the JOREK community (http://jorek.eu;)

Outline:

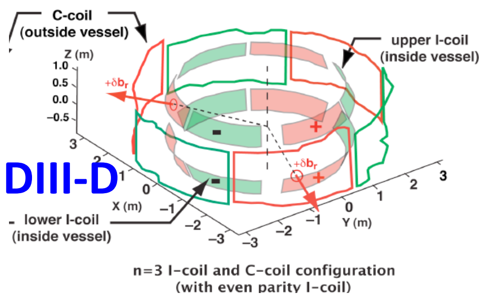
1. **Introduction. ELMs control by RMPs. Experimental observations.**
2. **Modelling of ELMs and ELMs suppression by RMPs:**

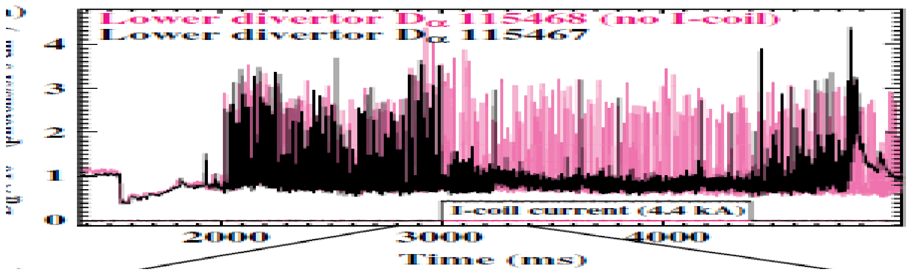
- *Rotating plasma response: screening/amplification.*
- *ELMs suppression criterion with plasma response: external kink is favorable.*
- *ELMs suppression modelling (AUG, DIII-D, KSTAR, EAST, HL2A=>ITER).*
- *3D SOL with RMPs, divertor footprints in ITER.*
- *Compatibility of RMPs with fueling by pellets in ITER without ELM triggering.*
- *Fast particle (alphas, NBI) losses due to RMPs.*
- *Neoclassical Toroidal Viscosity (NTV): pump-out, braking.*
- *Turbulence with RMPs.*

3. **Conclusions.**

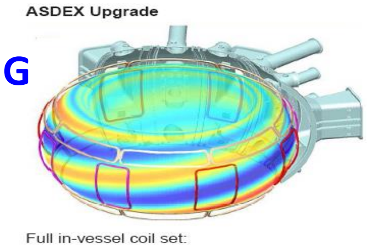
How to control ELMs? Strong mitigation/suppression of ELMs were achieved in different machines using RMP coils (main toroidal numbers N=1,2,3,4). Idea: slightly destroy magnetic surfaces at the edge=>increase edge transport, decrease gradP…

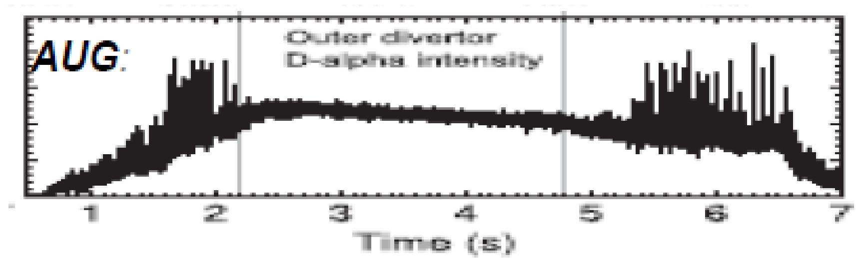
DIII-D



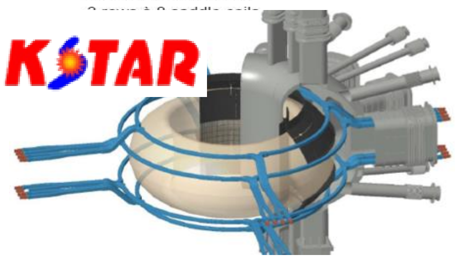


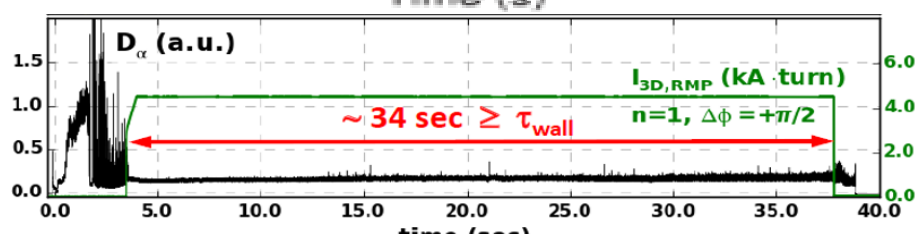
AUG



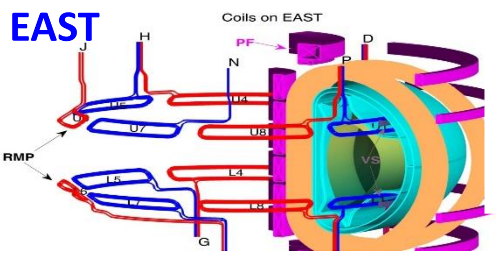


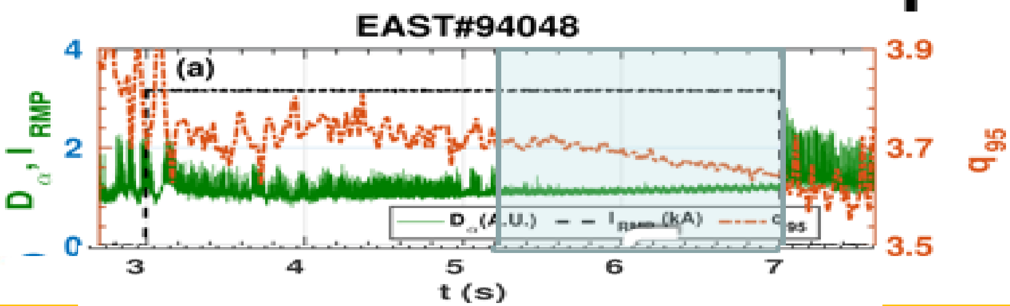
KSTAR





EAST

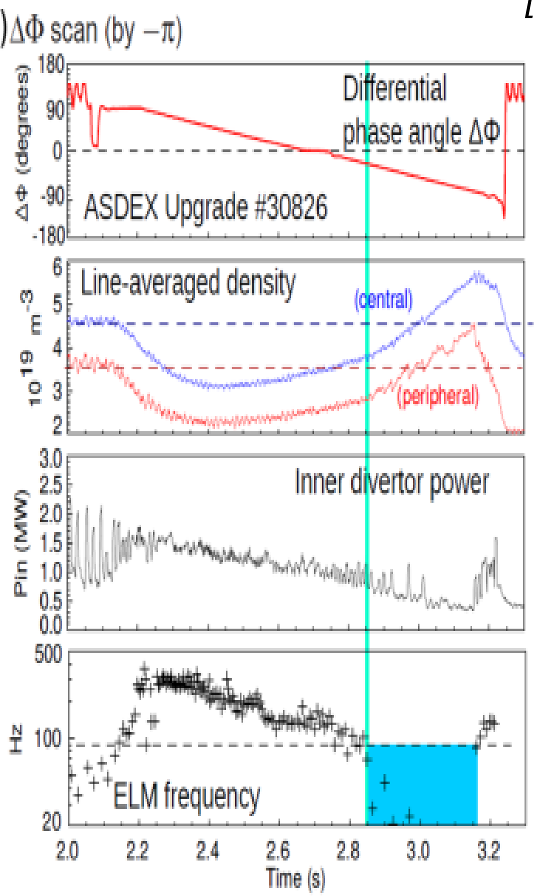




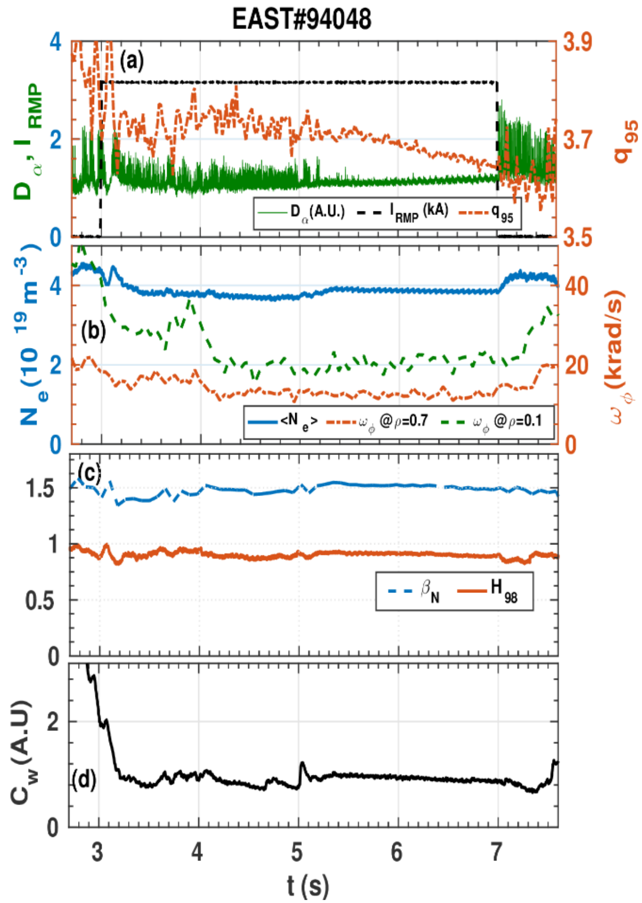
[DIII-D: Evans NF2005, JET: Liang PRL 2007, AUG:Suttrop PRL2011, KSTAR: Lee PRL2016, EAST: Sun, Loarte IAEA2021 etc….]

Generic features with RMP (not all always observed) are not fully explained: ELMs mitigation/ suppression criterion? density decrease (="pump-out")? rotation braking/acceleration? resonant window in q95?…

AUG: RMP N=2, phase scan
[Orain NF2017]



EAST:N=4,q95 scan, low torque, no loss of confinement
[Sun IAEA2021, Jia NF2021]

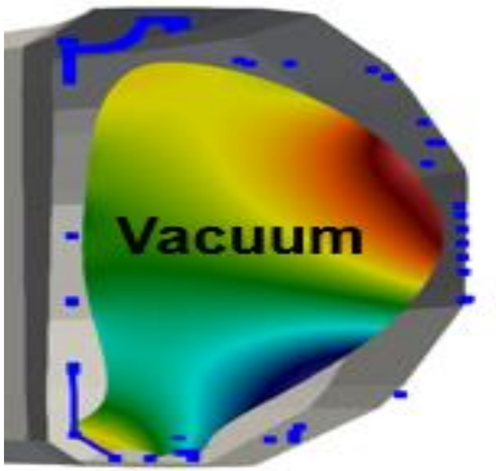


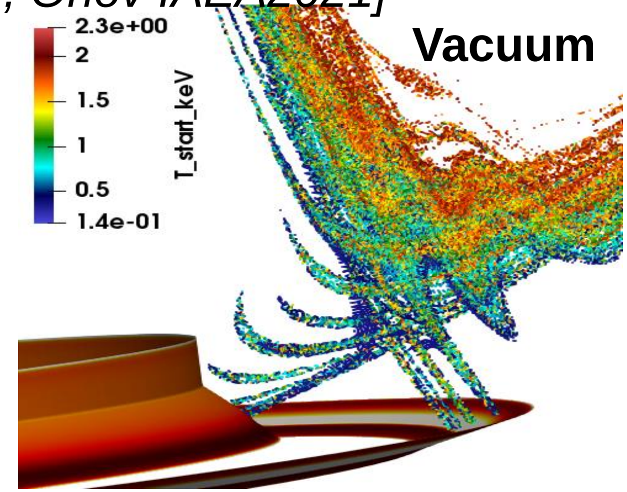
Observations during ELMs mitigation/suppression by RMPs (<u>not always all features!</u>):

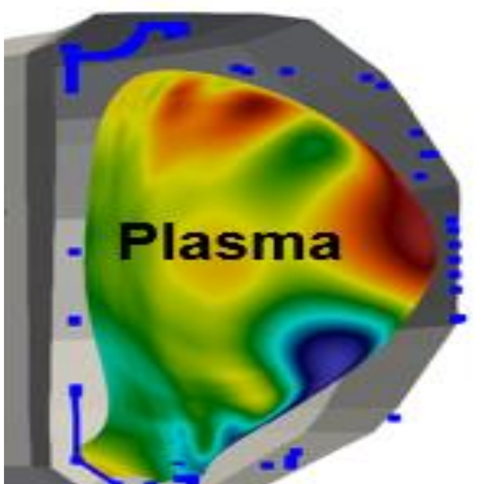
- **RMP amplitude threshold;**
- **density pump-out (not always, see EAST,N=4);**
- **degradation of confinement (0-20%);**
- **global toroidal rotation braking, edge acceleration;**
- **optimum RMP coils phase;**
- **q95 resonant window;**
- **« lobes » near X-point =>splitting of strike points=> footprints in divertor.**

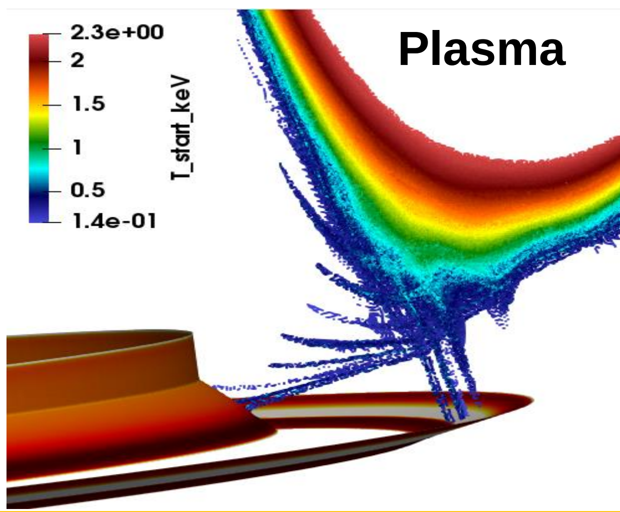
Non-linear resistive two fluid (el+ions) MHD (JOREK) in realistic geometry with SOL and diveror +wall shape. With RMPs: current perturbations on q=m/n=> screening (mainly)of RMPs. At the edge=>less screening at higher resistivity (since lower temperature).

[DIII-D, Becoulet EPS2019, Orlov IAEA2021]

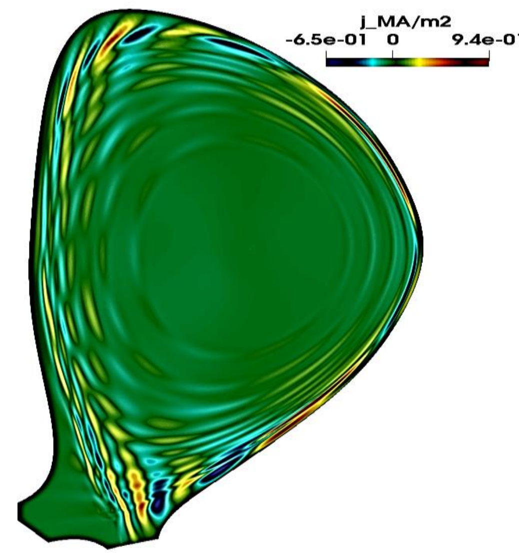




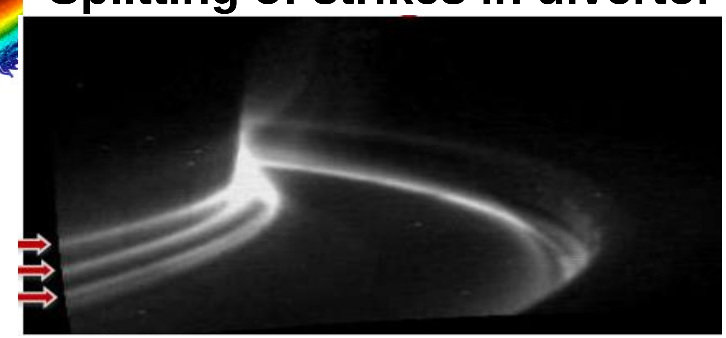




Response currents on rational surfaces q=m/n=>screening



Splitting of strikes in divertor



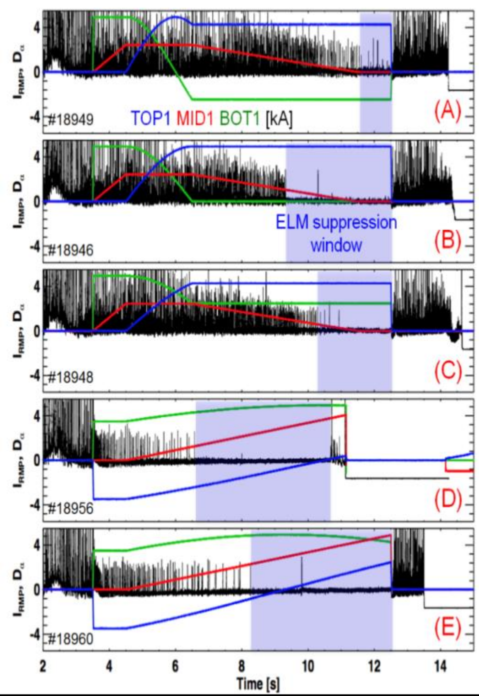
Not only screening! Ideal &resistive MHD+ experiment : edge kink-peeling response is needed for ELM suppression. It can be achieved by optimizing RMP coils phasing or change of safety factor profile (q95).

Maximum kink response is favorable for edge harmonics amplification and ELM suppression, but linear MHD doesn't explain why ELMs are suppressed? Non-linear modelling of ELMs with RMPs is needed (see next!).

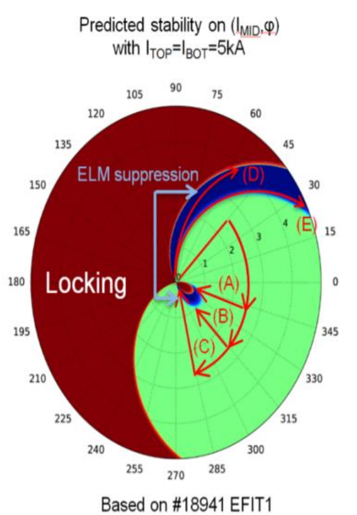
[KSTAR, JK Park Nature Phys 2018]

[Y.Q.Liu PPCF 2016, IAEA FEC 2021]

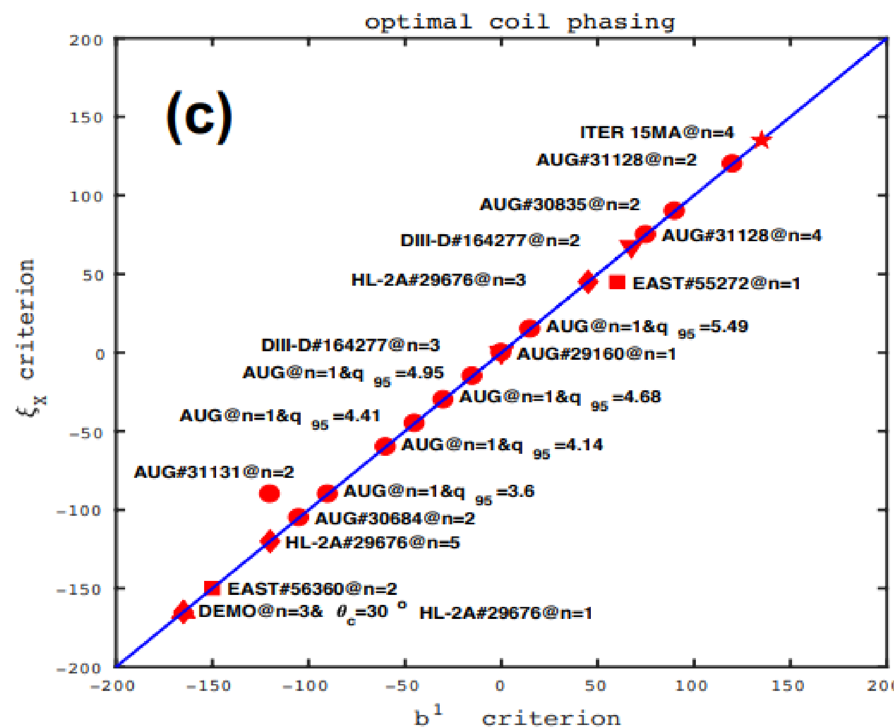
Ideal MHD (IPEC)



- Ideal plasma response for edge and core is the key to RMP coupling prediction – enabling sophisticated validation of ELM supp. windows



Resstive linear MHD (MARS-F)



Modelling (JOREK) of ELM suppression in AUG with phasing +90° (kink response), mitigation with phasing -90° at the same current in RMP coils 6kAt., N=2.

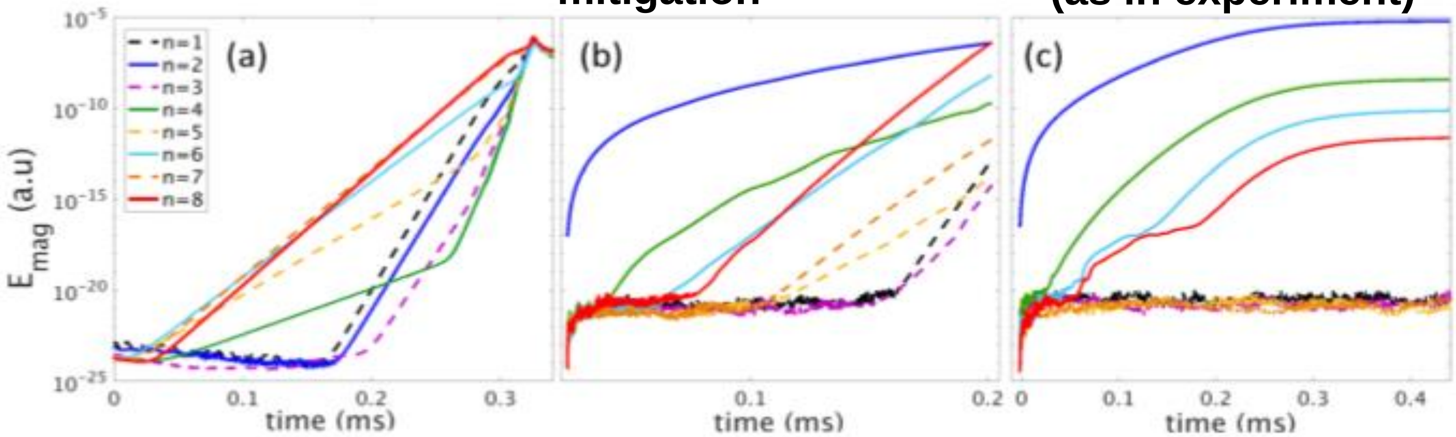
[AUG Orain Phys. Plasmas 2019]

Similar results for KSTAR, EAST, HL2A

w/o RMP=>ELMs

RMP N=2, 6kAt, non-resonant (ΔΦ=-90°) - mitigation

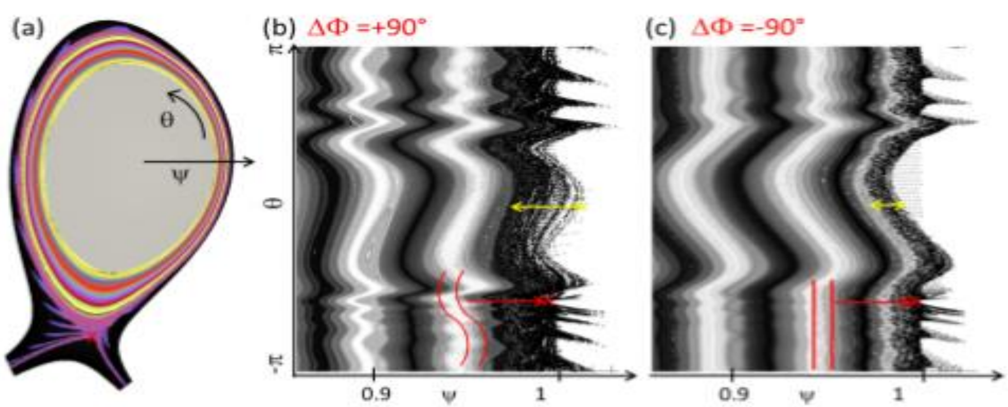
RMP N=2, 6kAt, resonant (ΔΦ=+90°) – external kink response, suppression (as in experiment)

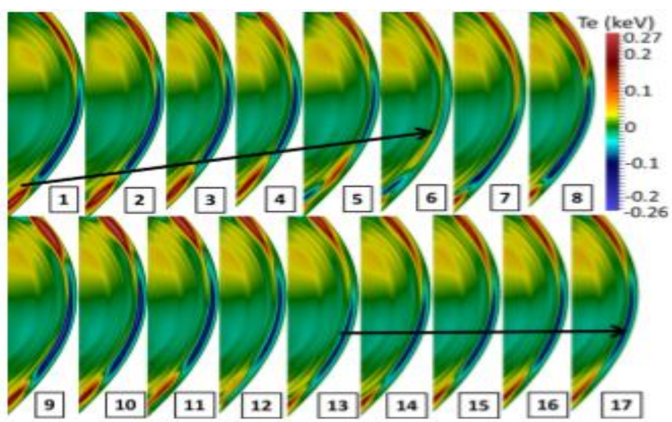


N=2(RMP)
N=4
N=6
N=8
(non-linearly coupled to N=2)

Other harmonics - noise level, no ELMs

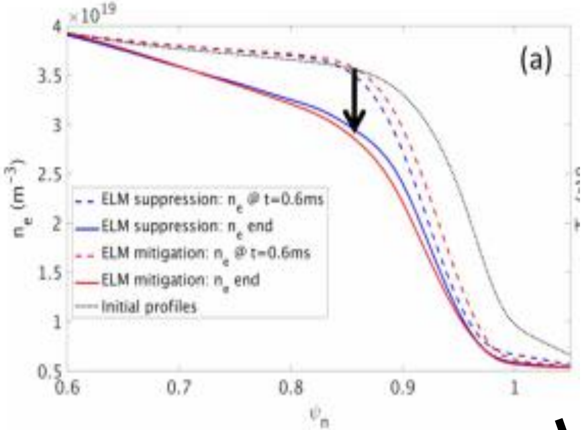
<u>Kink response when ELM suppression</u> (+90°) **Modes rotation locking when ELMs suppression**



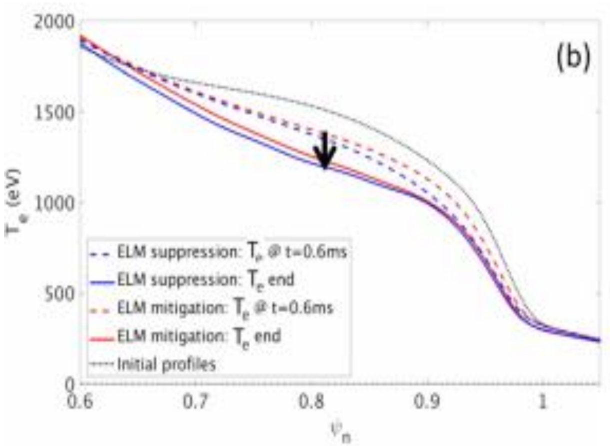


With RMPs: density decreases (convection ExB), electron temperature (parallel conduction), radial electric field 'well' decreases in the pedestal, braking of perpendicular electron rotation on the pedestal top=> less screening of RMPs, islands when ExB , Vel,perp~0

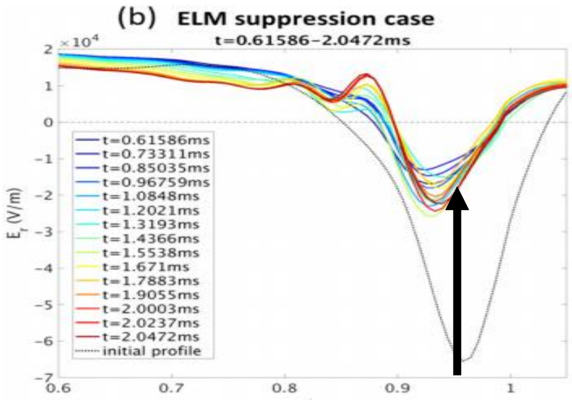
electron density (ExB)



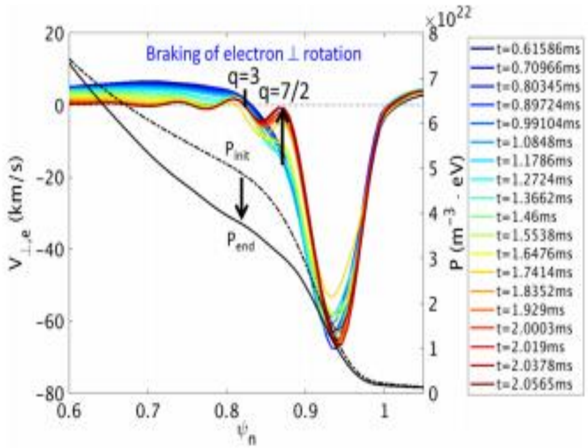
electron temperature



radial electric field well and ExB rotation

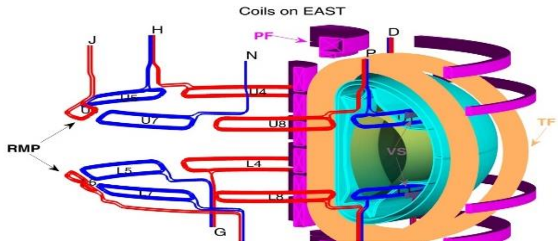


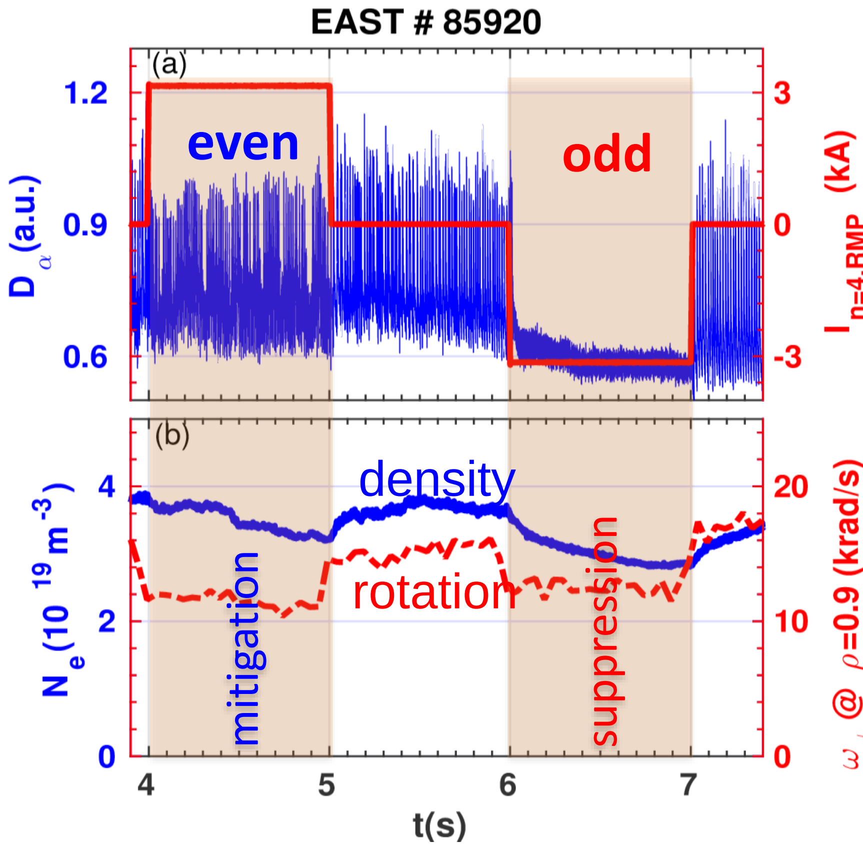
perp. electron rotation (no screening when ~zero)

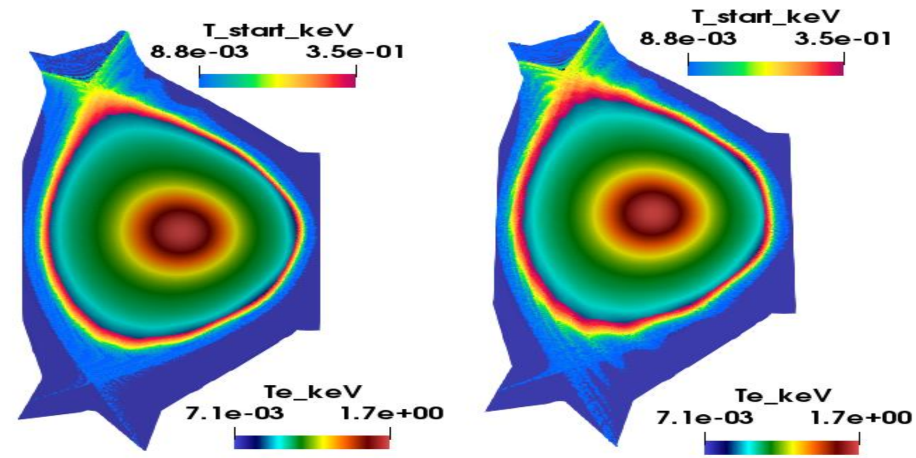


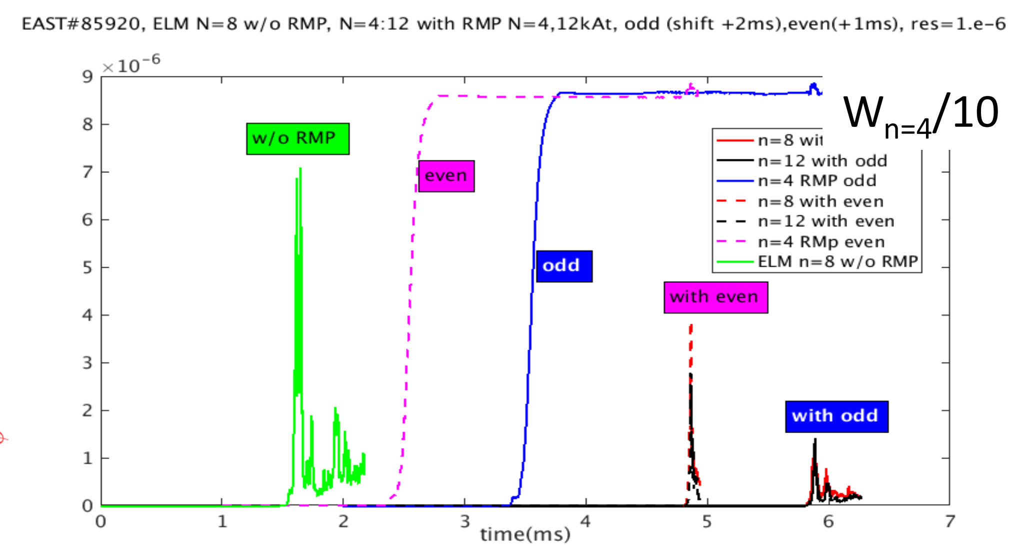
[AUG Orain Phys. Plasmas 2019]

Modelling of ELM mitigation by RMP N=4, 12kAt in odd parity, not in even. External kink response, larger lobes with odd phasing of RMP coils









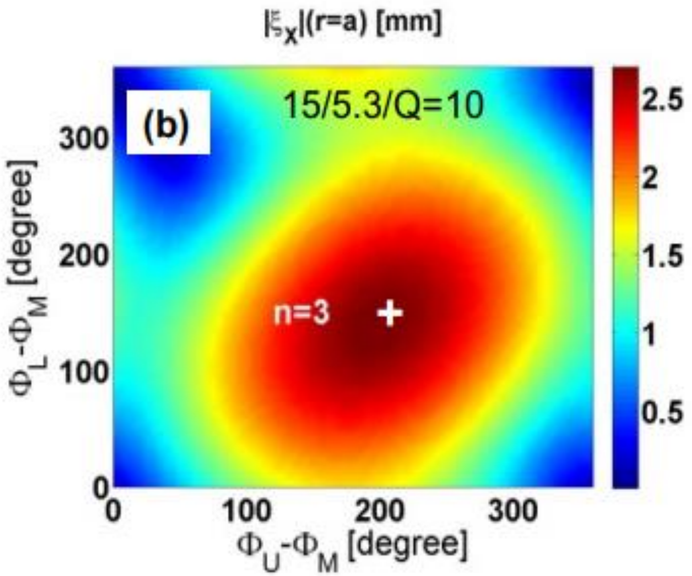
After validation of codes in existing experiments=>predictions for ITER. Non-linear resistive MHD modelling (JOREK) of ELMs suppression by RMPs in different ITER scenarios 15MA, 12.5MA, 10MA/5.3T.

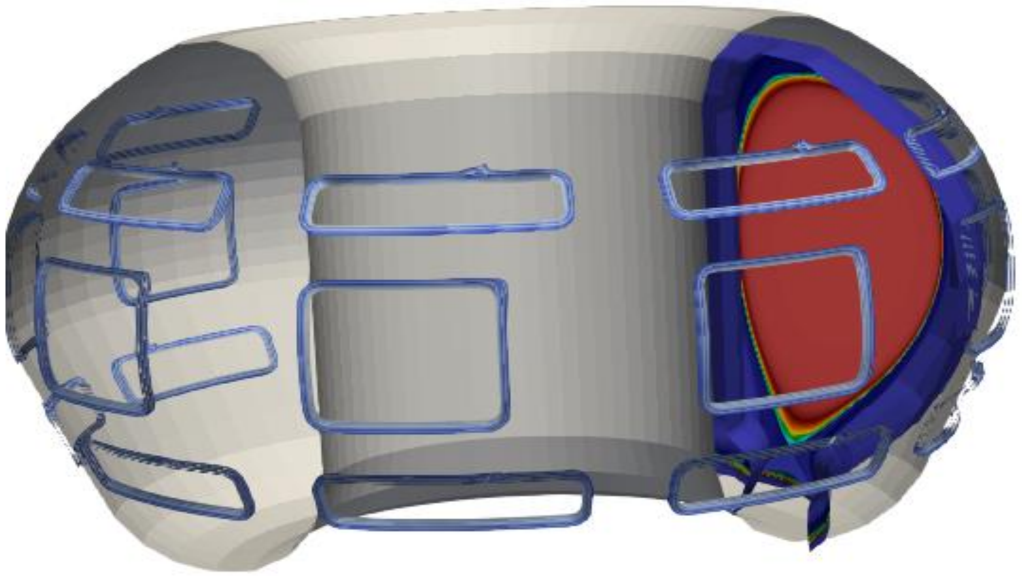
[Contract IO/19/CT/ 4300001841, Y Q Liu , M Becoulet IAEA FEC 2021]

Optimisation of spectrum (N) and phasing of RMP coils for maximum kink response near X-point in each ITER scenario was done by MARS-F (resistive, linear MHD single fluid, no X-point)

Vacuum RMP fields are applied at the computational boundary of the JOREK code Realistic ITER geometry(X-point, SOL, divertor, wall), realistic RMP coils. Resistive non-linear MHD, two fluid diamagnetic effects, toroidal rotation, multi-harmonics.

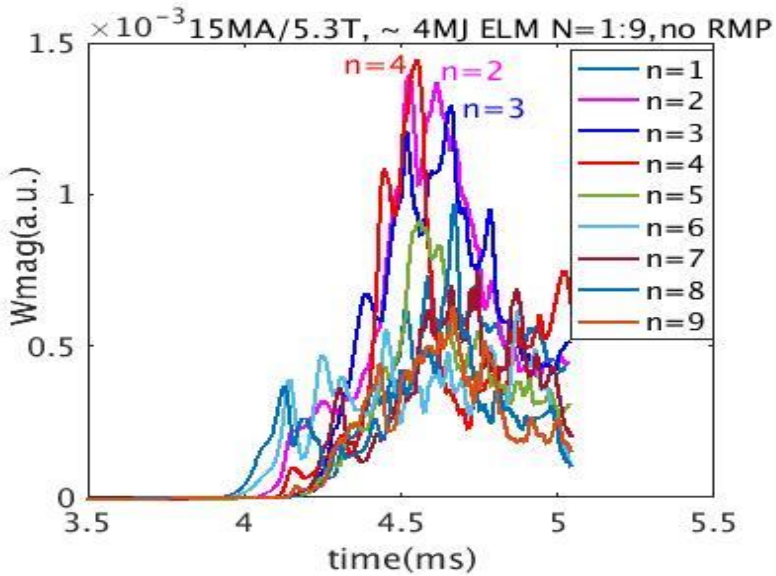
ITER: 3 rows of 9 in-vessel RMP coils, max 90kAt.

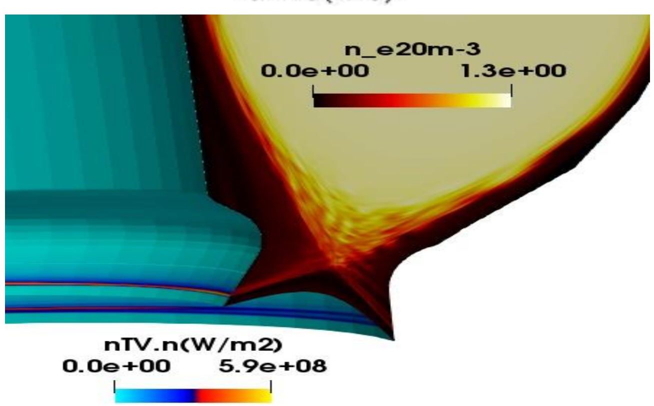




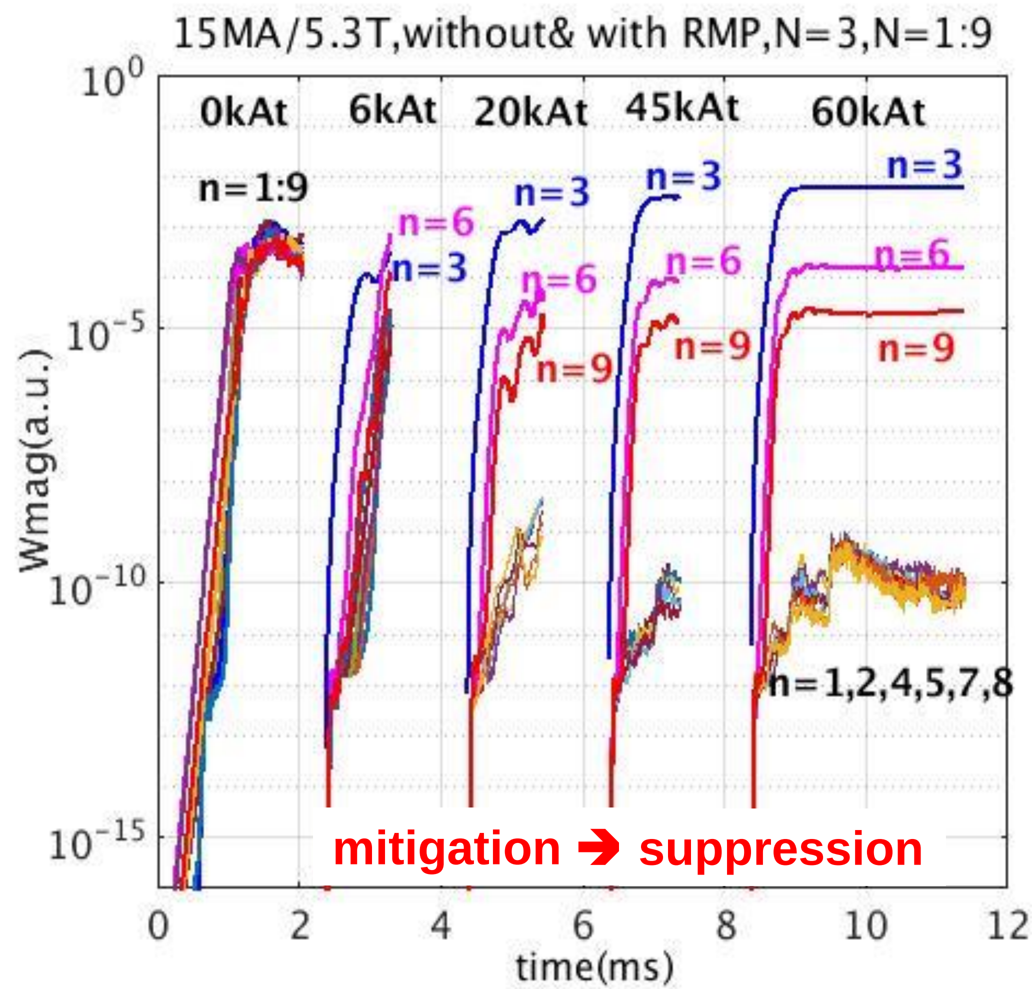
Modelling of ELMs suppression in ITER 15MA/5.3T. Threshold for RMP N=3 , >45kAt

Natural ELM (15MA/5.3T)

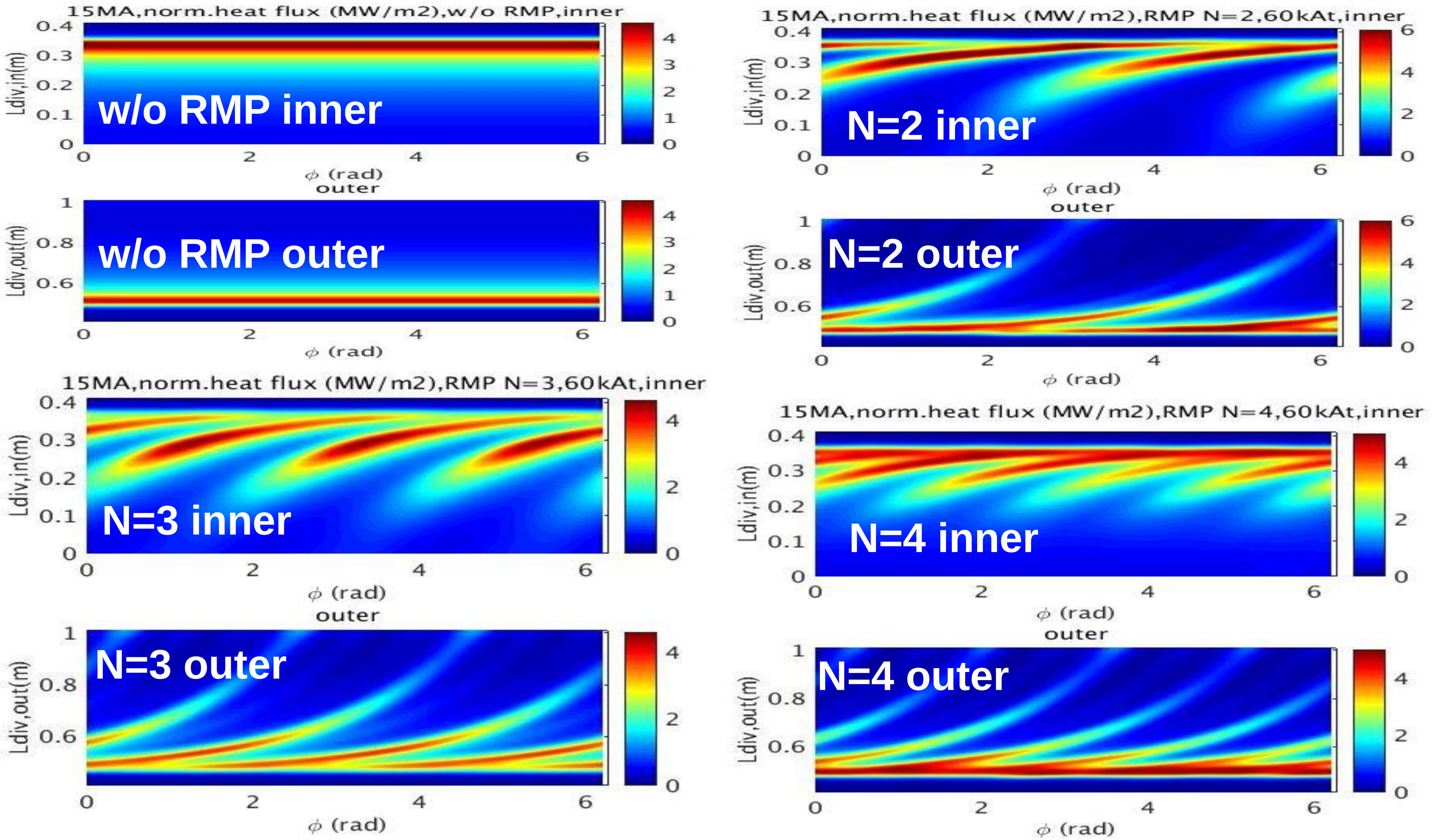




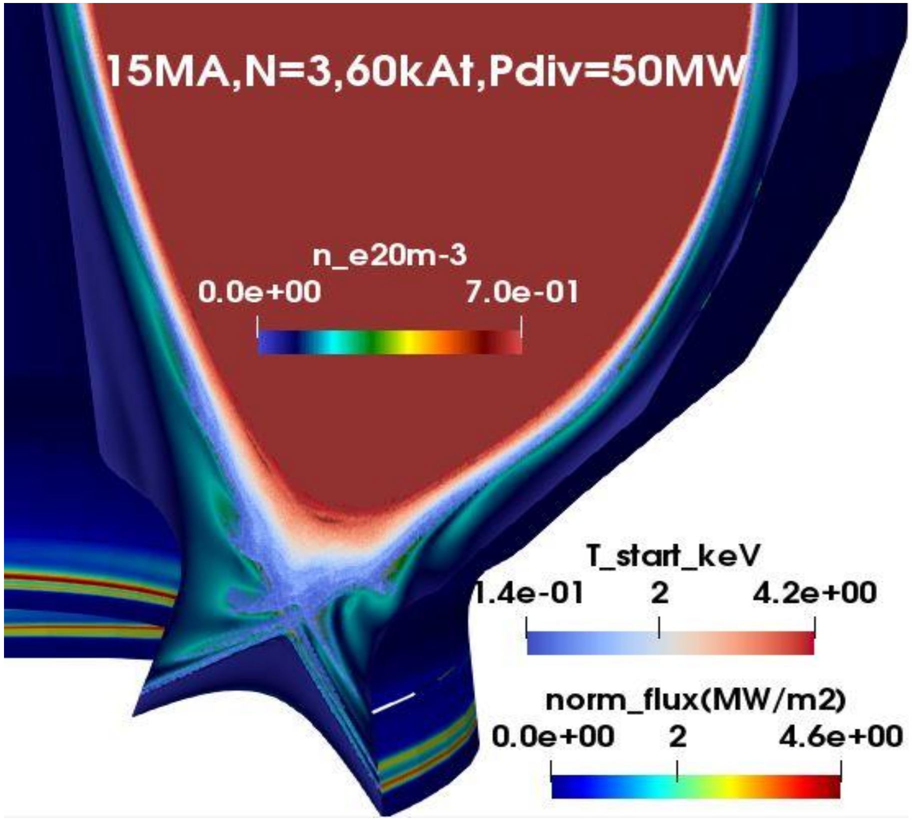
ELMs are suppressed for I_{RMP}>45kAt



15MA/5.3T, RMP N=2,3,4 60kAt. 3D SOL. Normalized stationary heat flux (50MW in divertor). Toroidal splitting with N of RMPs, radial extension is ~20 cm inner divertor and ~40cm in outer.

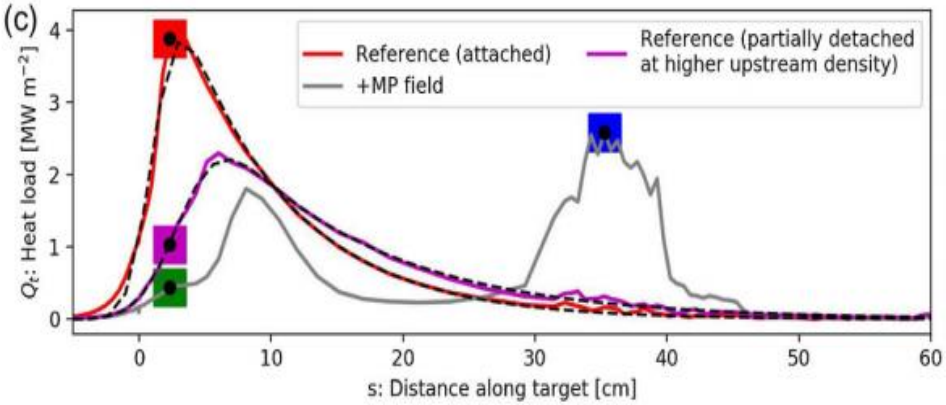


Normalized stationary heat flux in divertor (total heating power ~100MW, 50MW is supposed to be radiated –not in this modelling, no nuetrals here, 50MW in divertor): 5-2 MW/m2



However when RMPs are switched on => transient increase of heat fluxes. Solution? Switching RMP before L/H transition? Gas/impurities injection? Radiation? Note that in these results the main divertor physics : neutrals, ionizaton, radiation... are missing=> work in progress. Divertor physics is needed!

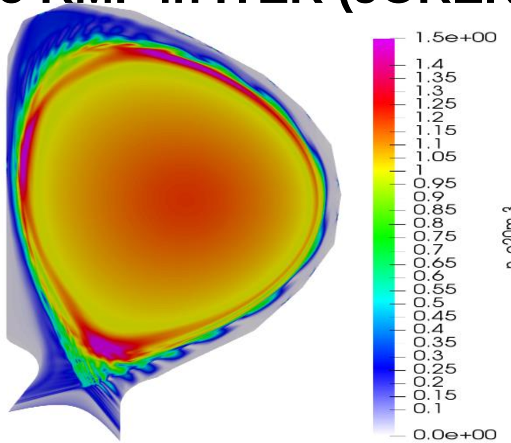
Divertor physics RMPs for ITER (EMC3-EIRENE) : screening of RMPs by plasma, but large edge lobes due to the kink response. 3D footprints. Far SOL is more difficult to keep detached with RMPs due to the direct link to the hot pedestal regions. *[H Frerichs PRL2020]*



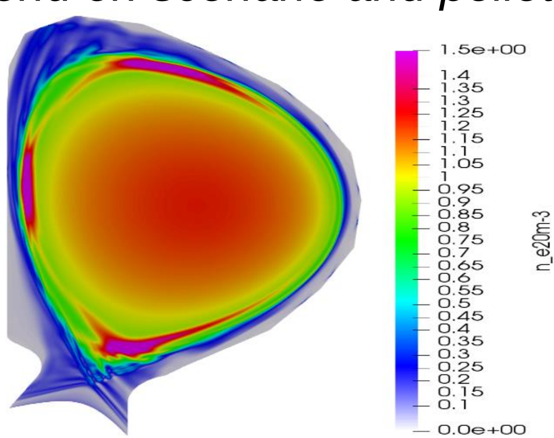
Fueling by pellets in ITER with RMPs: how not to trigger ELMs by a pellet (usually it does) ?

Fast particles (alphas, NBI) loss due to RMP fields?

HFS pellet (4.0x10^21 D) triggers ELM w/o RMP in ITER (JOREK)



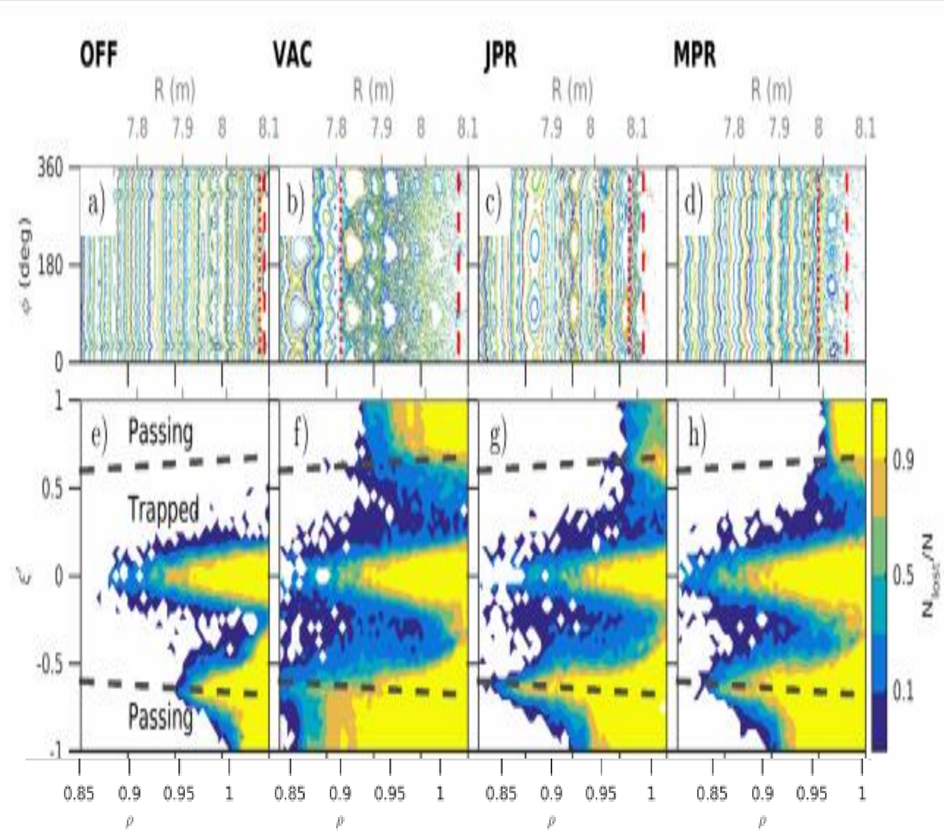
With RMP: no ELM, *however it depend on scenario and pellet size*



[JOREK, Curtesy to S. Futatani]

ASCOT + MARS-F&JOREK for plasma response: moderate loss of fast ions(mainly trapped) in ITER (33MW 1MeV beam=>~1MW; alphas~3MW)

JOREK **MARS-F**



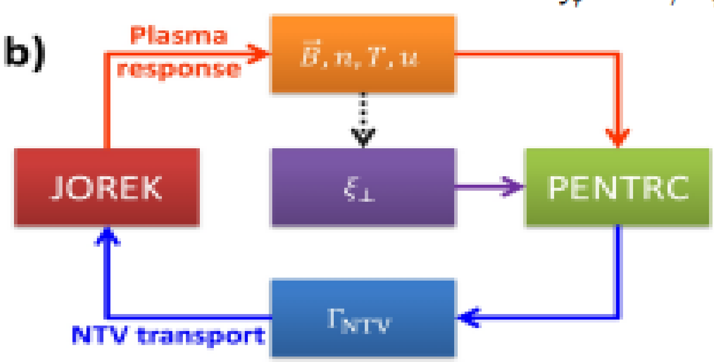
[ASCOT for ITER: Särkimäki NF2018]

Neoclassical Toroidal Viscosity (NTV): drift of particles in 3D fields (radial current) => pump-out of density and braking of rotation. NTV regimes strongly depend on plasma collisionality. At present - simplified analytical formulas coupled to MHD codes (MARS,JOREK)

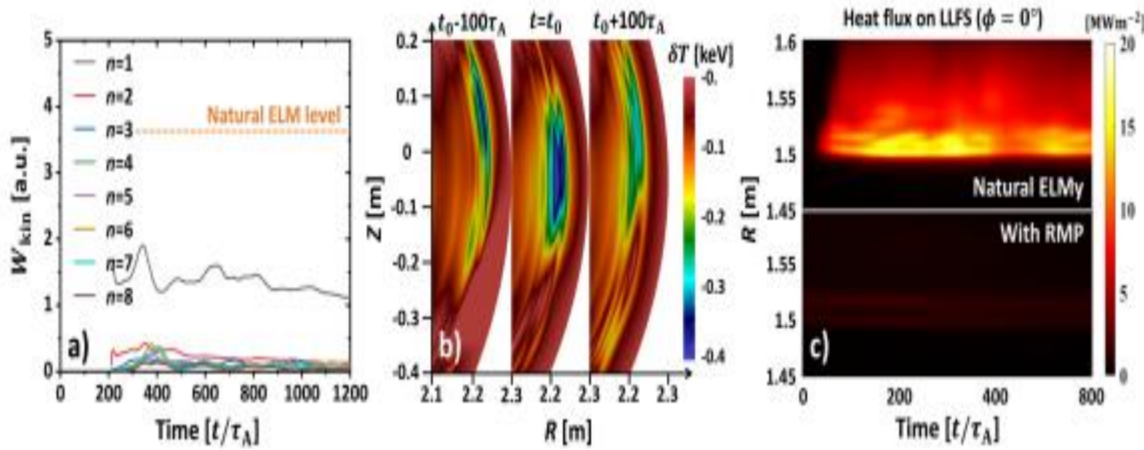
In non-linear 2 fluid (el.+ ions) resistive MHD : ExB convection for density and jXB braking at surfaces q=m/n. Not enough to explain pump-out and rotation braking in experiments.

NTV: drift kinetic equations for trapped + passing particles in 3D fields, more validation with experiment is still needed *[Shaing PoP2003, Becoulet NF2009, Sun PhysRev Let 2010,etc…]* .

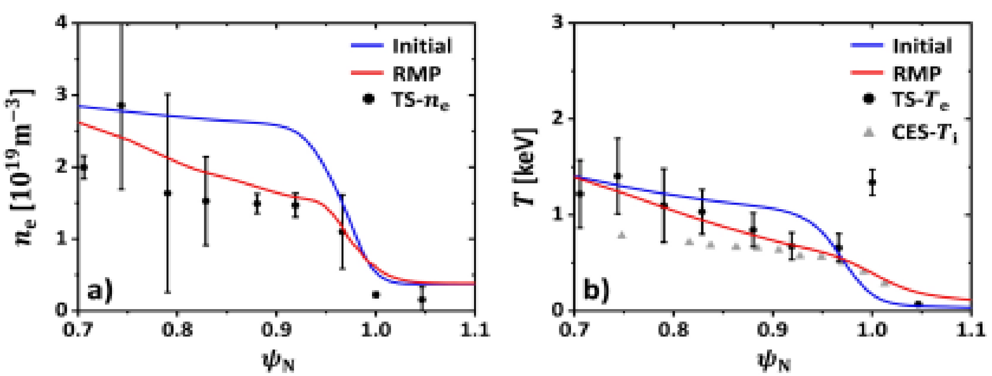
$$\xi_\psi = \delta T / \nabla_\psi T_0$$



JOREK (MHD) + PENTRC (NTV) *[SK Kim (NF sub 2022)]:* ELM suppression by RMP N=1 in KSTAR



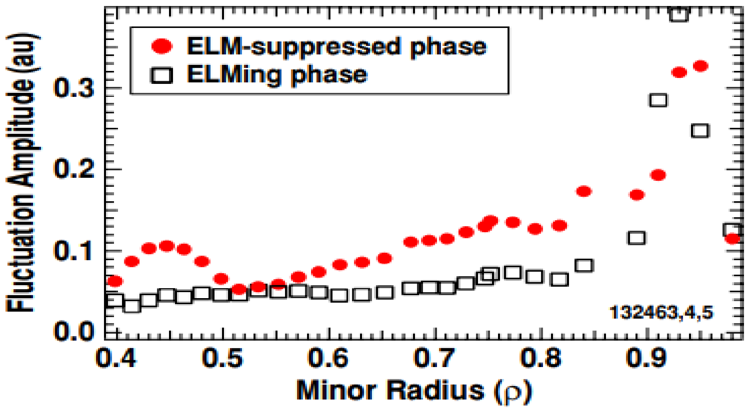
Plasma profiles with RMPs



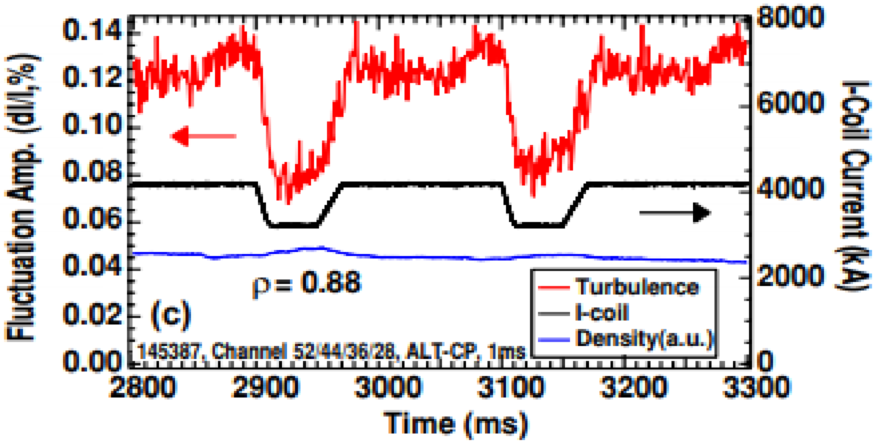
Experimentally turbulence increases with RMPs. Why? What kind of turbulence? Is it the reason of density pump-out?

Increase of fluctuations with RMPs

[DIIID,BES,McKee NF2013]

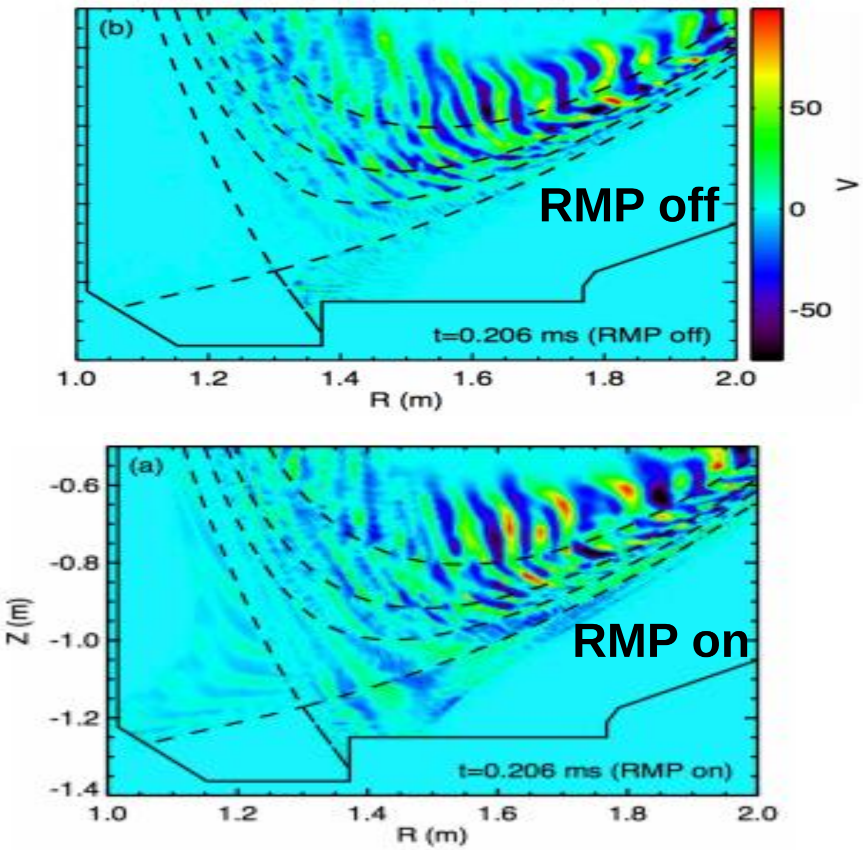


fast increase of turbulence with RMPs, but no density pump-out

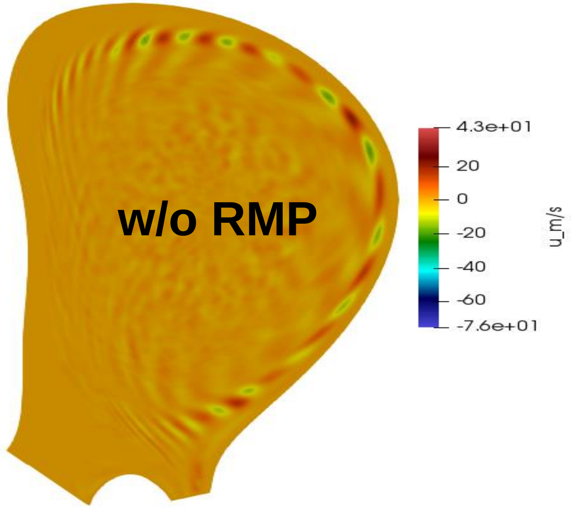


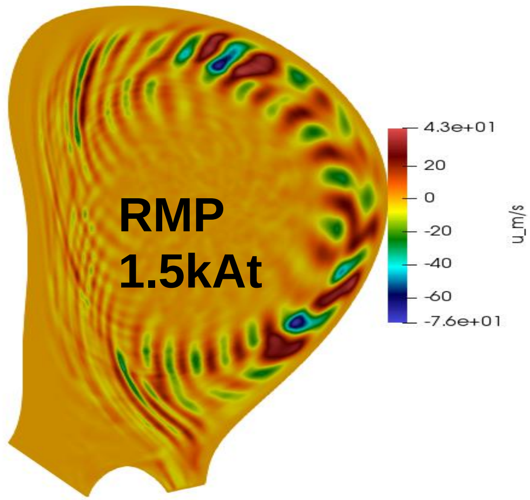
Gyrokinetic XGC+MHD M3D-C1 with RMPs: ITG increase in the centre, TEM in the pedestal (ψ_n>0.94)

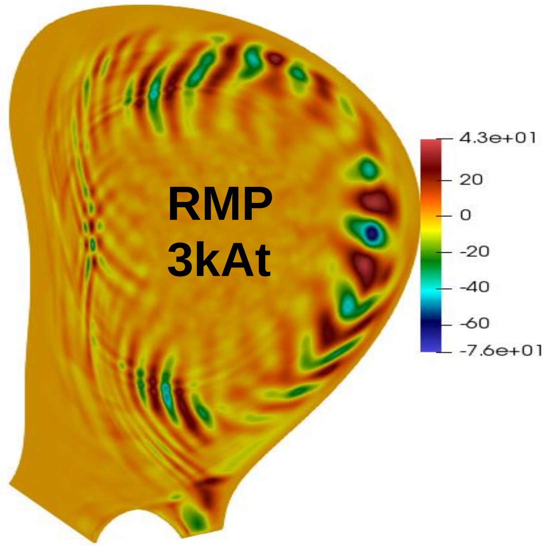
[DIIID,HagerPoP2020, IAEA FEC 2021]



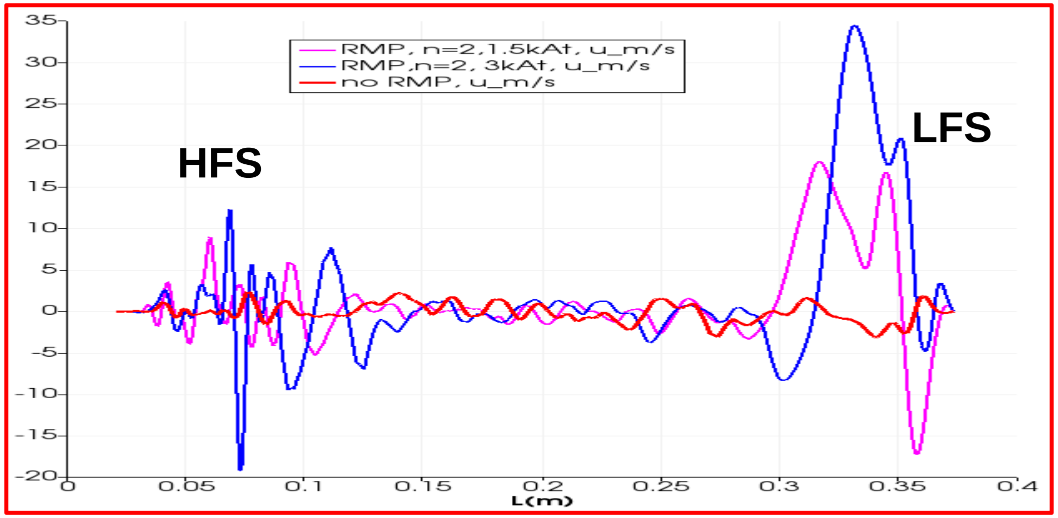
Modelling of gyro-kinetic ITGs with JOREK code for L-mode plasma (COMPASS # 8078, RMP N=2, 1.5kAt, 3kAt): increase of edge turbulence (increases with RMP current) in the ergodic region.

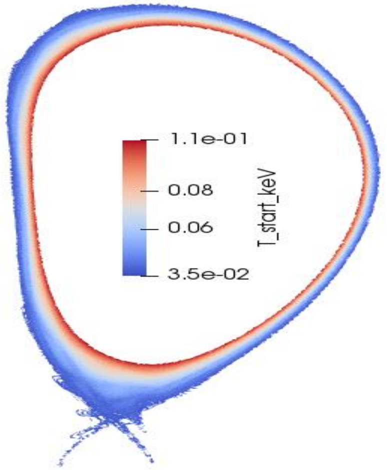






Mid-plane electrostatic potential fluctuations





Conclusions

1. ELMs suppression criterion with plasma response: external kink (maximum displacement near X-point) is favorable for suppression (experiment+ ideal/ linear MHD codes). q95 or/and RMP coils phasing can be optimized for it. Good for ITER – independent power supplies for RMP coils.

2. Modelling ELMs suppression by RMPs :

a. Realistic toroidal geometry (divertor, RMP coils, wall), self-consistent evolution of plasma profiles (non-linear MHD) two fluid diamagnetic effects, toroidal rotation, multi-harmonics –minimum model for modelling of ELMs and ELMs suppression by RMPs (code JOREK).

b. Response currents on q=m/n => screening or amplification of RMPs by external kink.

c. RMPs non-linearly generate continuous MHD turbulent transport stabilizing large ELMs AUG,KSTAR, EAST=>ITER (suppression threshold 45kAt, N=3, 15MA/5.3T)

d. 3D SOL with RMPs, divertor footprints in ITER: radial extension ~20 cm (inner); ~40cm(outer) at 60kAt. Steady state <5MW/m2 (at 50MW in divertor), but (attention!) transient increase when RMPs are switched on!

e. RMPs with fueling by pellets in ITER without ELM triggering depend of pellet size.

f. Fast particle (alphas, NBI) losses due to RMPs are moderate (1MW -NBI,3MW- alphas)

g. Neoclassical Toroidal Viscosity (NTV): pump-out, braking.

h. Turbulence (ITG,TEM) with RMPs increases.

Additional slides

Two fluid (electrons&ions) MHD equations used in JOREK

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

Magnetic field

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

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

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

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

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

ions w/o polarization, w/o NTV

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

Neoclassical poloidal viscosity *[Gianakon PoP2002]*

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

Ion poloidal velocity => neoclassical

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

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

Temperature dependent viscosity, resistivity, $K_{\parallel}$: $\nu_{\parallel,\perp}, \eta \sim (T/T_0)^{-3/2}$ $\quad K_{\parallel} \sim K_{\parallel,0}(T/T_0)^{5/2}$

Density equation with polarization for electron density, but ne=ni, then NTV flux is added:

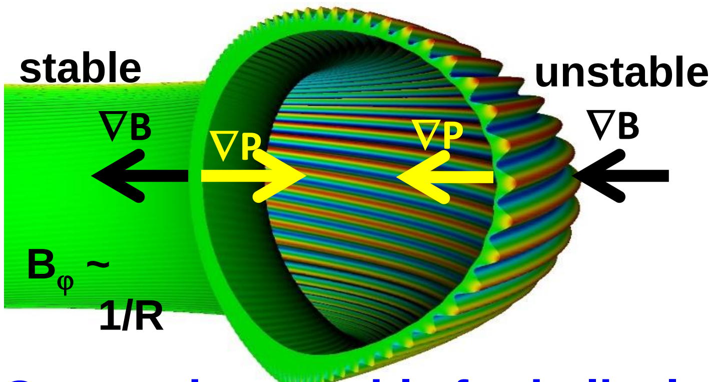
$$\underbrace{\frac{\partial n}{\partial t} + \vec{v}_E\cdot\nabla n = -n\nabla\cdot\vec{v}_E + \nabla\cdot n\vec{v}_{e*} - \nabla_{\parallel}(n v_{\parallel,i}) + \nabla\cdot(D_{\perp}\nabla n) + S_n}_{\text{Electron density equation}} + \underbrace{\frac{1}{e}\nabla\cdot\vec{j}_{\parallel}}_{\text{Polarization}} + \underbrace{\nabla\cdot\Gamma_{NTV}}_{\text{NTV}}$$

What is the physics of ELMs?

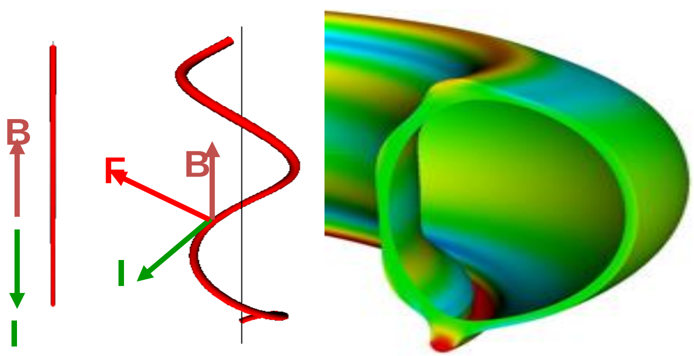
[Huysmans PPCF2009]

Ideal linear MHD: what instabilities?

ballooning instability driven by edge steep pressure gradient

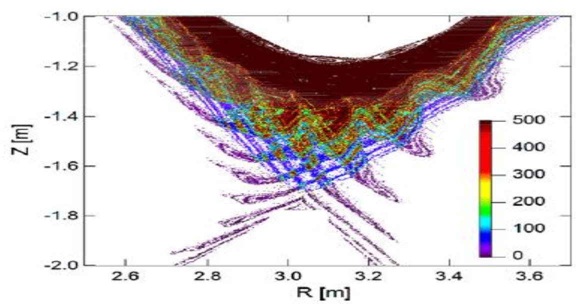


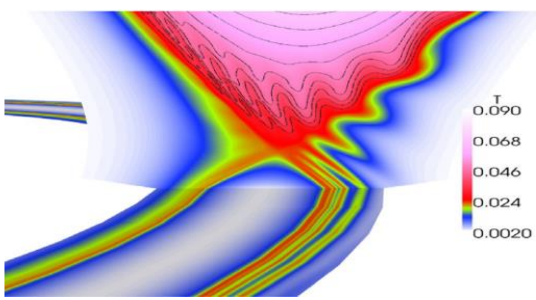
Current is unstable for helical perturbation: kink-peeling mode



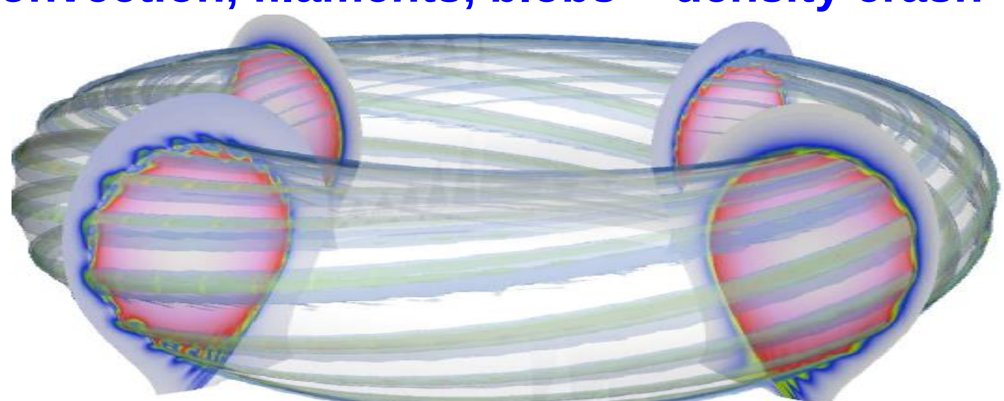
Resistive non-linear MHD(JOREK): why crash?

ELM=>magnetic perturbations=> reconnections(ergodic field)=> energy follows perturbed magnetic lines =>temperature crash



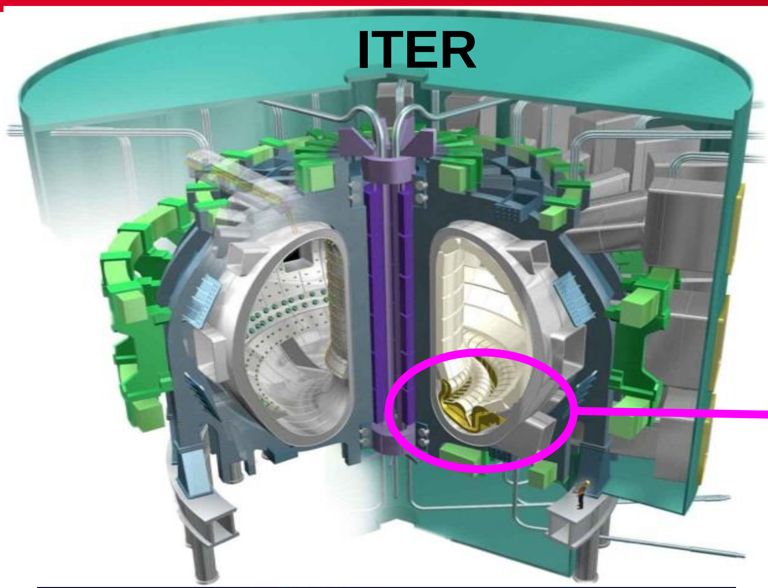


ELM=> potential perturbations=> ExB density convection, filaments, blobs=>density crash

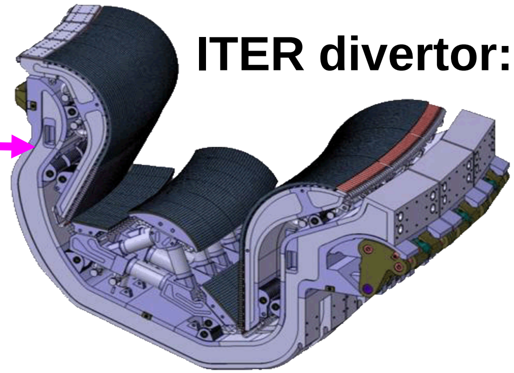


Divertor X-point configuration in ITER. Scrape Off Layer (SOL) : open field lines guide escaping heat and particles to divertor plates (<10-20MW/m2).

ELMs represent an issue for ITER and should be controlled!

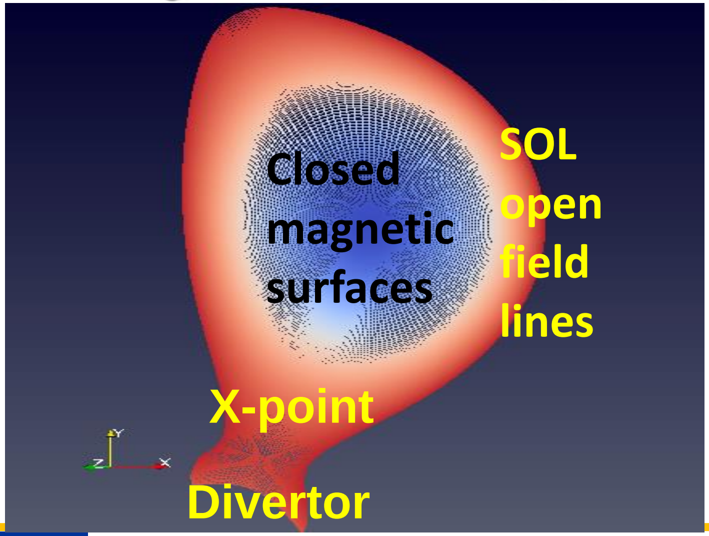


ELMs size scaled to ITER represent an issue for ITER tungsten divertor (W)=> melting, droplets ejection, cracks. "Safe" ELM if <1MJ, but predicted for ITER: ~20MJ!



ITER divertor: ~10 MW/m2 (stationary)
~20 MW/m2(transient)

For comparison: ~50MW/m^2 on the surface of the Sun



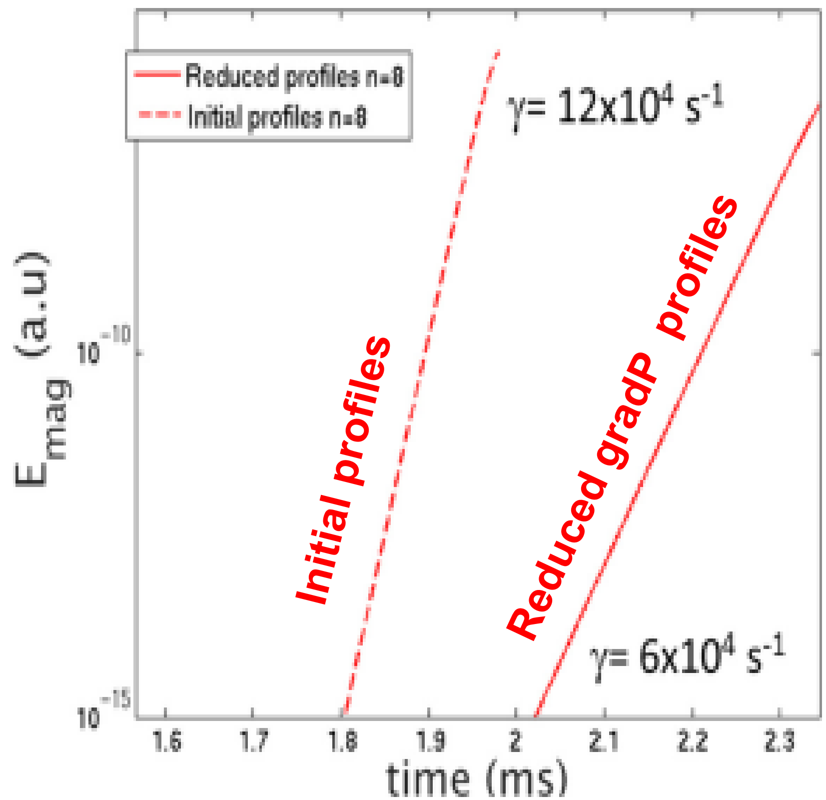
Tungsten sample under ELM-like heat flux:

Is ELMs suppression due to the reduced pressure gradient?

Not only: the same profiles as with RMP (lower gradP) but w/o RMP=> smaller growth rate, but ELM crash! Suppression is due to continuous MHD via non-linear coupling with RMPs.

[AUG Orain Phys. Plasmas 2019]

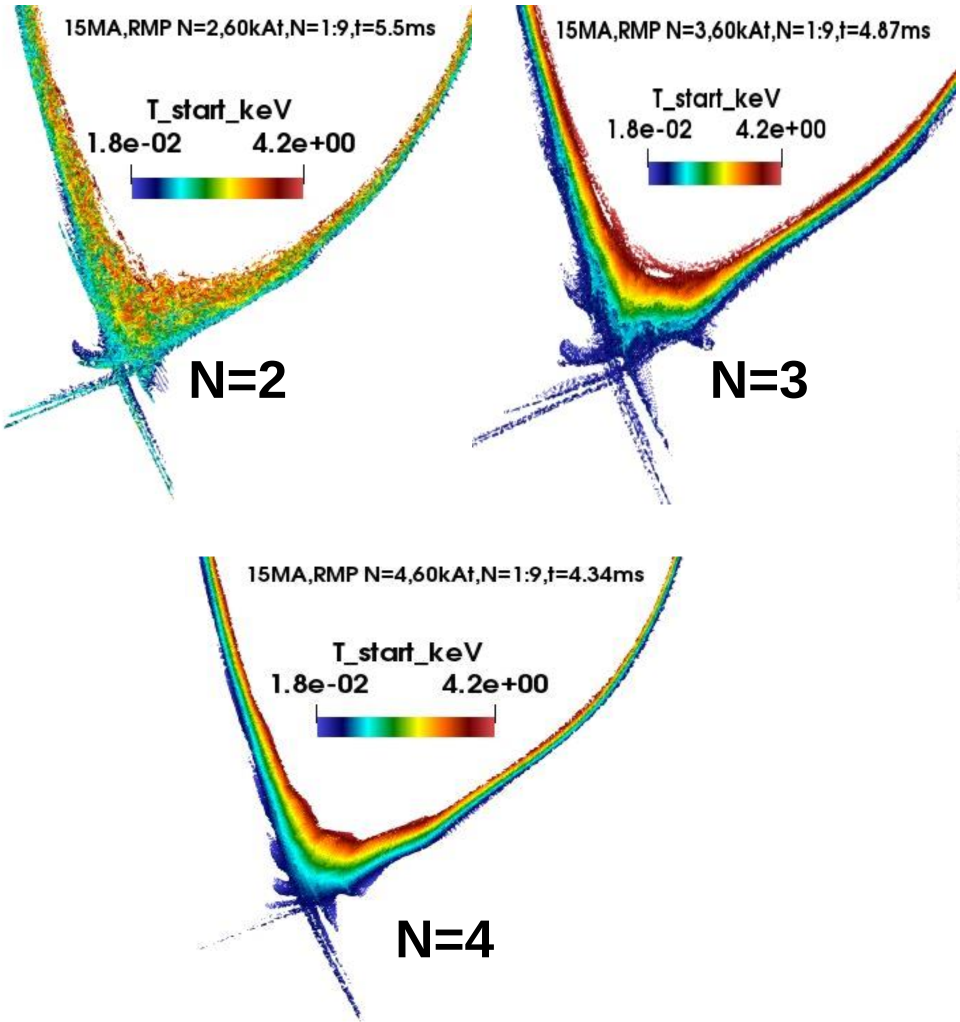
Magnetic energy of N=8 mode (ELM) without RMPs

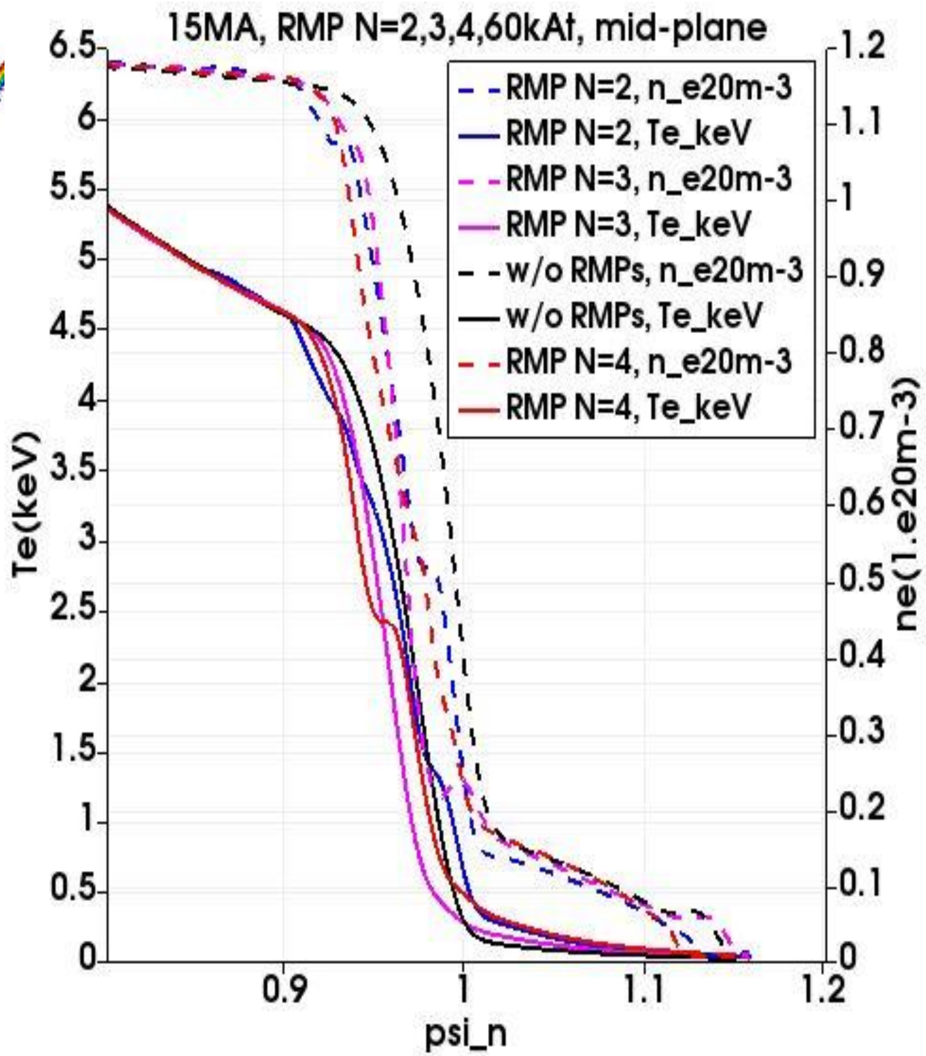


without RMP: edge gradP grows until MHD peeling-ballooning limit => ELM crash

with RMPs: continuous MHD coupled to RMP=> continuous transport=> no ELM crashes.

15MA/5.3T scenario, RMP N=2,3,4, 60kAt. Edge magnetic topology and profiles in ELM suppressed phase: density (ne) transport (here convective ExB and //), energy (Te) transport (// conductive along perturbed field lines).

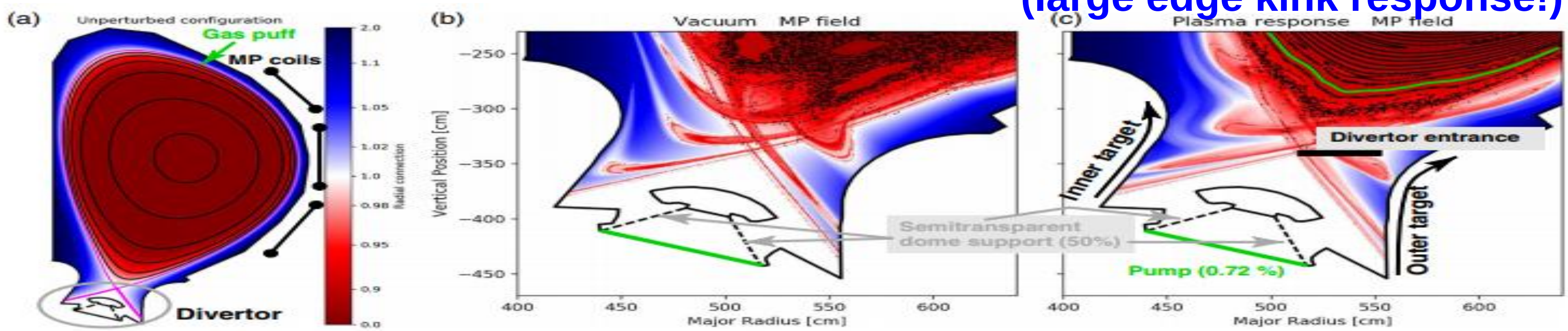


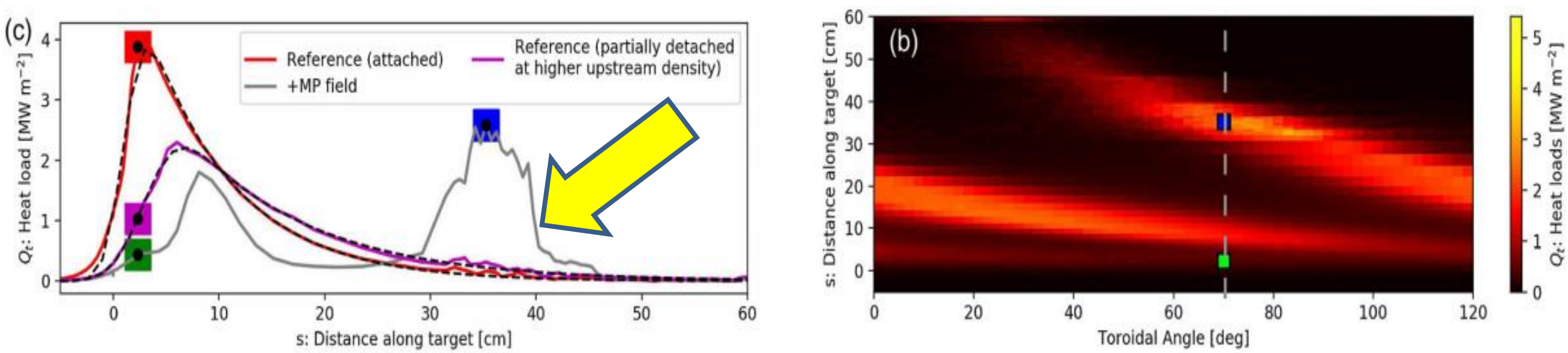


Divertor physics with RMPs for ITER: screening of RMPs by plasma, but large edge lobes due to the kink response. 3D footprints. Far SOL is more difficult to keep detached with RMPs due to the direct link to the hot pedestal regions.

Edge Monte-Carlo 3D EMC3-EIRENE code *[H Frerichs PRL2020,IAEA FEC 2021] :*
Stationary conditions for particle flux *(gas injection, neutrals, ionization, recombination*), momentum flux along field lines (momentum *source, loss via charge exchange with neutrals*), heat flux (*heating source, loss from ionization, radiation, including impurities*)

No RMP | **Vacuum RMP (N=3)** | **MARS-F plasma response (large edge kink response!)**





Special acknowledgments to the authors and co-authors of the papers and presentations used in this talk:

[1] M Fenstermacher et al Phys of Plasmas15(2008)56122 , + ITPA PEP 2021
[2] G T A Huysmans et al Plasma Phys Control Fusion 51 (2009) 124012
[3] F Orain et al Phys. Plasmas 26(2019), 042503
[4] S K Kim et al Nucl. Fusion 60(2020), 026009, + IAEA FEC 2021
[5] M Becoulet et al submitted Nucl. Fusion 2021, + IAEA FEC 2021
[6] Y Liu et al Plasma Phys. Control. Fusion,58(2016)114005, + IAEA FEC 2021
[7] H Frerichs et al Phys Rev Letter 125(2020)155001+IAEA FEC 2021
[8] R Hager et al Phys of Plasmas 27(2020)062301, + IAEA FEC 2021
[9] Q M Hu et al Phys. Plasmas 28, 052505 (2021), Nucl Fusion 2021+ IAEA FEC 2021
[10] M. Jia, Y Sun, A. Loarte et al, Nuclear Fusion 61 (2021), IAEA FEC 2021
[11] M Hoelzl et al Nucl. Fusion 61 (2021) 065001), + IAEA FEC 2021
[12] JK Park et al Nature Phys 14, (2018) 1223–1228
[13] D Orlov et al , IAEA FEC 2021
[14] K Särkimäki et al 2018 Nucl. Fusion 58 076021
[15] GR McKee et al Nucl. Fusion 53 (2013) 113011