On Effect of n=2 RMP to Edge Pedestal in KSTAR with Nonlinear MHD Simulation

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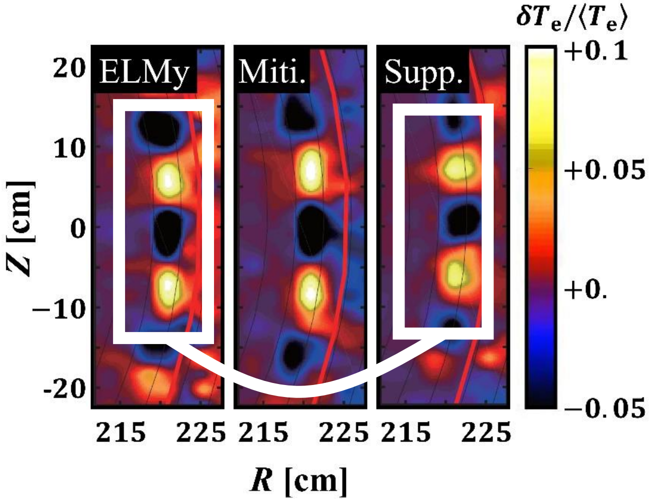
RMP-induced pedestal degradation are successful explanation for ELM suppression, but have some difficulties in explaining experiment

- **RMP is promising ELM suppression method** [T. Evans 2004]
  - ✓ Linearly stabilized ELMs with degraded pedestal by RMP-induced islands and stochastic region [Q. Hu PRL 2020].
    → One of promising/successful explanation.

- **Addition concept may be needed for full explanation**
  - ✓ Possible difficulty to solely describe pedestal degradation with islands.
    → Additional transport induced by RMPs.
  - ✓ Limitations to explain ELM-like mode during suppression. [J. Lee PRL 2016].
    → Contradiction to linearly stabilized ELMs by Degraded pedestal.



[ELM-like mode in suppression , J. Lee (PRL 2016)]

Previous work reveals that RMP can induce other transport mechanism and directly affect ELM stability as well as pedestal degradation

- **Previous studies on RMP-induced transport**
  - ✓ Micro-instabilities [1,2].
  - ✓ Edge kink response [3,4].
  - ✓ Neoclassical toroidal viscosity (NTV) [5,6].

➡ Focus on pedestal transport by plasma response and NTV

- **Direct effect of RMPs on the ELM stability**
  - ✓ Effect of RMP induced field structures on ELM stability [7,8].
  - ✓ ELM mitigation/suppression by RMP-ELM interaction [9-12].

➡ Direct ELM stabilization by RMPs

Nonlinear MHD simulation is performed to investigate the RMP-driven ELM crash suppression considering these aspects.

[1] I. Holod et al., Nucl. Fusion 57 (2017), 016005
[2] R. Hager et al., Nucl. Fusion 60 (2020),
[3] E. Nardon et al., Nucl. Fusion 50 (2010), 034002
[4] F. Orain et al., Nucl. Fusion 57 (2017), 102510
[5] Y.Liu et al., Nucl. Fusion 60 (2020), 036018
[6] J. Park et al., POP 16 (2009) 056115
[7] M. Willensdorfer et al., PRL 119 (2017), 085002
[8] M. L. Mou et al., Phys. Plasma 25 (2018), 082518
[9] M. Becoulet et al., PRL 113 (2014), 115001
[10] F. Orain et al., Phys. Plasma (2019), 042503
[11] J. Kim et al., Nucl. Fusion (2019), 096019
[12] S.K. Kim et al., Nucl. Fusion (2020), 026009

Contents

1. Simulation setup
2. Effect of RMP-induced plasma response on pedestal profile
3. RMP-induced ELM-crash suppression
4. Summary

JOREK and PENTRC coupled simulation is developed to simulate RMP-ELM dynamics including RMP response and NTV transport

- **JOREK (3D Nonlinear MHD)** [G. Huysmans 2009]
  - ✓ **Realistic geometries with scrape-off layer is included.**
  - ✓ **Reduced MHD equation [F. Orain 2013] is used.**

$$\boxed{\frac{1}{R^2}\frac{\partial\psi}{\partial t} = \eta(T)\nabla\cdot\left(\frac{1}{R^2}\nabla_\perp\psi\right) - \vec{B}\cdot\left(\nabla u - \tau_{\mathrm{IC}}\frac{\nabla p_{\mathrm{e}}}{\rho}\right)}$$

Ohm's law

w/ toroidal rotation
w/ ion diamagnetic
w/ $T_{\mathrm{i}} = T_{\mathrm{e}}$

$$\boxed{\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\vec{v}) + \nabla\cdot(D\nabla\rho) + S_{\rho}}$$

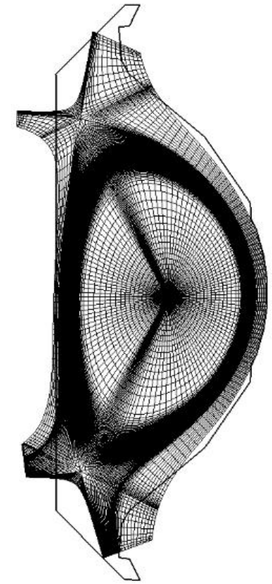
Continuity eqn.

$$\boxed{\rho\left(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla\right)\left(\vec{v}_{\mathrm{E}} + \vec{v}_{||}\right) = -\nabla(\rho T) + \vec{J}\times\vec{B} + S_{\mathrm{v}} - \vec{v}S_{\rho} + \mu\Delta\vec{v} - \nabla\cdot\overleftrightarrow{\Pi}_{\mathrm{neo}}}$$

Momentum eqn. ($v_{\parallel}$, w)

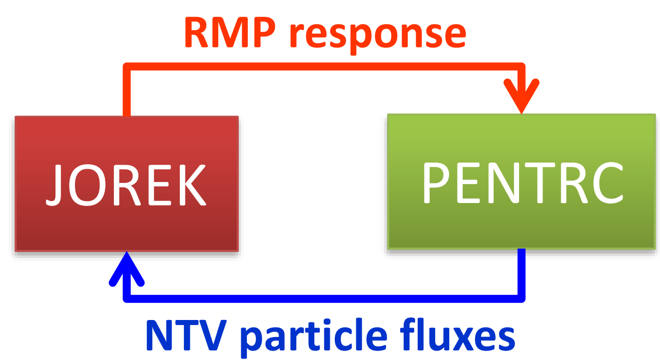
$$\boxed{\frac{\partial(\rho T)}{\partial t} = -\left(\vec{v}_{\mathrm{E}} + \vec{v}_{||}\right)\cdot\nabla\rho T - \gamma\rho T\,\nabla\cdot\left(\vec{v}_{\mathrm{E}} + \vec{v}_{||}\right) + \nabla\cdot(\kappa\nabla T) + (1-\gamma)S_{\mathrm{T}}}$$

Energy eqn.



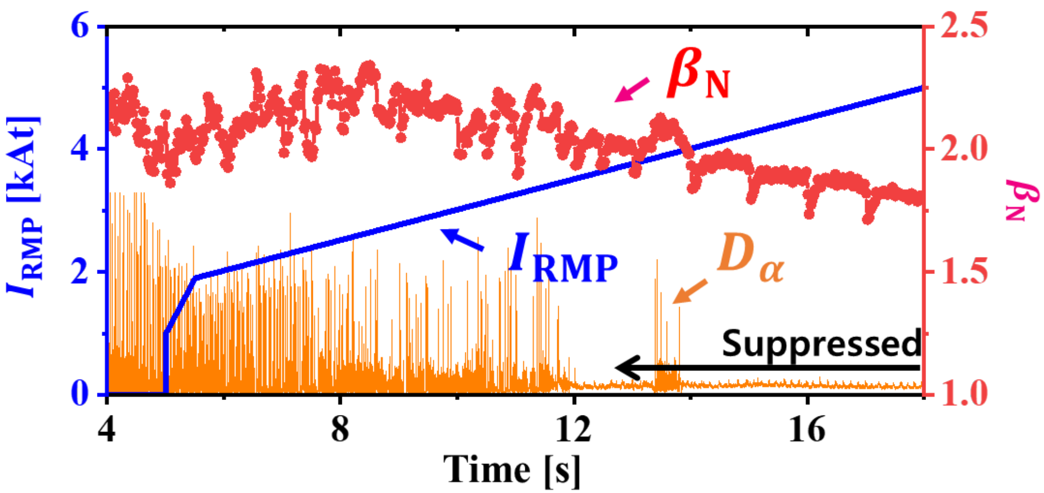
[Grid for KSTAR]

- **PENTRC (NTV)** [N. Logan 2013]
  - ✓ **NTV calculation code based on the given plasma equilibrium, profiles, and plasma displacements.**
  - ✓ **Inclusion of NTV by JOREK-PENTRC coupling.**



$n = 2$ RMP-driven ELM crash suppression in KSTAR is numerically reproduced

- **Reference discharge**
  - ✓ KSTAR ELM suppression discharge (#18594) with $n = 2$ ($\phi = 90°$) RMPs.
  - ✓ $I_p = 690$ kA, $q_{95} \sim 4, \beta_N \sim 2., \bar{n}_e = 3.3 \times 10^{19}$ m^{-3}.
  - ✓ Stable ELM suppression entry at $I_{RMP} \geq 3.5$ kA.
  - ✓ Simulation with x10 larger neoclassical resistivity due to numerical reasons.
  - ✓ Simulation with $I_{RMP} = 4$kA.



[#18594 overview]

RMP only simulation (n=0 and 2)

RMP simulation with ELMs (n up to 14)

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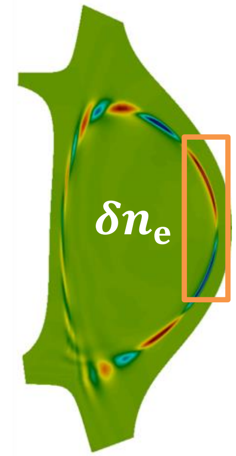
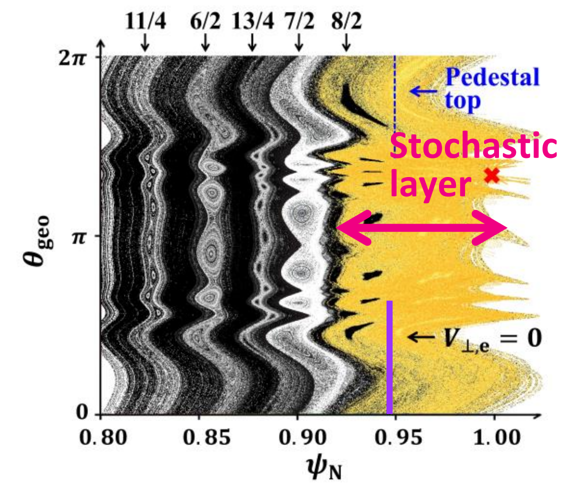
RMP response is the kink-tearing response which can contribute to the enhanced convective/conductive pedestal transport

- **Kink - tearing responses by RMP**
  - ✓ Kink + tearing response (KTM).
  - Kink { ✓ Edge localized perturbation.
  - Tearing { ✓ $V_{\perp e} = 0$ layer and finite resistivity.
  - ✓ Field penetration into the pedestal.



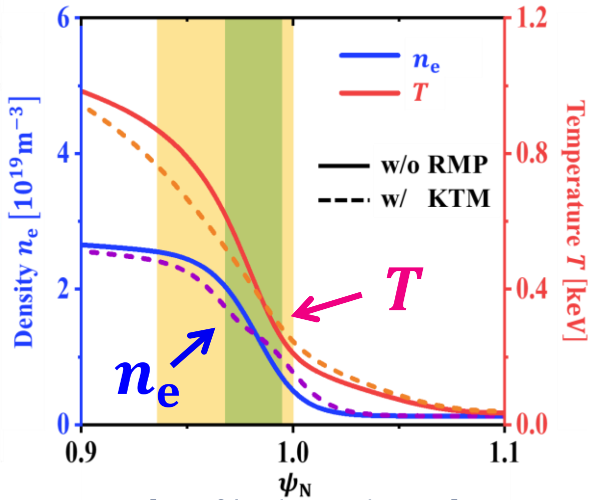
[*Perturbations*]



[*Poincare plot*]

- **Resulted pedestal degradation**
  - ✓ $V_{E\times B}$ and stochastic layer in the pedestal.
  - ✓ Degradation of the mean pedestal.
  - ✓ Increased radial flux due to
    - $\Gamma_{E\times B\perp}$ convection (Mainly n_e).
    - Island and stochastic layer (n_e and T).

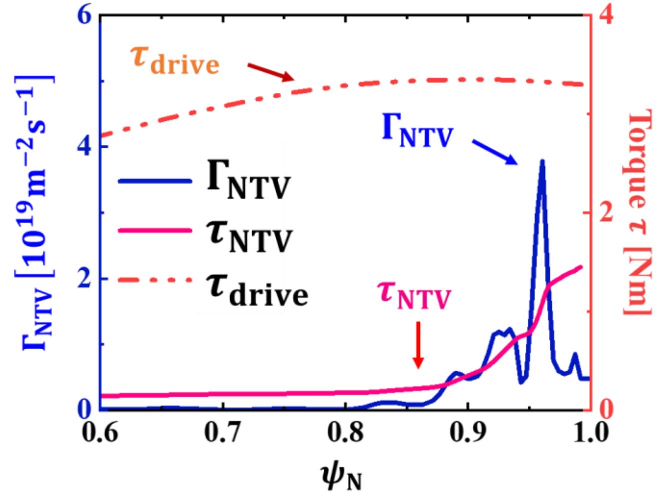
[$\Gamma_{E\times B\perp}$ *profiles*]



[*Profile degradation*]

Plasma response causes NTV particle transport, resulting in further pedestal degradation, partially explaining pump-out

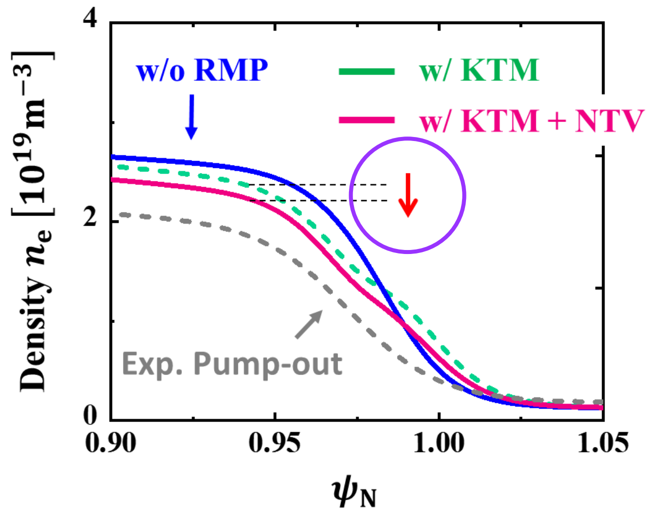
- **NTV induced by plasma response**
  - ✓ Plasma displacement ($\xi_\perp$) induced by RMPs.
  - ✓ Resulted NTV fluxes.
    - Torque τ_{NTV}
    - Particle flux Γ_{NTV}



[*NTV particle & momentum fluxes*]

- **Effect of NTV transport**
  - ✓ Further degradation of n_e pedestal by Γ_{NTV}
  - ✓ Kink + NTV (40% of Exp.).

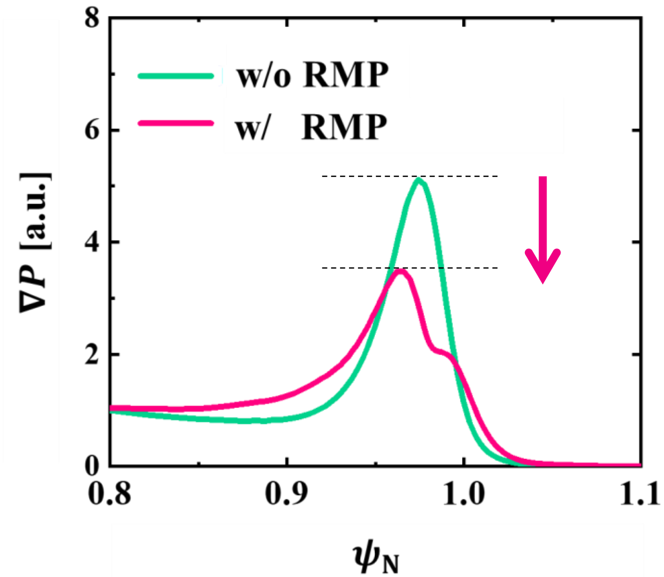
→ Considerable effect of kink and NTV on pump-out.



[*Further n_e degradation by NTV*]

MHD modeling with NTV explains pedestal degradation to some extent, but additional mechanism has to be introduced for full explanation

- **Net decrease in pedestal gradient**
  - ✓ Pedestal degradation by plasma response + NTV transport.
  - ✓ ~40% decrease in pressure gradient (close to Experimental level).



[Decreased *pressure gradient by RMP*]

- **Additional pump-out mechanisms**
  - ✓ RMP induced micro-instabilities [R. Hager 2020].
  - ✓ Particle transport by polarization drift [Q. Hu 2019].

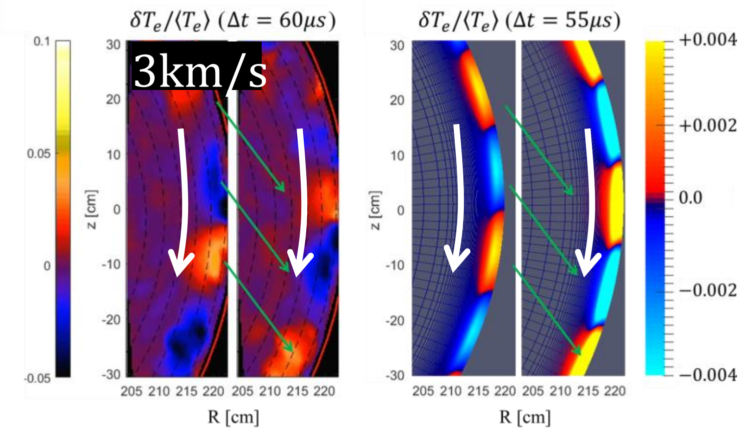
  → They will be needed to fully explain the pump-out.

ExB convection and NTV flux largely contribute to the pump-out, but full explanation requires additional transport mechanisms.

Contents

Natural ELM simulation (without RMPs) shows good agreement with experimental observations

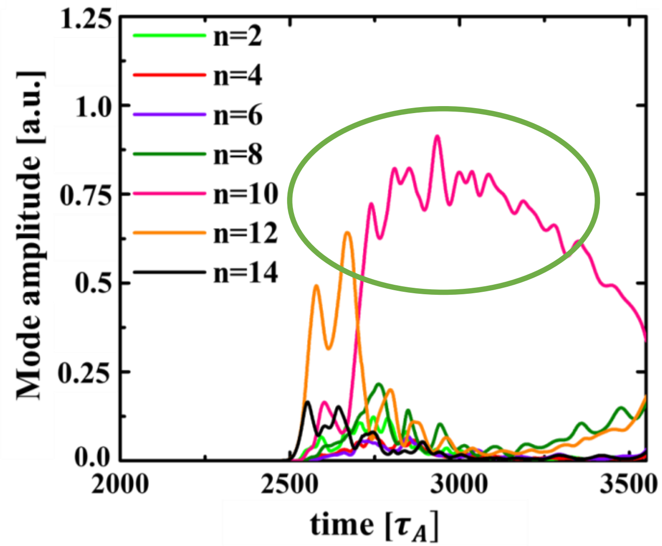
- **Linear ELM simulation**
  - ✓ **Consistent dominant $n_{\mathrm{ELM}} = 12$.**
  - ✓ **Consistent poloidal velocity $V_{\theta,\mathrm{ELM}} \sim 3\ \mathrm{km/s}$.**
  - ✓ **$V_{\theta,\mathrm{ELM}} \approx V_{\theta,\mathrm{E\times B}}$ (ion - diamagnetic) [1,2].**



[*ECEI and JOREK n=12 results*]

- **Nonlinear phase**
  - ✓ **Mode crash during nonlinear phase.**
  - ✓ **$\Delta W_{\mathrm{ELM,sim}} \approx 8\mathrm{kJ}$ ($\Delta W_{\mathrm{ELM,exp}} \approx 7 \pm 4\mathrm{kJ}$).**

→ Experimentally relevant ELM is obtained. ($V_{\theta,\mathrm{ELM}} \approx V_{\theta,\mathrm{E\times B}}$)

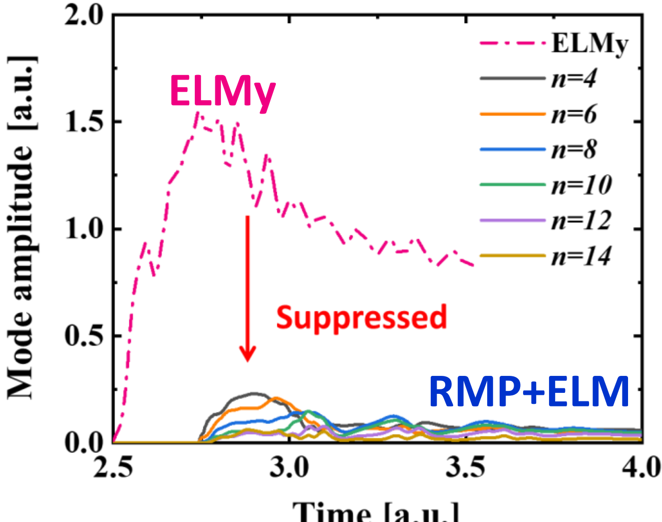


[*Mode amplitude in NL phase*]

[1] M. Becoulet M. et al, NF (2017), 116059
[2] J. Morales, POP (2016), 042513

ELM crash suppression by experimentally relevant RMP configuration is successfully reproduced in the simulation

- **RMP-driven ELM crash suppression**
  - ✓ **Strongly suppressed mode amplitude.**
  - ✓ **Disappeared bursty nonlinear mode crash.**

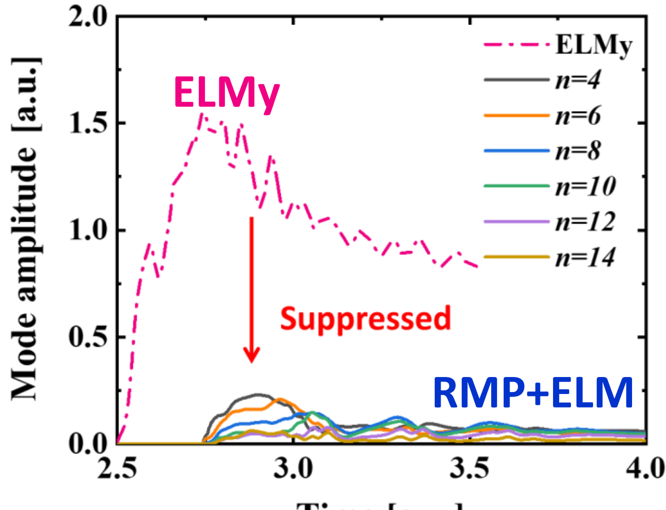


[*Nonlinear evolution of ELM*]

ELM crash suppression by experimentally relevant RMP configuration is successfully reproduced in the simulation

- **RMP-driven ELM crash suppression**
  - ✓ Strongly suppressed mode amplitude.
  - ✓ Disappeared bursty nonlinear mode crash.
  - ✓ Existing filament structures in suppression case.
  - ✓ Spatially locked structure [J. Lee 2019].

  → ELM is nonlinearly saturated rather than linearly stabilized, so filament can remain.



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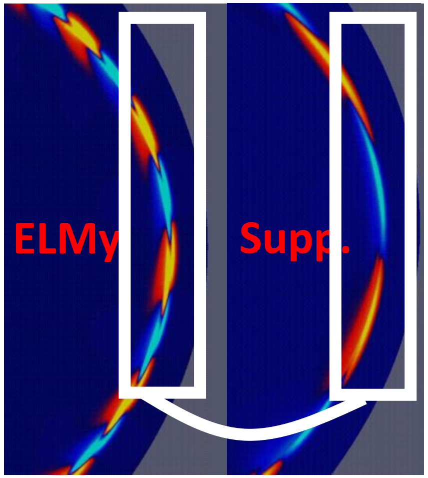

[*Filament motions*]

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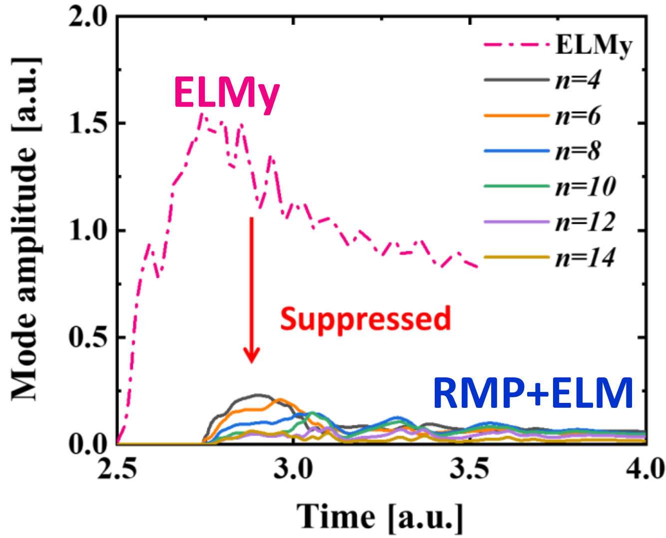
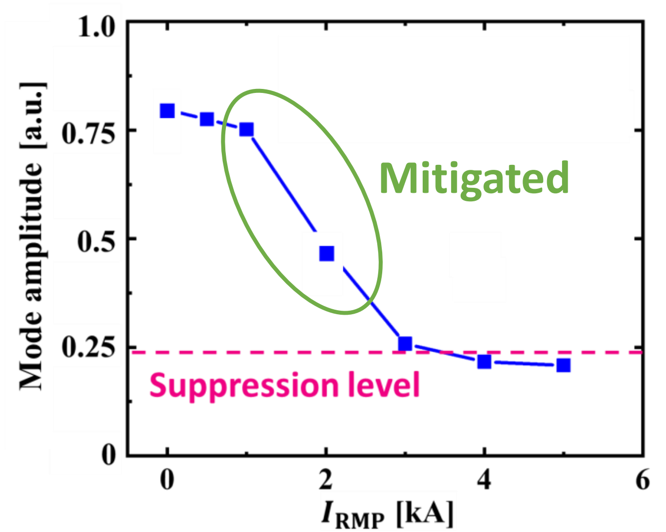


[Nonlinear evolution of ELM]

- **Suppression above RMP threshold**
  - ✓ Mitigated with small RMP amplitude.
  - ✓ Fully suppressed at $I_{\mathrm{RMP}} > 3\ \mathrm{kA}$.

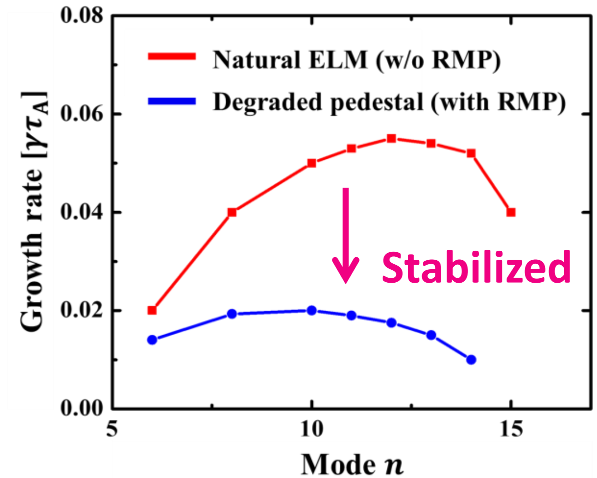
  → It is consistent to experimental level (~4kA).



[Mode amplitude vs RMP]

Degraded pedestal and RMP-ELM mode coupling make ELM crash suppression, but they must participate simultaneously

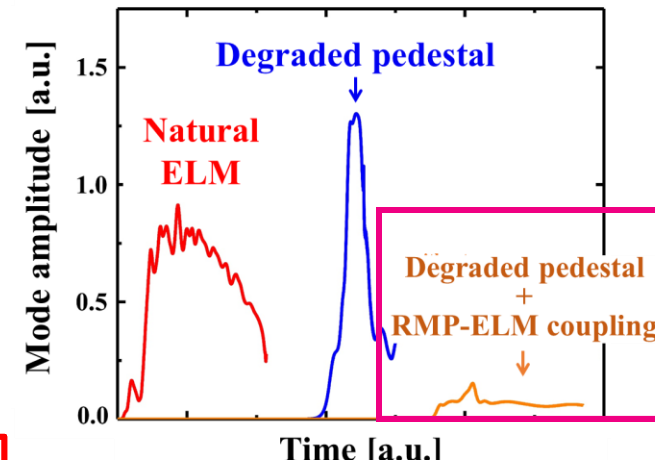
- **Effect of degraded pedestal on ELM stability**
  - ✓ **~40% decreased pedestal gradient by RMPs.**
  - ✓ **~65% decreased growth rate.**



[*ELM linear growth rate*]

- **Coupling between RMP and ELM harmonics**
  - ✓ **ELM suppression simulation contains two effects.**

    Degraded pedestal + **RMP-ELM coupling**
  - ✓ **No crash suppression without coupling effect. (Even with decreased growth rate)**
  - ✓ **ELM crash suppression by combined two effects.**



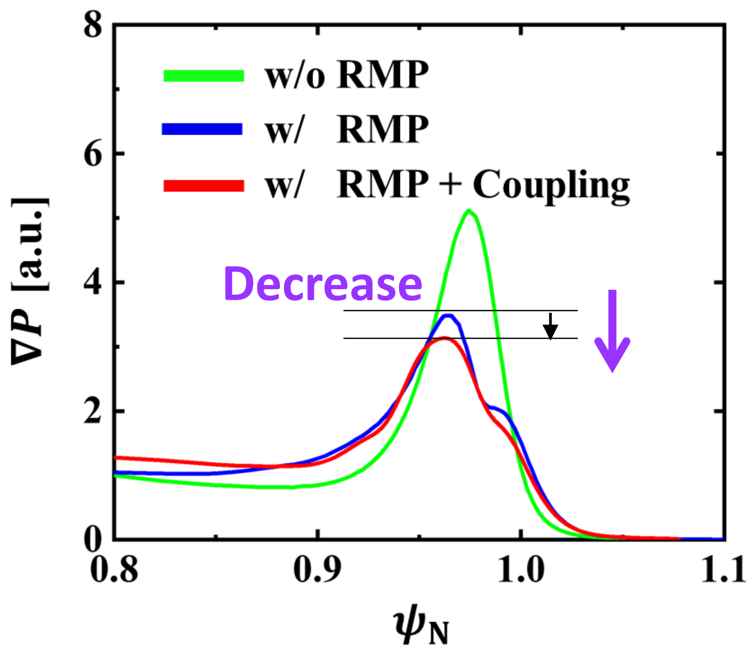
[*ELM amplitude comparison*]

How RMP-ELM coupling affects ELM suppression ?

RMP-ELM coupling further degrades the pedestal by increasing transport, resulting in the reduced ELM instability

- **Enhanced pedestal transport by coupling effect**
  - ✓ **~15% increased radial perturbed fields by coupling effect. (Tearing component)**
  - ✓ **Enhanced pedestal transport with increased island width.**
  - ✓ **Further decrease of pedestal gradient.**

→ Reduced ELM instability source



[Pedestal degradation by coupling]

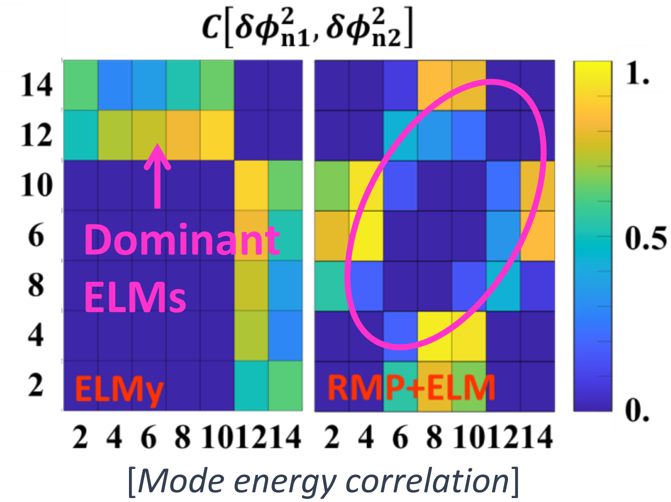
RMP-ELM coupling results in broad mode spectrum and increased interactions between ELM harmonics, preventing unstable ELM crash

- **Enhanced harmonic interactions by coupling effect**
  - ✓ Unlike ELMy, enhanced energy correlation among harmonics. [J. Kim NF 2019]
  - ✓ Broadened mode spectrum.
  - ✓ Large growth of unstable harmonic: ELM crash
  - ✓ Prevented mode crash due to broad spectrum and mode interactions. [P. W. Xi, PRL 2014]
  - ✓ Therefore, nonlinearly saturated ELMs by

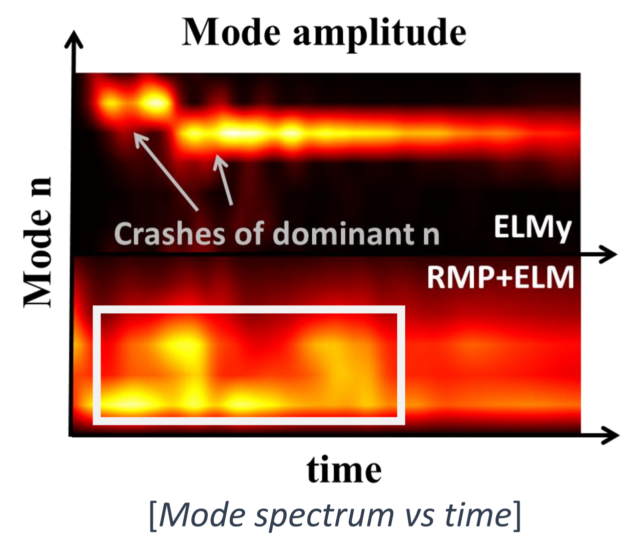
Degraded pedestal + Broadened spectrum / Enhanced interaction

Driving ↓ Dissipation ↑

- ✓ Important quantities for RMP-ELM coupling?



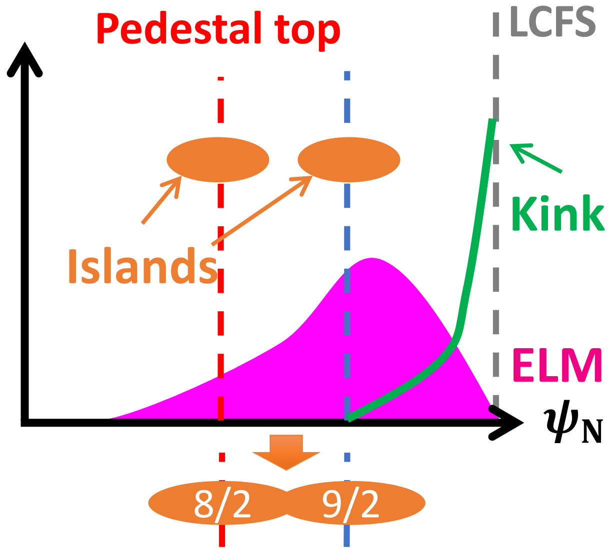
[Mode energy correlation]



[Mode spectrum vs time]

Overlap of magnetic islands near the pedestal top can be important to RMP-ELM coupling and ELM suppression

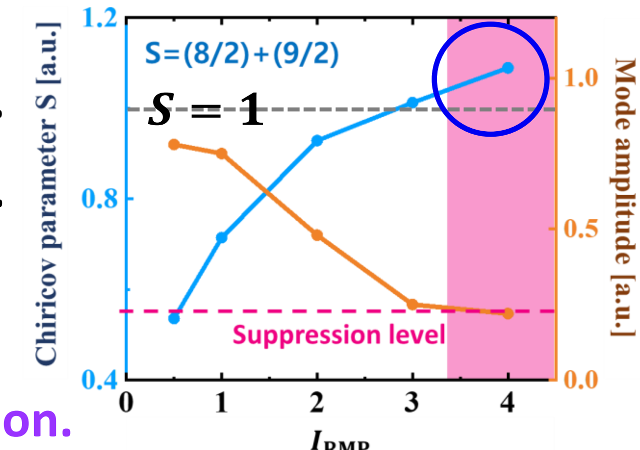
- **Spatial overlap of harmonics**
  - ✓ Overlap of harmonics: Favorable to their couplings [Rhee POP2015].
  - ✓ Existing harmonics,
    - ELM harmonics
    - RMP-Kink (peeling) → Localized to LCFS.
    - RMP-Tearing (island) → Wide radial range.



➢ n=2 Island overlap

- **Island overlap near the pedestal top**
  - ✓ I_{RMP} scan to adjust island width near pedestal top.
  - ✓ ELM suppression entry where island overlap starts. (Chiricov S =1 between 8/2+9/2)

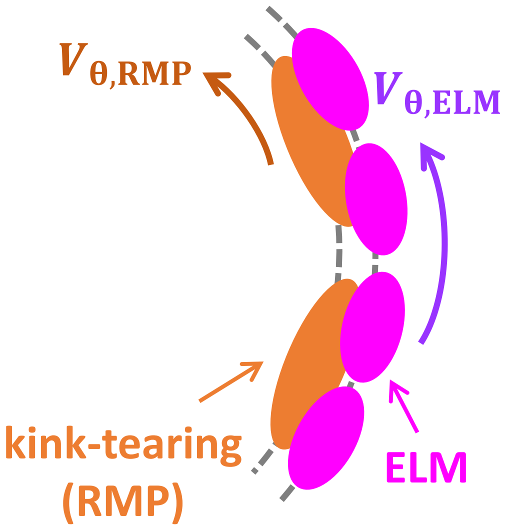
→ Overlap of RMP-induced islands can be advantageous for RMP-ELM coupling and suppression.



$[S_{(8,9)}$ *vs* $I_{RMP}]$

Slow poloidal rotation of ELM structure can be advantageous for enhancing the RMP-ELM interaction and achieving ELM suppression

- **Poloidal mode rotation and RMP-ELM coupling**
  - ✓ **Well sustained mode overlap: Favorable to coupling.**
  - ✓ **Sustained spatial overlap ($|V_{\theta,\mathrm{ELM}} - V_{\theta,\mathrm{RMP}}| \approx 0$).**
    → Stationary phase difference (δ) of RMP and ELM.



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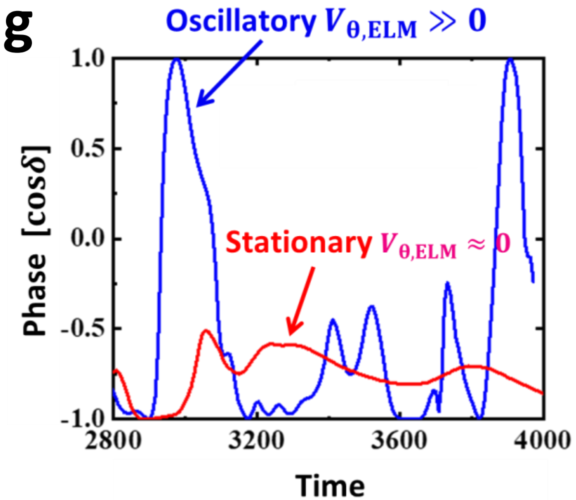
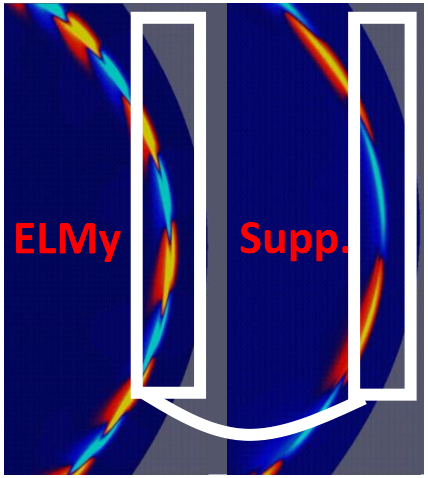
  - ✓ Static RMP, $V_{\theta,\mathrm{RMP}} = 0$.
    → $V_{\theta,\mathrm{ELM}} \approx 0$ to make stationary δ.



[*Time evolution of* $\cos\delta$]



[*Filament motions*]

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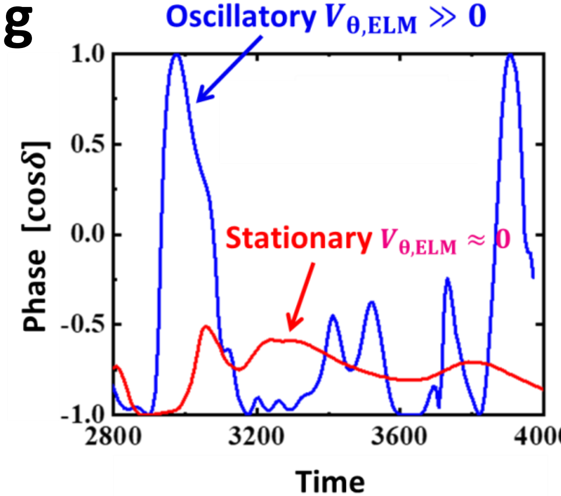
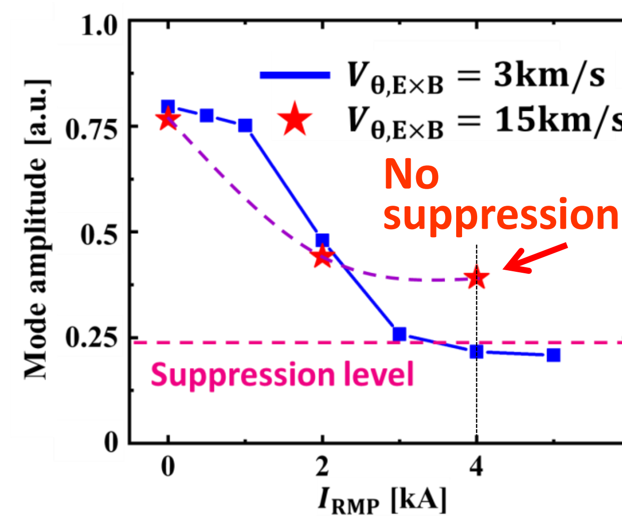


[*Time evolution of* $\cos\delta$]

- **Small $V_{\theta,E\times B}$ for RMP-ELM interaction**
  - ✓ $V_{\theta,\mathrm{ELM}} \approx V_{\theta,E\times B}$ [1, 2] at pedestal.
    → $V_{\theta,E\times B} \approx 0$ is favorable.
  - ✓ No suppression with <u>large</u> $V_{\theta,E\times B}$ at pedestal top.

  → Small $V_{\theta,\mathrm{ELM}}$ (or $V_{\theta,E\times B}$) be advantageous for RMP-ELM coupling and suppression.



[*ELM amplitude for* I_{RMP}]

[1] M. Becoulet M. et al, NF (2017), 116059
[2] J. Morales, POP (2016), 042513

Summary

- **n=2 RMP-driven pedestal degradation and ELM suppression**
  - ✓ Pedestal degradation by RMP response and NTV, explaining the experiment to some extent.
  - ✓ Numerical reproduction of nonlinearly saturated ELM suppression.
    - Reduced pedestal gradient.
    - Mode coupling between RMP and ELM.

- **RMP-ELM coupling contributes to the ELM-crash suppression**
  - ✓ Further decreasing pedestal gradient. → ELM driving source ↓
  - ✓ Enhanced interactions between ELM harmonics. → Prevent NL mode crash

- **Favorable conditions for RMP-ELM coupling**
  - ✓ Overlap of RMP-induced islands near the pedestal top.
  - ✓ Small rotation of ELM structure or $V_{\theta,E\times B} \approx 0$ at the pedestal.

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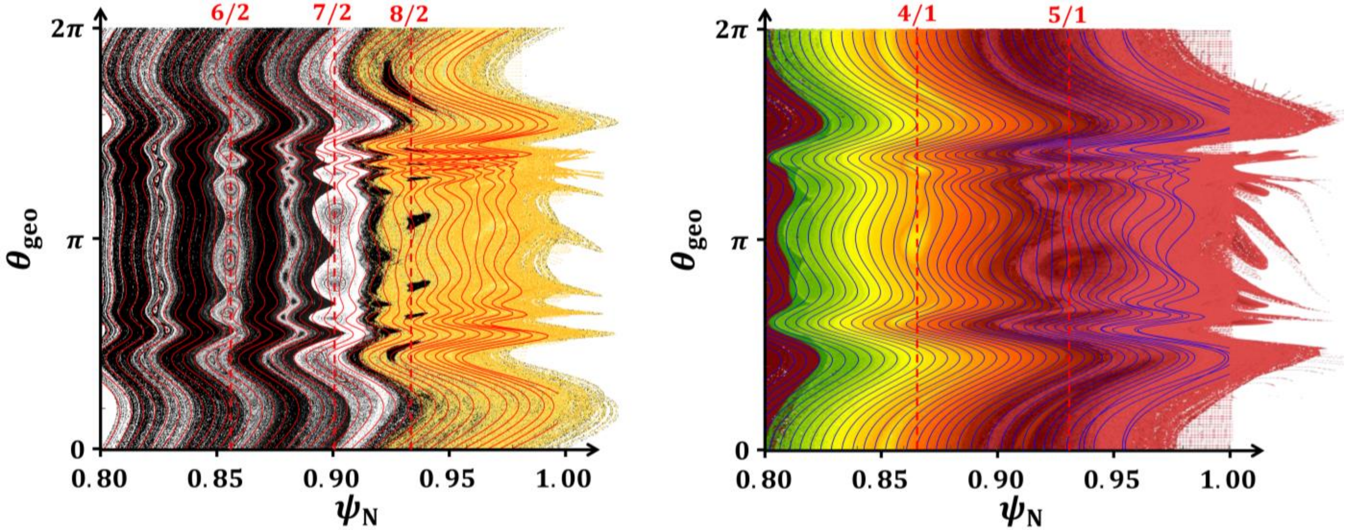
Backup – Plasma displacement from JOREK perturbation

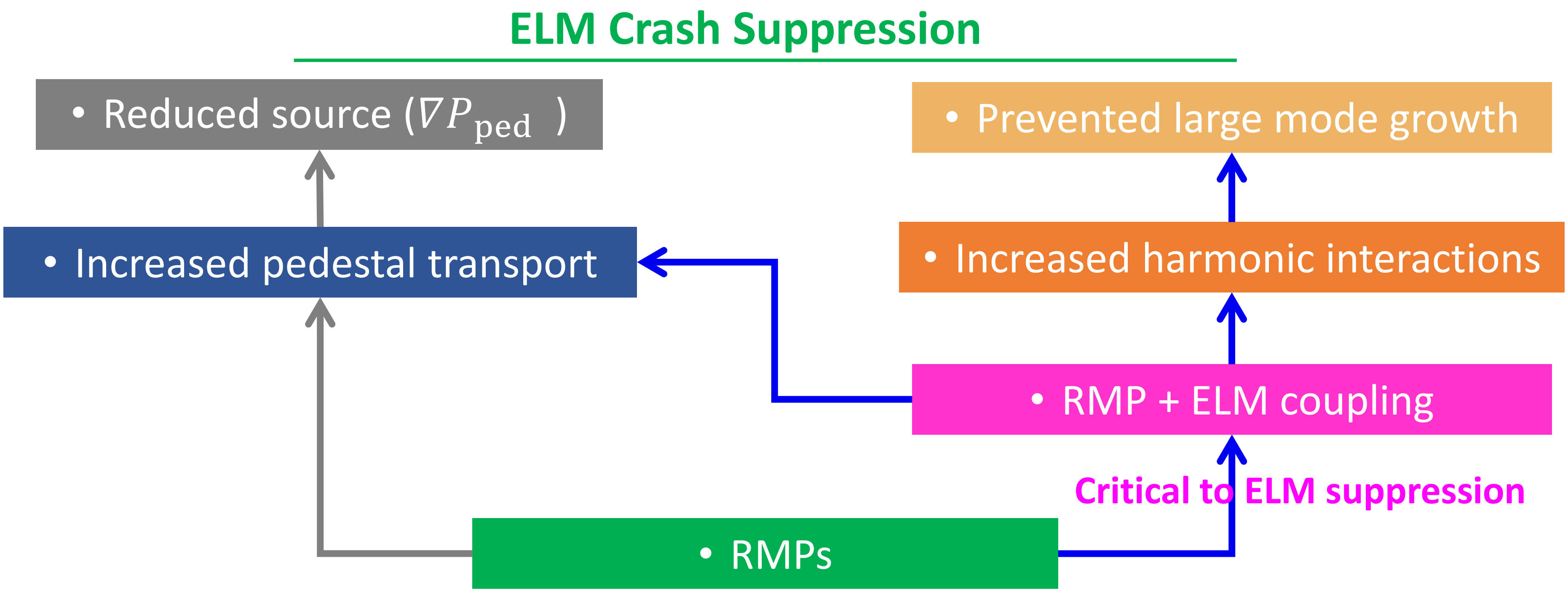
- **Approximated displacement from nonlinear perturbation**



- ✓ $T_{\mathrm{n=0}}$ is dominant.
- ✓ Uniformity of T on the flux surface due to large parallel heat conduction.
- ✓ Therefore, $\xi_{\perp,\mathrm{n,m}} \sim -\delta T_{\mathrm{n,m}} / \nabla T_{\mathrm{n'=0}}$
- ✓ Less accurate under the presence of stochastic layer.
- ✓ No $\delta B_{\parallel}$ component in reduced MHD.
- ✓ $\xi_{\parallel}$ derived from linearized force balance equation ($\delta F(\xi_{\perp}, \xi_{\parallel}) = 0$).

Backup - In summary, RMP-ELM coupling can contribute to ELM crash suppression in two aspects

- **Role of RMP-ELM coupling in ELM crash suppression**



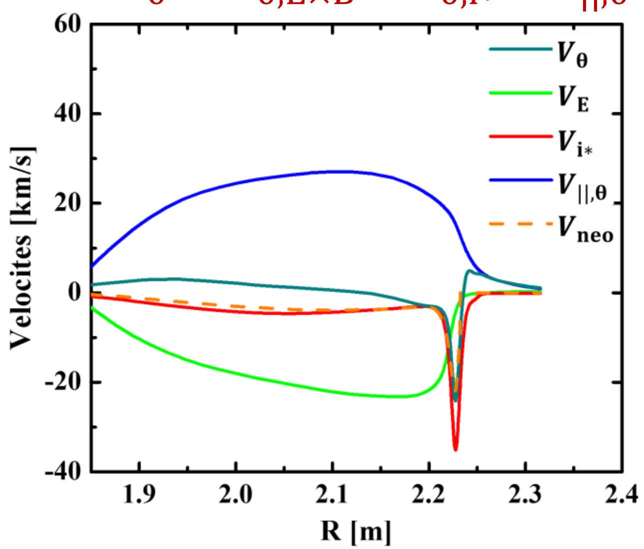
- **Important quantities for RMP-ELM coupling?**

→ **Spatial overlap between RMP-induced modes and ELM harmonics seems to be important.**

Backup – Simulation setup

- **Numerical setup**
  - ✓ **Neoclassical constraint (V_{neo}) is applied to construct the ion-poloidal flow.**
  - ✓ **$V_{\theta,\mathrm{E\times B}}$ in the pedestal region is in the ion-diamagnetic direction.**
  - ✓ **$T_{\mathrm{i}} = T_{\mathrm{e}}$ is assumed.**
  - ✓ **Adaptive diffusive profile and source are used to sustain the ρ, T, v_{ϕ} profiles.**
  - ✓ **x10 resistivity (x40 spitzer) and braginskii parallel conductivity are used.**

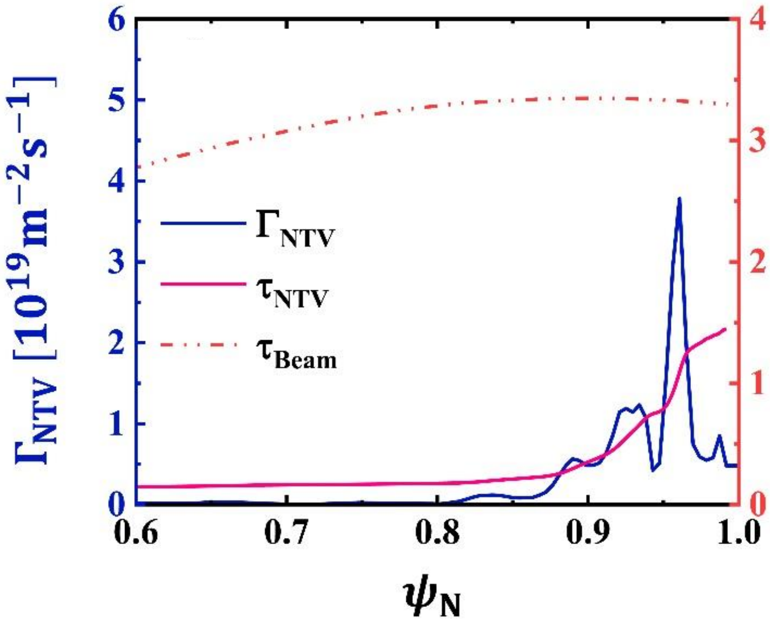
$$V_{\theta} = V_{\theta,\mathrm{E\times B}} + V_{\theta,\mathrm{i*}} + V_{||,\theta}$$



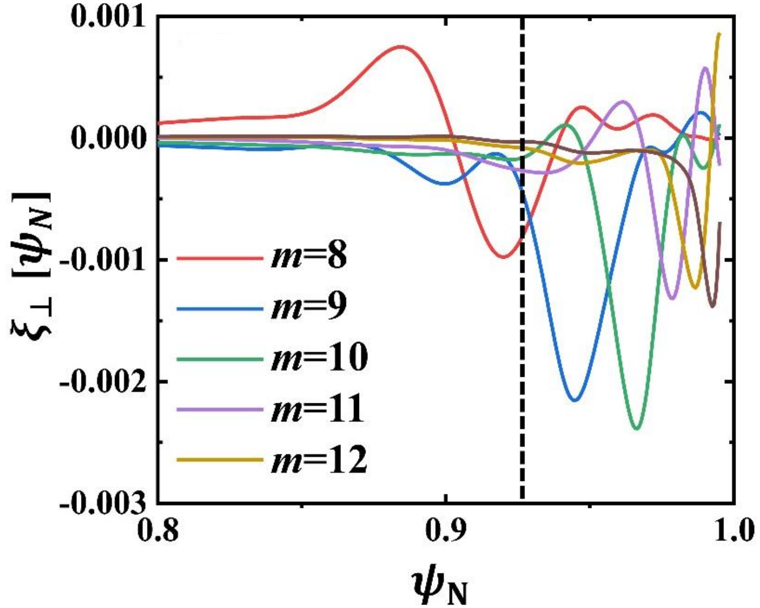
[Poloidal flow components]

Backup - Coupling simulation shows experimentally reasonable results

- **Code coupling test**
  - ✓ **Well reconstructed $\xi_\perp$ including kink and partial tearing component.**
  - ✓ **Successful calculation of NTV-driven particle flux and torque.**
  - ✓ **A reasonable value from code coupling.**

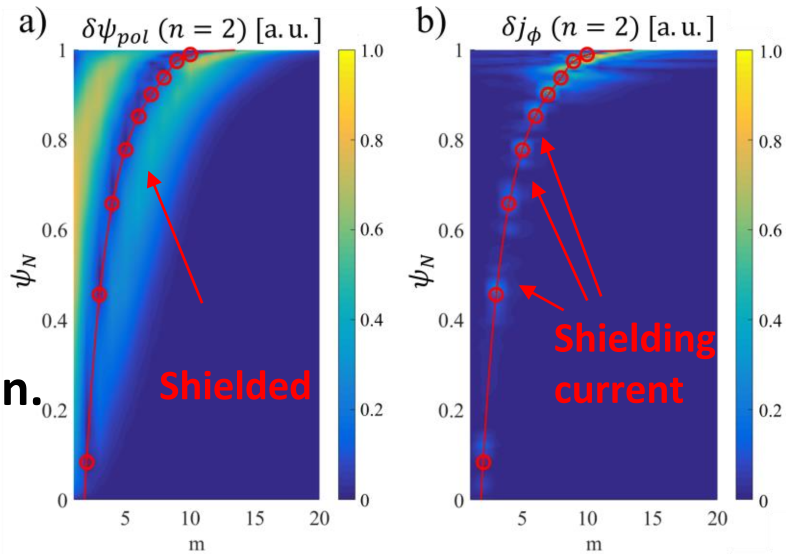


[NTV particle & momentum fluxes]

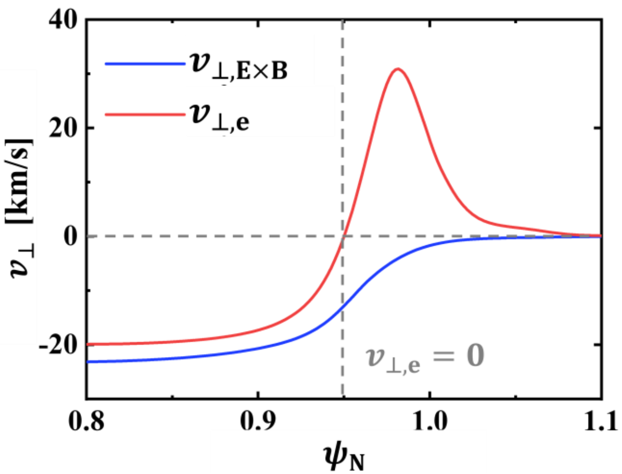


[$\xi_\perp$ profile form JOREK]

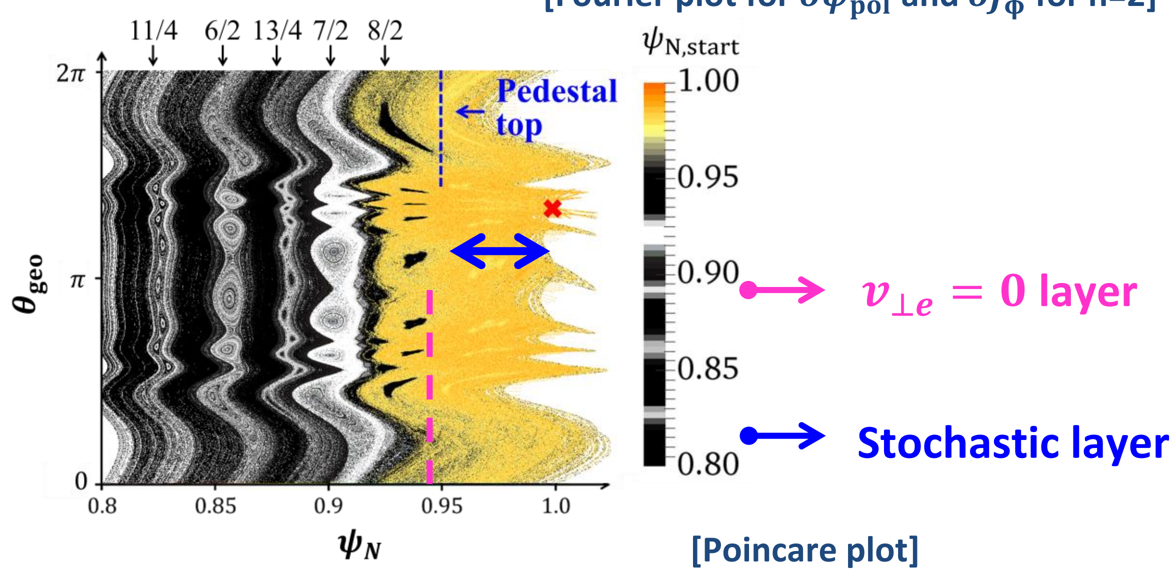
- **Tearing response**
  - ✓ **Perturbed current shields the external field.**
  - ✓ **$v_{\perp e} \approx 0$ layer and finite resistivity in the edge weaken the field shielding.**
  - ✓ **Field penetration occurs in the pedestal region.**
  - ✓ **As a result, stochastic layer is formed.**



[Fourier plot for $\delta\psi_{\rm pol}$ and δj_ϕ for n=2]



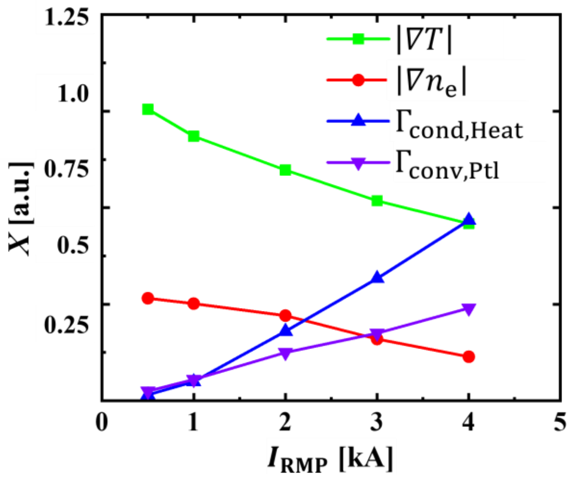
[Perpendicular flow profile]



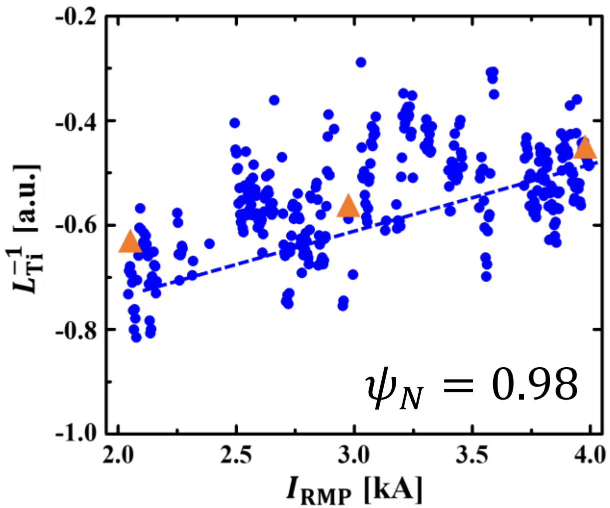
[Poincare plot]

Backup – profile comparison (kink-tearing only)

- **Pedestal profile degradation**
  - ✓ Radial transport increases due to
    - $v_{\mathrm{E\times B\perp}}$ convection (Kink).
    - Stochastic layer (Tearing).
  - ✓ Pedestal profile (n=0) is degraded.
  - ✓ Density pedestal is governed by $v_{\mathrm{E\times B,\perp}}$.
  - ✓ It is consistent with the trend that pump-out increases with kink response [1,2].
  - ✓ T pedestal shows a similar tendency in the experiment and simulation.



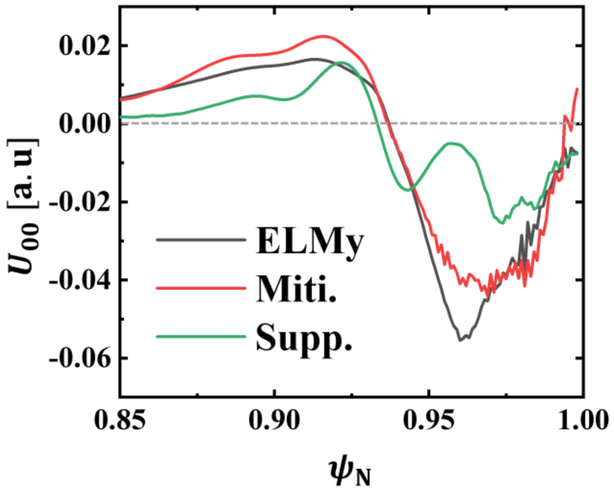
[Radial fluxes vs I_{RMP}]



[L_{Ti}^{-1} vs I_{RMP}]

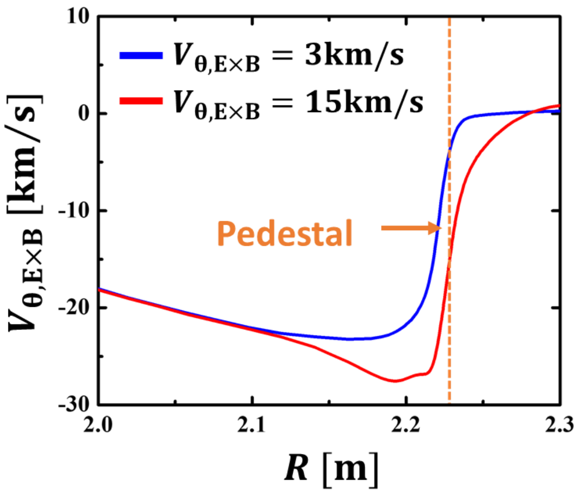
[1] Y. Liu et al., PPCF 58 (2016), 114005
[2] C. Paz-Soldan et al., Nucl. Fusion (2016), 056001

- **Vorticity and ExB profiles in the simulation**



✓ **Reduced vorticity U_{00} during ELM suppression**

- **Possibility of evenly distributed energy among harmonics [H. Jhang 2017].**

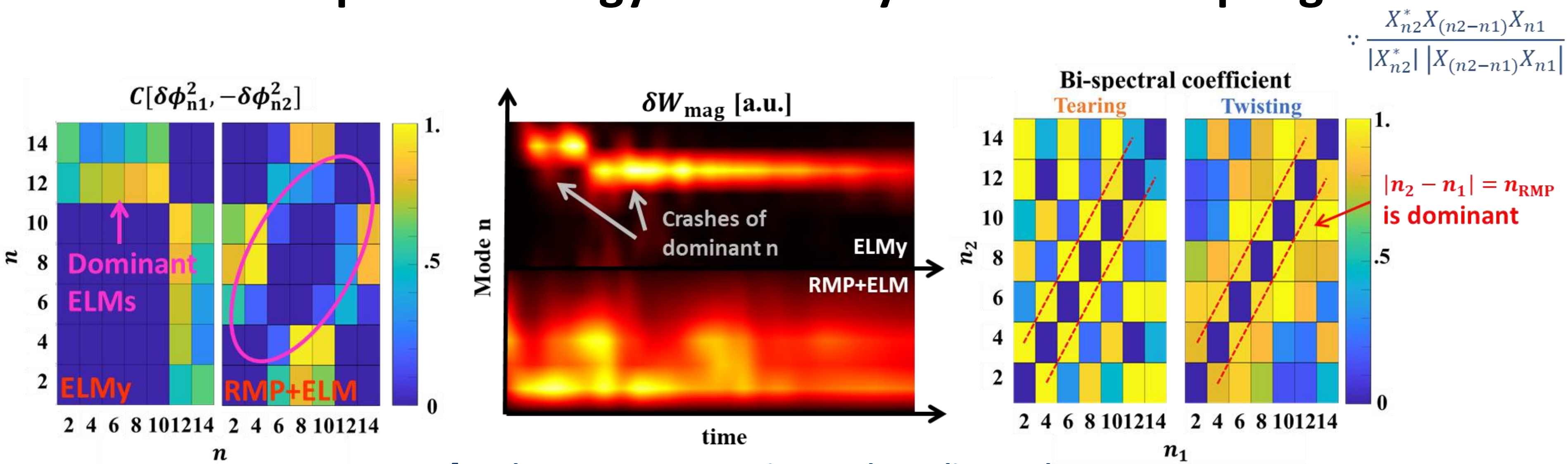


✓ **ExB radial profile comparison**

- **$V_{\theta,E\times B}$ is increased from 3 to 15 km/s.**
- **Decoupling of $V_{\theta,E\times B}$ and $V_{\theta,ELM}$ can occur in very nonlinear case.**

Backup - RMP-ELM interaction can increase spectral transfer and broaden mode spectrum of ELM, preventing crash of unstable ELM

- **Increased spectral energy transfer by RMP-ELM coupling**



[Mode spectrum comparison and coupling analysis]

✓ **Enhanced interaction between ELM harmonics with RMP** [M. Becoulet 2014].
  - **Amplified energy transfer between harmonics and broadened spectrum**

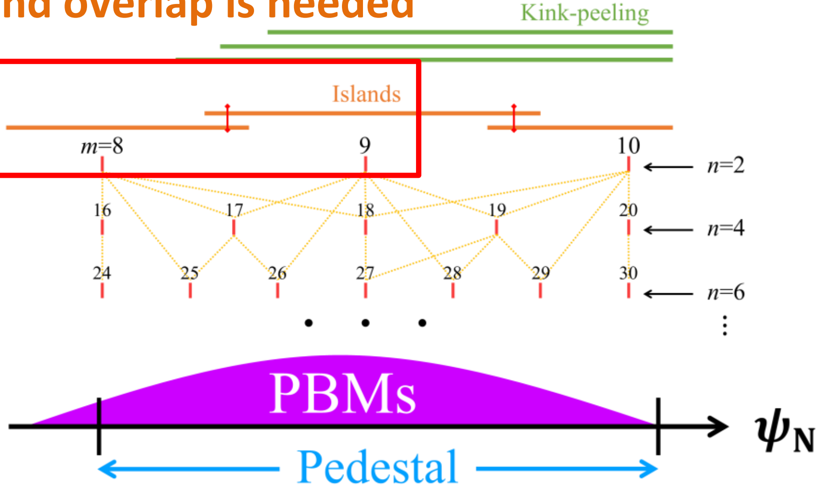
✓ **Prevented catastrophic growth and crash of unstable mode** [P. Xi 2014].

✓ **Participation of both tearing and twisting parity modes in the mode coupling.**
  - **Both kink and tearing part by RMP mediates the mode interactions.**

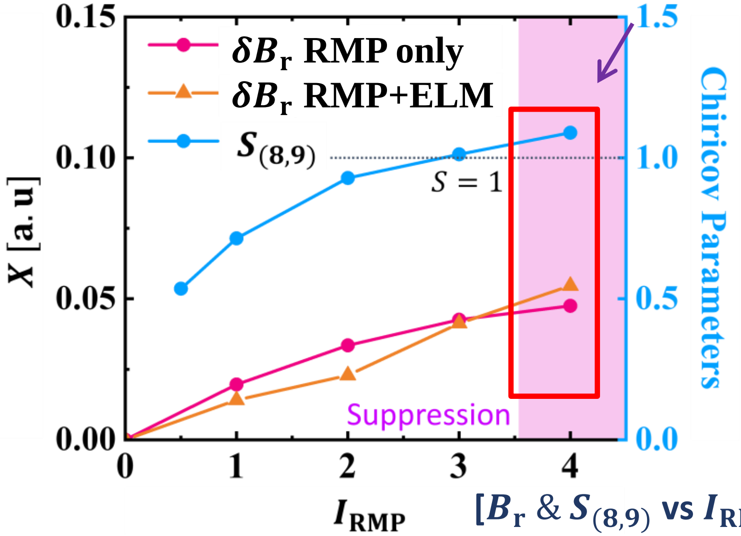
Backup - Both kink and tearing response by RMP have to spatialy cover pedestal to mediate interactions between ELM

- **Increased interactions between ELM by coupled RMP**

Island overlap is needed



Suppression starts



$[B_r$ & $S_{(8,9)}$ vs $I_{RMP}]$

- ✓ **Covering the pedestal and overlapping of RMP mode to mediate interactions.**
  - Kink-peeling → Overlap is easy, but localized to LCFS.
  - Tearing → Wide radial range, but sufficient island width needed for overlap.
- ✓ **Chiricov parameter (> 1) near the pedestal top (S_{89}).**
  - $n = n_{\mathrm{RMP}}$ island overlap to couple with higher n's.
  - ELM suppression as island overlap occurs.

Position of rational surfaces and island width are important.

Backup - Importance of RMP-ELM coupling addresses required or advantageous conditions for RMP-driven ELM crash suppression

- **Conditions for the interactions between RMP and ELM**
  - ✓ **Kink-peeling favorable MP configuration.**
  - ✓ **Rational surface ($q = m/n_{\mathrm{RMP}}$) near the pedestal top.**
    - **Island to cover the entire pedestal and dominant ELMs.**
  - ✓ **Chiricov parameter ($S > 1$) near the pedestal top.**
    - **$n = n_{\mathrm{RMP}}$ island overlap to couple with higher n's.**
  - ✓ **$V_{\theta,\mathrm{ELM}} \approx 0$ before RMP application.**
    - **Favorable to the locking of ELM.**