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First principles modelling of the edge and diveror physics of Edge Localized Modes (ELMs) suppression by Resonant Magnetic Perturbations (RMPs) in ITER

Marina Becoulet

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First principles modelling of the edge and diveror physics of Edge Localized Modes (ELMs) suppression by Resonant Magnetic Perturbations (RMPs) in ITER.

Marina Becoulet

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

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

Outline

1. Introduction

- **ITER –international next-step magnetic fusion project.**
- **MHD instabilities control is essential in ITER.**

2. Physics of Resonant Magnetic Perturbations (RMPs) for Edge Localized Modes (ELMs) control.

- **Understanding of ELMs suppression by RMPs in existing tokamaks proposed by MHD modelling. What is ELMs suppression criterion?**
- **Modelling of ELMs suppression by RMPs in ITER.**
- **3D Scrape off Layer (SOL) and divertor physics with RMPs.**

3. Discussion on related physics of RMPs: ***polarization, Neoclassical Toroidal Viscosity(NTV), compatibility of pellets fueling with RMPs, fast ions losses with RMPs, turbulence with RMPs…***

4. Conclusions.

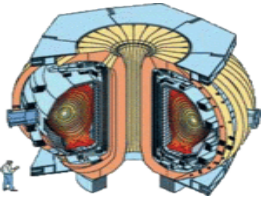
Magnetic fusion -carbon free source of energy. ITER: amplification in power Q>10; self heating by alpha-particles; effective plasma control.

$Q=P_{fusion}/P_{input}$ - amplification factor

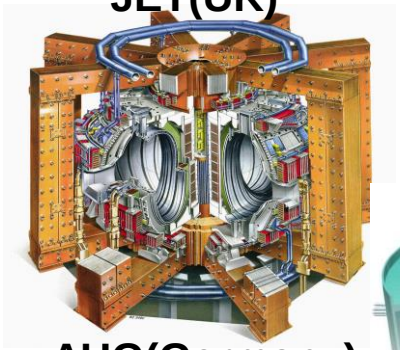
$nT\tau_E>5.10^{21}$ [m^{-3} keV s] - ignition condition for D-T (Lawson)

$\tau_E=W_{th,plas}/P_{loss}$ - confinement time increases with size~I_pR^2

DIII-D(US)

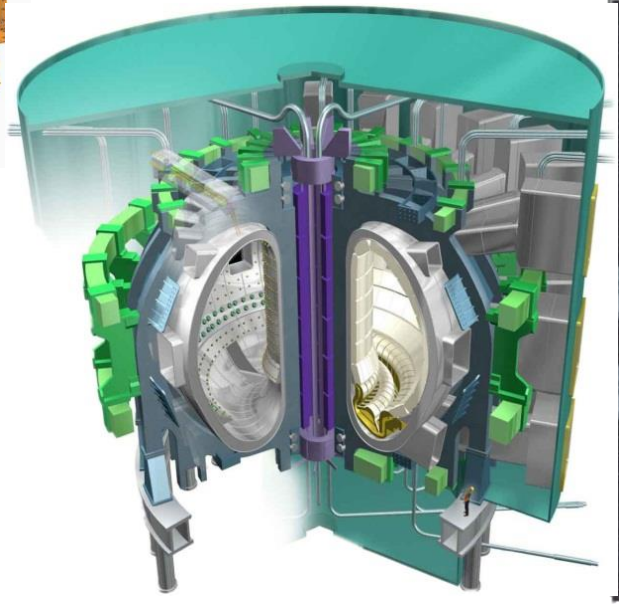


JET(UK)

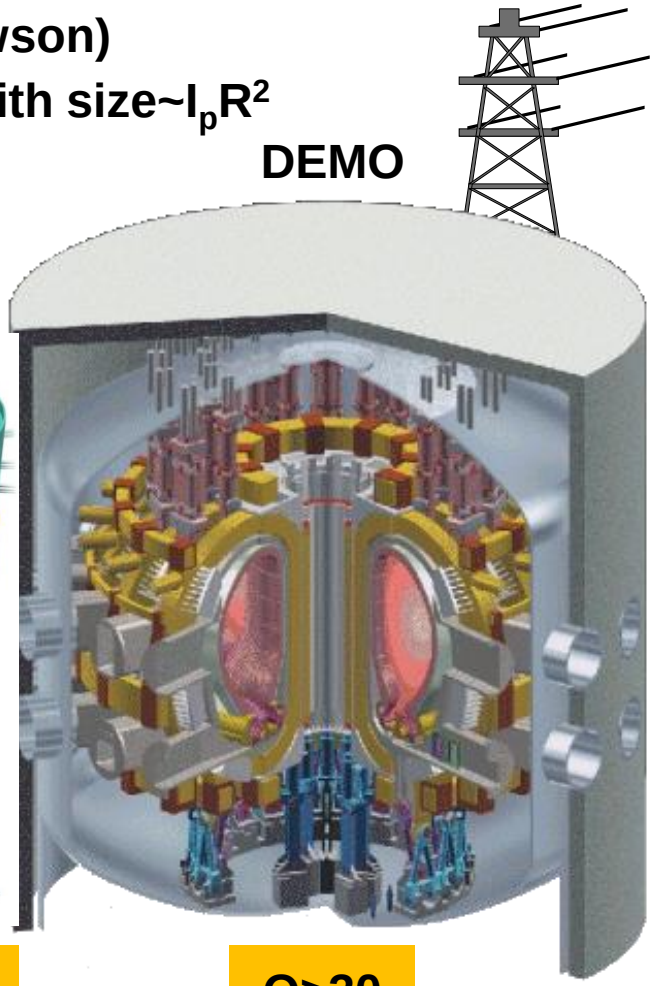


ITER

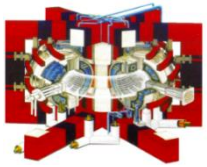
(construction in France)



DEMO

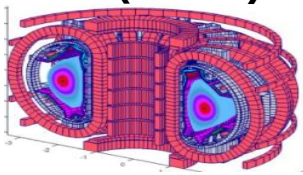


WEST(France)

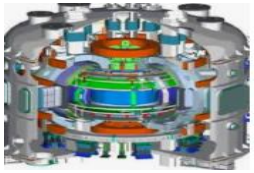


AUG(Germany)

EAST(China)



KSTAR(Korea)



Now: Q<1, Q_{JET} ~0.67 (DT, 1997)

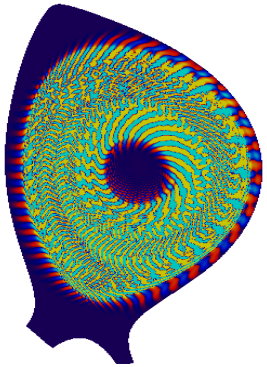
Ignition: Q>10

Q>30

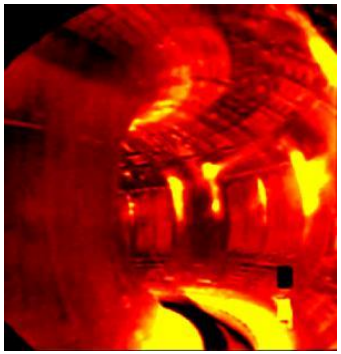
Fusion research: strong synergy between experiment, theory, numerical modelling and computer science (HPC) to guarantee the success of ITER.

Modelling is very important in fusion! Difficult: extreme conditions, very complex geometry, electro-magnetic fields, turbulent transport, MHD instabilities, large variation in space (0.1mm-few m) and time (10^{-6}s- 1000s) scales.

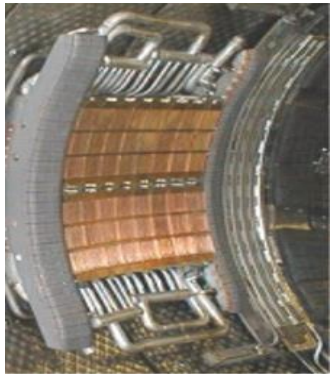
1. Achieve maximum confinement (=performance) => understand and minimize heat and particle transport (=turbulence) in tokamaks.



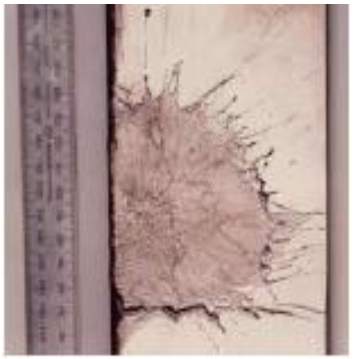
3. Equilibrium, MHD stability, safe and high confinement scenarios, plasma control (this talk)



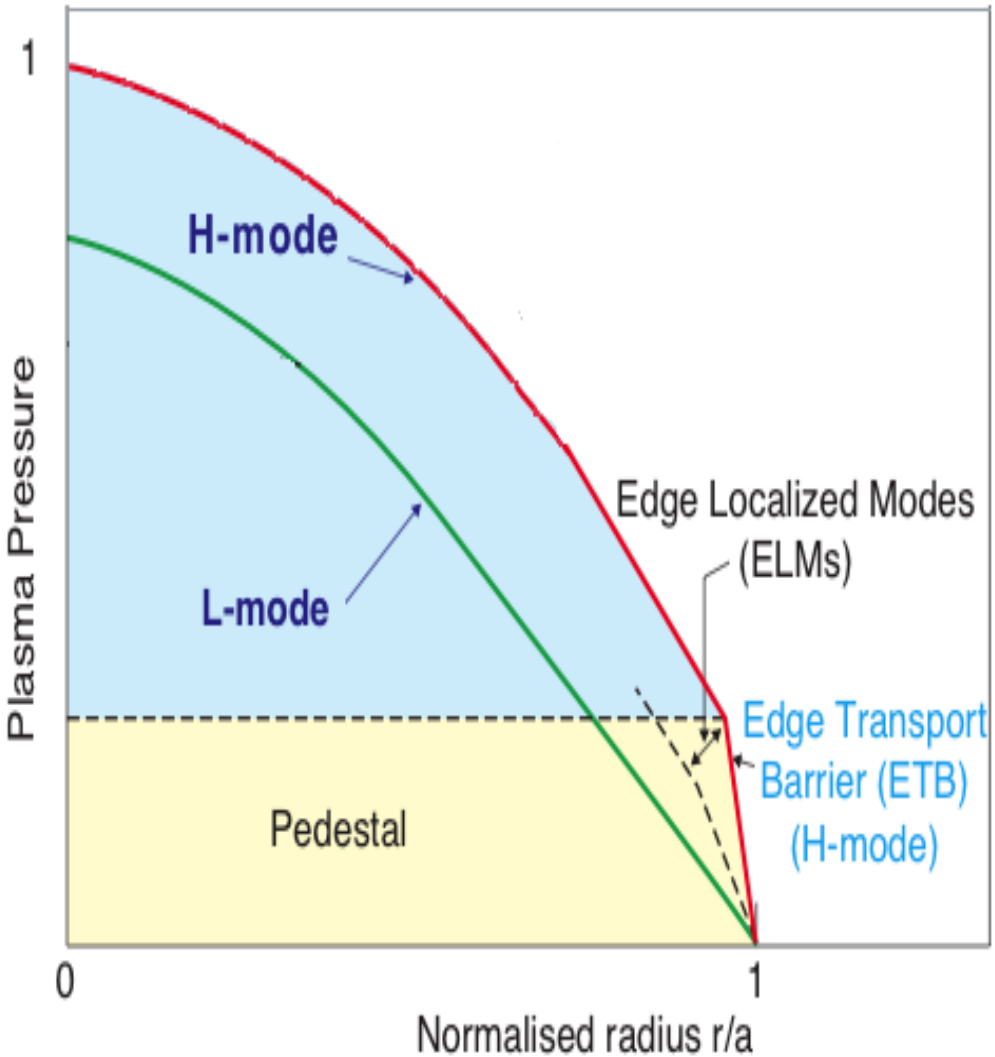
2. Efficient heating and current drive.

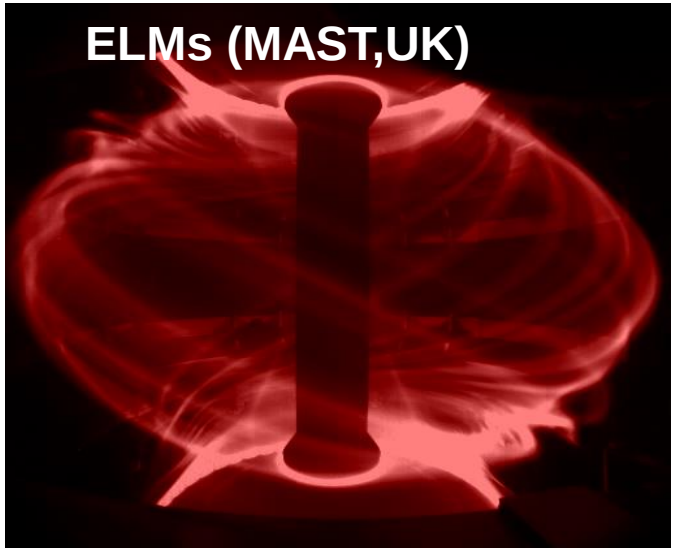


4. Plasma surface interaction. Materials under extreme heat and particle fluxes (this talk)



ITER H-mode scenarios. Edge Transport Barrier (turbulence is suppressed) =>steep gradients in “pedestal” =>MHD instabilities, Edge Localized Modes (ELMs) =>fast quasi-periodic relaxation (~0.2ms)of profiles, heat and particle fluxes to walls



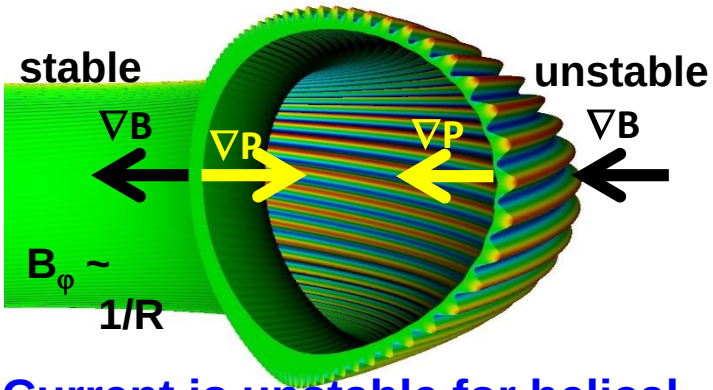


What is the physics of ELMs?

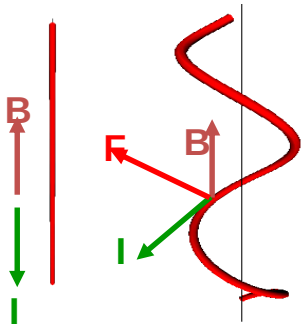
[Huysmans PPCF2009]

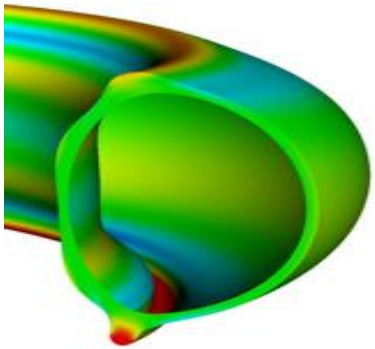
Ideal linear MHD: what instabilities?

ballooning instability driven by edge steep pressure gradient



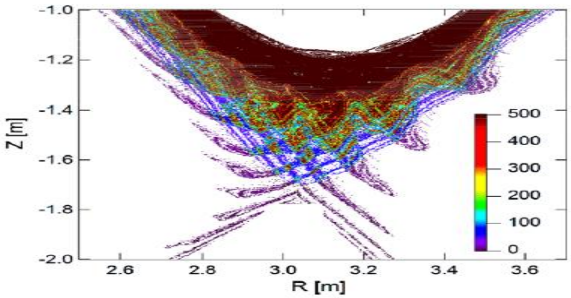
Current is unstable for helical perturbation: kink-peeling mode

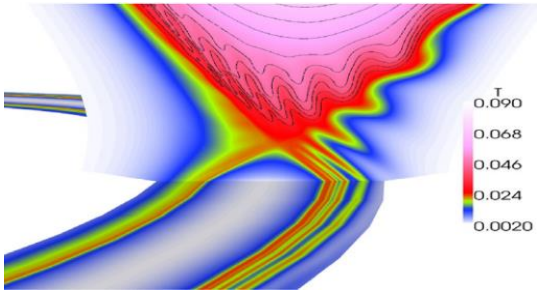




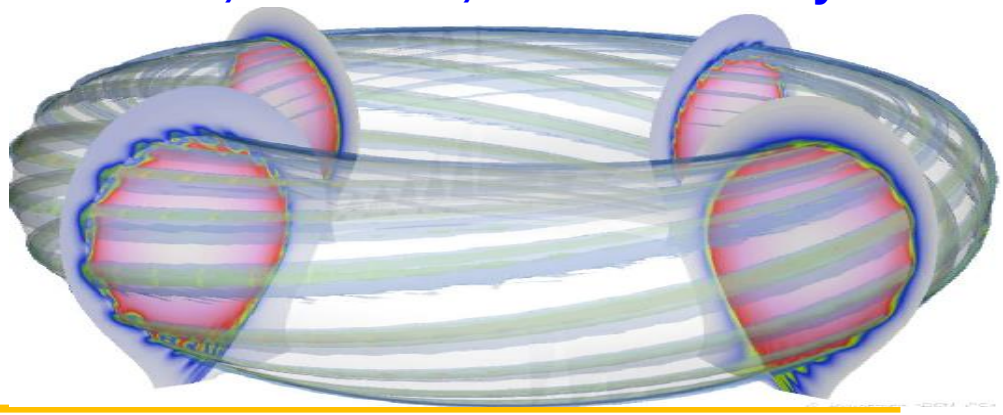
Resistive non-linear MHD(JOREK): why crash?

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



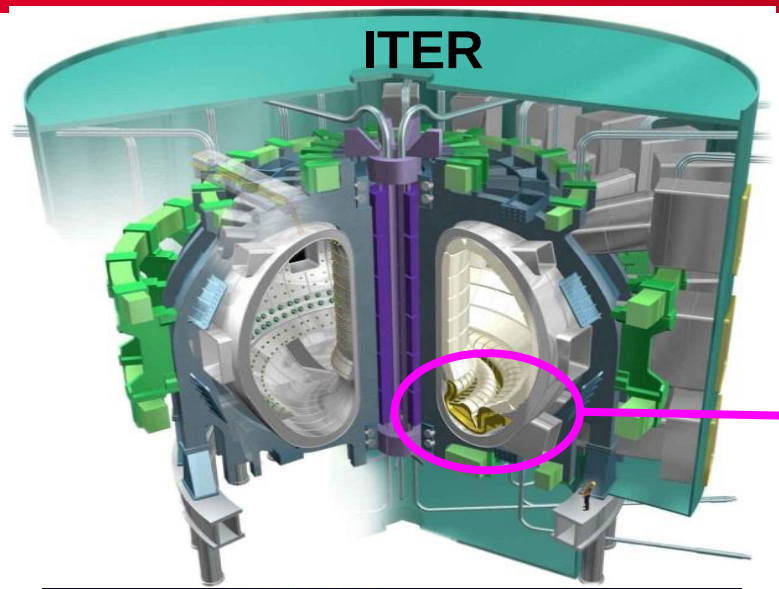


ELM=> potential perturbations=> ExB density convection, filaments, blobs=>density crash

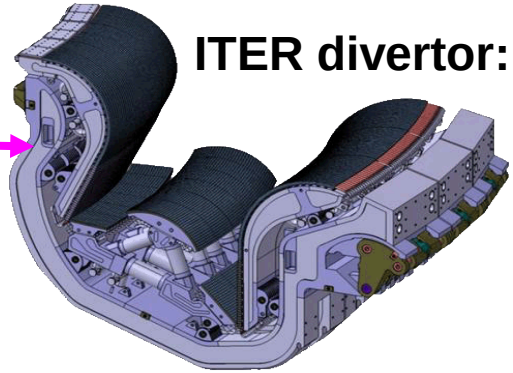


Divertor X-point configuration in ITER. Scrape Off Layer (SOL) : open field lines guide escaping heat and particles to divertor plates (<10-20MW/m2).

ELMs represent an issue for ITER and should be controlled!

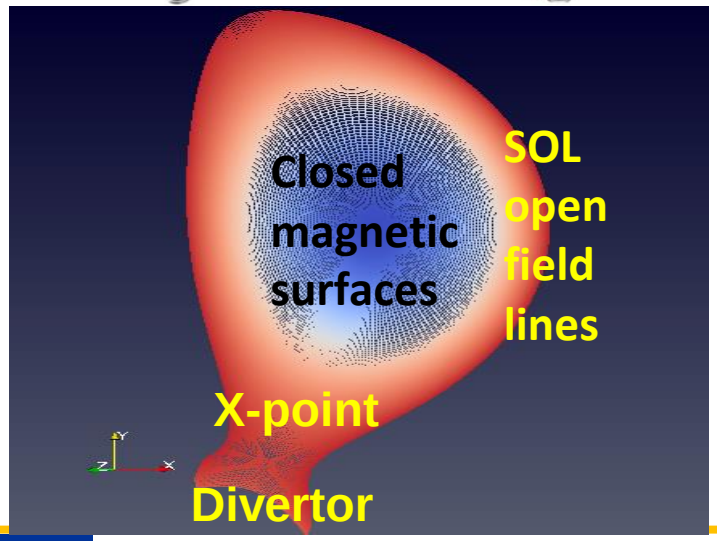


ELMs size scaled to ITER represent an issue for ITER tungsten divertor (W)=> melting, droplets ejection, cracks. "Safe" ELM if <1MJ, but predicted for ITER: ~20MJ!



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

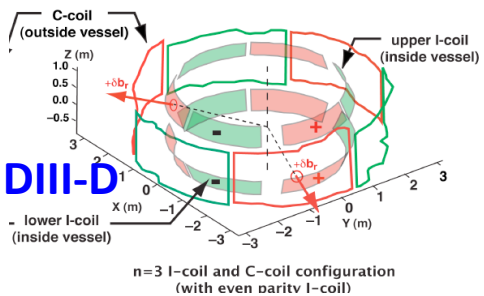
For comparison: ~50MW/m² on the surface of the Sun

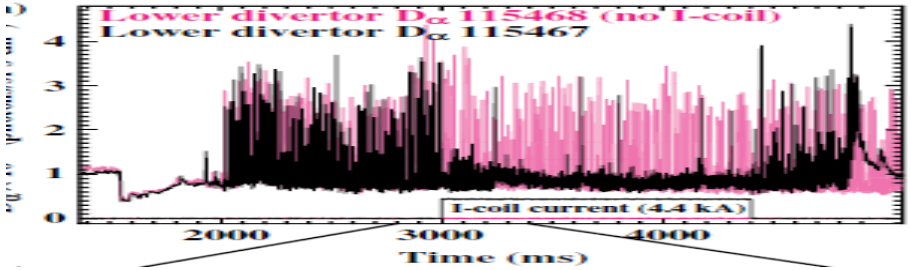


Tungsten sample under ELM-like heat flux:

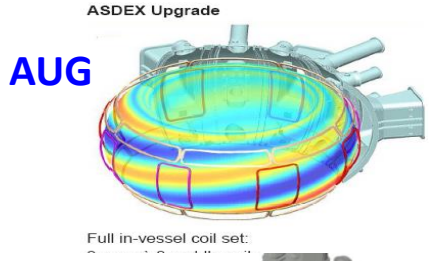
How to control ELMs? Strong mitigation/suppression of ELMs were achieved in different machines using RMP coils (main toroidal numbers N=1,2,3,4). Idea: slightly destroy magnetic surfaces at the edge=>increase edge transport, decrease gradP…

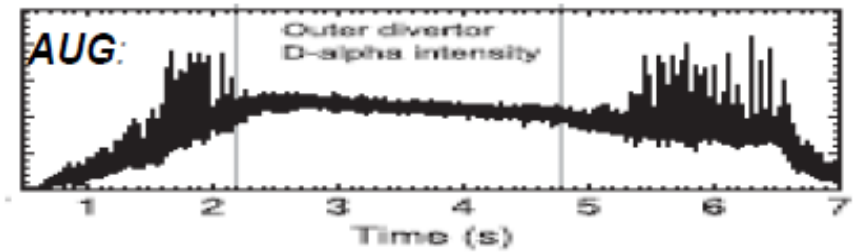
DIII-D



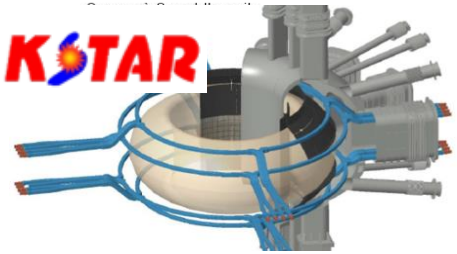


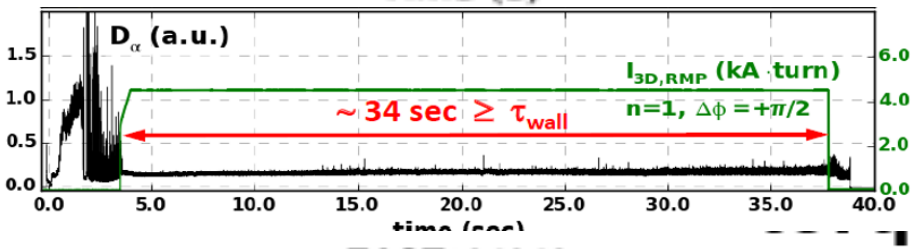
AUG



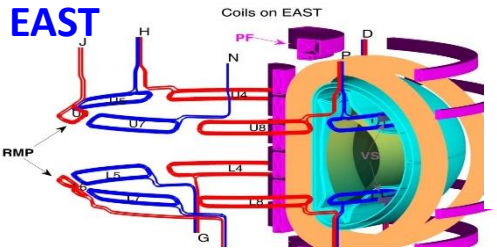


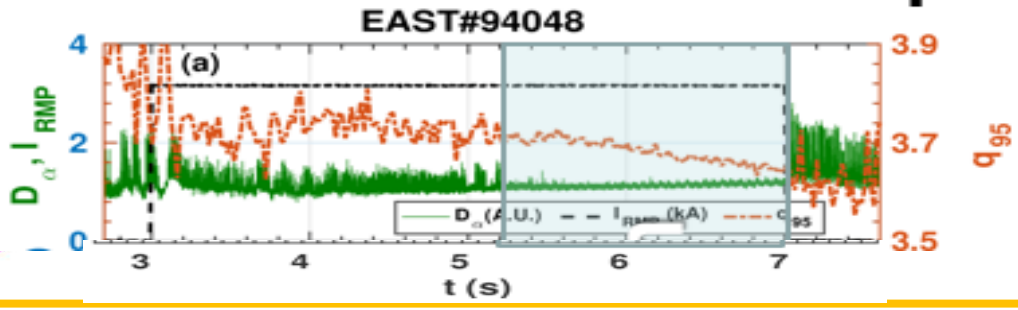
KSTAR





EAST

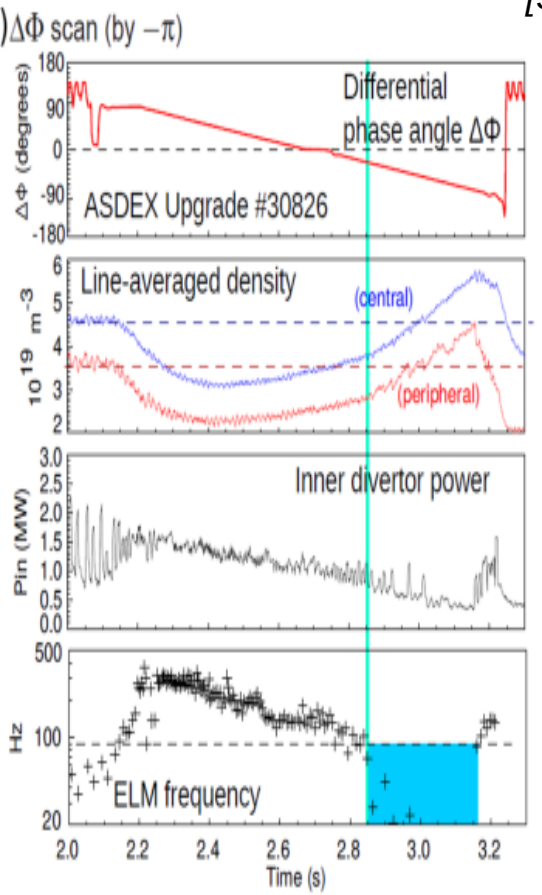




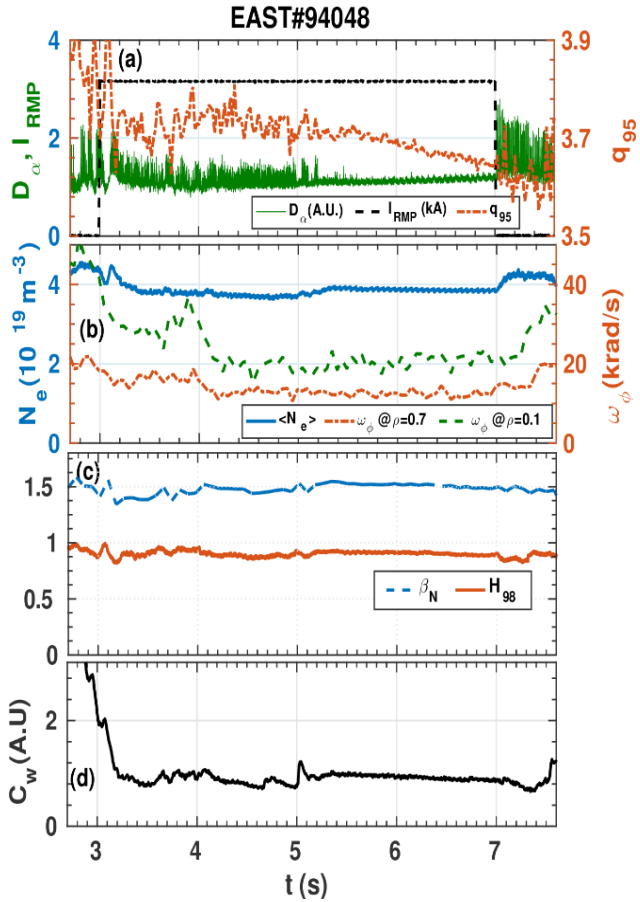
[DIII-D: Evans NF2005, JET: Liang PRL 2007, AUG:Suttrop PRL2011, KSTAR: Lee PRL2016, EAST: Sun, Loarte IAEA2021 etc….]

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]

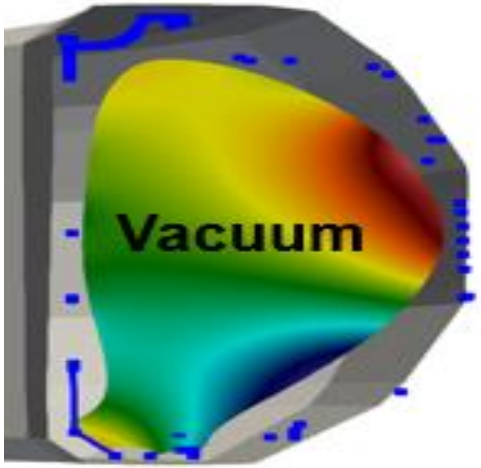


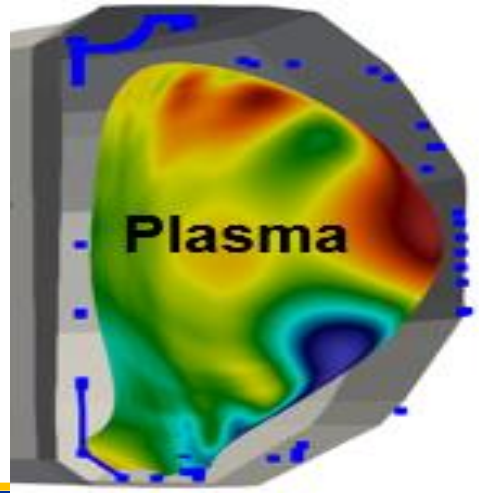
Observations during ELMs mitigation/suppression by RMPs (<u>not always all features!</u>):

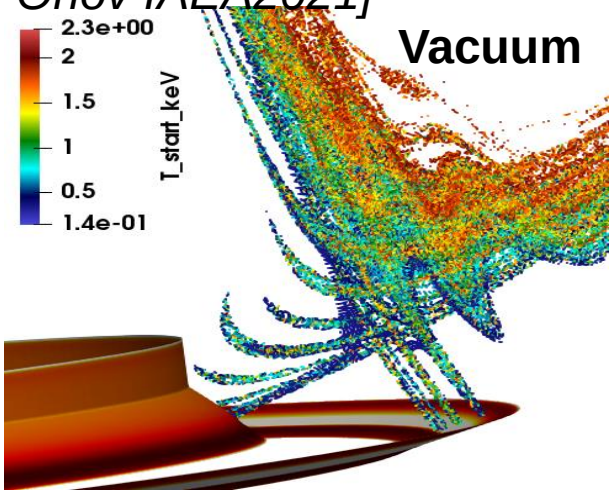
- **RMP amplitude threshold;**
- **density pump-out (not always, see EAST,N=4);**
- **degradation of confinement (0-20%);**
- **global toroidal rotation braking, edge acceleration;**
- **optimum RMP coils phase;**
- **q95 resonant window;**
- **« lobes » near X-point =>splitting of strike points=> footprints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

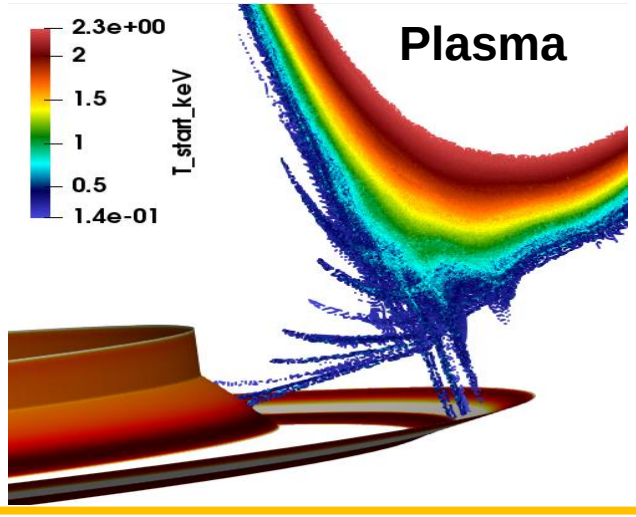
Typical rotating plasma response to RMPs: current perturbations on rational surfaces q=m/n=> screening (mainly)of RMPs. At the edge=>less screening at higher resistivity (since lower temperature).

[DIII-D, Becoulet EPS2019, Orlov IAEA2021]

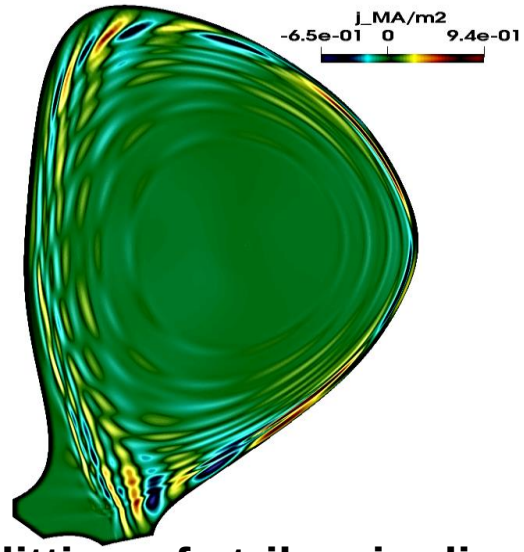




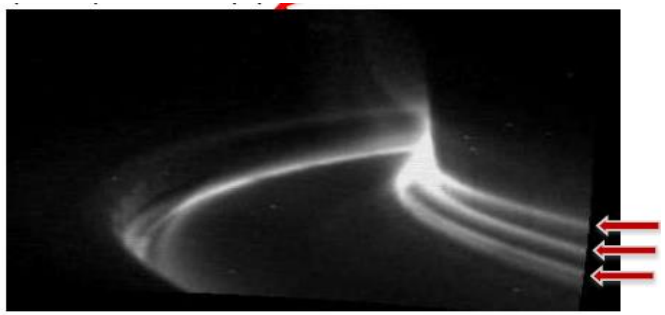




Response currents on rational surfaces q=m/n=>screening



Splitting of strikes in divertor

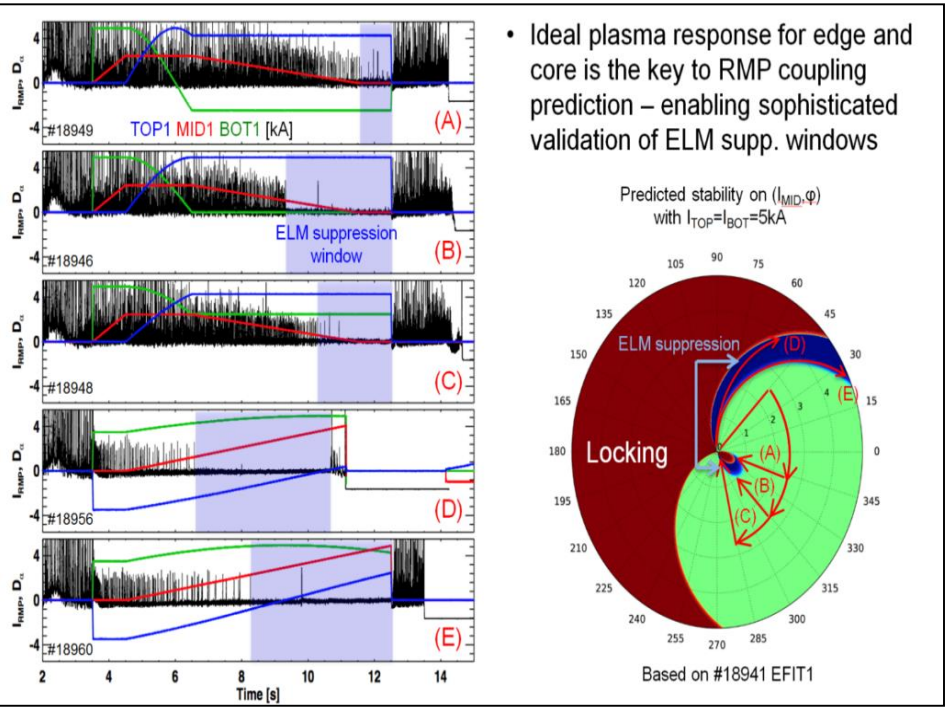


Not only screening! Ideal &resistive MHD+ experiment :edge kink-peeling response is needed for ELM suppression. It can be achieved by optimizing RMP coils phasing or change of safety factor profile (q95).

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

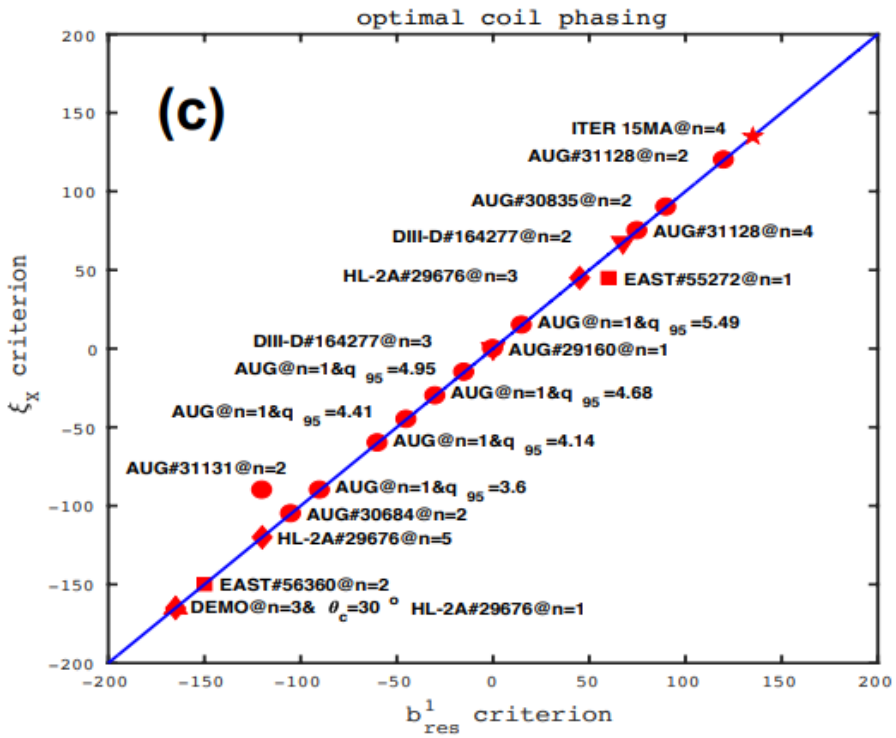
[KSTAR, JK Park Nature Phys 2018]

Ideal MHD (IPEC)



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

Resstive linear MHD (MARS-F)



Non-linear resistive MHD modelling (code JOREK) of ELM suppression in AUG. Realistic geometry, divertor, RMP coils, two fluid (el+ions) diamagnetic effects, toroidal rotation, multi-harmonics

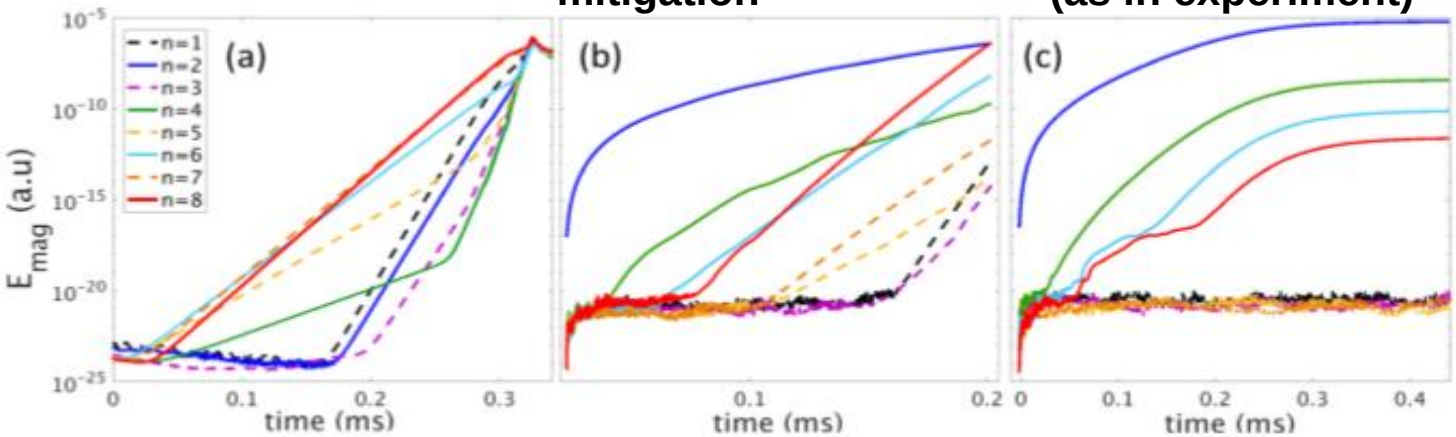
[AUG Orain Phys. Plasmas 2019]

Similar results for KSTAR, EAST

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

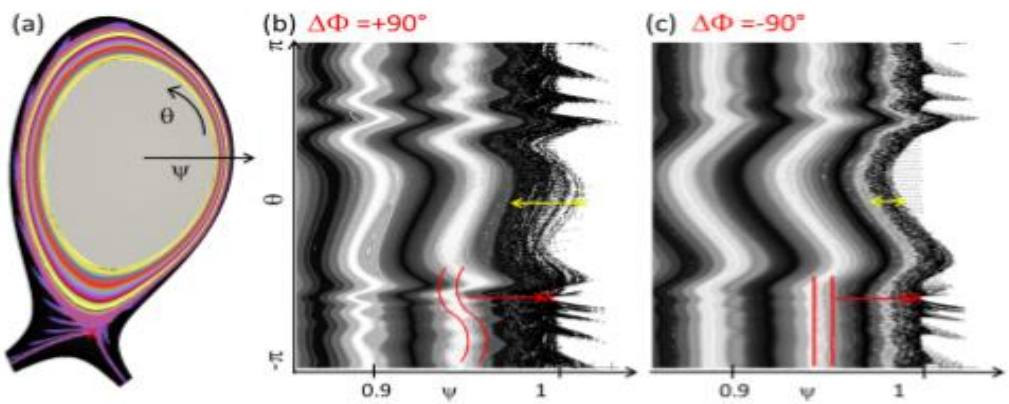
N=6

N=8

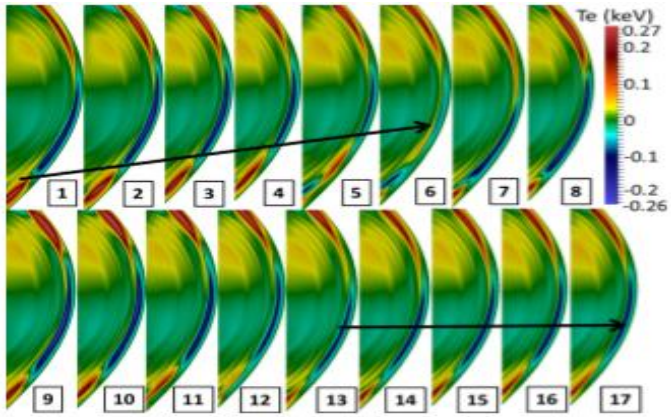
(non-linearly coupled to N=2)

Other harmonics - noise level, no ELMs

Kink response when ELM suppression (+90°)

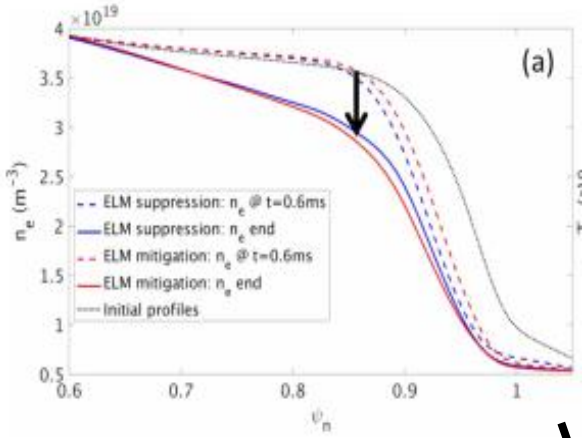


Modes rotation locking when ELMs suppression

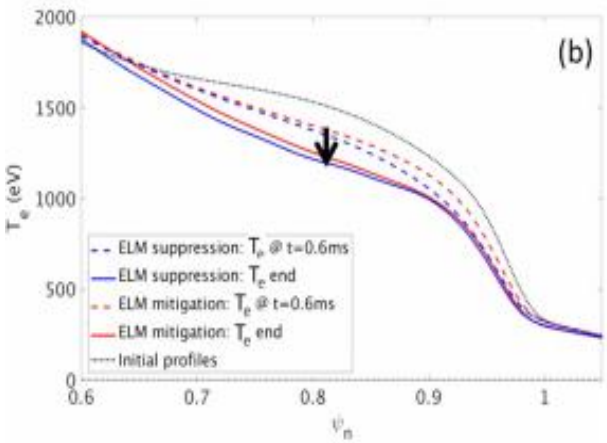


With RMPs: density decreases (convection ExB), electron temperature (parallel conduction), radial electric field 'well' decreases in the pedestal, braking of perpendicular electron rotation on the pedestal top=> less screening of RMPs, islands when ExB , Vel,perp~0

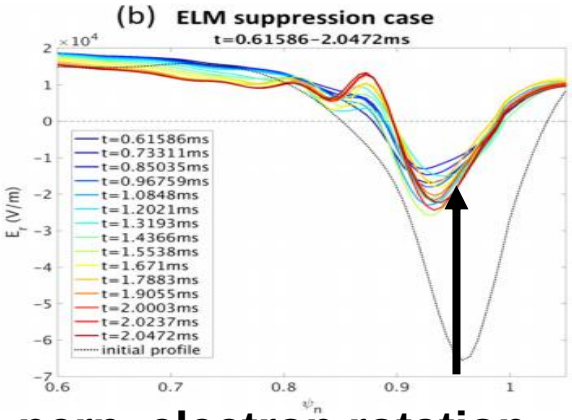
electron density (ExB)



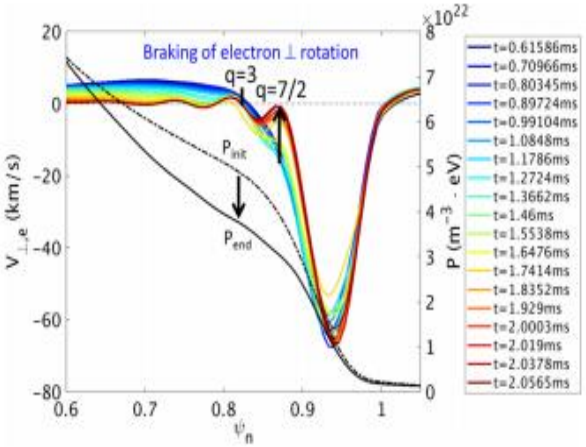
electron temperature



radial electric field well and ExB rotation



perp. electron rotation (no screening when ~zero)



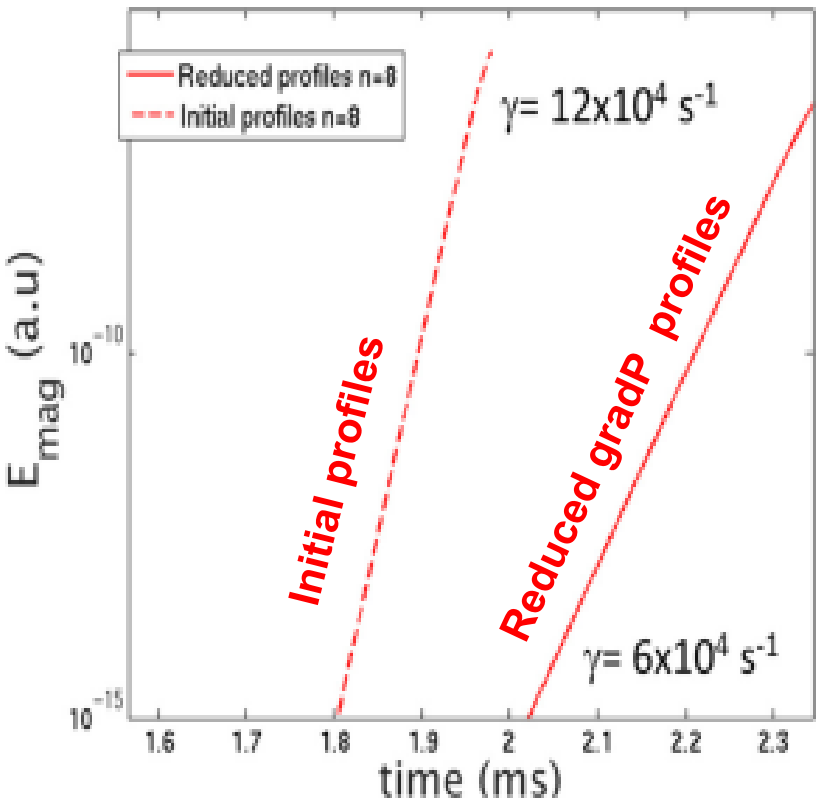
[AUG Orain Phys. Plasmas 2019]

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.

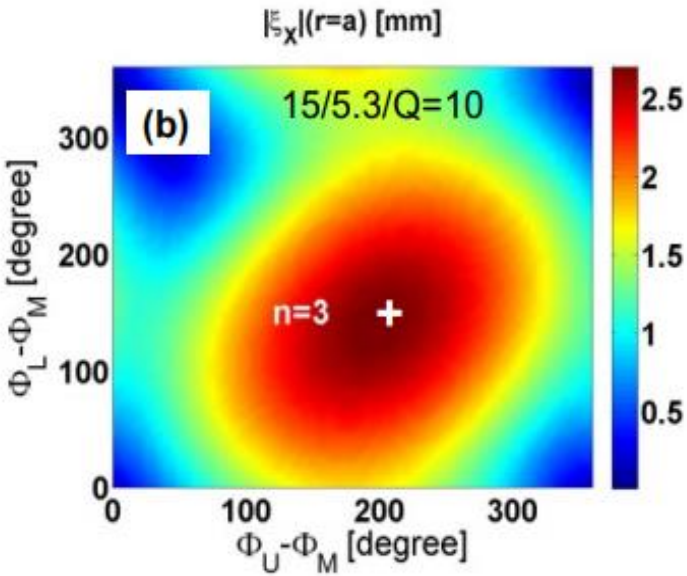
After validation of codes in existing experiments=>predictions for ITER. Non-linear resistive MHD modelling (JOREK) of ELMs suppression by RMPs in different ITER scenarios 15MA, 12.5MA, 10MA/5.3T.

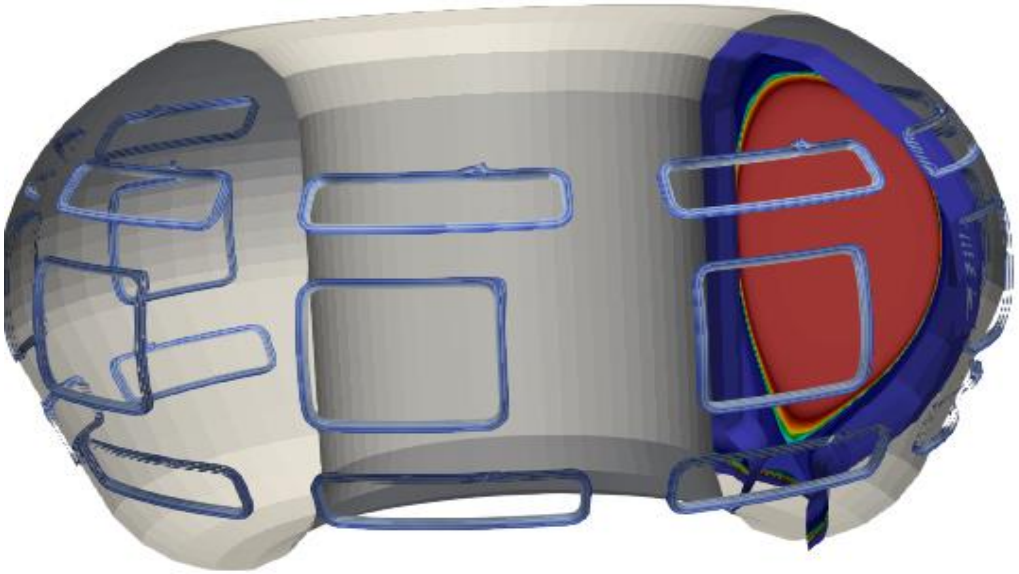
[Contract IO/19/CT/ 4300001841, Y Q Liu , M Becoulet IAEA FEC 2021]

Optimisation of spectrum (N) and phasing of RMP coils for maximum kink-peeling 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.

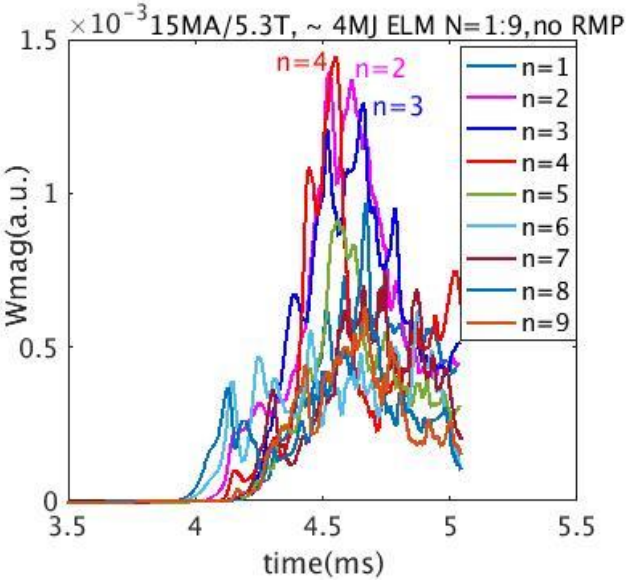
ITER: 3 rows of 9 in-vessel RMP coils, max 90kAt.

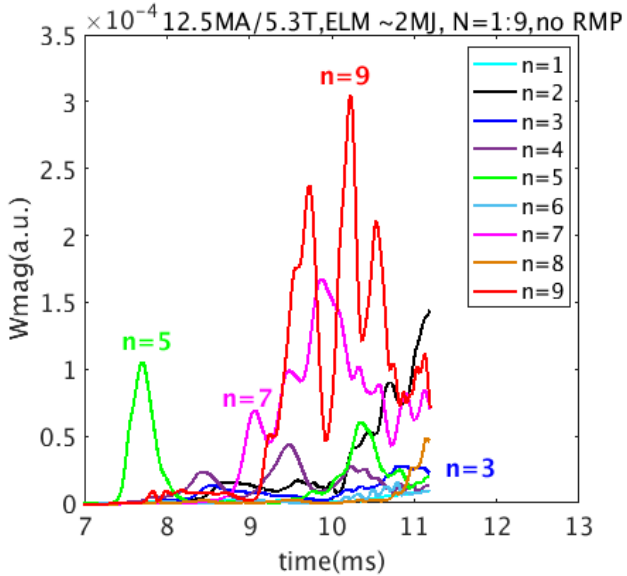


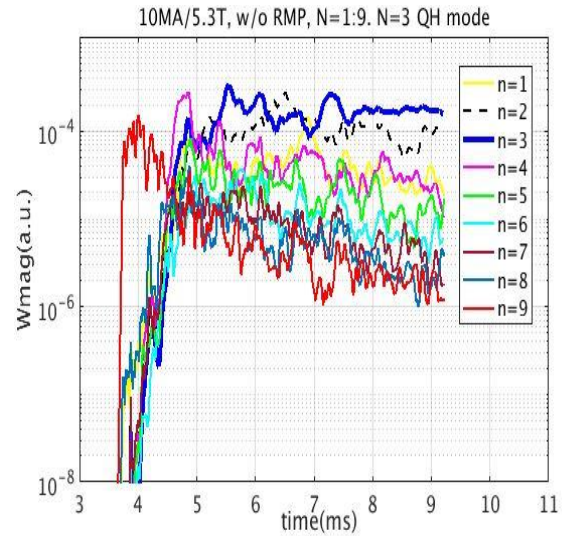


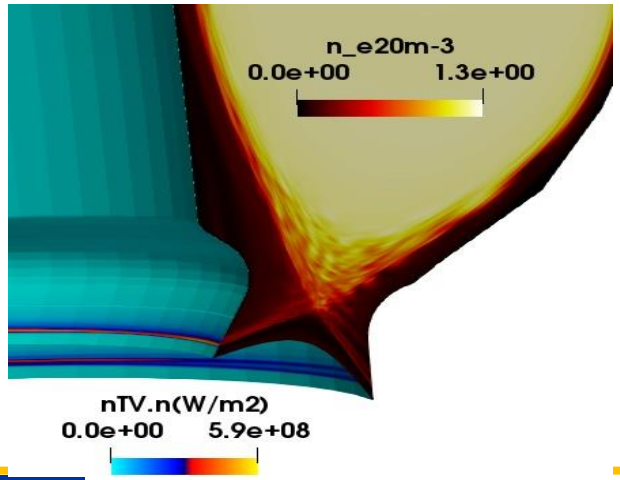
Natural ELMs w/o RMPs (toroidal harmonics N=1:9).

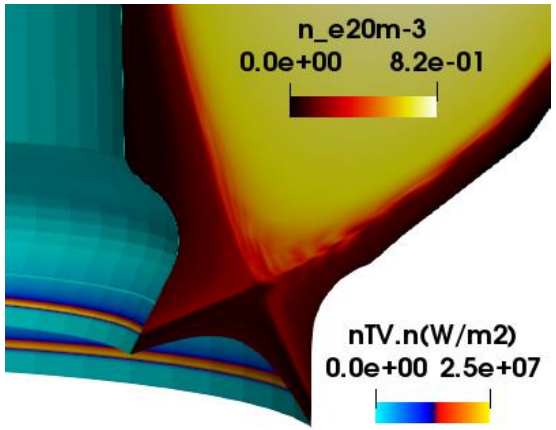
- 15MA/5.3T: low N-s (N=2,3,4) are most unstable;
- 12MA/5.3T: N=5 precursor, then N=9,7 are most unstable;
- 10MA /5.3T (high beta) : natural N=3 rotating (el dia) QH-mode

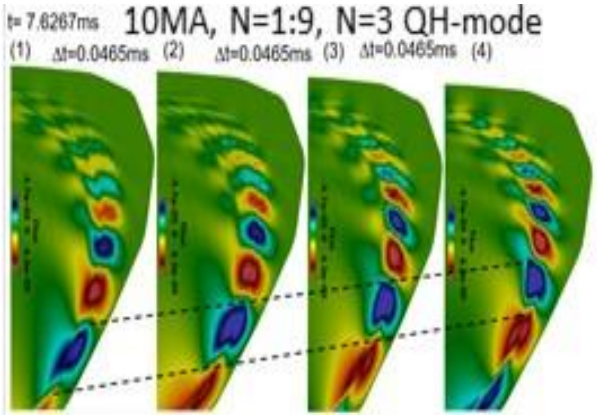




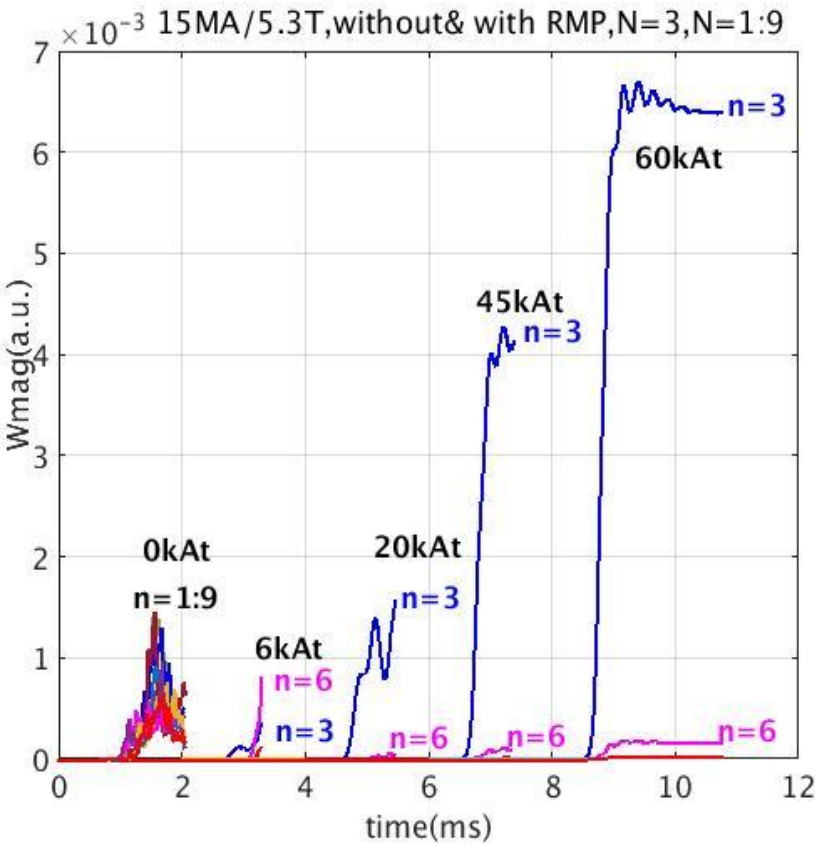


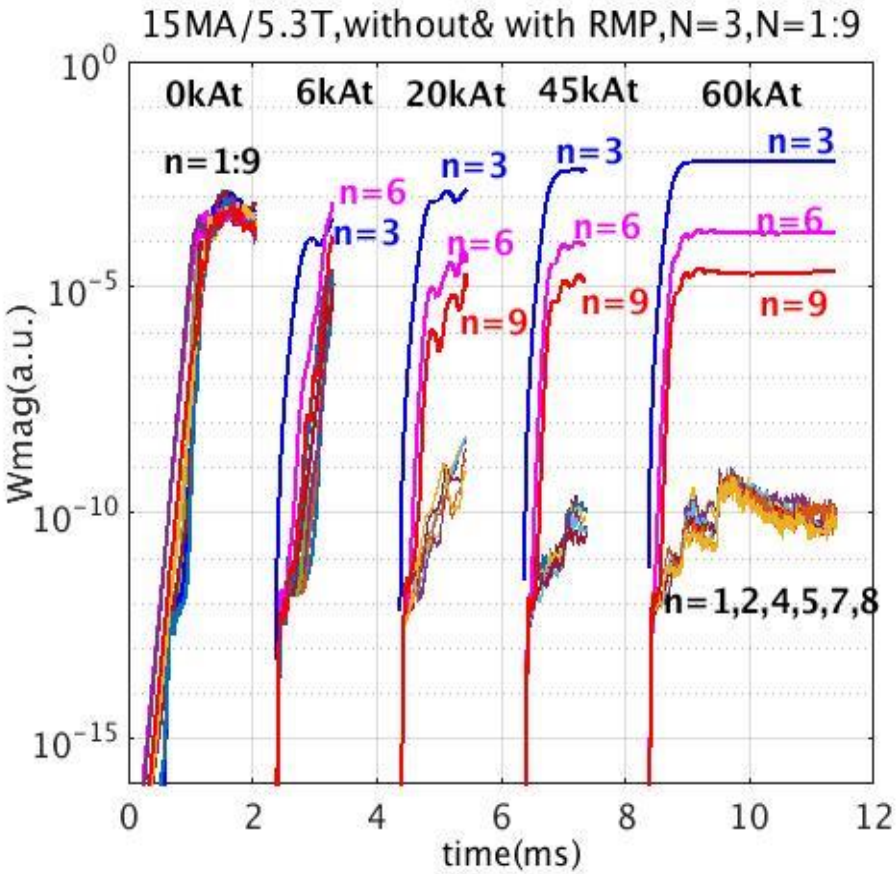




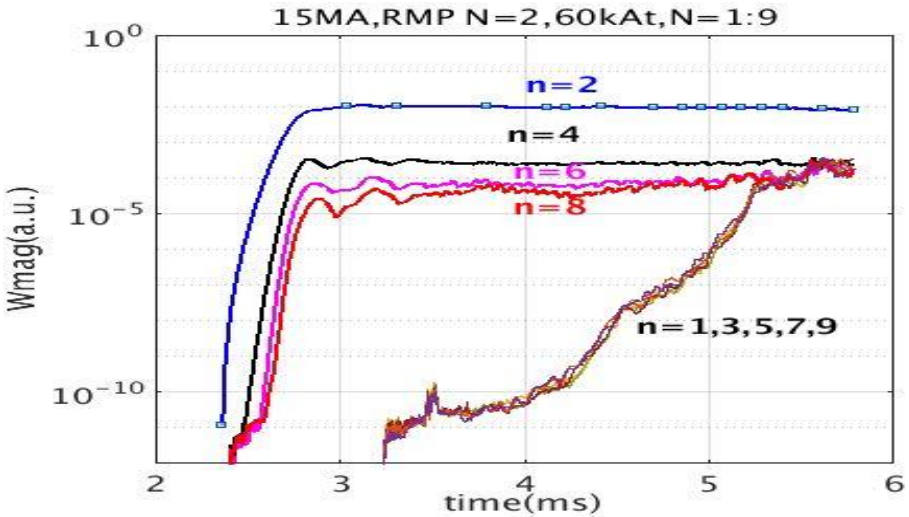


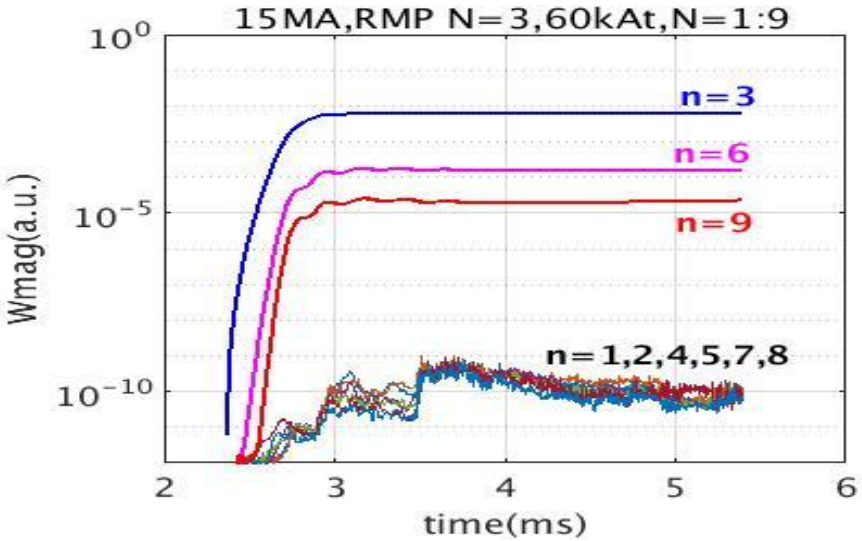
15MA/5.3T scenario, RMP N=3. ELMs (here N=1:9 harmonics) suppression threshold: maximum current in RMP coils 45-60kAt. Coils max capacity 90kAt.

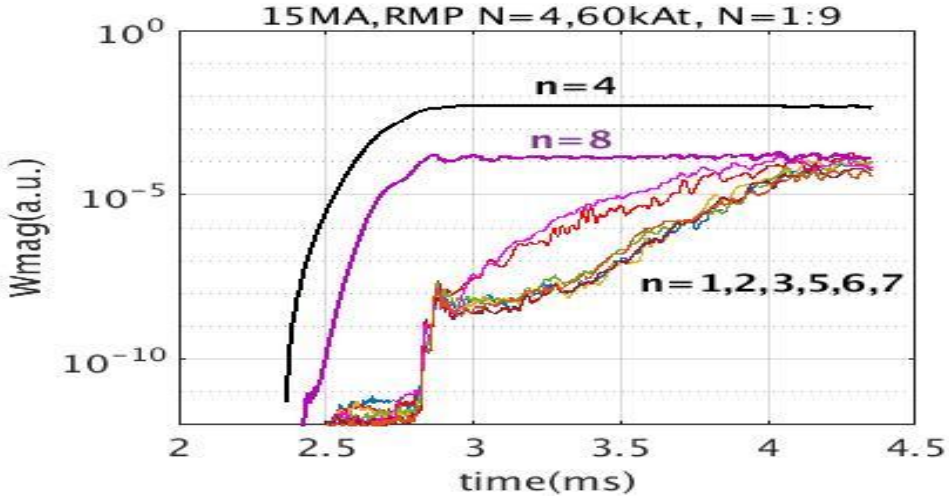




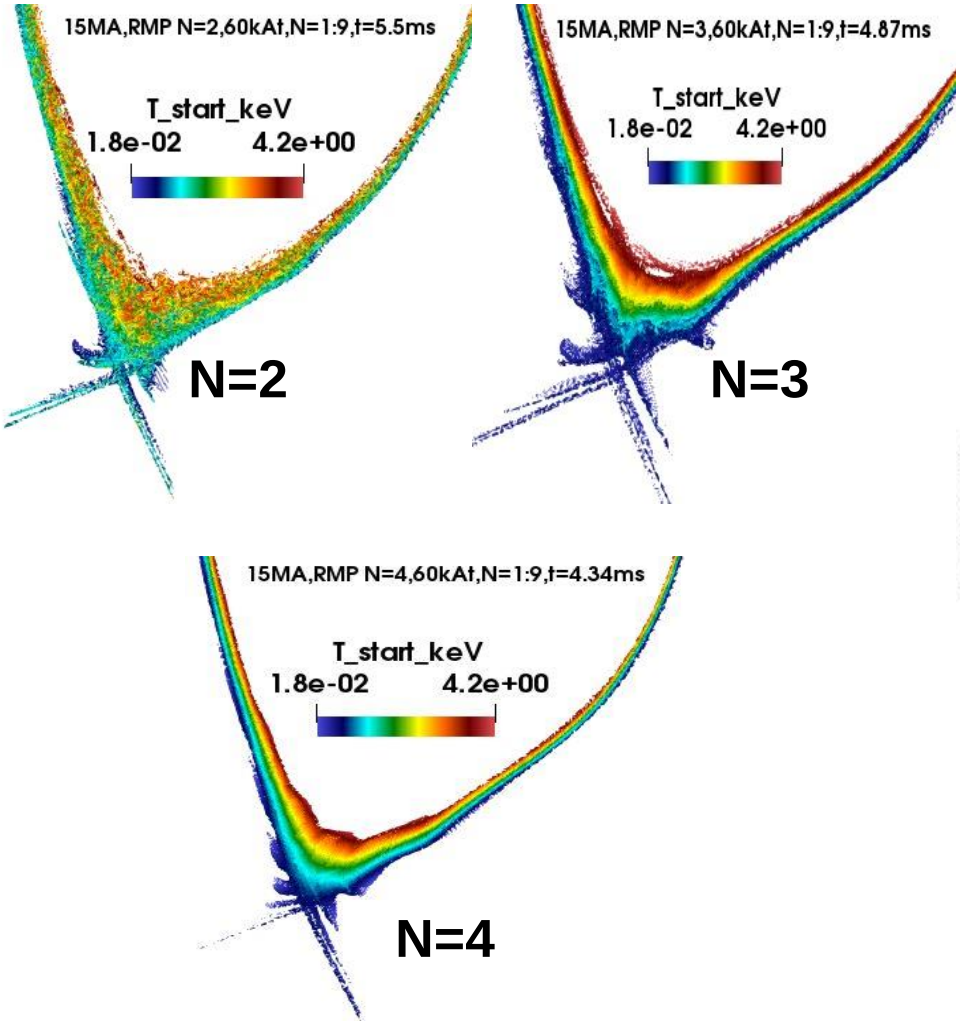
15MA/5.3T scenario, RMP N=2,3,4, 60kAt. ELMs are suppressed. MHD coupled to main RMP N + side harmonics k*N, other harmonics saturates at low level. Note similarity to AUG,KSTAR,EAST modelling results.

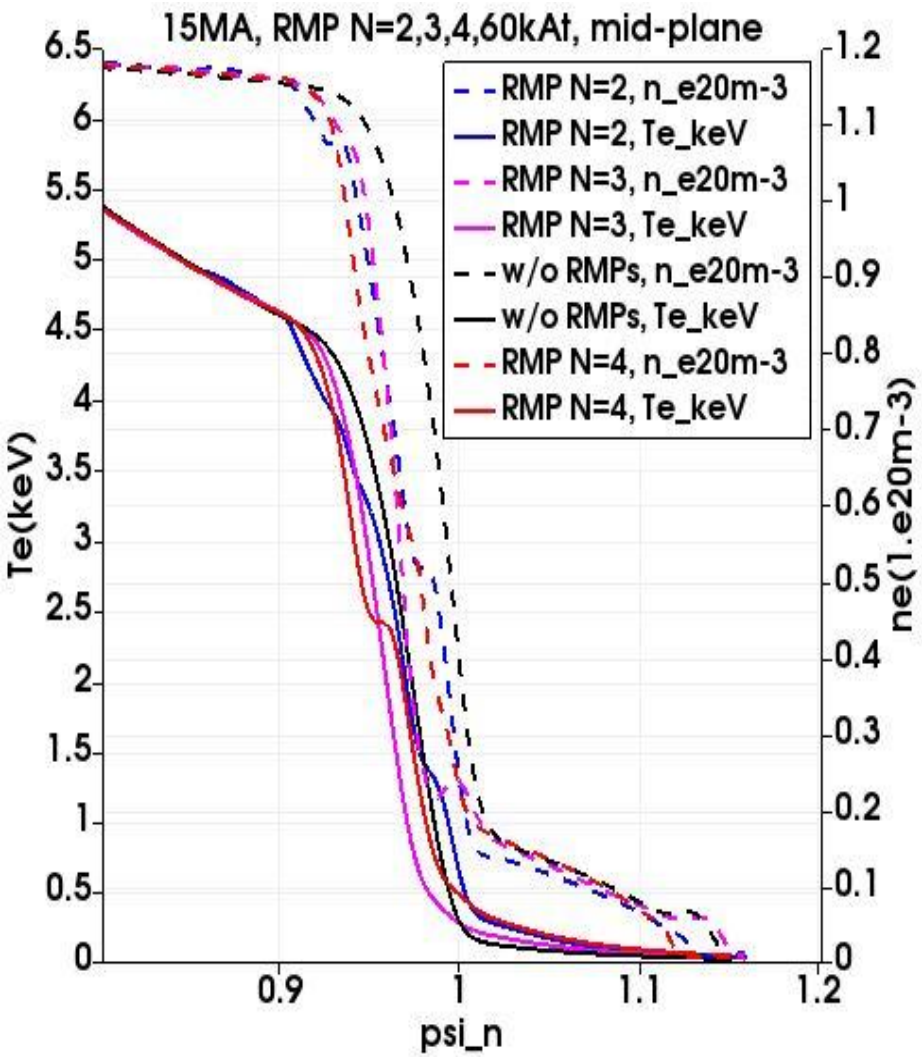




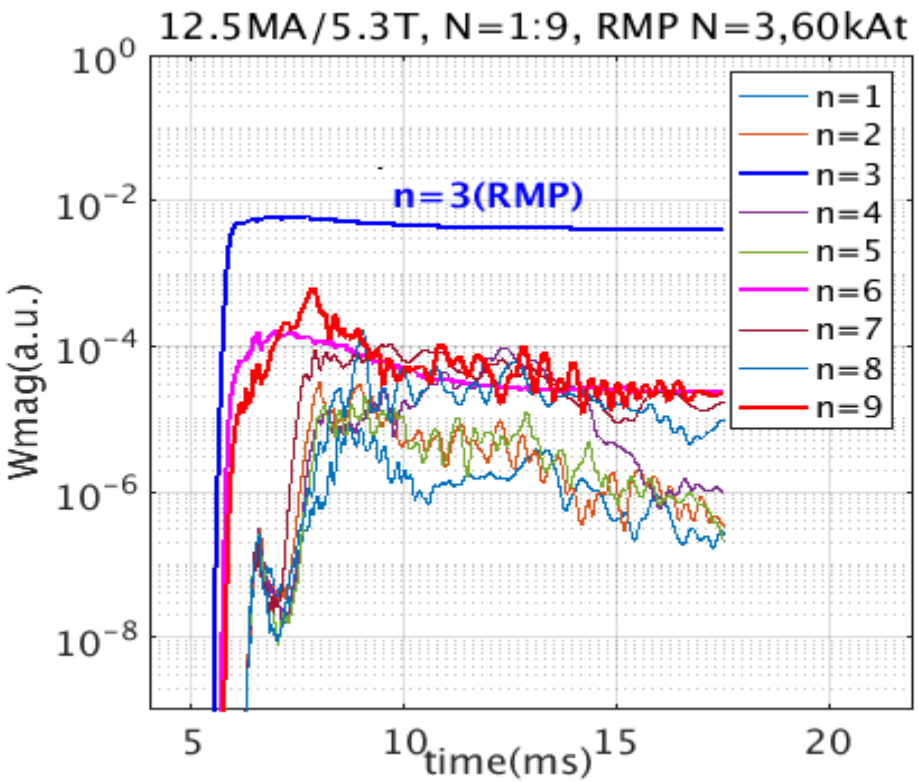


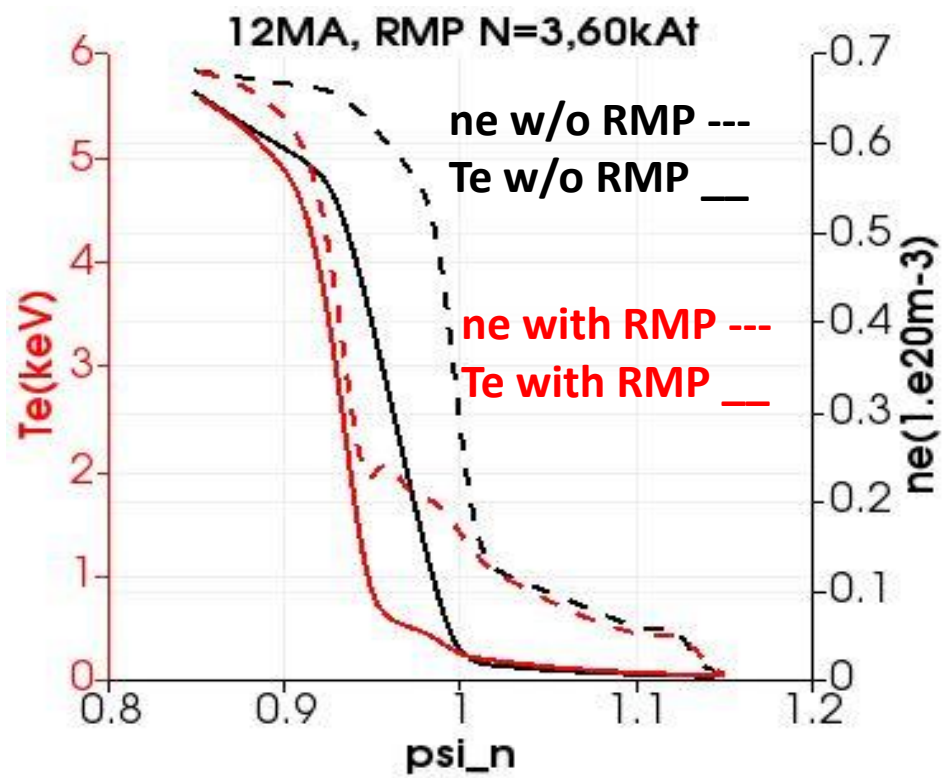
15MA/5.3T scenario, RMP N=2,3,4, 60kAt. Edge magnetic topology and profiles in ELM suppressed phase: density (ne) transport (here convective ExB and //), energy (Te) transport (// conductive along perturbed field lines).



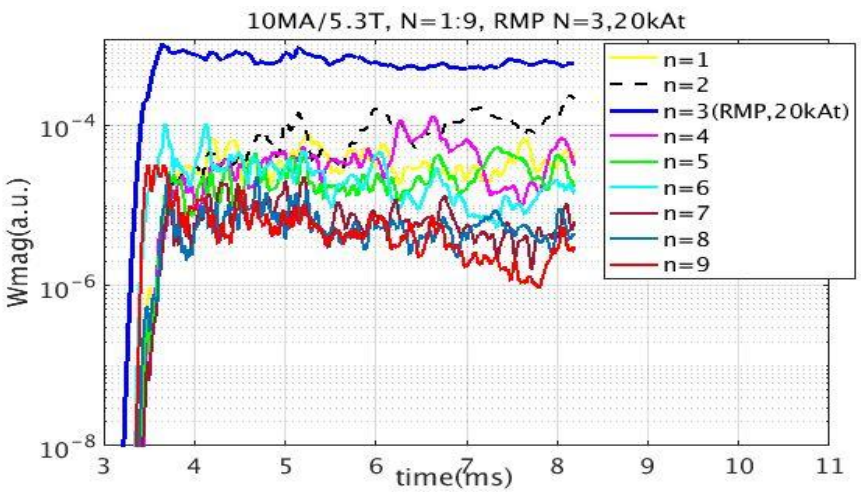


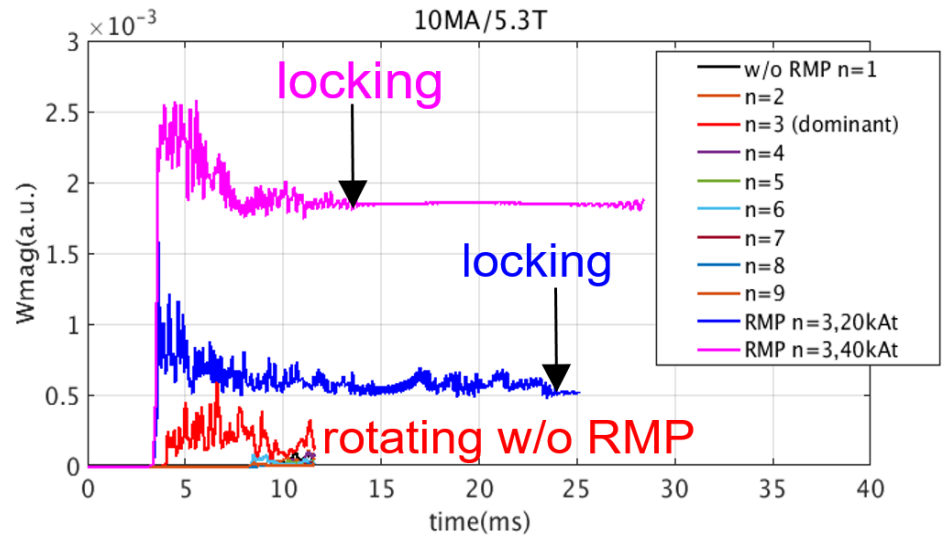
12.5MA/5.3T scenario, ELMs suppression by RMP N=3, 60kAt. Profiles: more density(ne) transport compared to energy (Te)

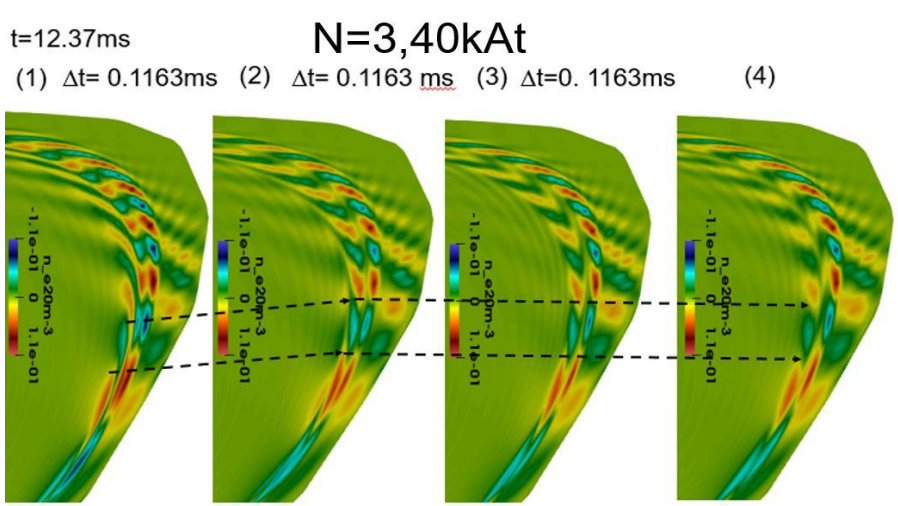


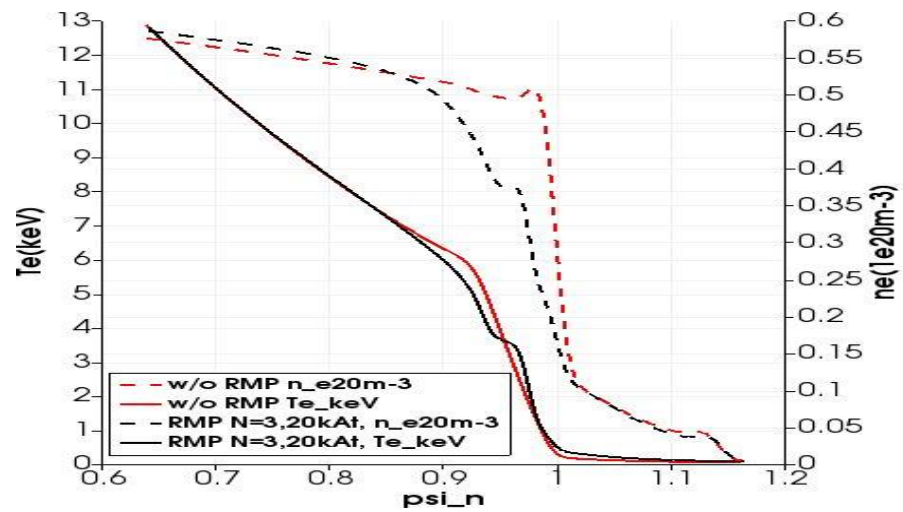


In high beta steady state 10MA/5.3T scenario w/o RMPs: natural N=3 rotating in el dia direction QH mode. With RMPs N=3 (20kAt,40kAt): induced QH mode, locking to static RMPs (earlier for higher RMP current). Density transport mainly (not much in Te)

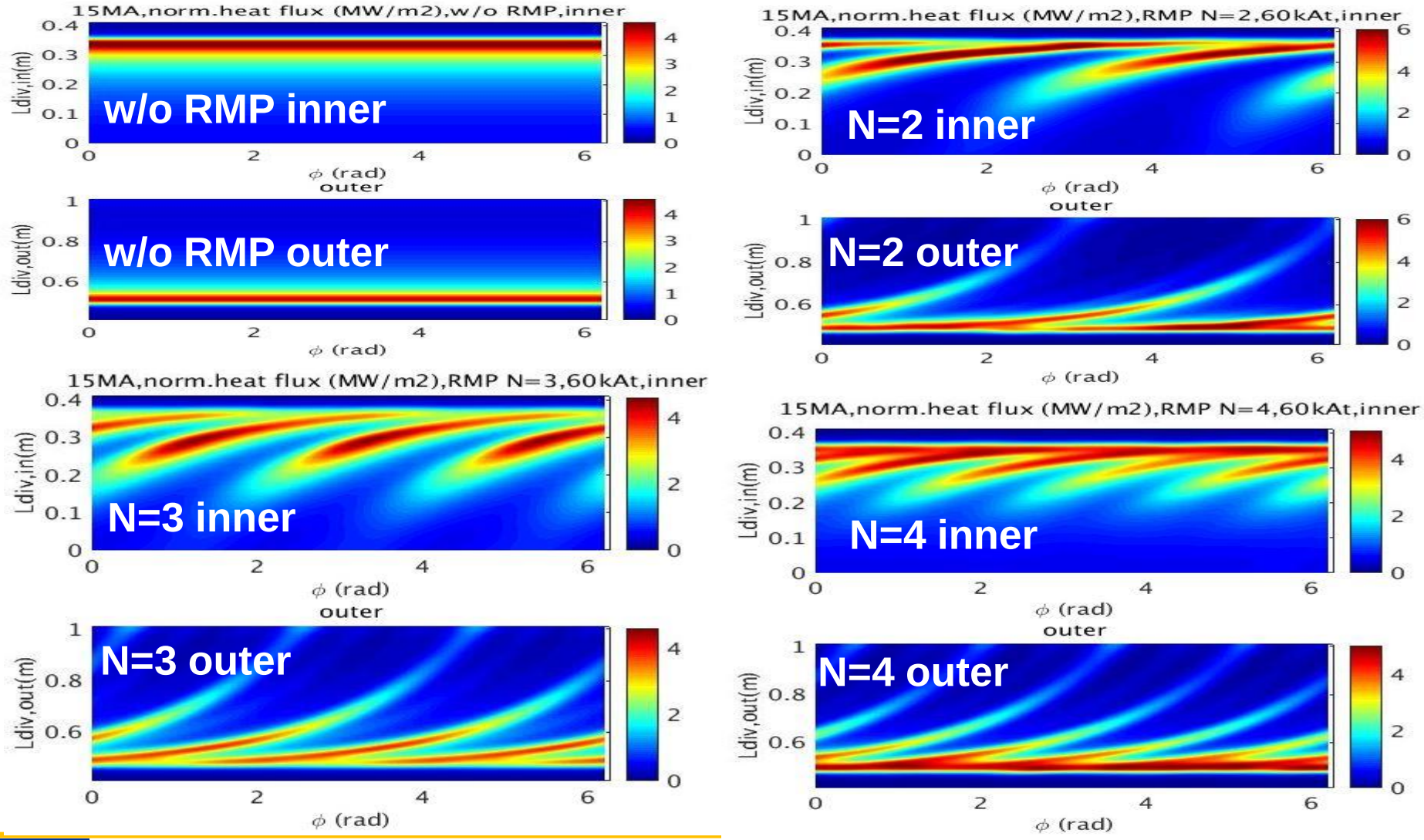




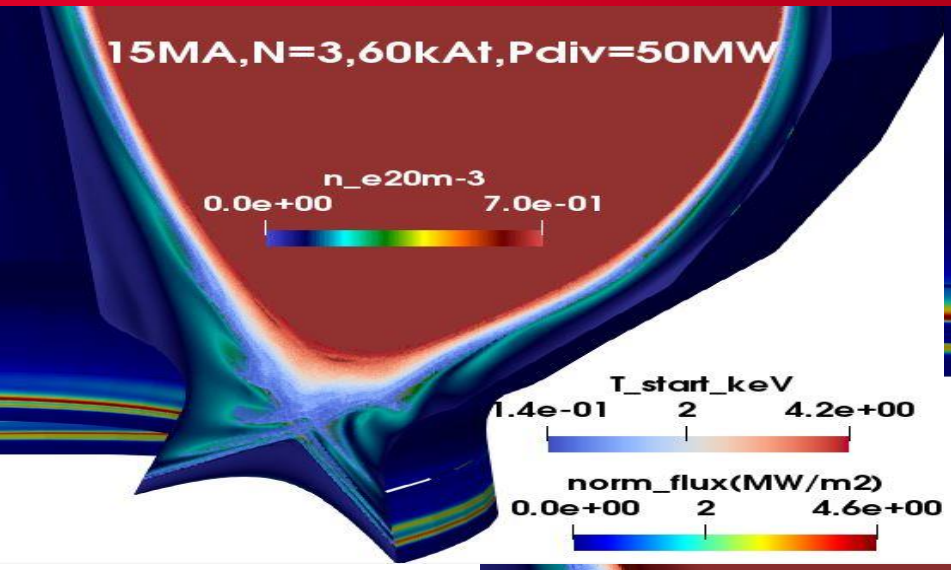


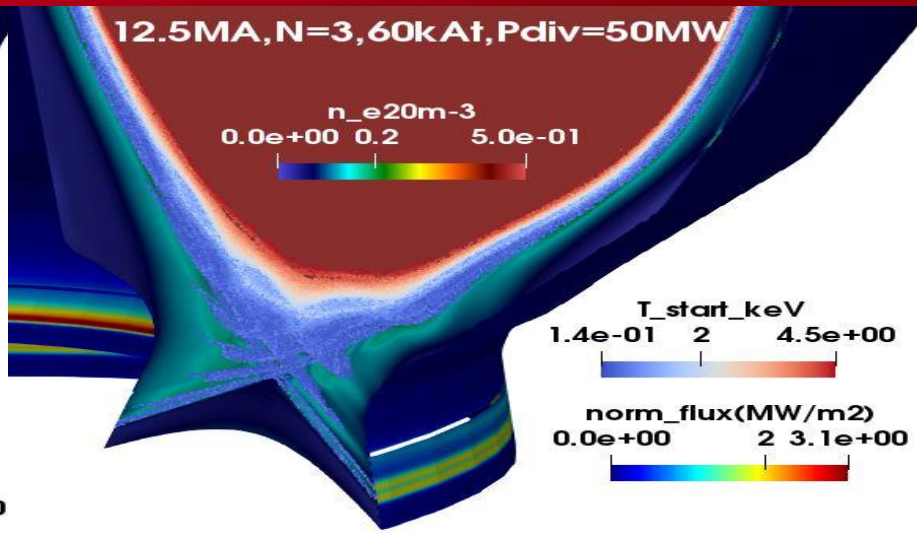


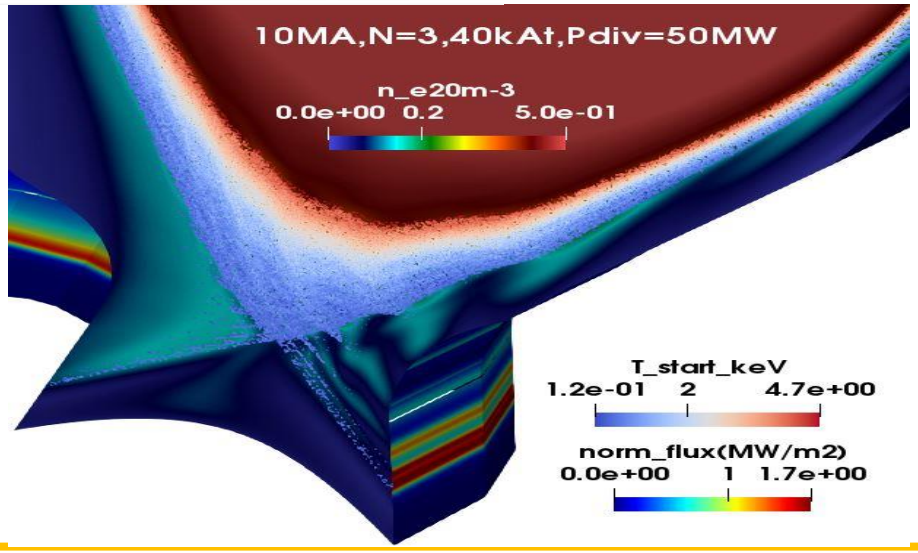
15MA/5.3T, RMP N=2,3,4 60kAt. 3D SOL. Normalized stationary heat flux (50MW in divertor). Toroidal splitting with N of RMPs, radial extension is ~20 cm inner divertor and ~40cm in outer.



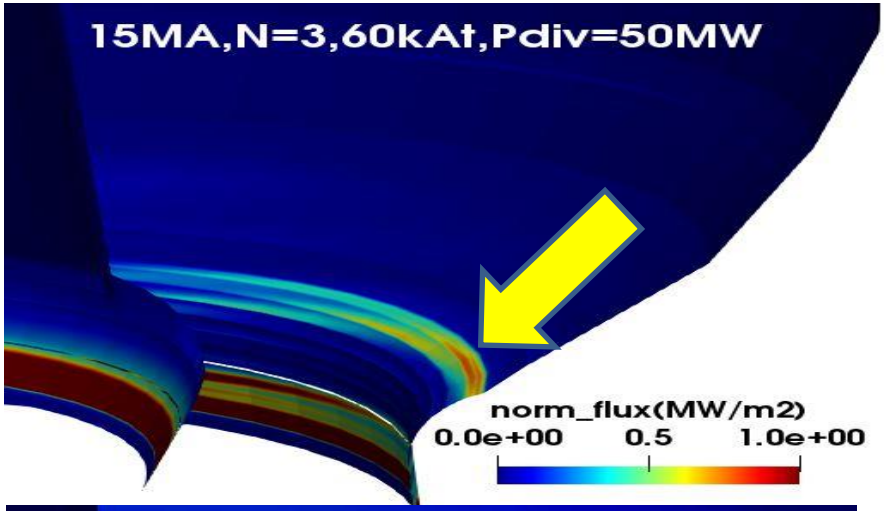
Normalized stationary heat flux in divertor (*total heating power ~100MW, 50MW is supposed to be radiated –not in this modelling, 50MW in divertor***): 5-2 MW/m2. Scenarios: 15MA, 12.5MA,10MA/5.3T, RMP N=3, 60kAt.**

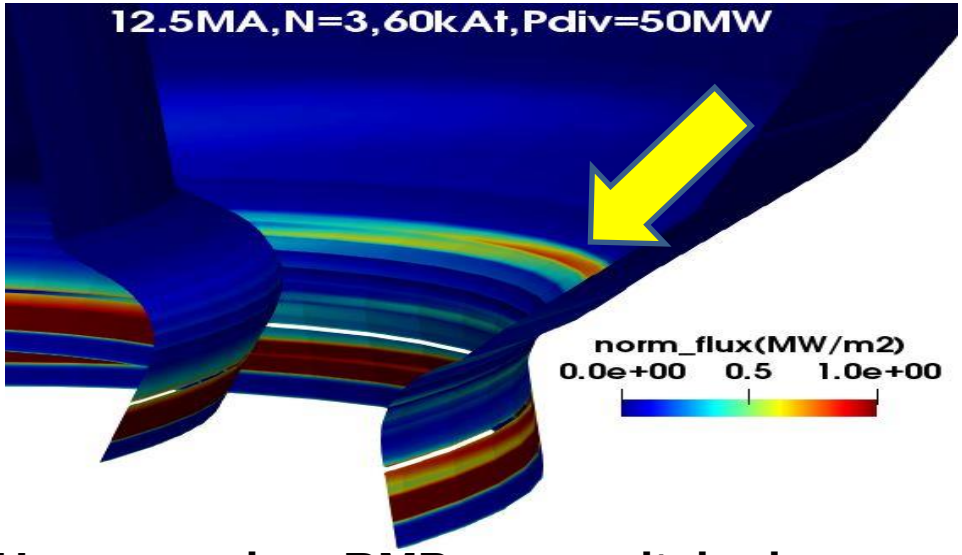


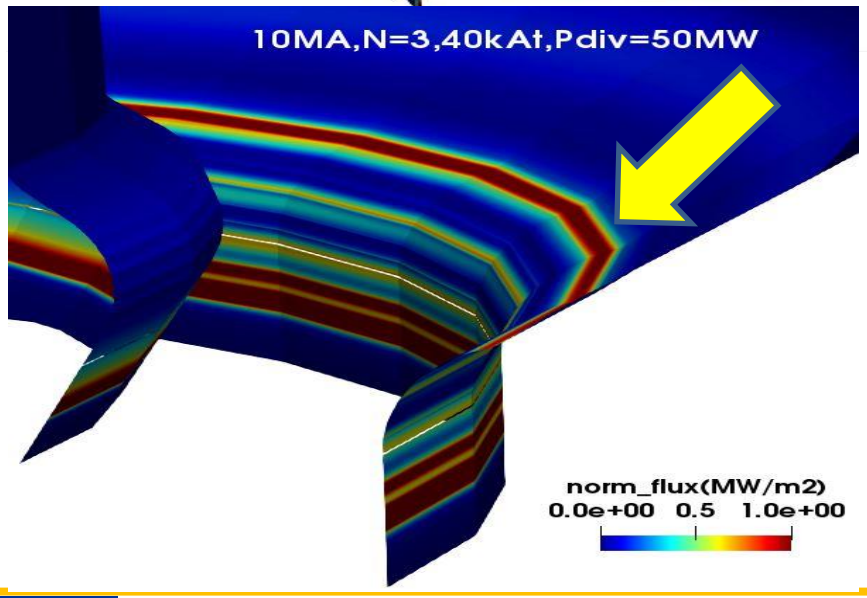




Stationary heat fluxes (50MW in divertor) with RMPs remain within limits for divertor target (5-6MW/m2<10MW/m^2), baffle (1MW/m2< 5 MW/m^2) and first wall (<1MW/m^2).





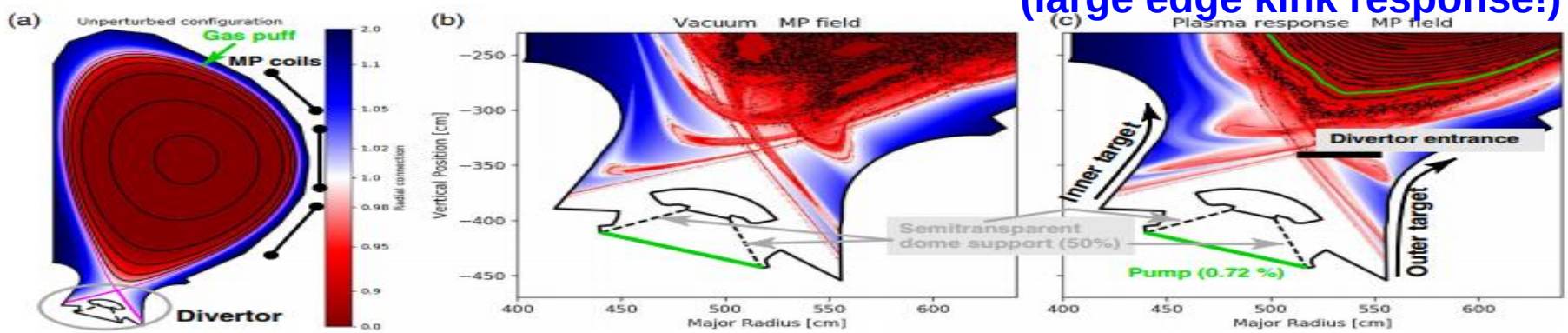


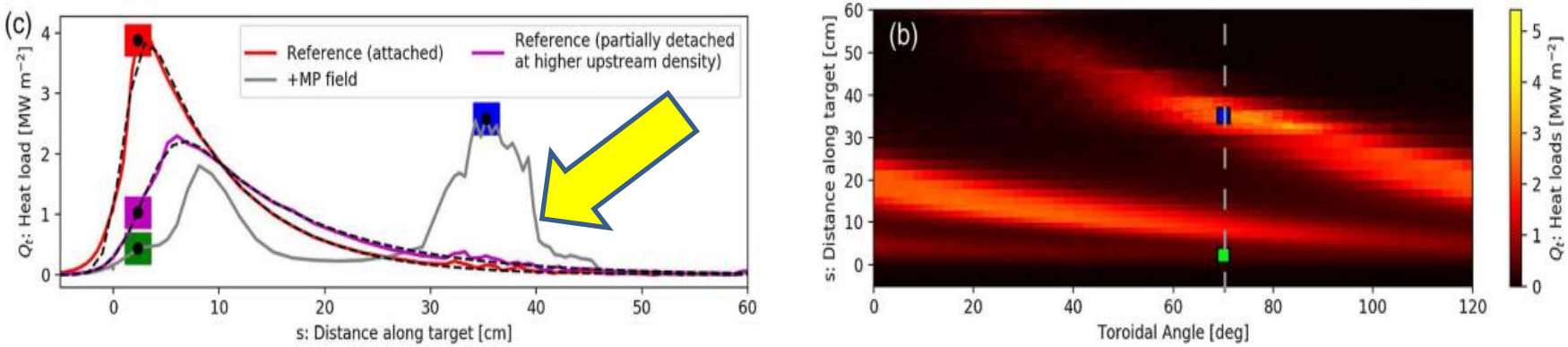
However when RMPs are switched on => transient increase of heat fluxes. Solution? Switching RMP before L/H transition? Gas/impurities injection? Radiation? Note that in these results the main divertor physics : neutrals, ionizaton, radiation... are missing=> work in progress. Divertor physics is needed!

Divertor physics 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!)**





Discussion.

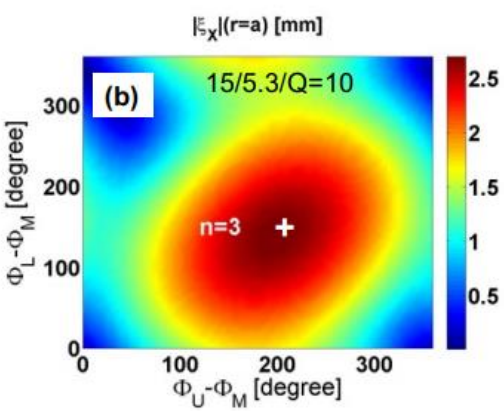
Why narrow q95 window for ELM suppression?

Criterion with MHD plasma response (IPEC,GPEC,MARS-F, JOREK): special RMP alignment with magnetic field=> <u>kink-peeling response can be achieved in specific q95 window or RMP phasing optimization</u>. Tested in many experiments. *However, no X-point in linear MHD (stabilizing for kink-mode) , ELMs+RMPs can be modelled only with non-linear MHD, but at present still large resistivity for ITER(*100).*

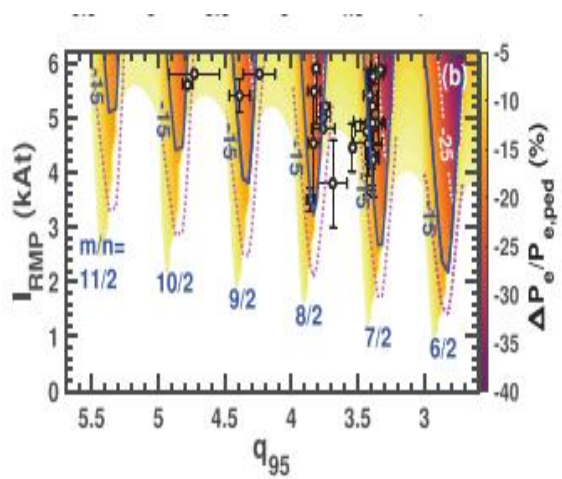
Two fluid resistive non-linear circular MHD with polarization current (TM1 code) : density 'pump-out' near <u>islands at pedestal foot and top</u> (achieved at special q profile=>q95 window) , gradP is reduced. Tested in many experiments. Larger q95 window for N=4 in ITER. *However, ELMs can't be modelled, no toroidal coupling (circular), should be compared with toroidal codes, work in progress.*

[Q M Hu PoP2021,NF 2021 accepted]

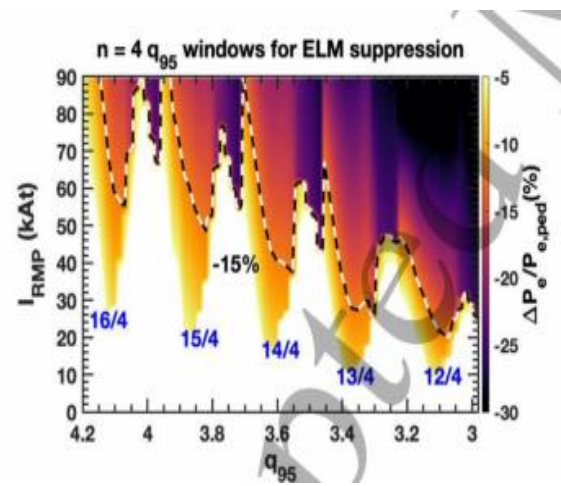
MARS-F for ITER



TM1 for KSTAR. N=2



TM1 for ITER. N=4



Discussion.

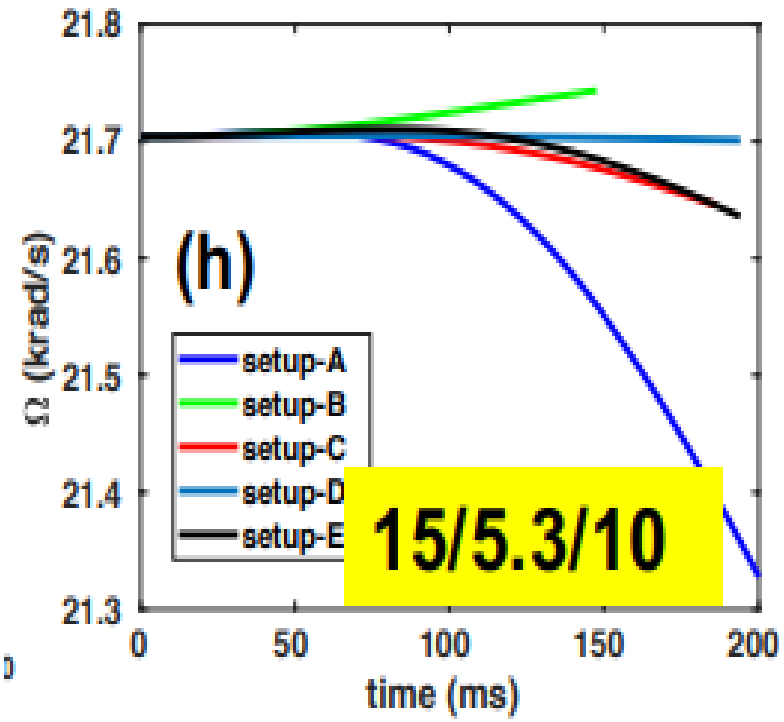
Why toroidal rotation braking? Why density pump-out (note: not always= ELM suppression)? Neoclassical Toroidal Viscosity (NTV).

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

Neoclassical Toroidal Viscosity (NTV): drift of particles in 3D fields (radial current) => pump-out of density and braking of rotation (resonant-local and non-resonant-global)? NTV regimes strongly depend on plasma collisionality.

Drift kinetic equations for trapped + passing particles in 3D fields, but at present mainly simplified analytical formulas coupled to MHD codes, more validation with experiment is still needed [Shaing PoP2003, Becoulet NF2009, Sun PhysRev Let 2010, Logan PoP2013 etc…] .

MARS-Q : NTV for ITER –moderate rotation braking, 15MA/5.3T, N=3,60kAt [*Y Liu, IAEA 2021]*

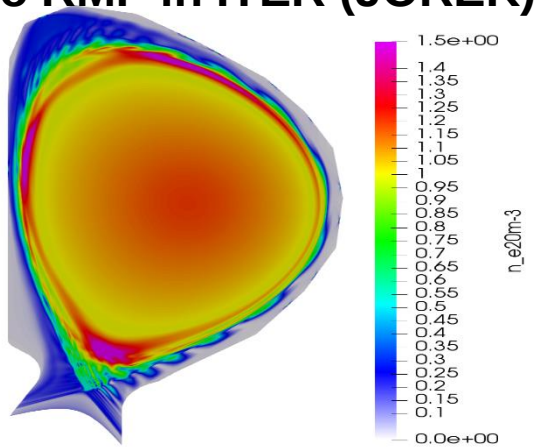


Discussion.

Fueling by pellets in ITER with RMPs: how not to trigger ELMs?

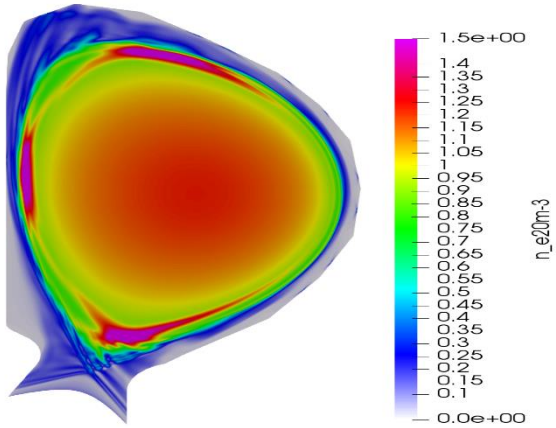
Fast particles (alphas, NBI) loss due to RMP fields?

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



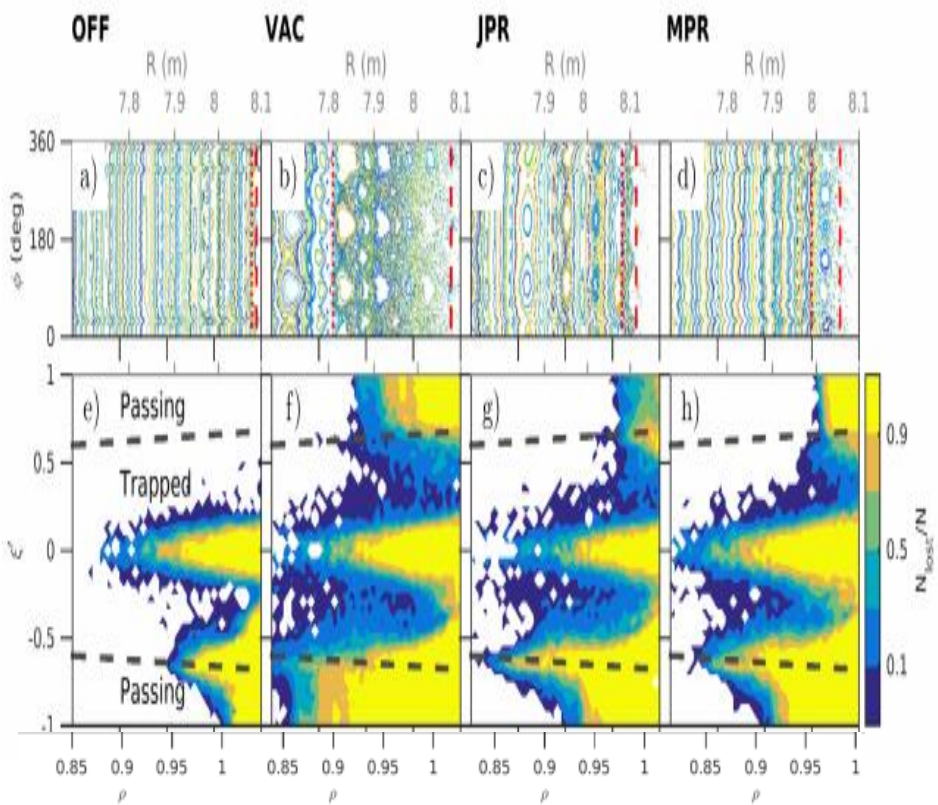
[JOREK, Curtesy to S. Futatani]

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



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]

Discussion.

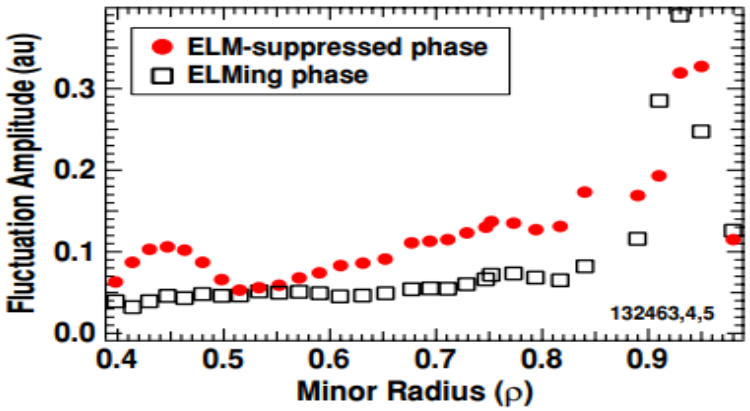
Turbulence increases with RMPs: reason or consequence for density pump-out?

1) ExB decreases => destabilizing for turbulence.

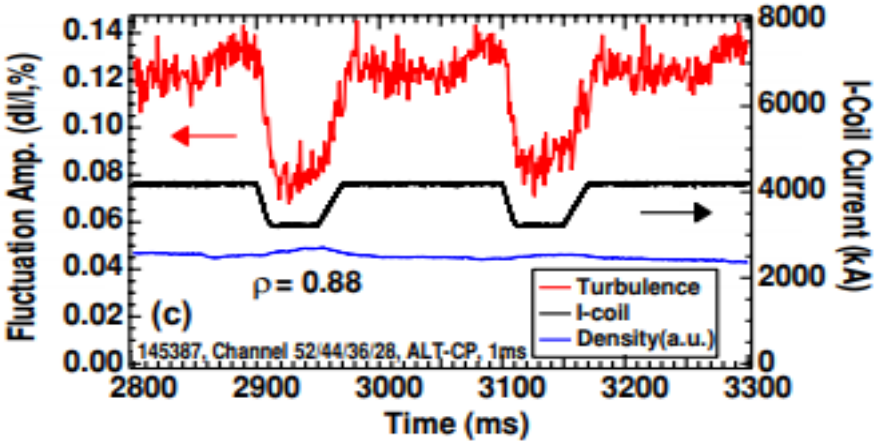
2) Fast (ms) change of RMPs =>fast response in turbulence w/o pump-out.

Increase of fluctuations with RMPs

[DIIID,BES,McKee NF2013]

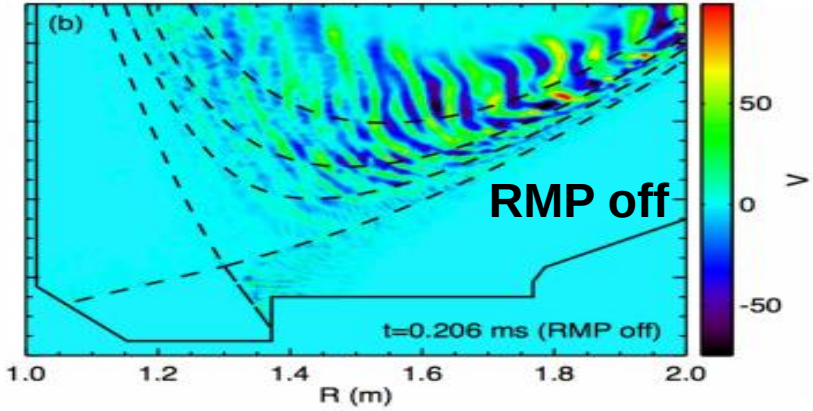


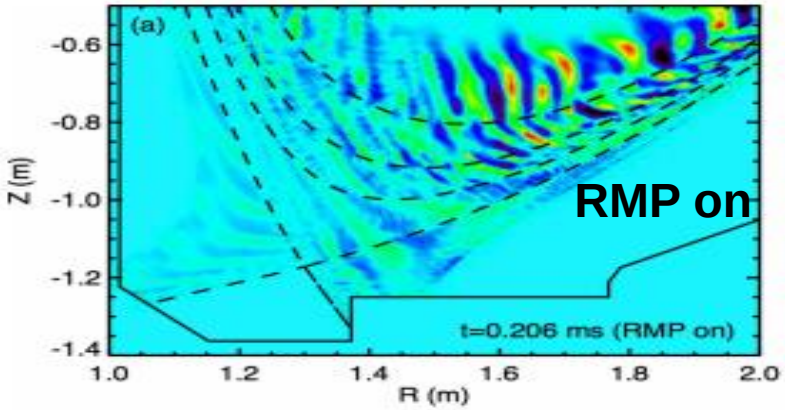
fast increase of turbulence with RMPs, but no density pump-out



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]





Conclusions

1. **Synergy between experiment, theory, modelling and computer science for ITER.**

2. **Physics of Resonant Magnetic Perturbations for Edge Localized Modes control.**

- **From existing experiments to ITER:** ***non-linear MHD, realistic toroidal geometry (divertor, RMP coils, wall), two fluid diamagnetic effects, toroidal rotation, multi-harmonics – minimum model for modelling of ELMs and ELMs suppression by RMPs. Response currents on q=m/n, screening/amplification, self-consistent evolution of plasma profiles. RMPs non-linearly generate continuous MHD turbulent transport stabilizing large ELMs in ITER: 15MA,12.5MA,10MA/5.3T. The RMP spectra at N=2,3,4, threshold :45-60kAt (coils capacity 90kAt). Similar to ELM suppression modelling in AUG,KSTAR, EAST.***
- **ELM suppression criterion with plasma response :** ***kink-peeling response (max displacement at X-point): q95 or/and RMP coils phasing can be optimized for it. Good for ITER –independent power supplies for RMP coils.***
- **The 3D divertor heat and particle fluxes splitting *with toroidal N of RMPs.*** ***The 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!***

3.* Discussion on related physics of RMPs*: polarization, NTV –candidates for + to ExB density pump-out, pellets with RMPs , fast ions losses, increase of turbulence with RMPs.

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:

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

Mass density:

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

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

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

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

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

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

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