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

S.K. Kim\textsuperscript{1,2}, S. Pamela\textsuperscript{3}, M. Becoulet\textsuperscript{4}, G. Huijsmans\textsuperscript{4}, O. Kwon\textsuperscript{5}, Y. In\textsuperscript{6}, J.H. Lee\textsuperscript{7}, M. Kim\textsuperscript{7}, S.M. Yang\textsuperscript{2}, J.K. Park\textsuperscript{2}, N. Logan\textsuperscript{8}, Yong-Su Na\textsuperscript{9}, and JOREK team

\textsuperscript{1}Princeton University, USA
\textsuperscript{2}Princeton Plasma Physics Laboratory, USA
\textsuperscript{3}Culham Centre for Fusion Energy, CCFE, UK
\textsuperscript{4}CEA, France
\textsuperscript{5}Department of Physics, Daegu University, Korea
\textsuperscript{6}Department of Physics, UNIST, Korea
\textsuperscript{7}Korea Institute of Fusion Energy, Korea
\textsuperscript{8}Lawrence Livermore National Laboratory, USA
\textsuperscript{9}Department of Nuclear Engineering, Seoul National University, Korea

E-mail: sk42@princeton.edu

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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.
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) \([5,6]\).

- **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 \([9-12]\).

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

1. Simulation setup

2. Effect of RMP-induced plasma response on pedestal profile

3. RMP-induced ELM-crash suppression

4. Summary
JOEREK and PENTRC coupled simulation is developed to simulate RMP-ELM dynamics including RMP response and NTV transport

- **JOEREK (3D Nonlinear MHD)** [G. Huysmans 2009]
  - Realistic geometries with scrape-off layer is included.
  - Reduced MHD equation [F. Orain 2013] is used.
    
    \[
    \frac{1}{R^2} \frac{\partial \psi}{\partial t} = \eta(T) \nabla \cdot \left( \frac{1}{R^2} \nabla \psi \right) - \vec{B} \cdot \left( \nabla u - \tau_{IC} \frac{\nabla p_e}{\rho} \right) 
    \]
    Ohm’s law

    \[
    \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) + \nabla \cdot (D \nabla \rho) + S_\rho
    \]
    Continuity eqn.

    \[
    \rho \left( \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) \left( \vec{v}_E + \vec{v}_\parallel \right) = -\nabla (\rho T) + \vec{j} \times \vec{B} + S_v - \vec{v} S_\rho + \mu \Delta \vec{v} - \nabla \cdot \vec{I}_{\text{neo}}
    \]
    Momentum eqn. \((v_\parallel, w)\)

    \[
    \frac{\partial (\rho T)}{\partial t} = - (\vec{v}_E + \vec{v}_\parallel) \cdot \nabla \rho T - \gamma \rho T \nabla \cdot (\vec{v}_E + \vec{v}_\parallel) + \nabla \cdot (k \nabla T) + (1 - \gamma) S_T
    \]
    Energy eqn.

- **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 \( n = 2 \) (\( \phi = 90^\circ \)) RMPs.
  - \( I_p = 690 \text{ kA}, \ q_{95} \sim 4, \ \beta_N \sim 2.., \bar{n}_e = 3.3 \times 10^{19} \text{ m}^{-3}. \)
  - Stable ELM suppression entry at \( I_{RMP} \geq 3.5 \text{ kA}. \)
  - Simulation with \( I_{RMP} = 4 \text{ kA}. \)

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[Graph showing \( I_{RMP} \) and \( \beta_N \) over time]

- 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.

- **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 $T$).

[Diagram showing perturbations and 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 $\tau_{\text{NTV}}$
    - Particle flux $\Gamma_{\text{NTV}}$

- Effect of NTV transport
  - Further degradation of $n_e$ pedestal by $\Gamma_{\text{NTV}}$
  - Kink + NTV (40% of Exp.).

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

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

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

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

→ Experimentally relevant ELM is obtained.
  (\( v_{\theta,\text{ELM}} \approx v_{\theta, \text{E} \times \text{B}} \))

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.

![Graph](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.

- **Suppression above RMP threshold**
  - Mitigated with small RMP amplitude.
  - Fully suppressed at $I_{\text{RMP}} > 3$ kA.
    
    → It is consistent to experimental level (~4kA).
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.

- 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.

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
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?
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.

- **Island overlap near the pedestal top**
  - ✓ $I_{\text{RMP}}$ 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 ($|\mathbf{V}_{\theta,\text{ELM}} - \mathbf{V}_{\theta,\text{RMP}}| \approx 0$).
    - Stationary phase difference ($\delta$) of RMP and ELM.

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- Poloidal mode rotation and RMP-ELM coupling
  - Well sustained mode overlap: Favorable to coupling.
  - Sustained spatial overlap ($|V_{\theta,\text{ELM}} - V_{\theta,\text{RMP}}| \approx 0$).
    → Stationary phase difference ($\delta$) of RMP and ELM.
  - Static RMP, $V_{\theta,\text{RMP}} = 0$.
    → $V_{\theta,\text{ELM}} \approx 0$ to make stationary $\delta$.

[Image showing phase overlap and filament motions]
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 (\( |V_{\theta,ELM} - V_{\theta,RMP} | \approx 0 \)).
    → Stationary phase difference (\( \delta \)) of RMP and ELM.
  
  ✓ Static RMP, \( V_{\theta,RMP} = 0 \).
    → \( V_{\theta,ELM} \approx 0 \) to make stationary \( \delta \).

- **Small \( V_{E \times B} \) for RMP-ELM interaction**
  
  ✓ \( V_{\theta,ELM} \approx V_{E \times B} \) [1, 2] at pedestal.
    → \( V_{E \times B} \approx 0 \) is favorable.
  
  ✓ No suppression with large \( V_{E \times B} \) at pedestal top.
    
    → Small \( V_{\theta,ELM} \) (or \( V_{E \times B} \)) be advantageous for RMP-ELM coupling and suppression.

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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 $V_{E\times B} \approx 0$ at the pedestal.
• 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 ($\delta F(\xi_\perp, \xi_\parallel) = 0$).
In summary, RMP-ELM coupling can contribute to ELM crash suppression in two aspects:

- Role of RMP-ELM coupling in ELM crash suppression
  - Reduced source ($\nabla P_{\text{ped}}$)
  - Increased pedestal transport
  - Prevented large mode growth
  - Increased harmonic interactions
  - RMP + ELM coupling
  - Spatial overlap between RMP-induced modes and ELM harmonics seems to be important.

- Important quantities for RMP-ELM coupling?
  - RMPs
  - Critical to ELM suppression
Backup – Simulation setup

• Numerical setup

✓ Neoclassical constraint ($V_{\text{neo}}$) is applied to construct the ion-poloidal flow.
✓ $V_{\theta,E\times B}$ in the pedestal region is in the ion-diamagnetic direction.
✓ $T_i = T_e$ is assumed.
✓ Adaptive diffusive profile and source are used to sustain the $\rho, T, \nu_{\phi}$ profiles.
✓ $x10$ resistivity ($x40$ spitzer) and braginskii parallel conductivity are used.

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

[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.

![Graphs showing $\Gamma_{NTV}$, $\tau_{NTV}$, and $\tau_{Beam}$ against $\psi_N$](image1)

![Graph showing $\xi_\perp$ profile form JOREK](image2)
• 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.
• Pedestal profile degradation
  ✓ Radial transport increases due to
    - $\nu_{E \times B, \perp}$ convection (Kink).
    - Stochastic layer (Tearing).
  ✓ Pedestal profile ($n=0$) is degraded.
  ✓ Density pedestal is governed by $\nu_{E \times B, \perp}$.
  ✓ 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.

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

- 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 spatially 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 pedestal top ($S_{89}$).
  • $n = n_{\text{RMP}}$ island overlap to couple with higher $n$’s.
  • ELM suppression as island overlap occurs.

Position of rational surfaces and island width are important.
• Conditions for the interactions between RMP and ELM

✓ Kink-peeling favorable MP configuration.

✓ Rational surface \( (q = m/n_{\text{RMP}}) \) near the pedestal top.
  ▪ Island to cover the entire pedestal and dominant ELMs.

✓ Chiricov parameter \( (S > 1) \) near the pedestal top.
  ▪ \( n = n_{\text{RMP}} \) island overlap to couple with higher \( n' \)s.

✓ \( v_{\theta,\text{PBM}} \approx 0 \) before RMP application.
  ▪ Favorable to the locking of ELM.