Max-Planck-Institut für Plasmaphysik

Interplay between ELMs and Resonant Magnetic Perturbations in ASDEX Upgrade

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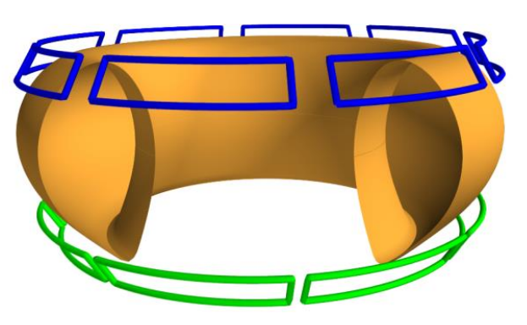
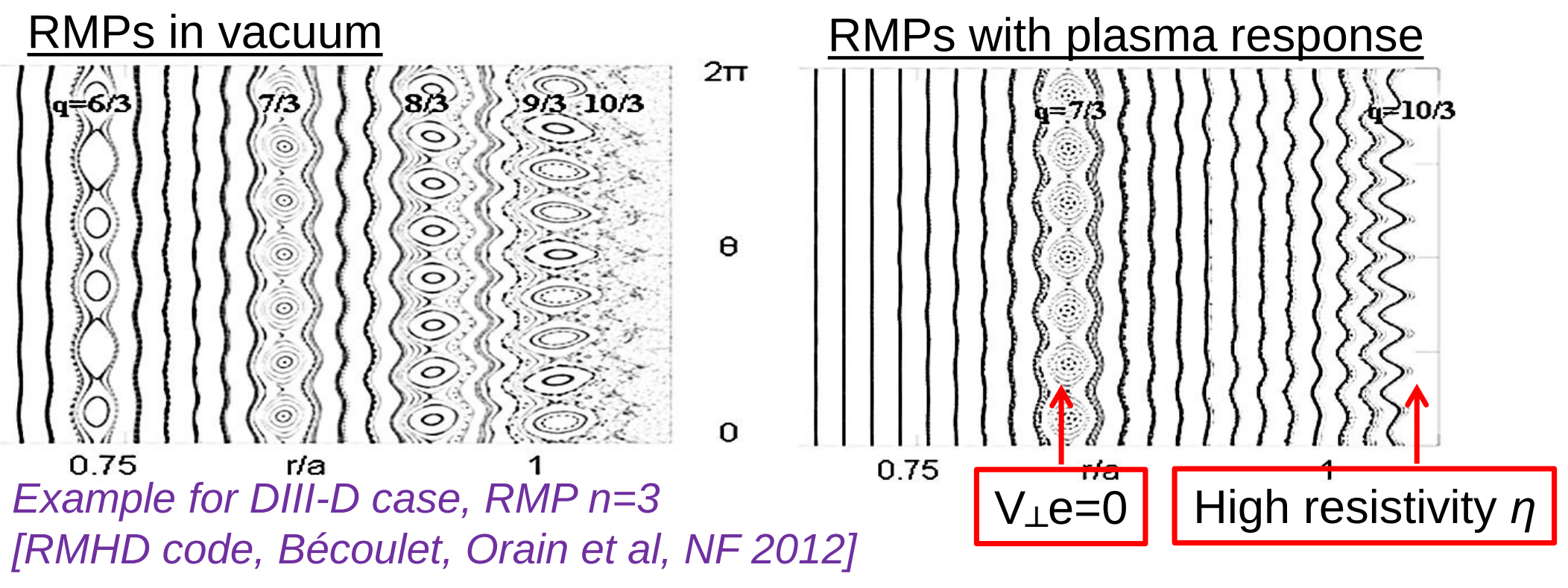
1/ Motivation

- Edge Localized Modes (ELMs) : Peeling-Ballooning (P-B) instabilities
  → needs better understanding of dynamics
  → mandatory control in ITER
- Promising control method: application of non-axisymmetric Resonant Magnetic Perturbations (RMPs)
- Plasma response to RMPs not fully understood:
  RMPs screened or amplified by plasma flows
  Screening: explanation: Ohm's law ⇒ $\eta J_{nm}=-b^r_{nm}(V_{E,\theta}+V^e_{p,\theta})$
  perpendicular electron flow screens RMPs



AUG RMP coils [Ryan PPCF15]



Example for DIII-D case, RMP n=3 [RMHD code, Bécoulet, Orain et al, NF 2012]

"Kink response": **amplification** of stable peeling-kink modes by RMPs

Aims:

➔ better understanding of resonant (tearing) and kink responses of the plasma
→ effect on ELMs?

➔ explain features observed in experiments + predictive capabilities for ITER.

2/ JOREK simulations: model and input

- JOREK: resistive reduced MHD model with two-fluid effects: *[Huysmans PPCF 2009, Orain PoP13]*

Ohm's law:
$$\frac{1}{R^2}\frac{\partial\psi}{\partial t}=\eta\frac{J}{R^2}-\vec{B}\cdot\left(\nabla_\parallel u\boxed{+\frac{\tau_{IC}}{\rho}\nabla_\parallel p}\right)$$

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

Parallel momentum:
$$\vec{B}\cdot\left\{\left[\rho\left(\frac{\partial}{\partial t}+\vec{V}\cdot\nabla\right)\vec{V}_E+\left(\frac{\partial}{\partial t}+\vec{V}\cdot\nabla\right)\vec{V}_{\parallel,i}\right]+\nabla(\rho T)+\boxed{\nabla\cdot\Pi_i^{neo}}-\vec{J}\times\vec{B}+\boxed{\vec{S}_V}-\vec{V}S_p-\nu_\parallel(\nabla\nabla)\vec{V}\right\}=0$$

Poloidal momentum (vorticity):
$$\nabla\varphi\cdot\nabla\times\left\{\left[\rho\left(\frac{\partial}{\partial t}+\vec{V}\boxed{\cdot\nabla)\vec{V}_E}+\left(\frac{\partial}{\partial t}+\vec{V}\cdot\nabla\right)\vec{V}_{\parallel,i}\right]+\nabla(\rho T)+\boxed{\nabla\cdot\Pi_i^{neo}}-\vec{J}\times\vec{B}+\vec{S}_V-\vec{V}S_p-\nu_\parallel(\nabla\nabla)\vec{V}\right\}=0$$

Temperature:
$$\frac{\partial(\rho T)}{\partial t}=-(\vec{V}_E+\vec{V}_{\parallel,i})\cdot\nabla(\rho T)-\gamma\rho T\nabla\cdot(\vec{V}_E+\vec{V}_{\parallel,i})+\nabla\cdot\left(K_\perp\nabla_\perp T+K_\parallel\nabla_\parallel T\right)+(1-\gamma)S_T+0.5V^2S_p$$

Flows included in the model:

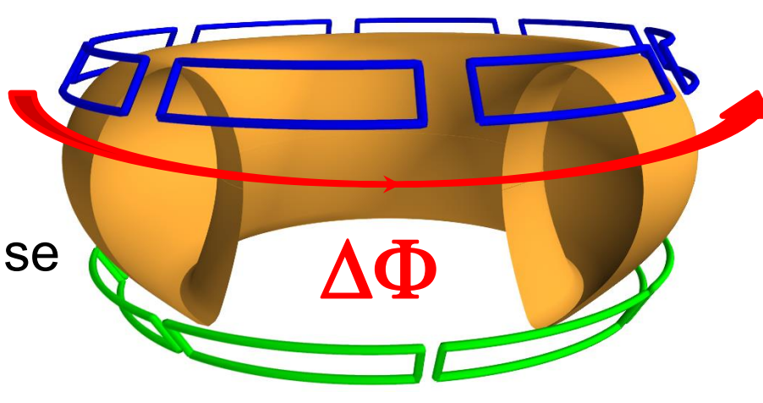
➔ ExB + diamagnetic rotation:
$$\vec{V}_i=\underbrace{-R^2\nabla u\times\nabla\varphi}_{\vec{V}_E\sim\vec{E}\times\vec{B}}\underbrace{-\tau_{IC}\frac{R^2}{\rho}\nabla p\times\nabla\varphi}_{diamagnetic}+V_{\parallel,i}\vec{B}$$

➔ Source of toroidal rotation S_V

➔ Neoclassical poloidal friction:
$$\nabla\cdot\Pi_i^{neo}\approx\mu_{i,neo}\rho(B^2/B_\theta^2)(V_{\theta,i}-V_{\theta,neo})\vec{e}_\theta$$
$$V_{\theta,i}\to V_{\theta,neo}=-k_{i,neo}\tau_{IC}(\nabla_\perp\psi\cdot\nabla_\perp T)/B_\theta$$

❖ Main numerical limitation: resistivity η≈ 10-100x $\eta_{Spitzer}$

- Input: ASDEX Upgrade discharges (#31128, #30835) ELM mitigation with n=2 RMPs
- RMP spectrum applied as boundary condition
  1/ RMP field calculated in vacuum (VACFIELD)
  2/ Applied at the boundary of JOREK domain and increased in 1000 t_A
  → penetration takes into account plasma response



Rotation of differential phase ΔΦ between upper and lower coil currents

→ change applied RMP spectrum

→ change plasma response to RMP

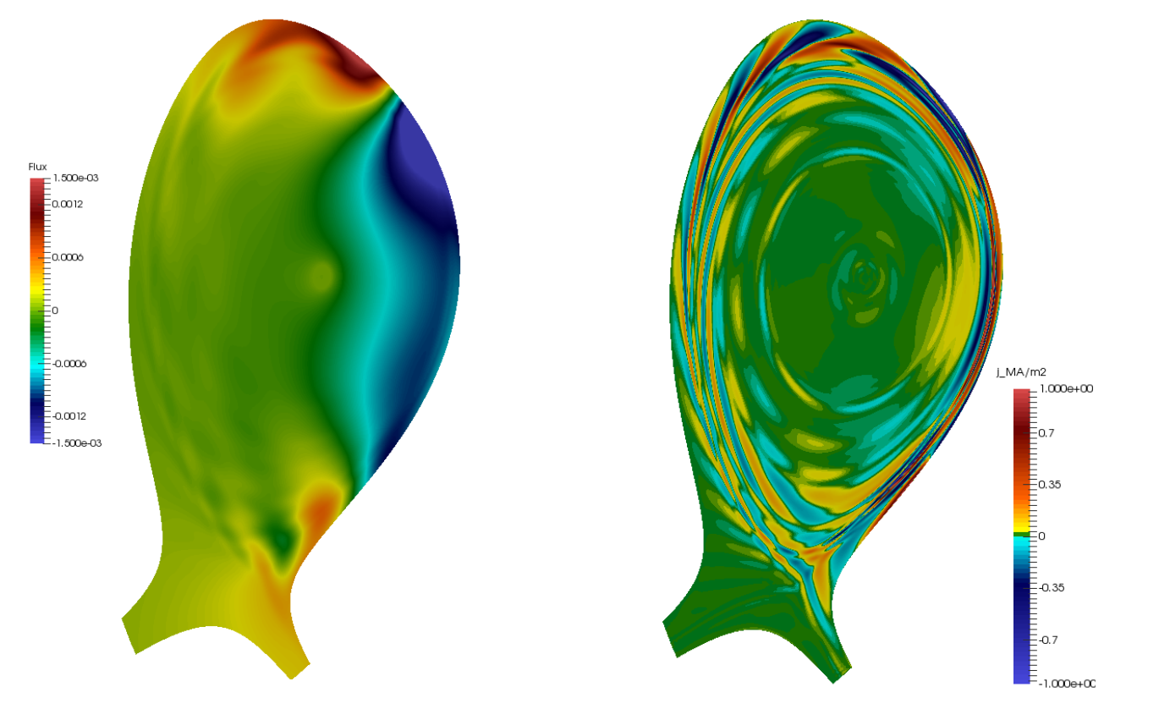
- Simulation:
  1/ Axisymmetric equilibrium from equilibrium reconstruction with CLISTE *[Dunne NF2012]*
  2/ add n≠0 modes → ELM growth without/with RMPs

3/ Plasma response to RMPs

- **General features of plasma response:**

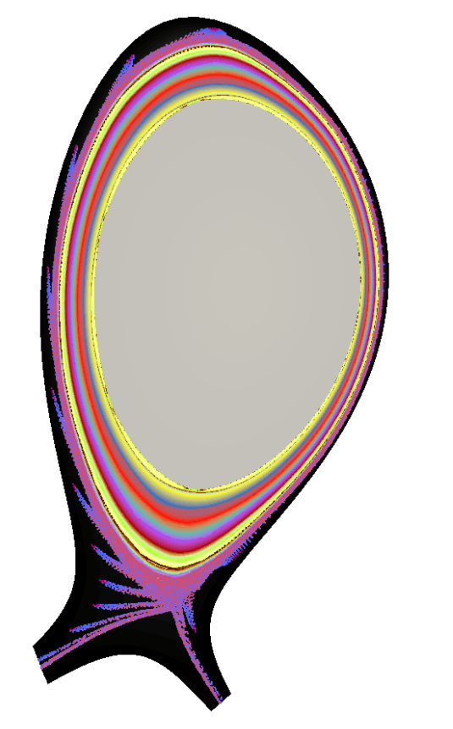
➔ Penetration of n=2 magnetic flux perturbation

➔ Response currents on resonant surfaces

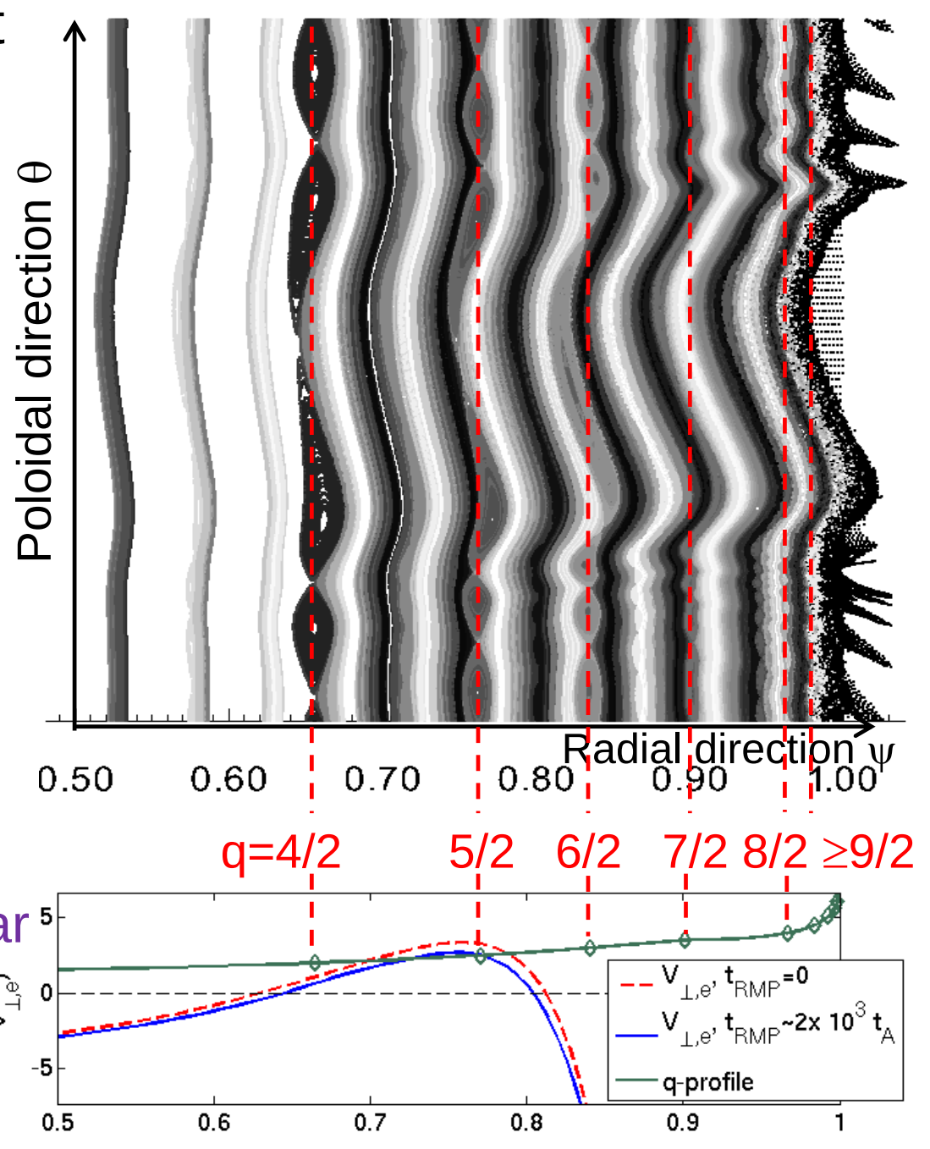


➔ Magnetic island chains induced on resonant surfaces where $V_{\perp,e}$ small + ergodic layer for ψ≥0.98

❖ RMP-induced magnetic topology:
- Edge ergodic layer
- Lobe structures near X-point

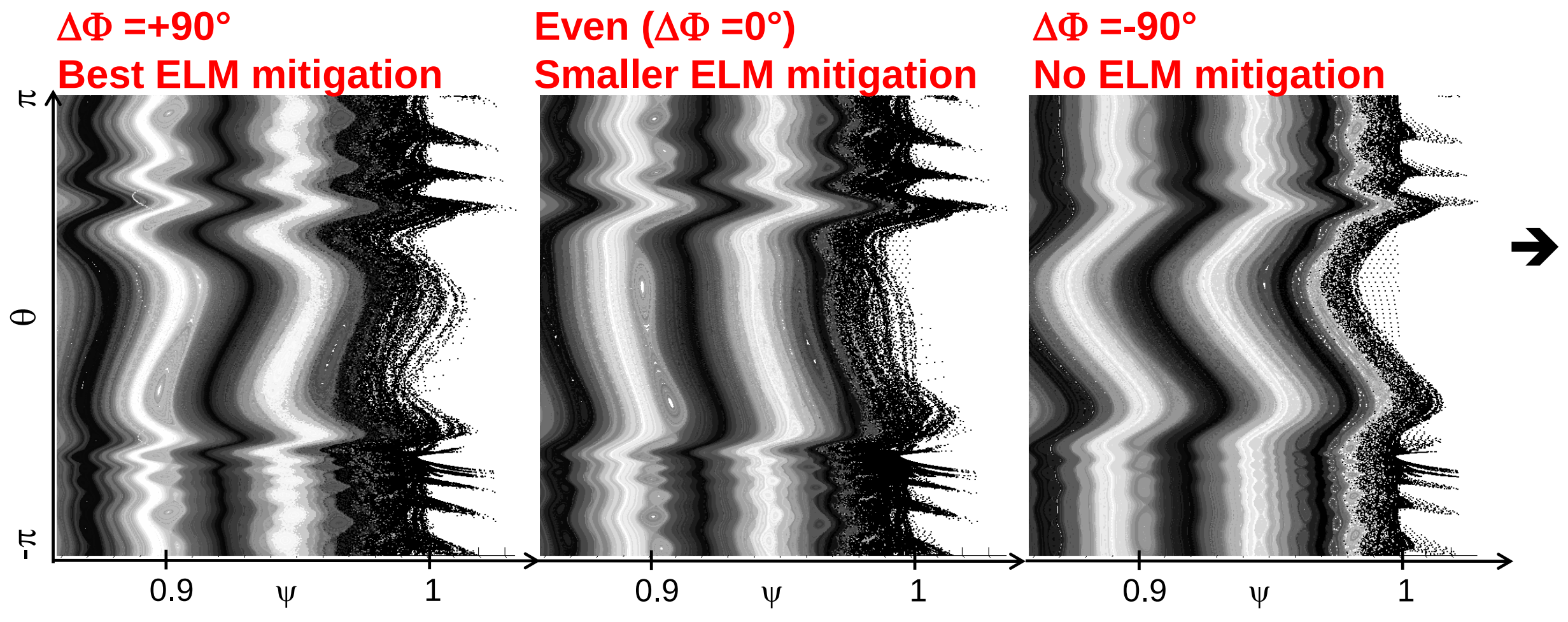


❖ Magnetic islands on resonant surfaces

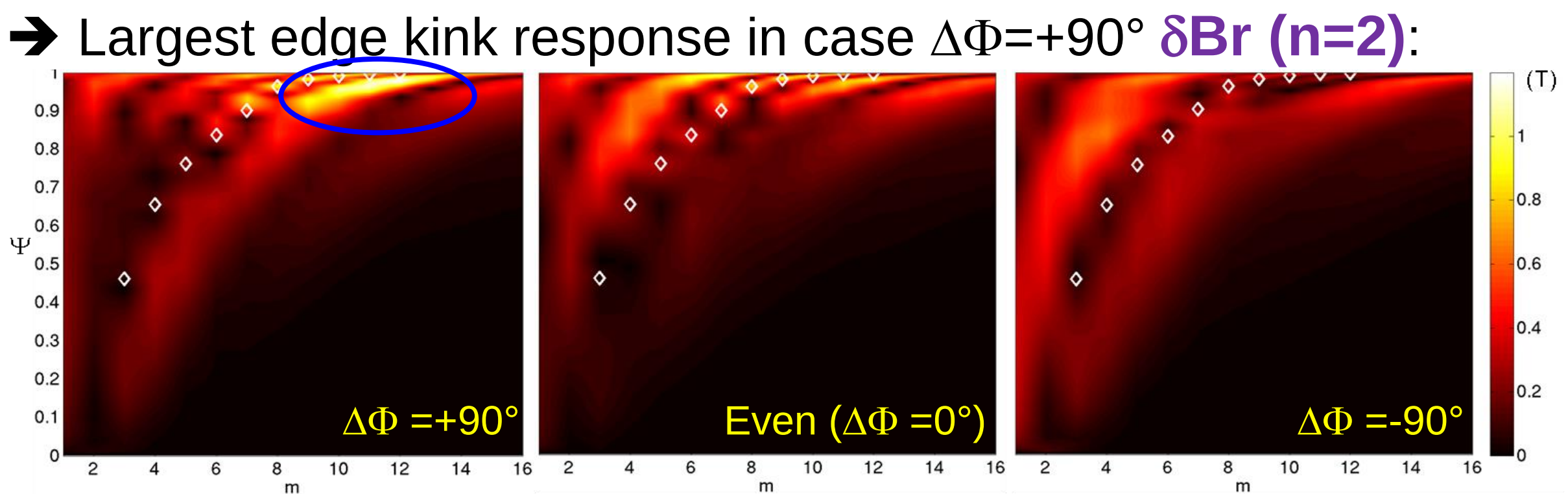


- **Influence of applied RMP spectrum :**

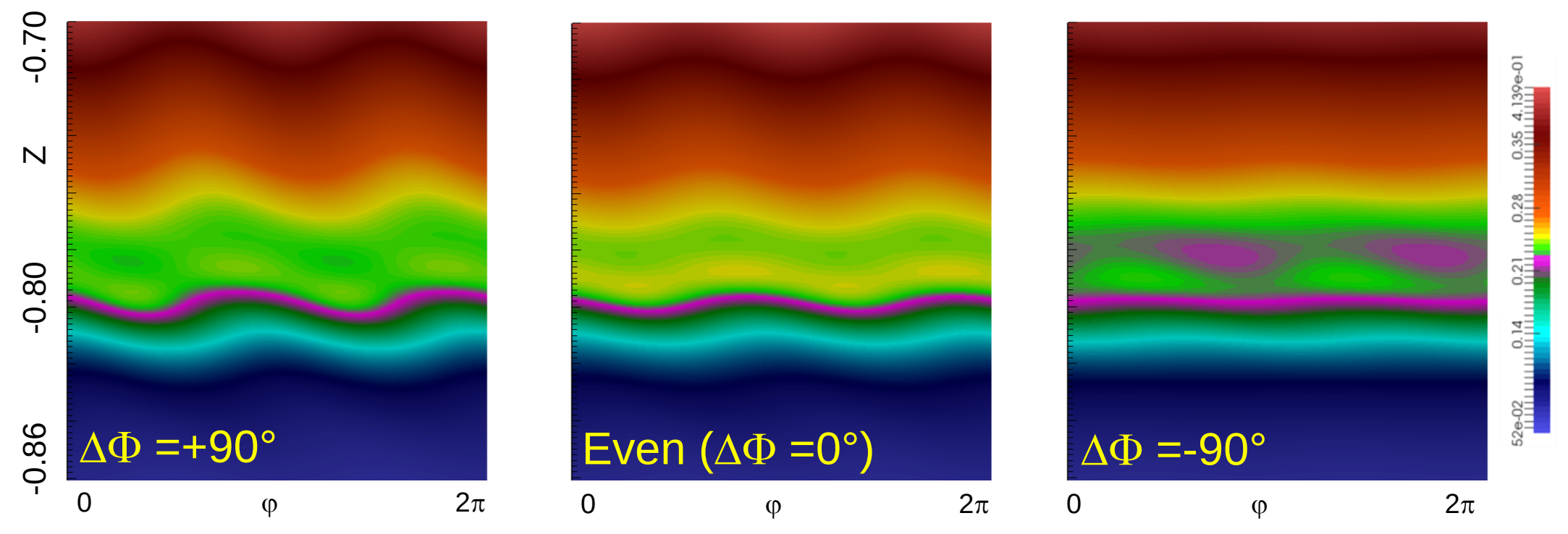
➔ Larger ergodic layer in case ΔΦ=+90° + larger field line kinking near X-point



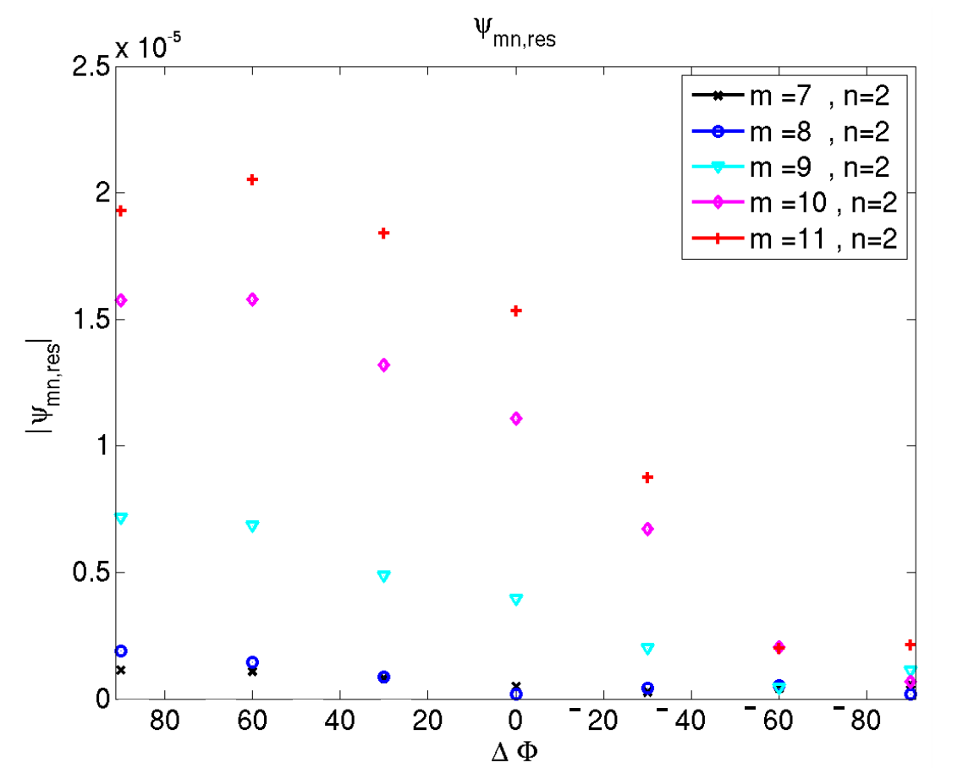
➔ Largest edge kink response in case ΔΦ=+90° **δBr (n=2)**:



➔ Largest displacement near X-point in case ΔΦ=+90°:



➔ Screening in pedestal in all cases. ΔΦ =+60 to +90°: most resonant at very edge (ψ>0.97)



Case ΔΦ =+90°: strongest ELM mitigation in experiments

In modeling:
Coupling of *m>nq* 'kink mode' with *m* resonant component
→ amplification of resonant response

[Orain et al, NF 2016]

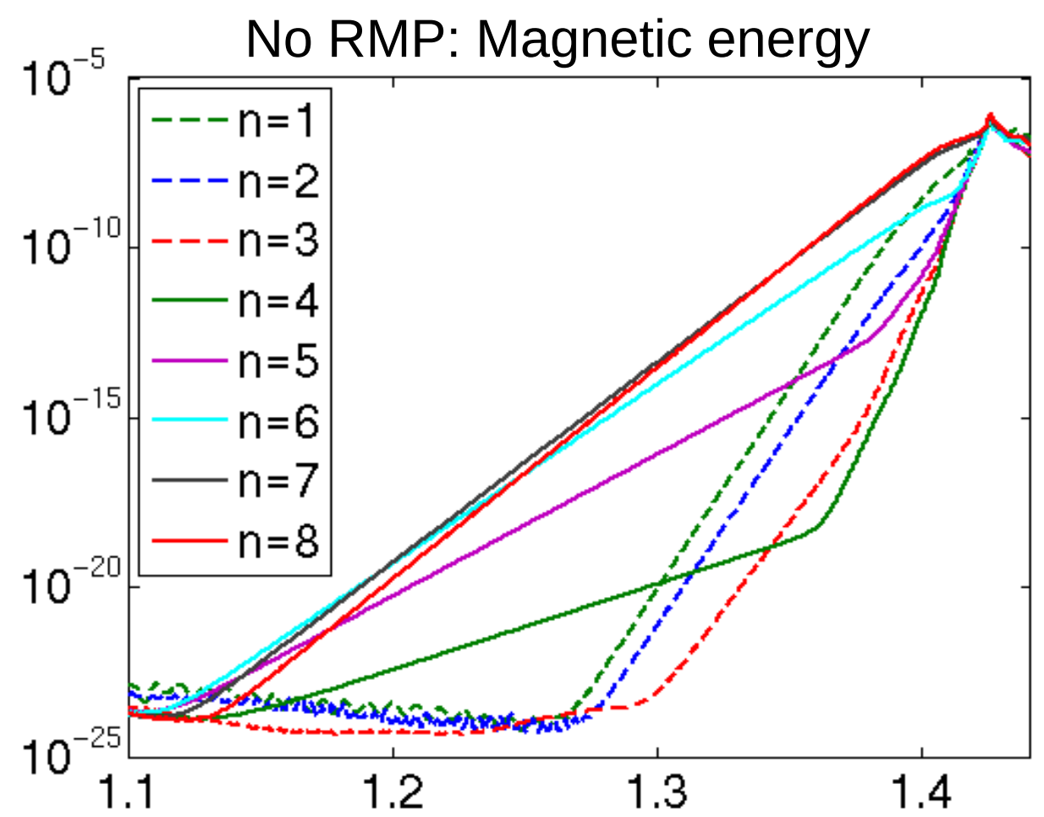
4/ ELM/RMP interaction

- Modeling for #31128 (multi-harmonic n=1-8) of ELM without and with RMP for ΔΦ=+90/-90°:

➔ Start from P-B unstable profiles (n=8 most P-B unstable)

➔ ELM without RMP:
First linear growth of modes, then non-linear mode coupling, mode saturation and ELM crash:

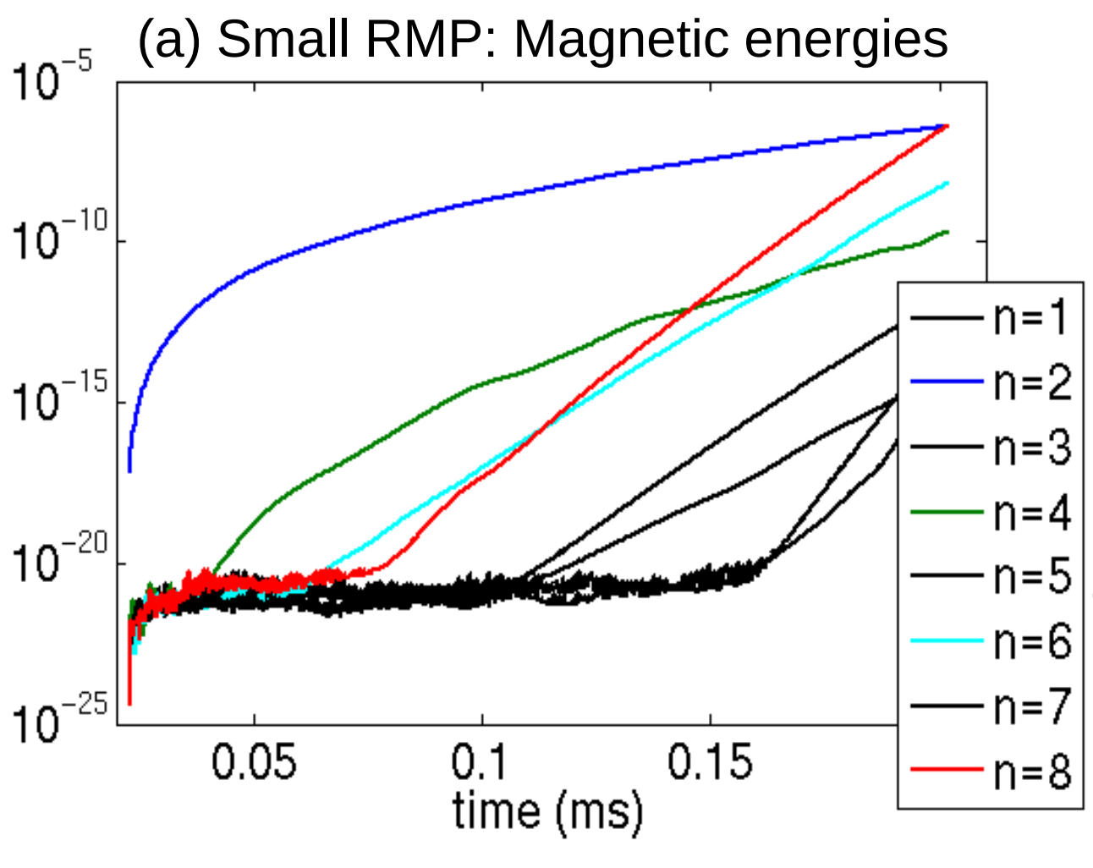
No RMP: Magnetic energy



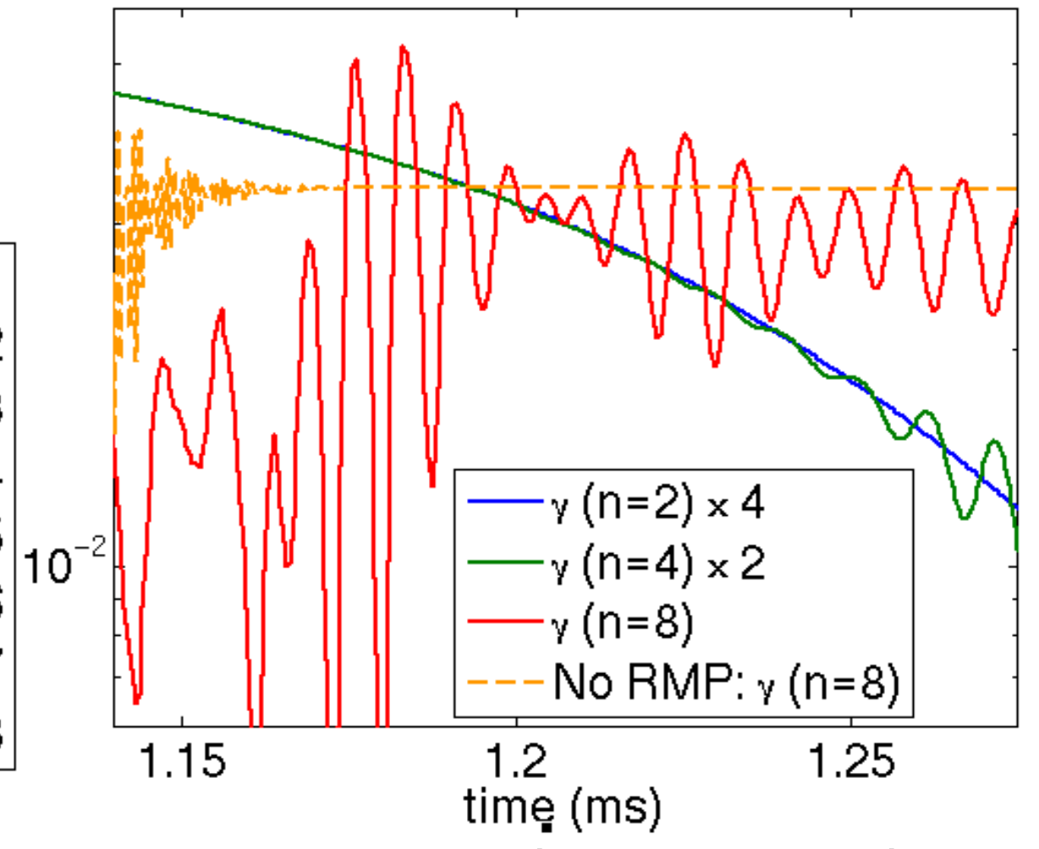
➔ ELM with RMP:
2 opposite behaviours:

→ (a) for small "penetrated" RMP amplitude:
n=8 and n=6 not coupled to RMPs
→ modes grow as unmitigated ELM, with only reduced growth rate γ

(a) Small RMP: Magnetic energies

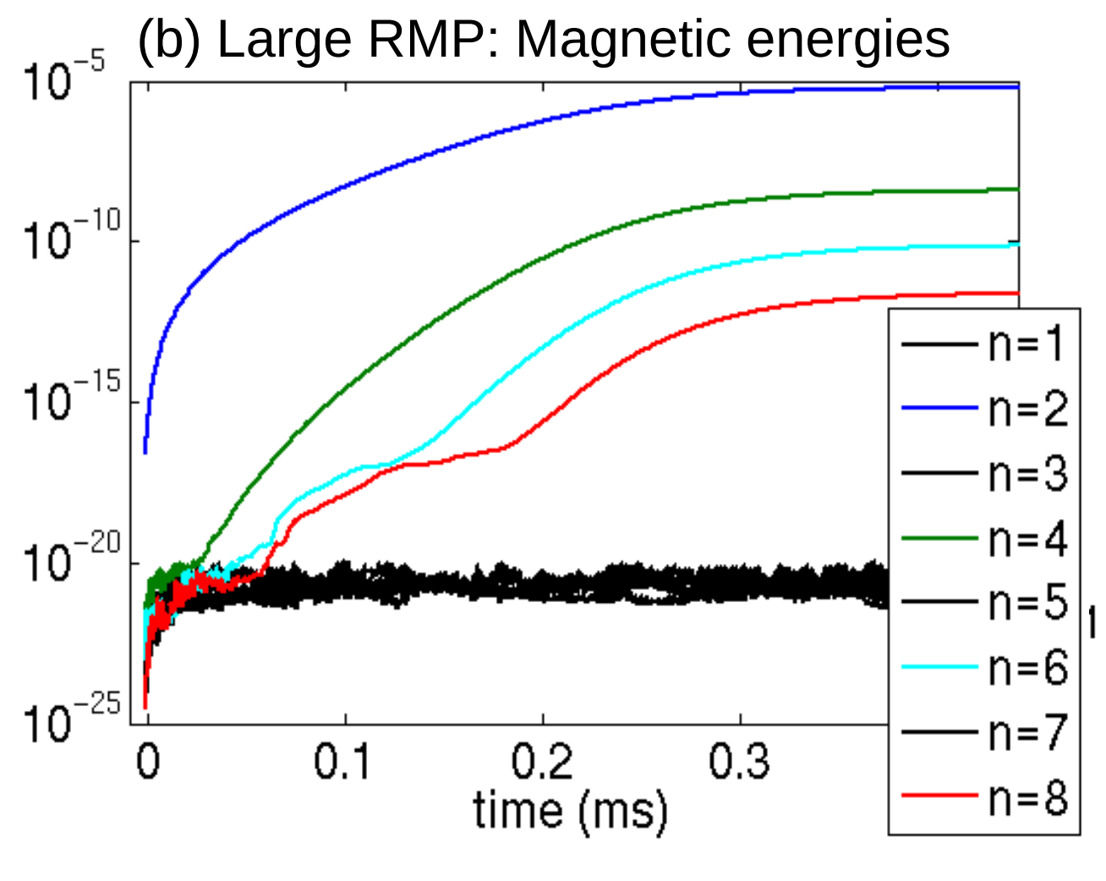


ΔΦ=-90°: growth rates not coupled

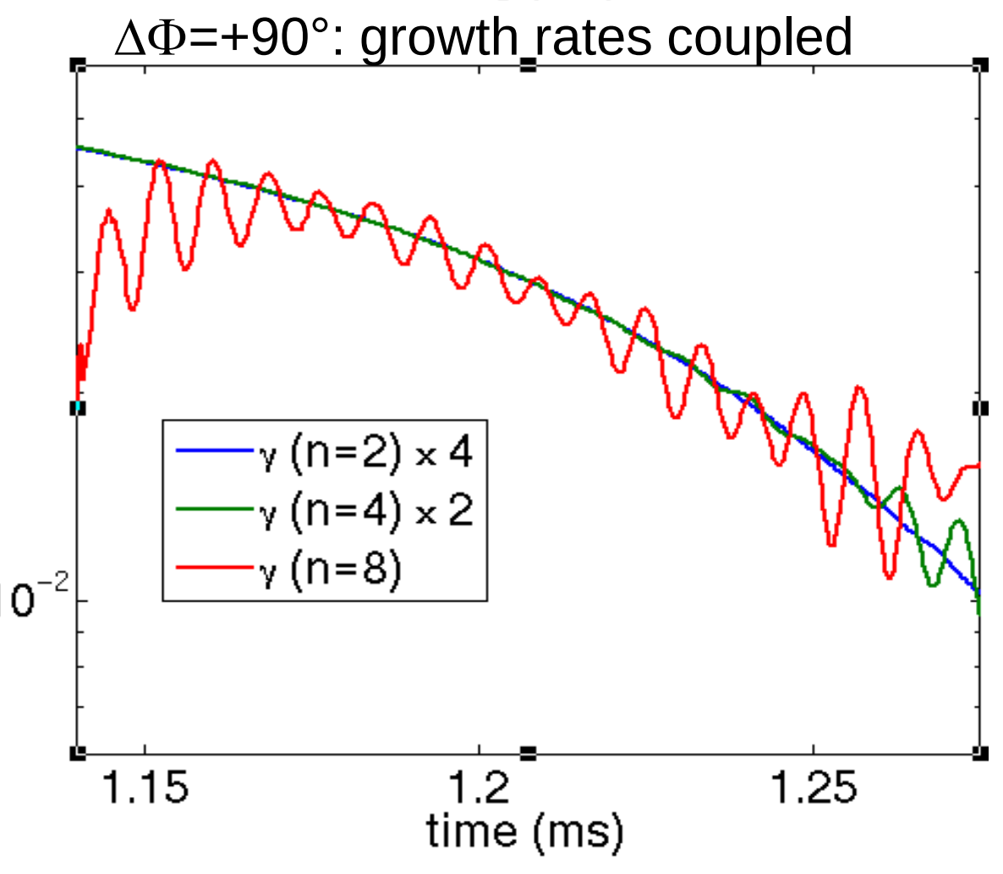


→ (b) for large penetrated" RMP amplitude or large viscosity:
even modes driven by n=2 RMP
→ full stabilization of ELM

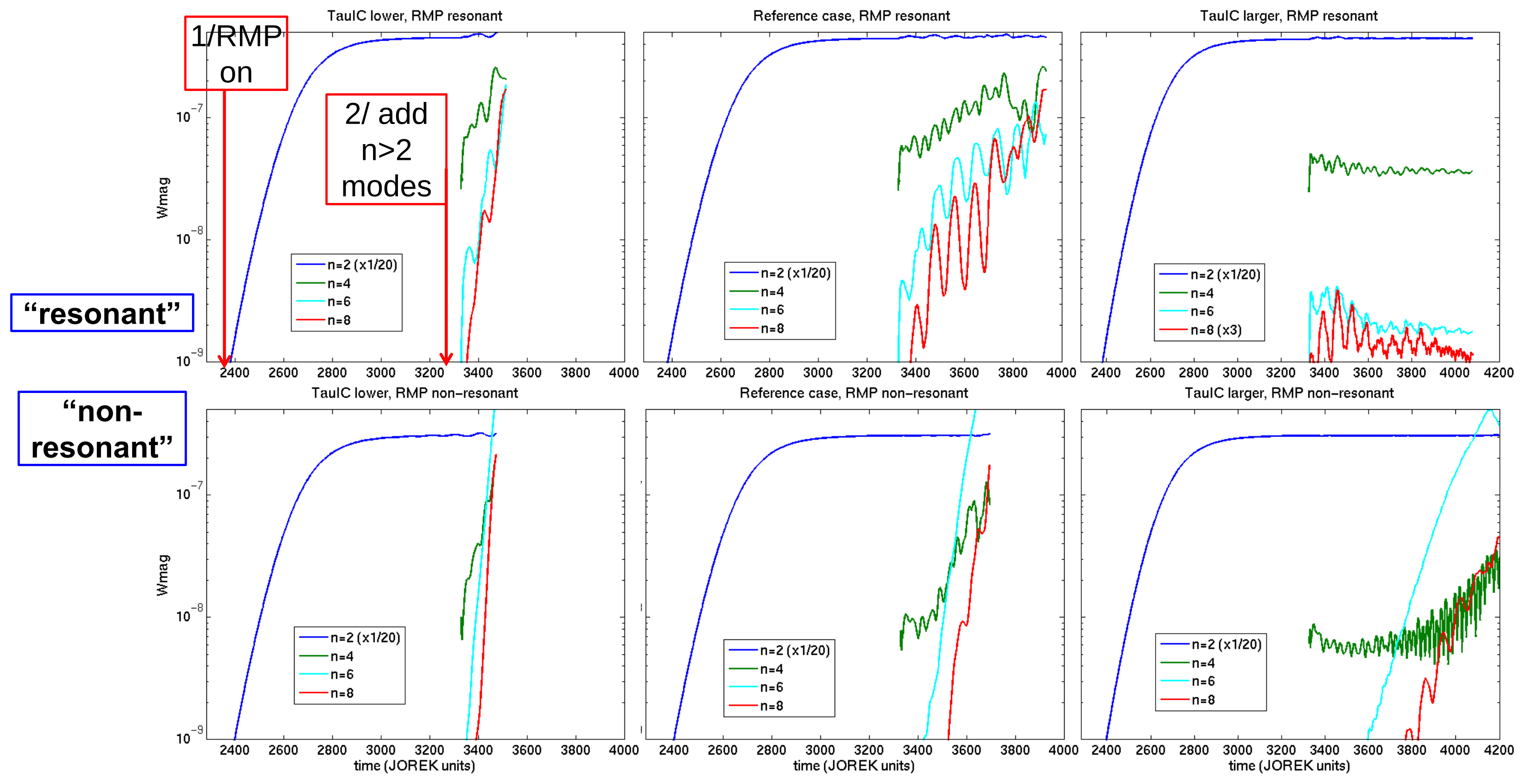
(b) Large RMP: Magnetic energies



ΔΦ=+90°: growth rates coupled



➔ Scan in diamagnetic rotation: → When increasing perpendicular diamagnetic rotation V_{dia}: bifurcation from unstable ELM to stabilized ELM (ELM suppression?) via partially stabilized ELM (ELM mitigation?) → Threshold depends on resonant spectrum (kink amplification)



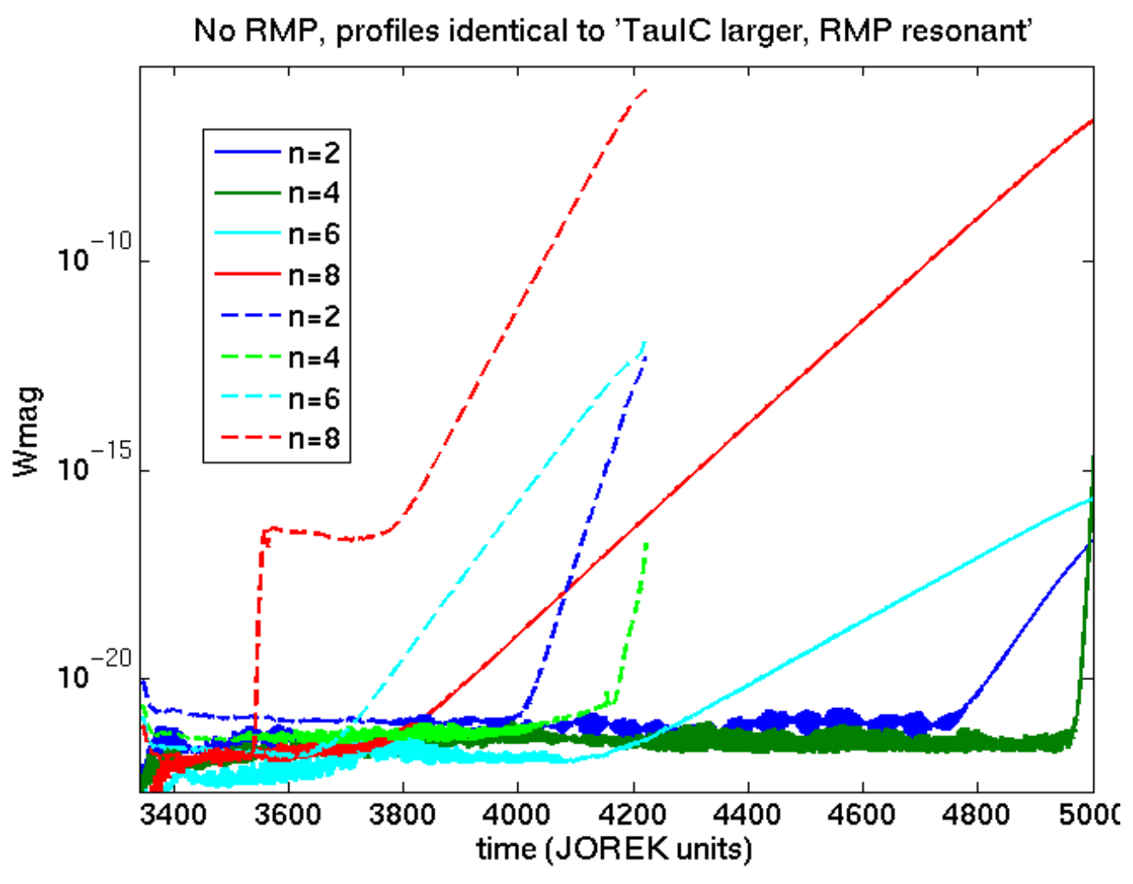
➔ Other important parameters:
→ resistivity η ++: destabilizing since makes ELMs more unstable
→ viscosity ν ++: stabilizing since increases RMP penetration

ELM mitigation/suppression=f(ν,η,V_{dia}) + RMP amplitude +other parameters?

➔ Simulation with pressure profile degraded (similar to RMP effect) but without RMP:

→ Reduction of pressure gradient by RMP is NOT responsible for ELM suppression
→ **needs presence of mode coupling to get QH-mode-like behaviour.**

No RMP, profiles identical to 'TauIC larger, RMP resonant'



Conclusions

- Plasma response to n=2 RMPs and ELM/RMP interaction modeled in JOREK using AUG experimental input.

- Plasma response to RMPs:
  Best ELM mitigation related to strongest kink response
  → mechanism: coupling between *m>nq* kink component with *m* resonant component
  → **amplification of resonant perturbation**.
  → Consistent with MARS-F *[Ryan et al, PPCF2015]* and NEMEC *[Strumberger 2014]* modeling.
- ELM/RMP interaction:
  Depending on plasma response, either coupling of high-n modes with RMPs or barely affected development of ELM.
  → ELM mitigation/suppression NOT due to reduction of pressure gradient by RMPs
  → ELM mitigation possibly induced by strong coupling of even modes with n=2 RMP + damping of odd modes.
  → changing ELMs into saturated peeling-kink modes?
- Perspectives: Current and future works:
  → Further understanding of ELM mitigation or suppression by RMPs with quantitative comparisons to experiments
  → improved model to observe density pumpout in simulations
  → RMP coils directly in JOREK-STARWALL *[Hoelzl et al, JCP 2012]*
  → Modeling of ELM cycles with/without RMPs

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