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

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Introduction – Additional mechanisms to fully explain suppression

RMP is promising ELM suppression method [1].

- Linearly stabilized ELMs with degraded pedestal by RMP-induced islands [2]

→ **One of promising/successful explanation.**

Additional concept may be needed for full explanation.

- Possible difficulty to solely describe degraded pedestal by islands.

→ **Additional transport induced by RMPs.**

- Limitations to explain ELM-like mode during suppression [3].

→ **Contradiction to linearly stabilized ELM by Degraded pedestal.**

Simulation tool – Integrated nonlinear MHD simulation with NTV

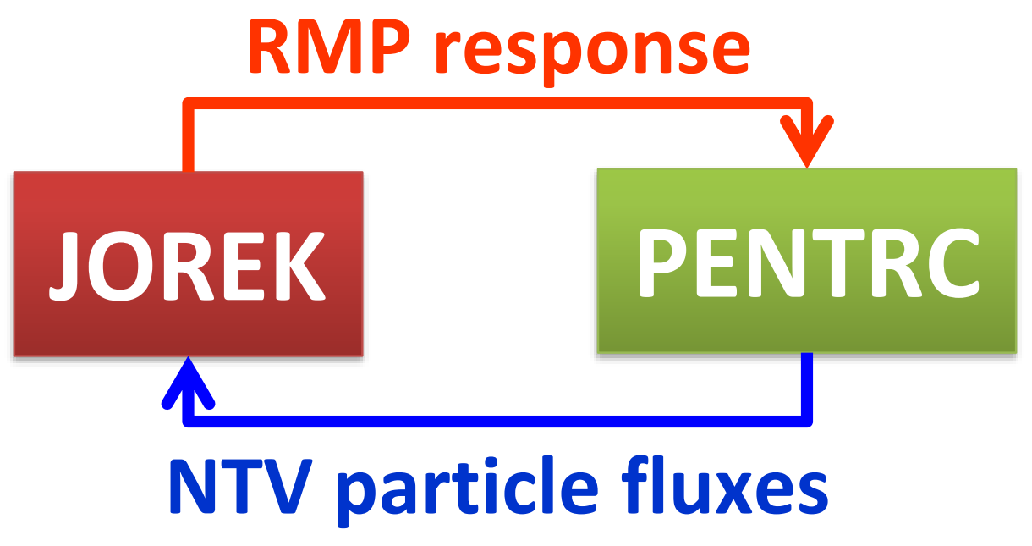
JOREK (3D Nonlinear MHD) [4].

- Realistic geometries with SOL.
- 5 fields reduced MHD equation.

w/ toroidal rotation
w/ ion diamagnetic
w/ $T_i = T_e$

PENTRC (NTV code) [5].

- NTV calculation based on the given plasma equilibrium, profiles, and plasma displacements.
- Inclusion of NTV by JOREK-PENTRC coupling.



Reference plasma – RMP-induced ELM crash suppression in KSTAR

KSTAR discharge (#18594) with $n = 2$ ($\phi = 90°$) RMPs.

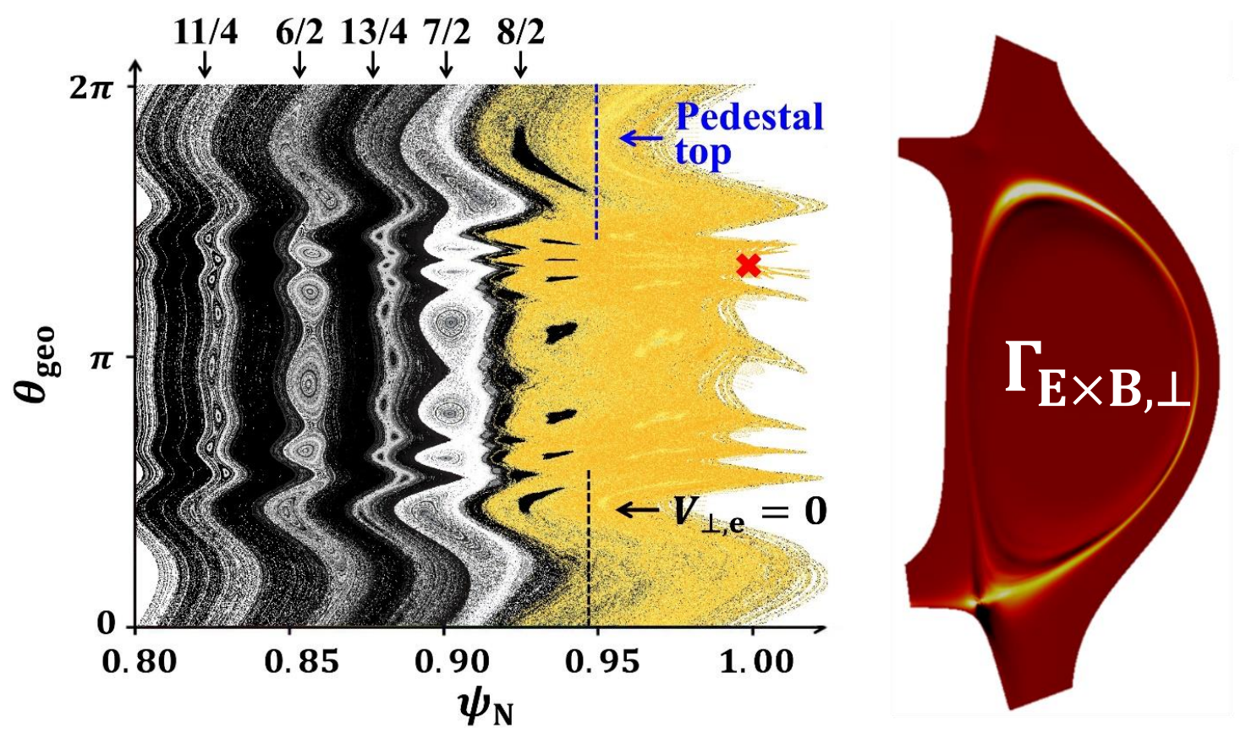
- $I_p = 690$ kA, $q_{95} \sim 4$, $\beta_N \sim 2.$, $\bar{n}_e = 3.3 \times 10\text{^}19\ \mathrm{m}^{-3}$.
- **Stable ELM suppression entry by $I_{\mathrm{RMP}} \geq 3.5$ kA.**
- Simulation with x10 larger neoclassical resistivity due to numerical reasons.
- Two simulation steps for the analysis.

RMP only simulation (n=0 and 2) → **RMP simulation with ELMs (n up to 14)**

RMP response – Kink-tearing + NTV induced pedestal degradation

Kink-tearing response (KTM).

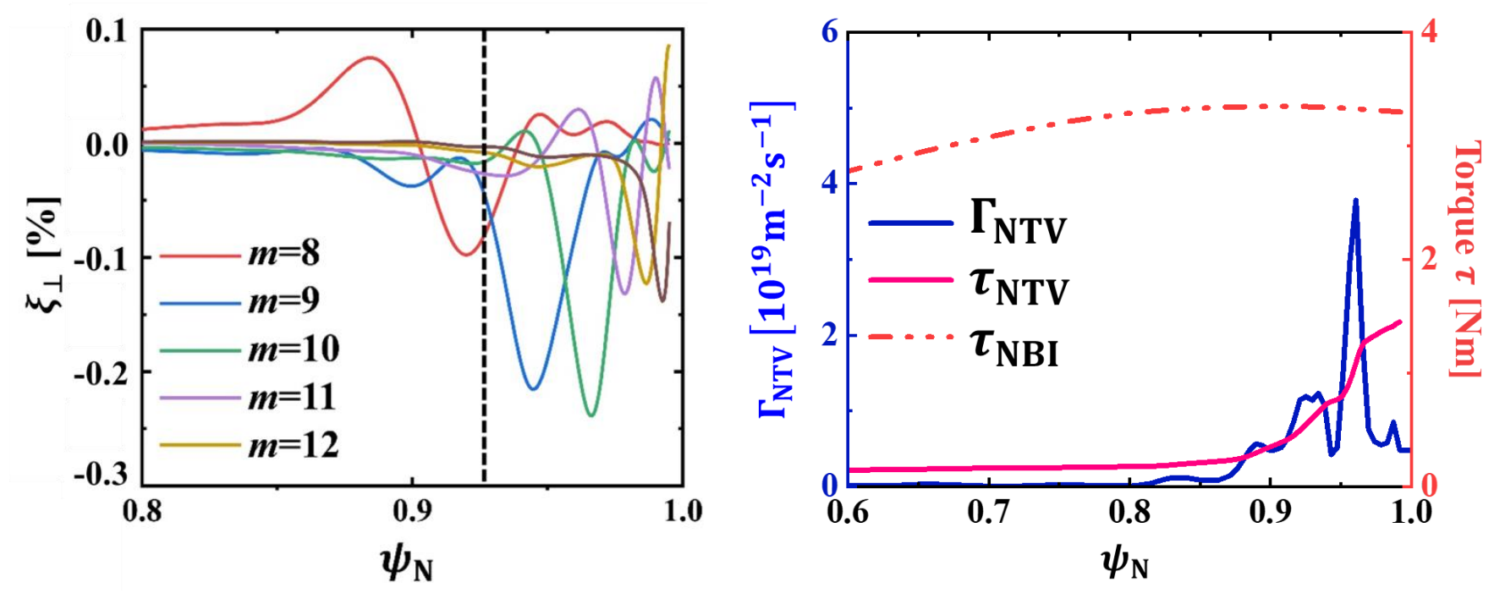
- Edge localized deformation of plasma (kink).
- Field penetration into the pedestal (tearing).
- Increased radial flux due to
  - $v_{E\times B\perp}$ convection (Mainly n_e).
  - Island and stochastic layer (n_e and T).



[Poincare plot & $\Gamma_{E\times B\perp}$ profile]

NC toroidal viscosity (NTV).

- Edge localized NTV by displacement.
- NTV torque (τ_{NTV}) and flux.

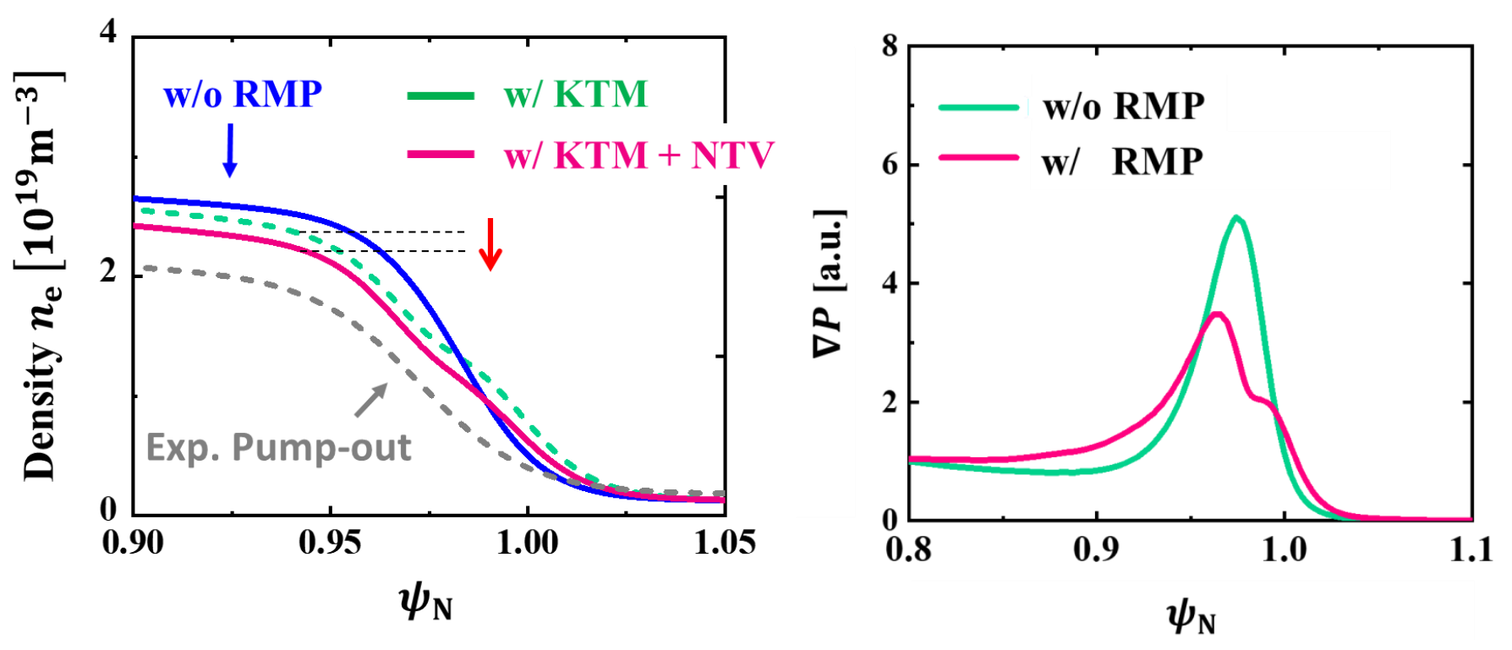


[Displacement & NTV fluxes]

Net pedestal degradation.

- By KTM [6-8] and NTV [9].
  - **net torque (90% of Exp.).**
  - **n_e pedestal (40% of Exp.).**
  - **P gradient (~ of Exp.)**

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



[Degraded density and gradient of pedestal]

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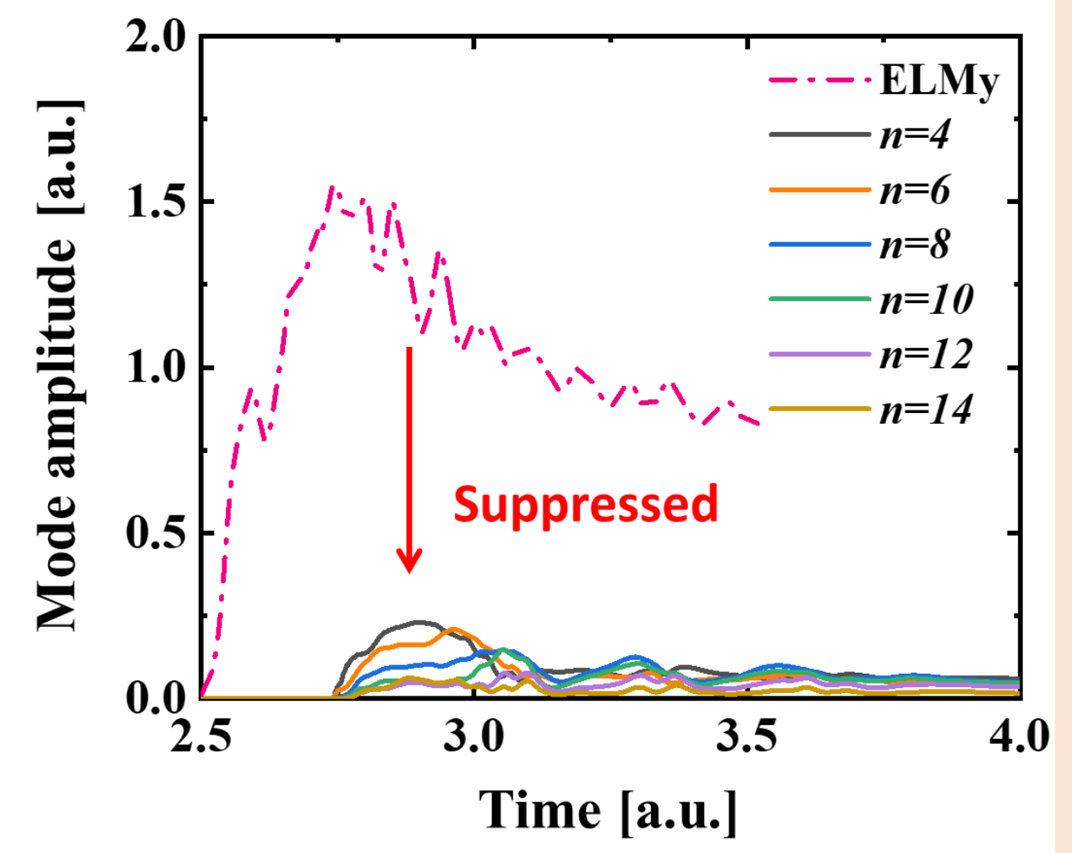
RMP-ELM response – Nonlinearly saturated ELMs by RMP coupling

RMP-driven ELM crash suppression.

- Strongly suppressed mode amplitude [10-11].
- Disappeared bursty mode crash [12].
- Existing mode structure during suppression [13].

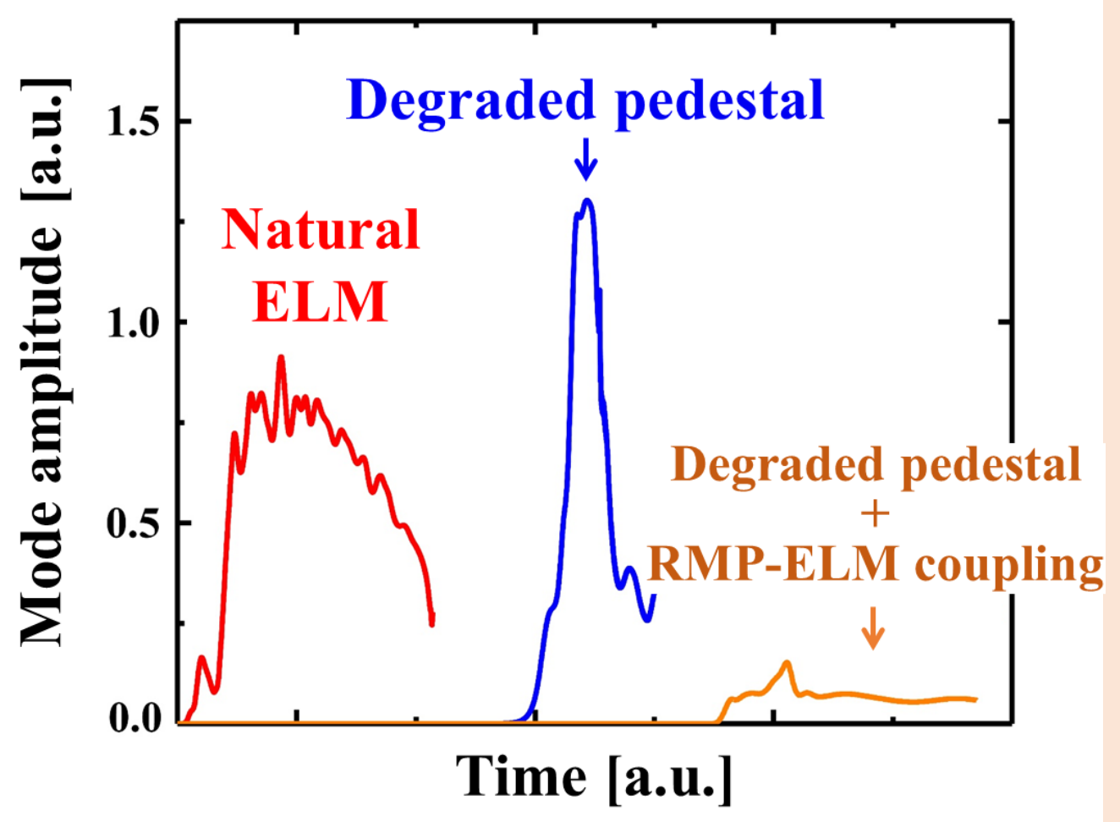
→ **ELM is nonlinearly saturated rather than linearly stabilized, so filament can remain.**



[Nonlinear evolution of ELM]

Contributors to suppressed ELM crash.

- Two major components in simulation.
  - **Degraded pedestal by RMPs**
  - **Interactions between RMP and ELMs**
- No crash suppression without mode coupling.
- **ELM crash suppression by combined effects.**



[ELM amplitude comparison]

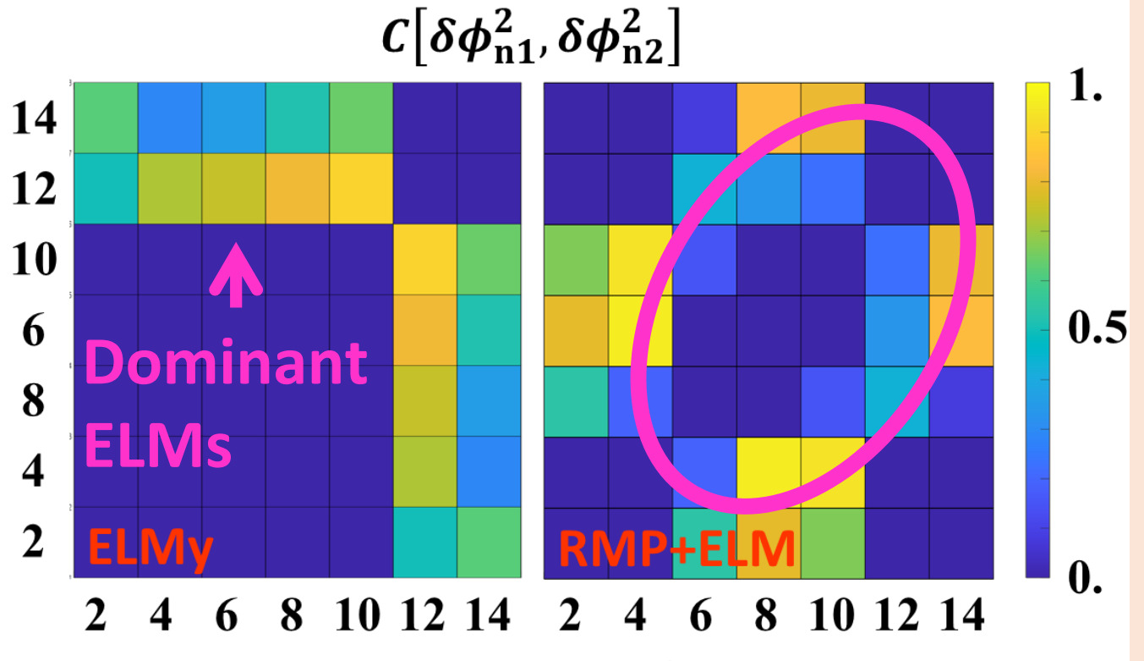
Role of RMP-ELM coupling – Enhanced interactions between ELMs

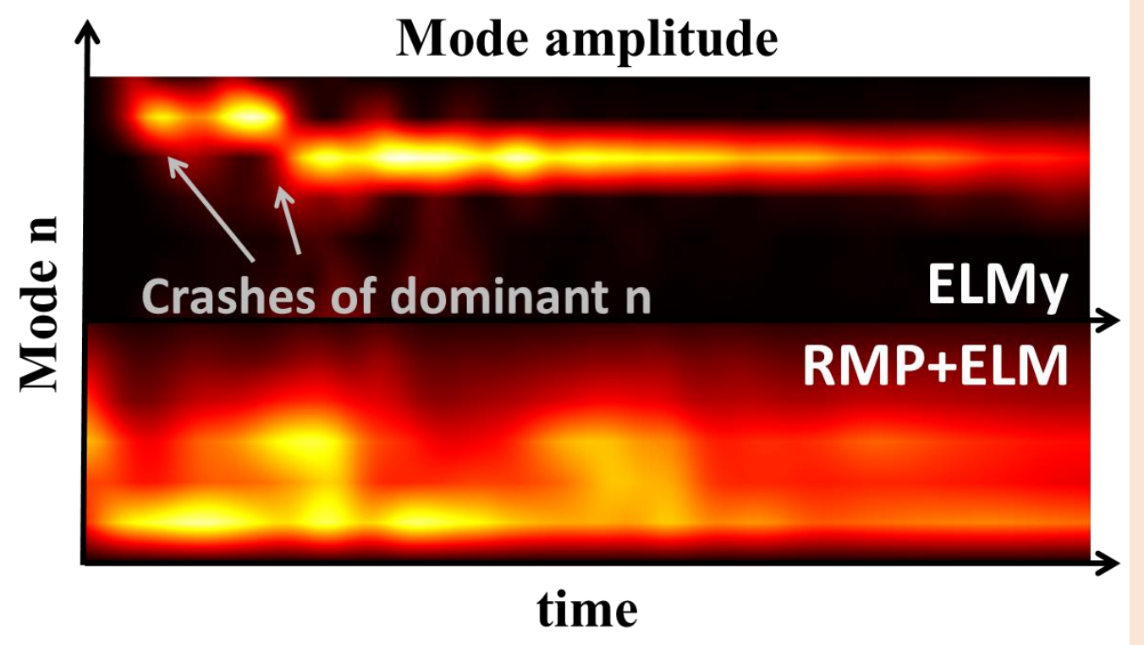
Enhanced ELM harmonic interactions.

- ① Unlike ELMy, enhanced energy correlation among harmonics. [14]
- ② Broadened mode spectrum.
- **Prevented mode crash due to ① + ② [15].**
- Nonlinearly saturated ELMs by

Degraded pedestal (Driving ↓) + **Broadened spectrum Enhanced interaction (Dissipation ↑)**

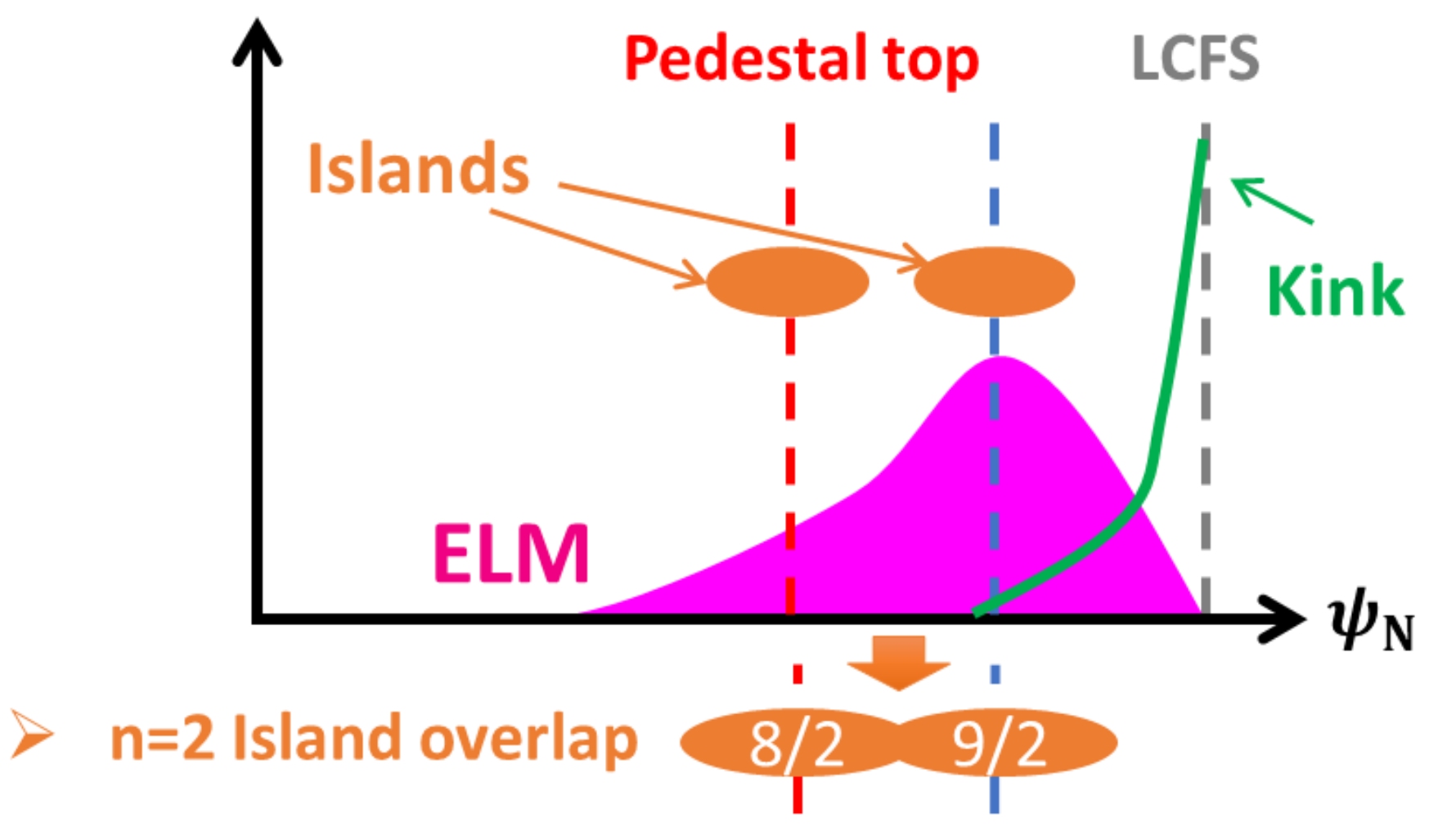
- **Large RMP-ELM interaction is favorable!**

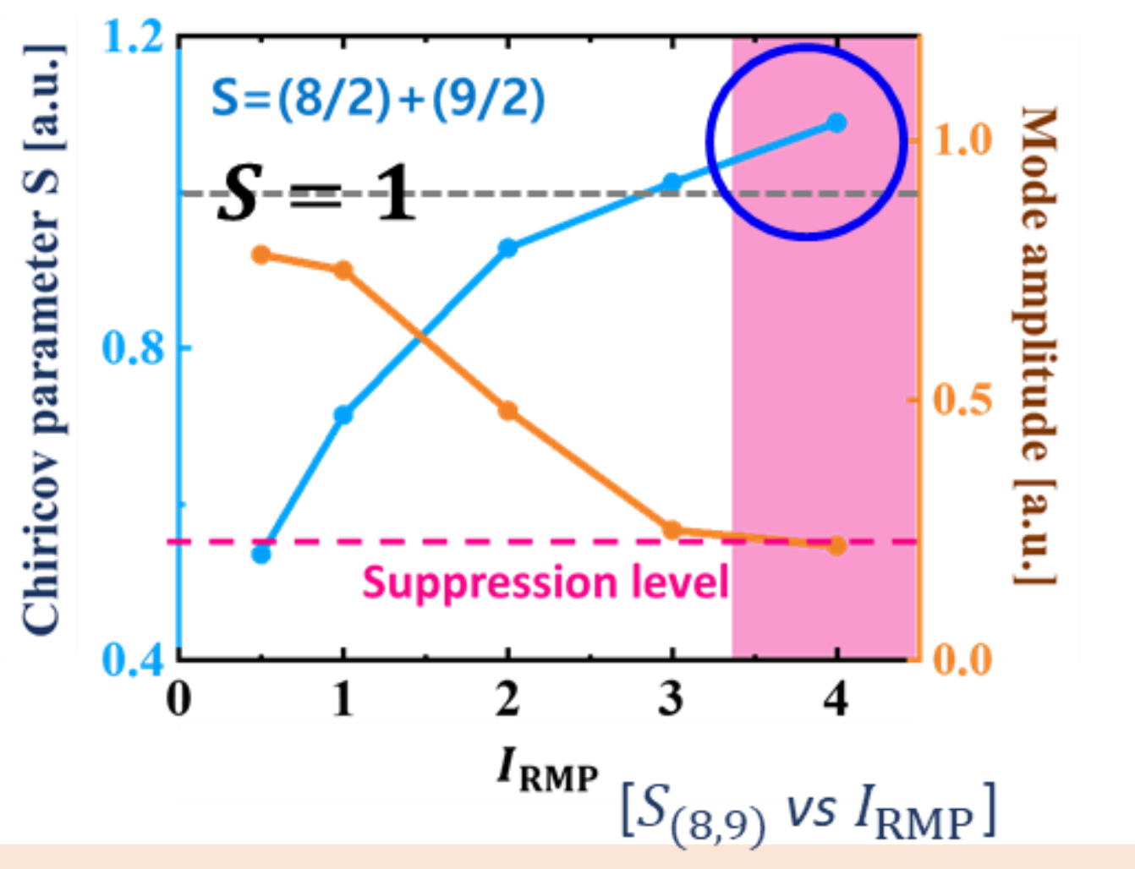




Overlap of magnetic islands near pedestal top can be important to RMP-ELM coupling and ELM suppression

ELM suppression entry where island overlap starts (S =1).



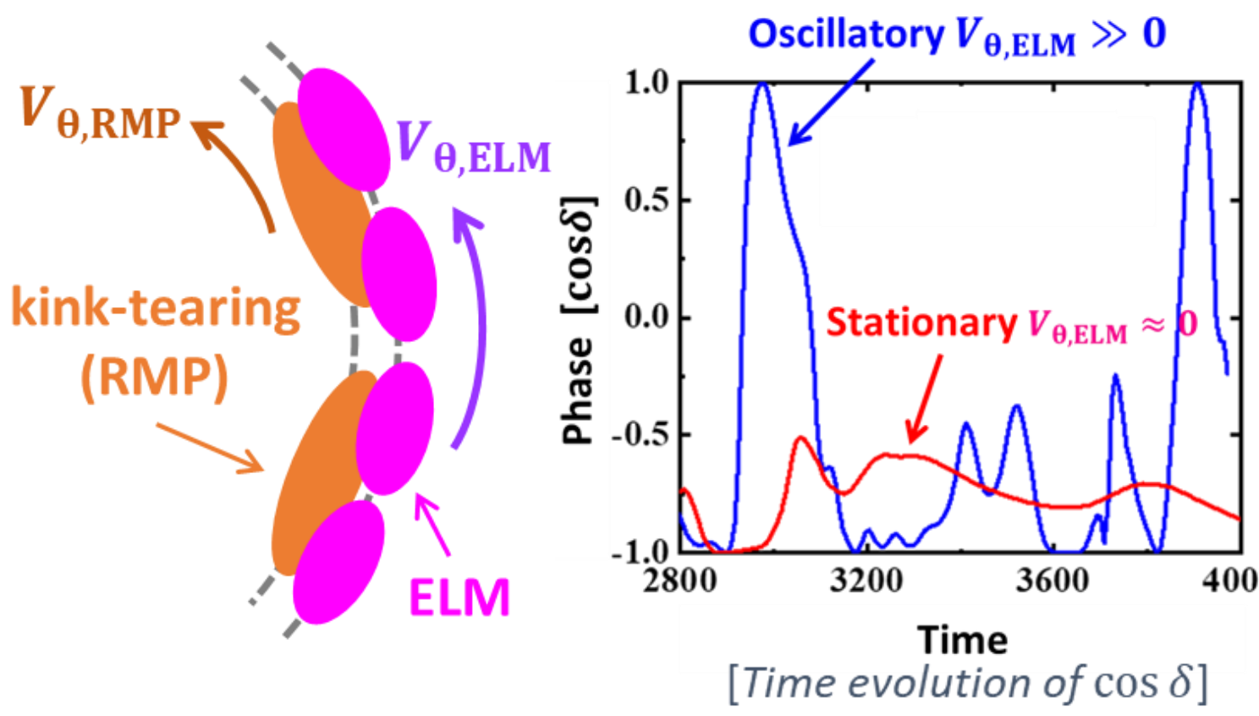


ELM Supp. w/ island overlap.

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

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

Stationary mode overlap: Favorable to mode interaction.



δ is phase difference between RMP&ELM structures.

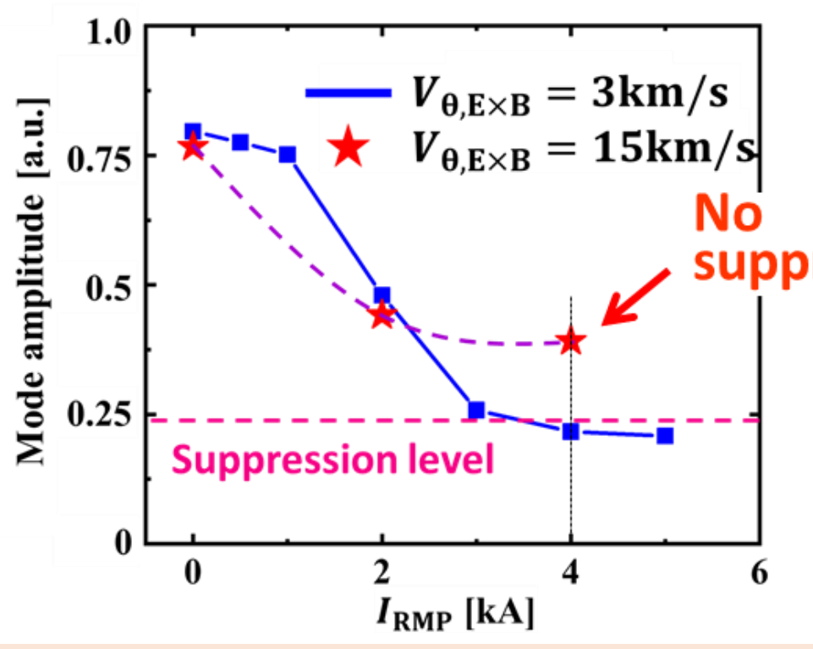
[Time evolution of cos δ]

- Static RMP, $V_{\theta,\mathrm{RMP}} = 0$

→ **$V_{\theta,\mathrm{ELM}} \approx 0$ for stationary δ or overlap.**

- $V_{\theta,\mathrm{ELM}} \approx V_{\theta,\mathrm{E\times B}}$ [16,17].

→ **$V_{\theta,\mathrm{E\times B}} \approx 0$ at pedestal is favorable [18].**



No ELM suppression with large $V_{\theta,\mathrm{E\times B}}$ at pedestal top.

CONCLUSION

n=2 RMP-driven pedestal degradation and ELM suppression

- Degradation by RMP response + NTV, explaining 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 mode crash**

Favorable conditions for RMP-ELM coupling

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