Mechanical and Aerospace Engineering

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

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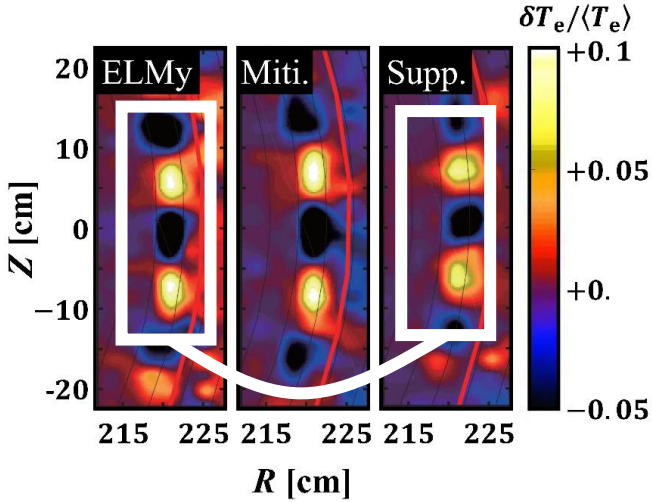
RMP-induced pedestal degradation are successful explanation for ELM suppression, but have some difficulties in explaining experiment

- **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

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.**

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

Ohm's law

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

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

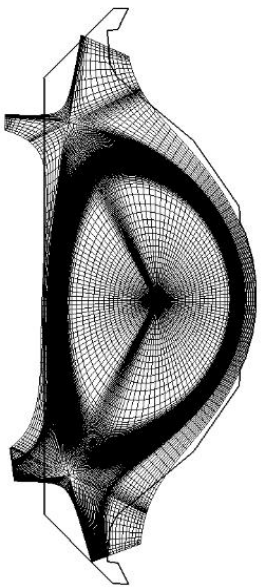
Continuity eqn.

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

Momentum eqn.
($v_{||}$, w)

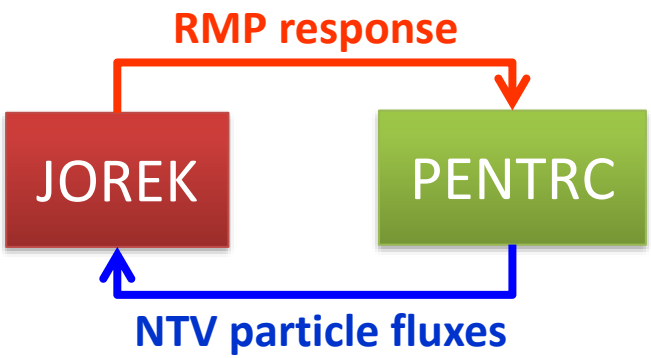
$$\frac{\partial(\rho T)}{\partial t} = -\left(\vec{v}_{\mathrm{E}} + \vec{v}_{||}\right)\cdot\nabla\rho T - \gamma\rho T\,\nabla\cdot\left(\vec{v}_{\mathrm{E}} + \vec{v}_{||}\right) + \nabla\cdot(\kappa\nabla T) + (1-\gamma)S_{\mathrm{T}}$$

Energy eqn.



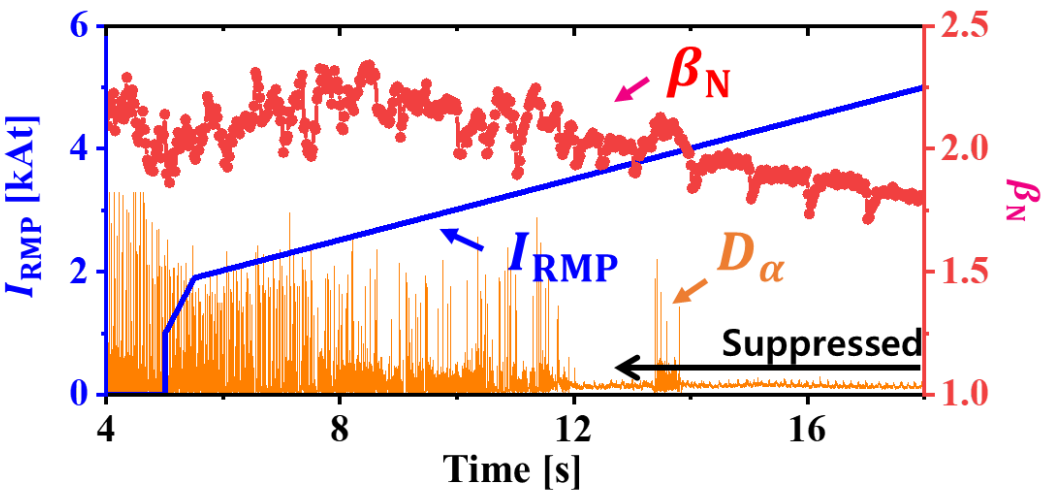
[Grid for KSTAR]

- **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)

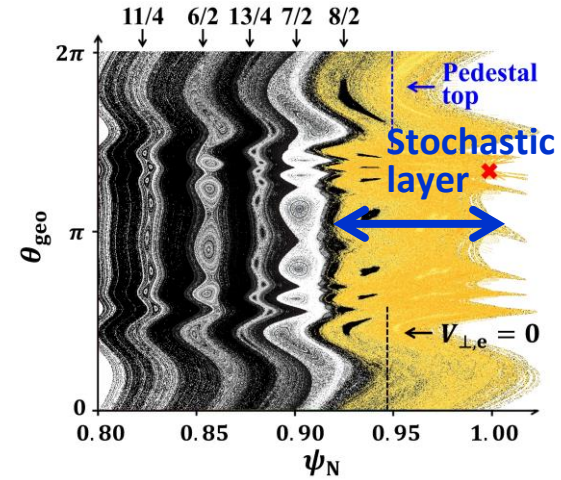
RMP simulation with ELMs (n up to 14)

Contents

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.

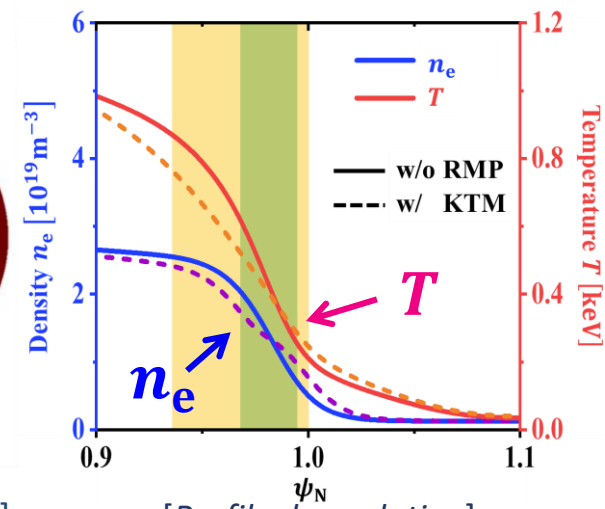
[*Perturbations*]



[*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).

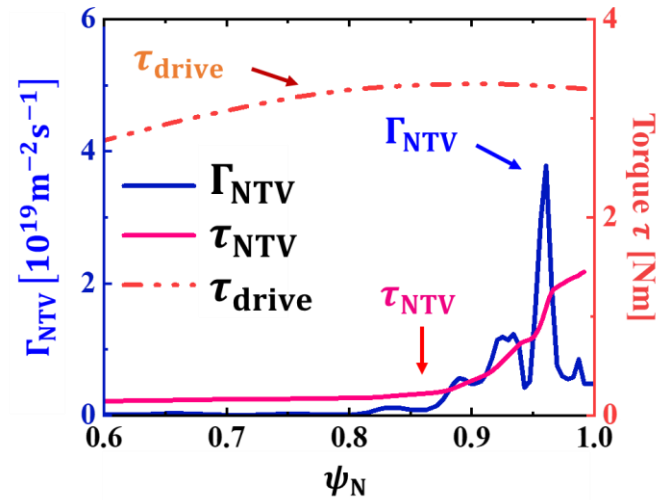
[$\Gamma_{E\times B\perp}$ *profiles*]



[*Profile degradation*]

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

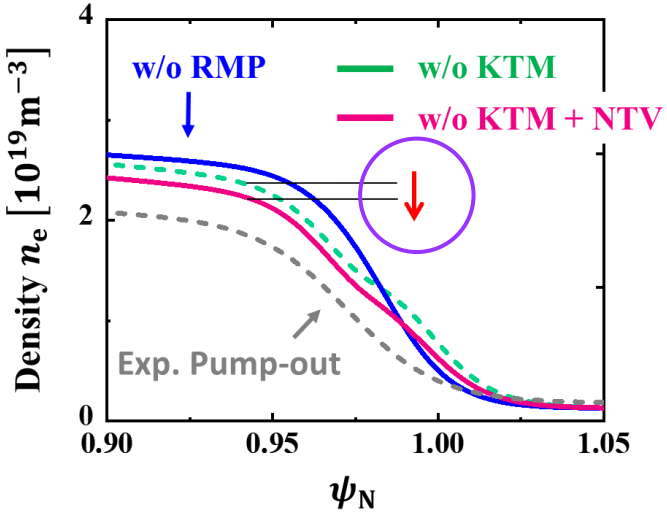
- **NTV induced by plasma response**
  - ✓ Plasma displacement ($\xi_\perp$) induced by RMPs.
  - ✓ Resulted NTV fluxes.
    - Torque τ_{NTV}
    - Particle flux Γ_{NTV}



[NTV particle & momentum fluxes]

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

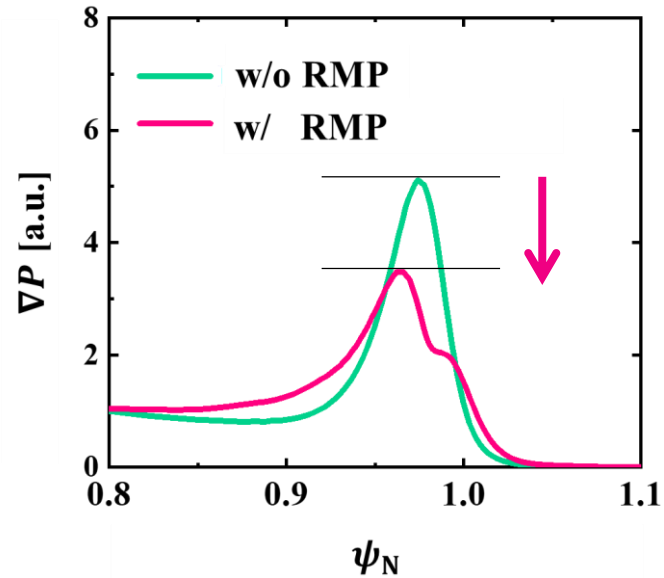
→ Considerable effect of kink and NTV on pump-out.



[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].**

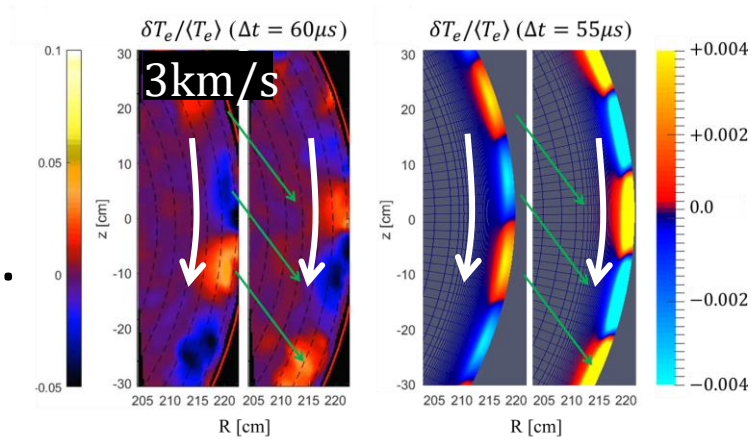
→ **They will be needed to fully explain the pump-out.**

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

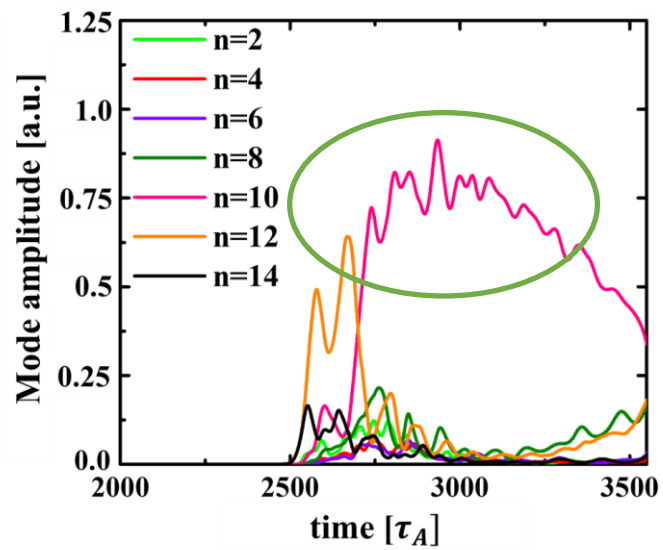
- **Linear ELM simulation**
  - ✓ Consistent dominant $n_{\mathrm{ELM}} = 12$.
  - ✓ Consistent poloidal velocity $v_{\theta,\mathrm{ELM}} \sim 3\ \mathrm{km/s}$.
  - ✓ $v_{\theta,\mathrm{ELM}} \approx v_{\theta,\mathrm{E\times B}}$ (ion - diamagnetic) [1,2].



[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. ($v_{\theta,\mathrm{ELM}} \approx v_{\theta,\mathrm{E\times B}}$)

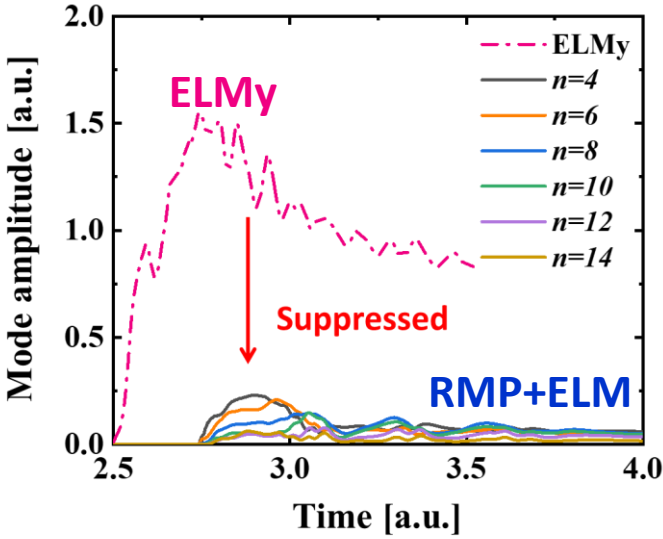


[Mode amplitude in NL phase]

[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.**

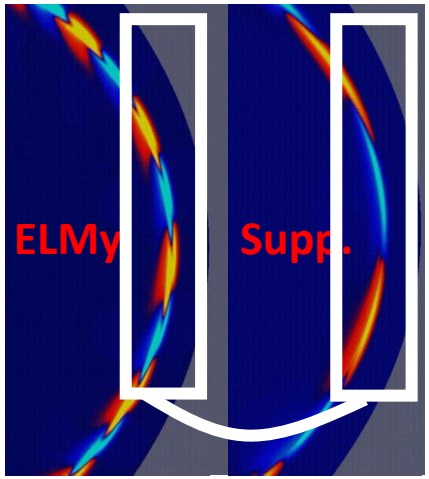


[*Nonlinear evolution of ELM*]

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].

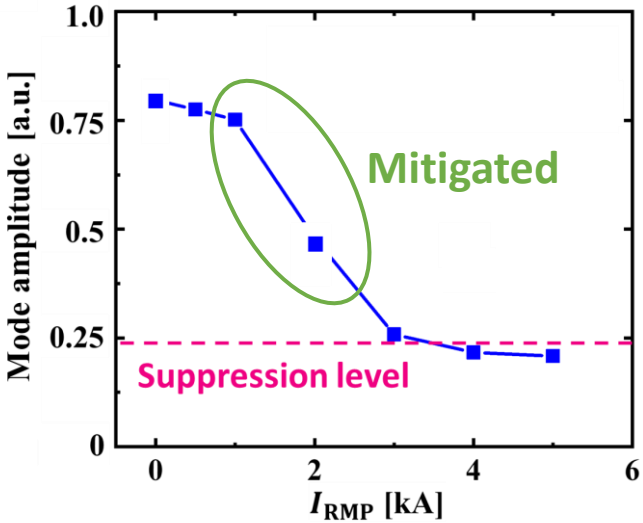
    → ELM is nonlinearly saturated rather than linearly stabilized, so filament can remain.



[*Filament motions*]

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

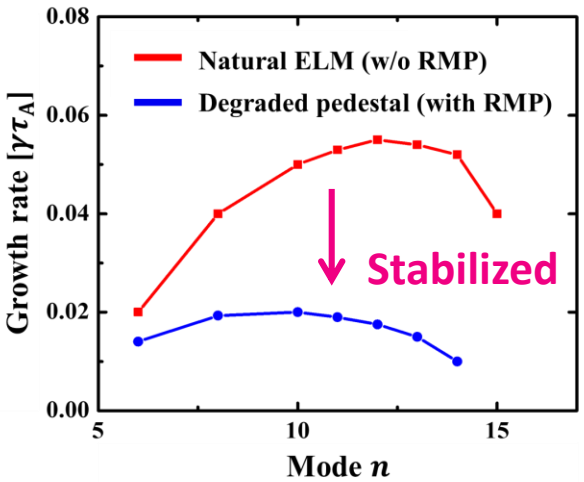
    → It is consistent to experimental level (~4kA).



[*Mode amplitude vs RMP*]

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

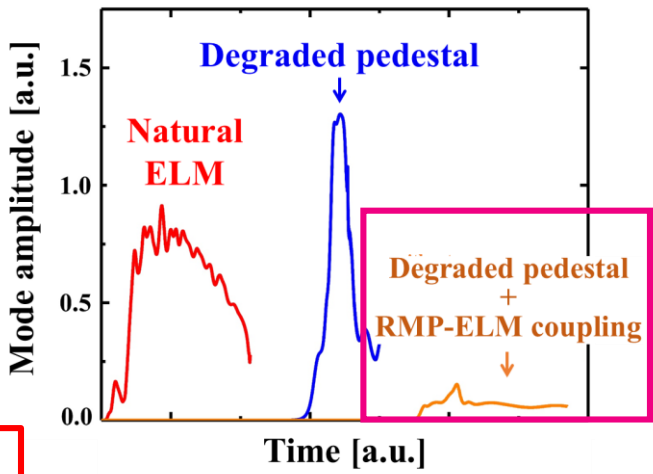
- **Effect of degraded pedestal on ELM stability**
  - ✓ **~40% decreased pedestal gradient by RMPs.**
  - ✓ **~65% decreased growth rate.**



[*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

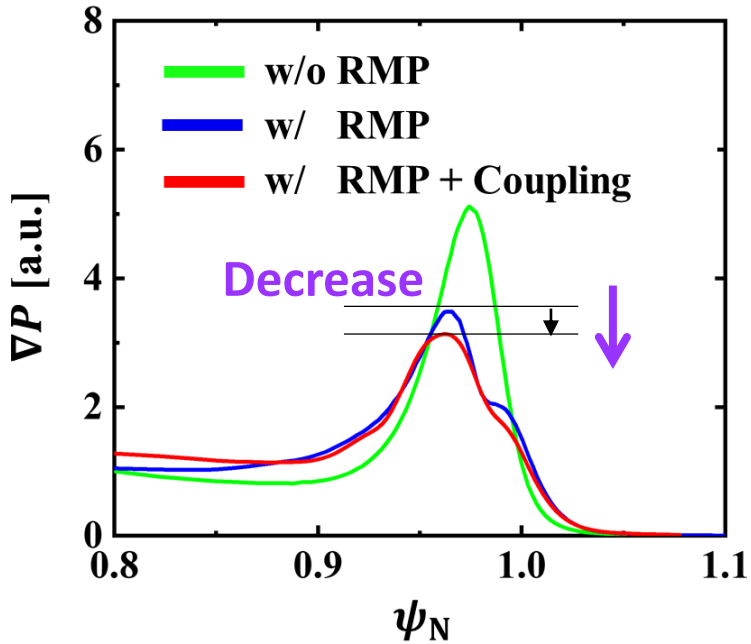
- **Enhanced pedestal transport by coupling effect**

✓ **~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*]

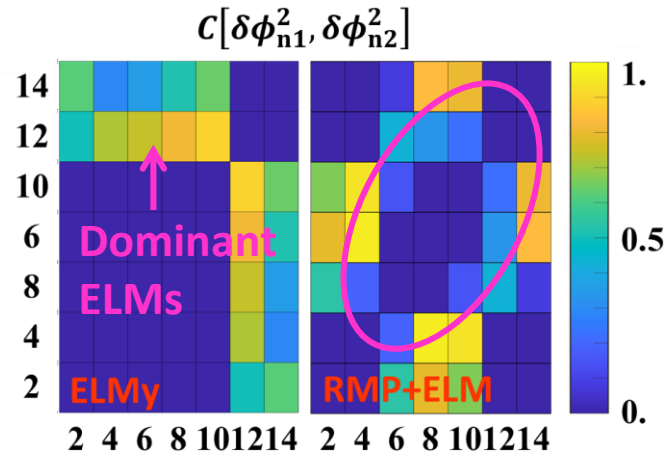
RMP-ELM coupling results in broad mode spectrum and increased interactions between ELM harmonics, preventing unstable ELM crash

- **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

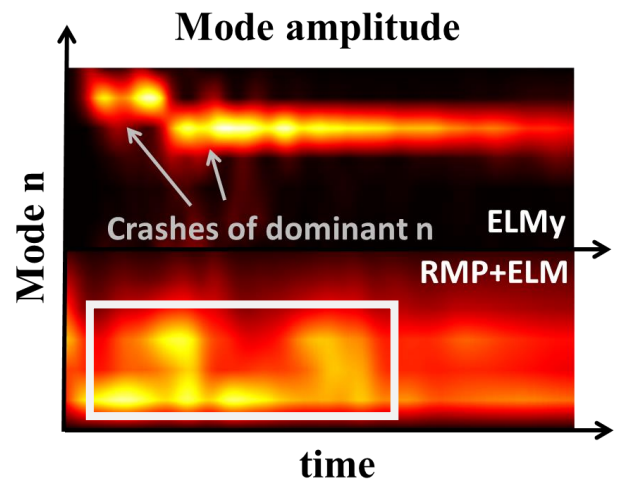
Degraded pedestal + Broadened spectrum Enhanced interaction

Driving ↓ Dissipation ↑

✓ Important quantities for RMP-ELM coupling?



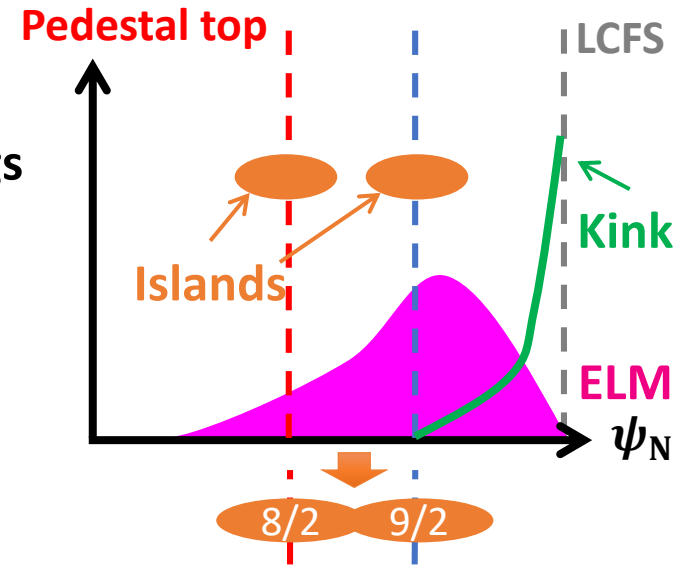
[Mode energy correlation]



[Mode spectrum vs time]

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

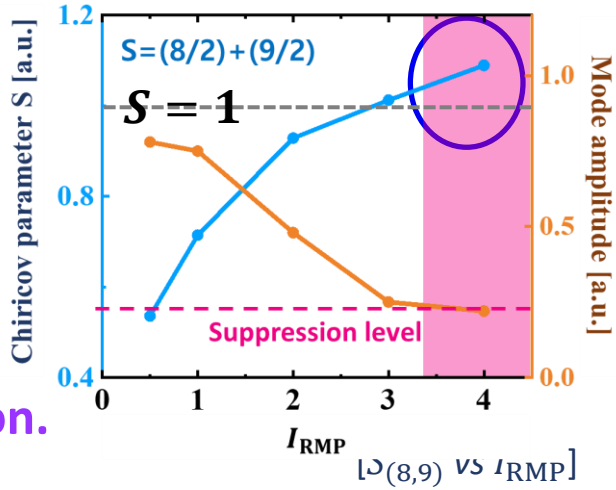
- **Spatial overlap of harmonics**
  - ✓ **Overlap of harmonics: Favorable to their couplings [Rhee POP2015].**
  - ✓ **Existing harmonics,**
    - **ELM harmonics**
    - **RMP-Kink (peeling) → Localized to LCFS.**
    - **RMP-Tearing (island) → Wide radial range.**



➢ **n=2 Island overlap**

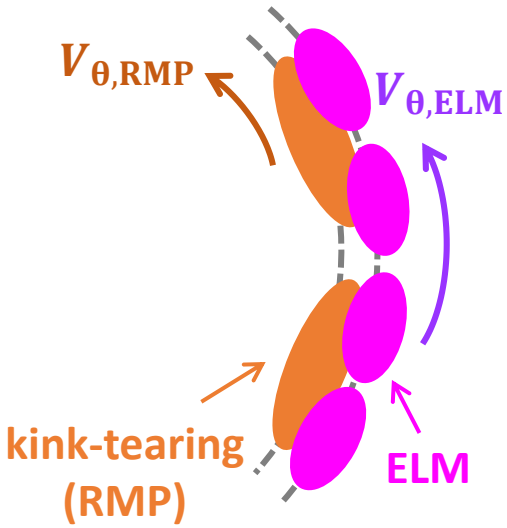
- **Island overlap near the pedestal top**
  - ✓ I_{RMP} **scan to adjust island width near pedestal top.**
  - ✓ **ELM suppression entry where island overlap starts. (Chiricov *S* =1 between 8/2+9/2)**

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



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 ($\left|V_{\theta,\mathrm{ELM}} - V_{\theta,\mathrm{RMP}}\right| \approx 0$).**
    → **Stationary phase difference (δ) of RMP and ELM.**



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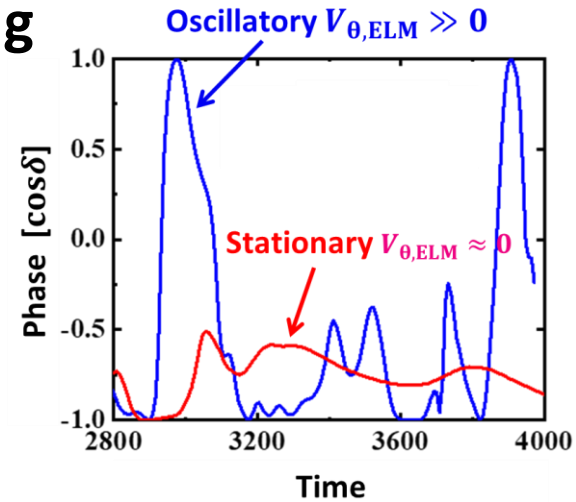
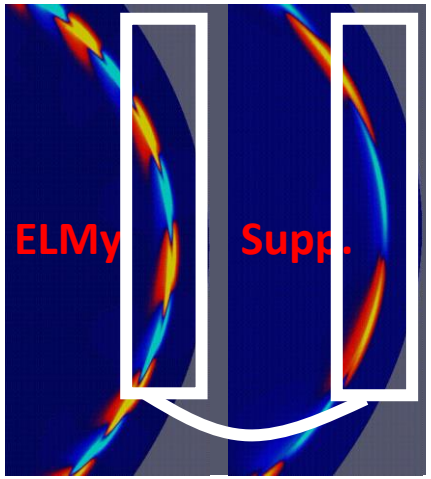
    → Stationary phase difference (δ) of RMP and ELM.
  - ✓ **Static RMP, $V_{\theta,\mathrm{RMP}} = 0$.**
    →$V_{\theta,\mathrm{ELM}} \approx 0$ to make stationary δ.



[*Time evolution of* cos δ]



[*Filament motions*]

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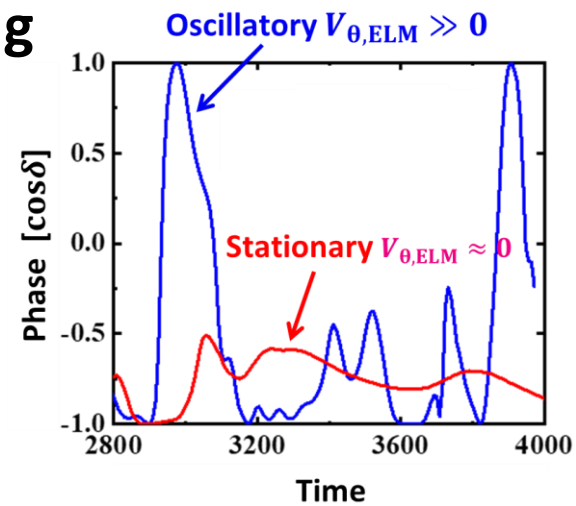
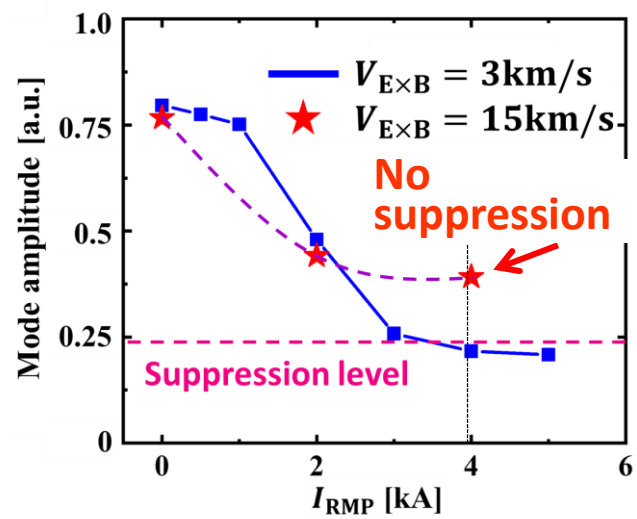


[*Time evolution of* cos δ]

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

    → Small $V_{\theta,\mathrm{ELM}}$ (or $V_{\mathrm{E\times B}}$) 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 $V_{\mathrm{E}\times\mathrm{B}} \approx 0$ at the pedestal.**

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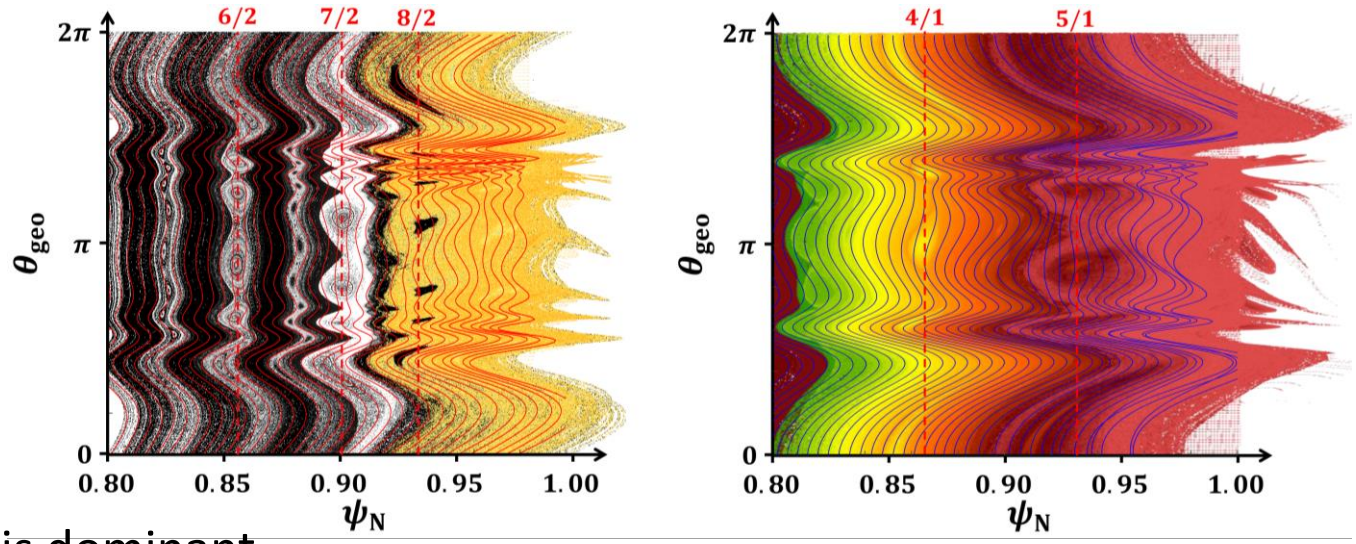
Thank You

Plasma Laboratory for Advanced REsearch

Backup – Plasma displacement from JOREK perturbation

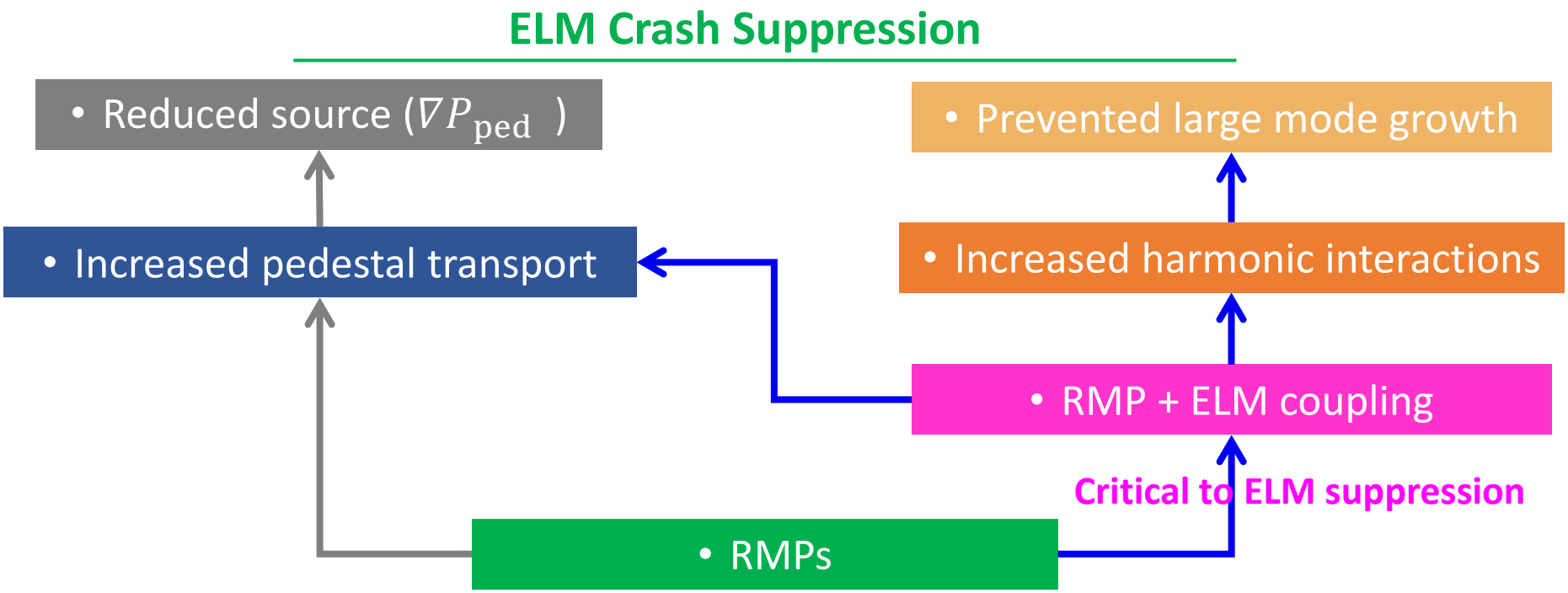
- **Approximated displacement from nonlinear perturbation**



- ✓ $T_{n=0}$ is dominant.
- ✓ Uniformity of T on the flux surface due to large parallel heat conduction.
- ✓ Therefore, $\xi_{\perp,n,m} \sim -\frac{\delta T_{n,m}}{\nabla T_{n'=0}}$
- ✓ 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**



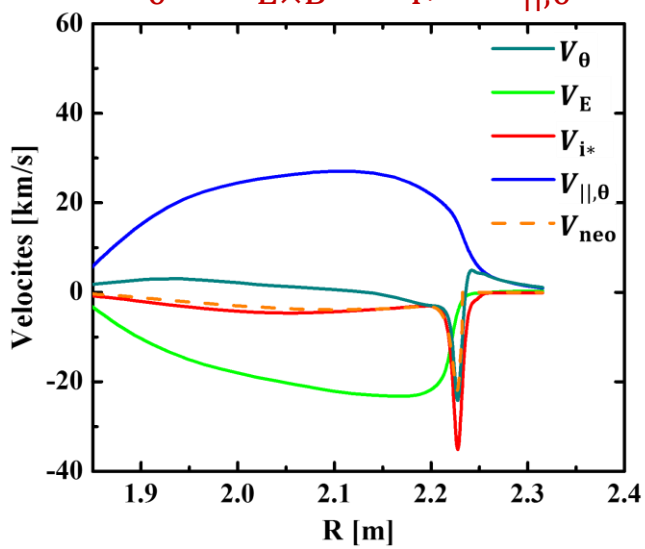
- **Important quantities for RMP-ELM coupling?**

→ **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 <u>ion-diamagnetic</u> 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.**

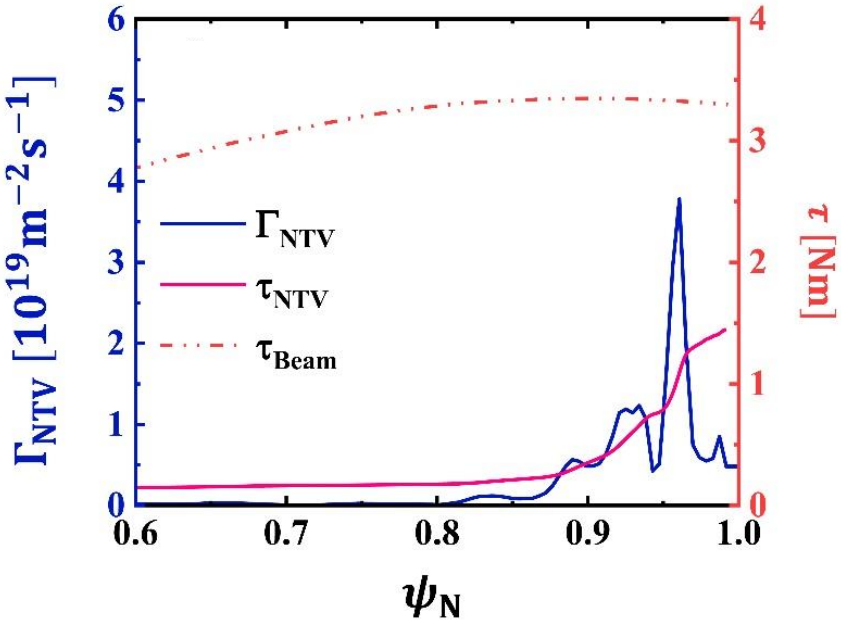
$$V_{\theta} = V_{\mathrm{E\times B}} + V_{\mathrm{i}*} + V_{||,\theta}$$



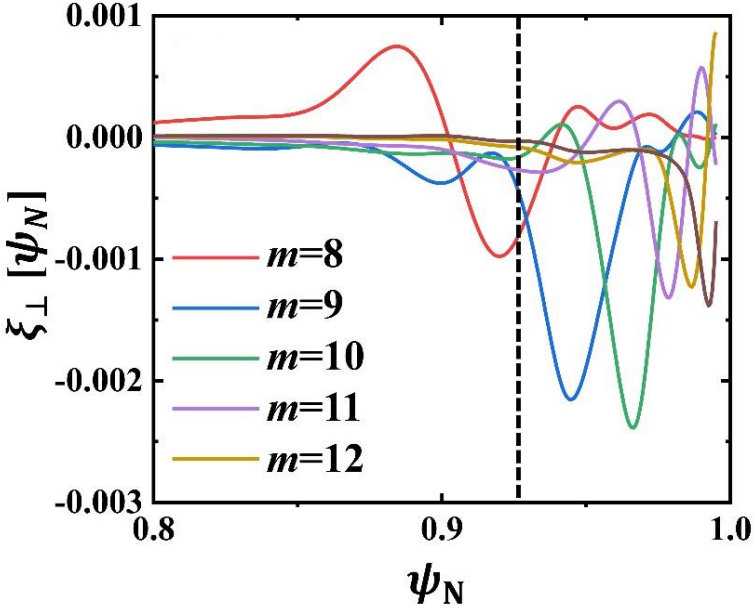
[Poloidal flow components]

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.**



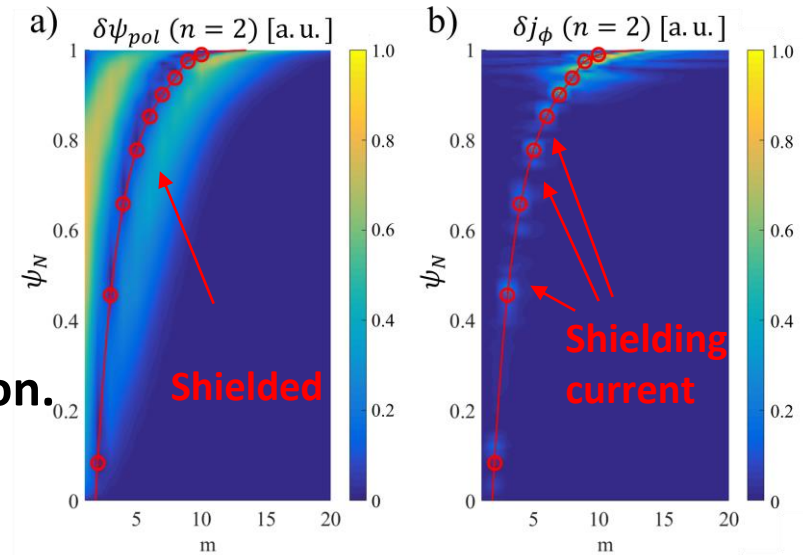
[NTV particle & momentum fluxes]



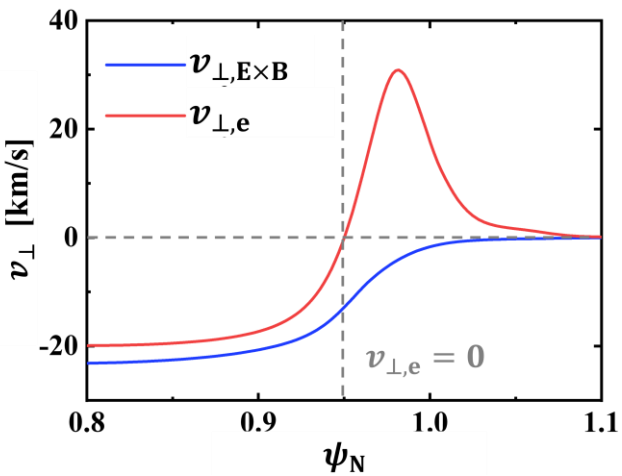
[$\xi_\perp$ profile form JOREK]

Backup – tearing response

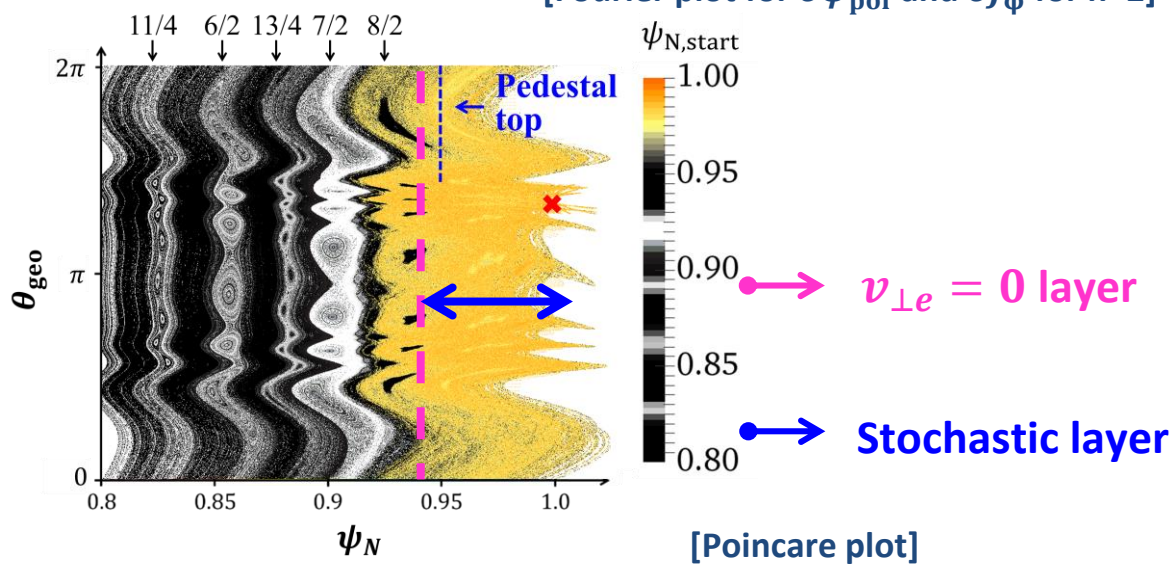
- **Tearing response**
  - ✓ **Perturbed current shields the external field.**
  - ✓ **$v_{\perp e} \approx 0$ layer and finite resistivity in the edge weaken the field shielding.**
  - ✓ **Field penetration occurs in the pedestal region.**
  - ✓ **As a result, stochastic layer is formed.**



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



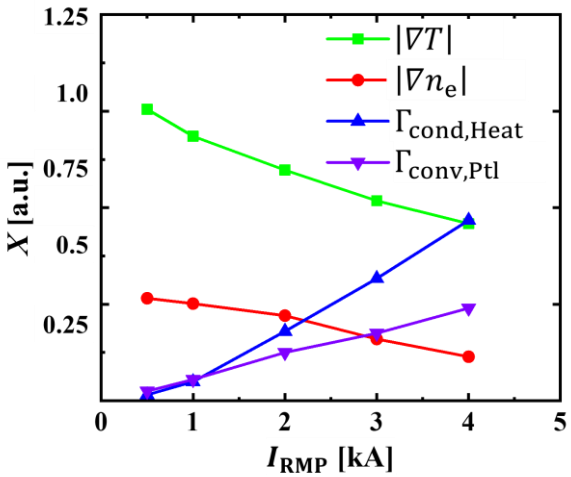
[Perpendicular flow profile]



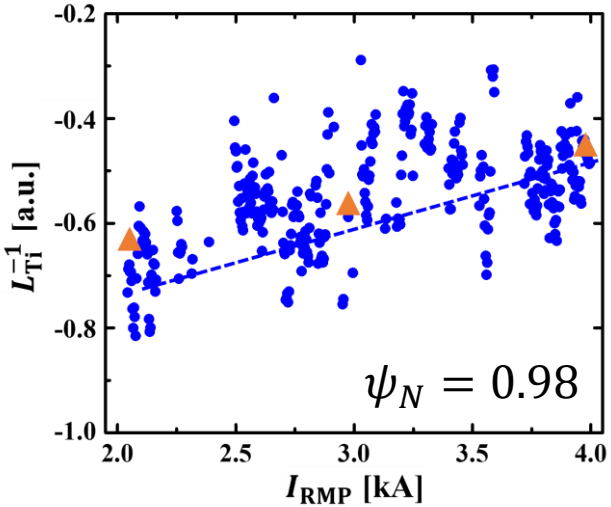
[Poincare plot]

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}]

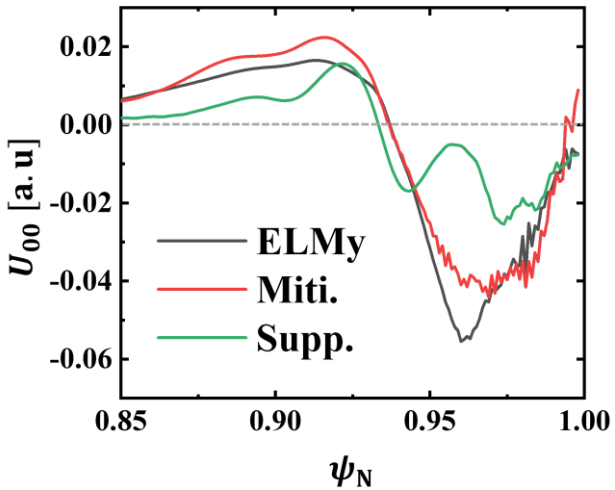


[L_{Ti}^{-1} vs I_{RMP}]

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

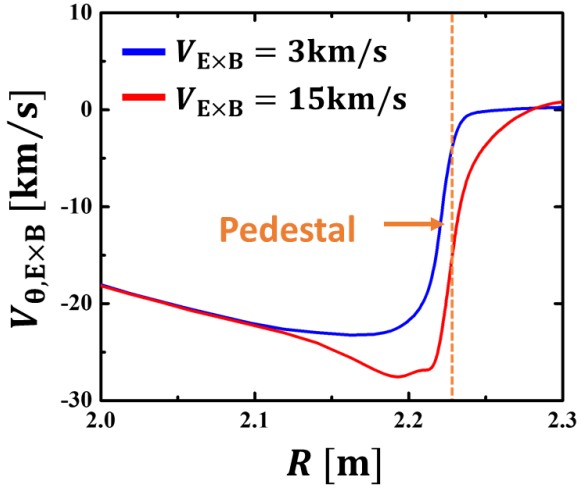
Backup – Vorticity and ExB profiles

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



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

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



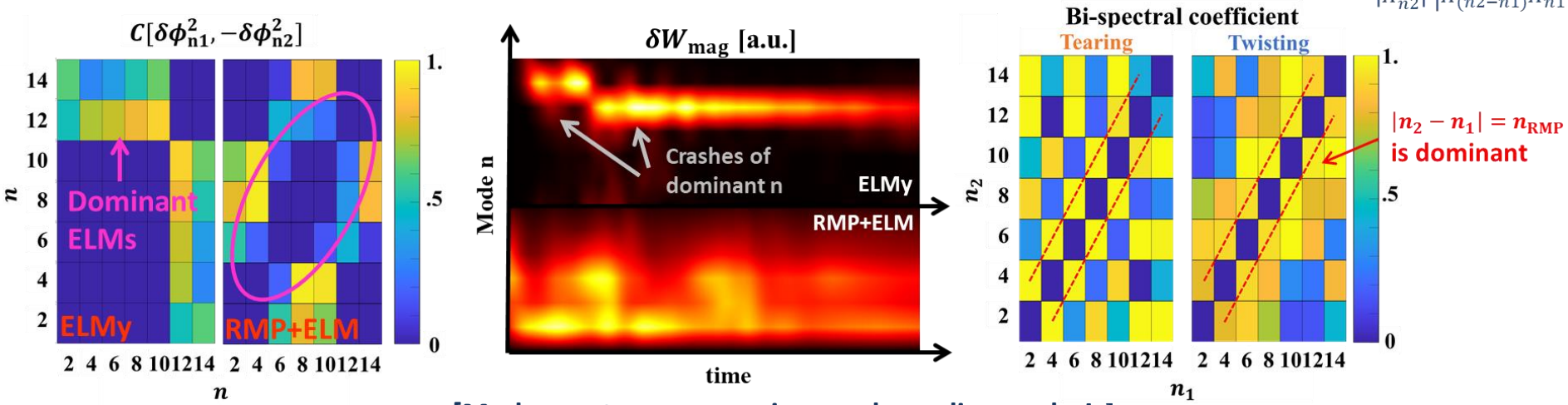
✓ **ExB radial profile comparison**

- **$V_{\theta,E\times B}$ 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**

$$\because \frac{X^*_{n2} X_{(n2-n1)} X_{n1}}{|X^*_{n2}|\,|X_{(n2-n1)} X_{n1}|}$$

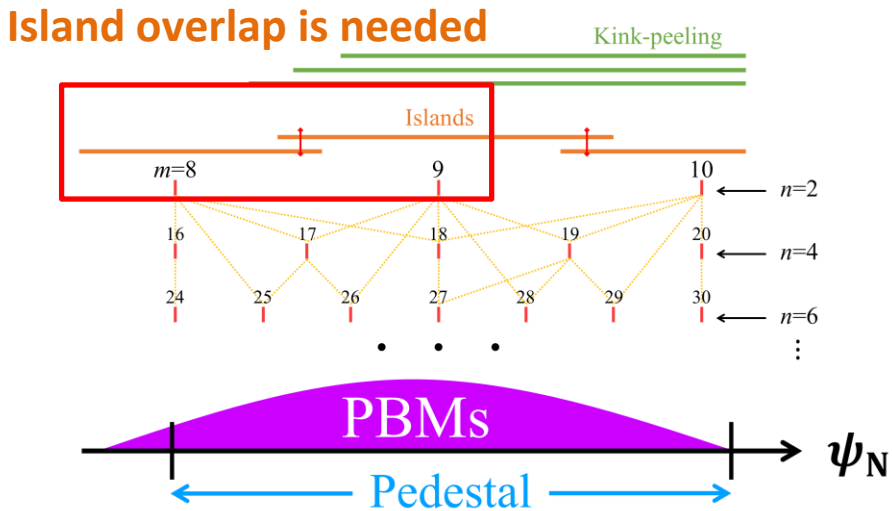


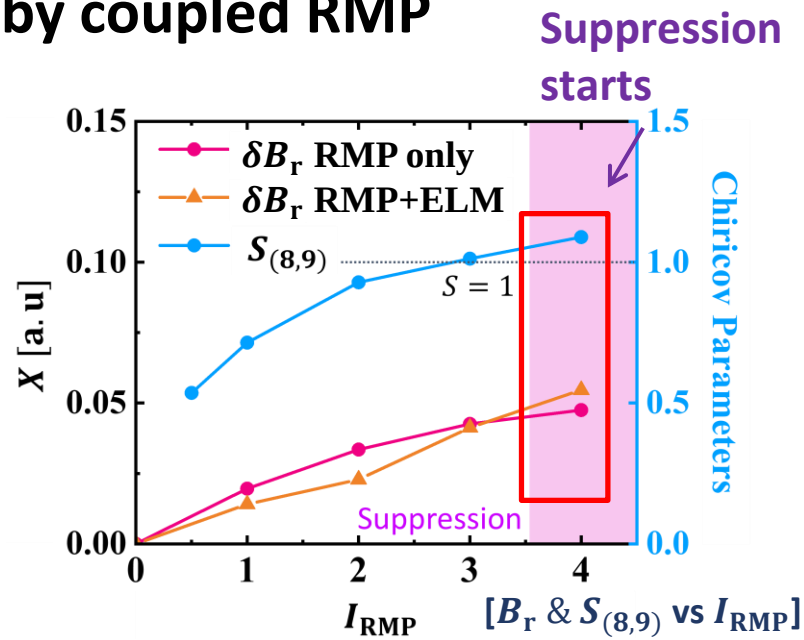
[Mode spectrum comparison and coupling analysis]

- ✓ **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**





✓ **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 <u>pedestal top</u> (S_{89}).**

- **$n = n_{RMP}$ 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.**
  - ✓ **$v_{\theta,\mathrm{PBM}} \approx 0$ before RMP application.**
    - **Favorable to the locking of ELM.**