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

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2021. May. 11
IAEA-FEC 2021. May. 10-15
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].

- **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.

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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.

\[
\frac{1}{R^2} \frac{\partial \psi}{\partial t} = \eta(T) \nabla \cdot \left( \frac{1}{R^2} \nabla \psi \right) - \frac{\vec{B}}{R^2} \cdot \left( \nabla u - \tau_{\text{IC}} \frac{Vp_e}{\rho} \right)
\]

**Ohm’s law**

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

**Continuity eqn.**

\[
\rho \left( \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) (\vec{v}_E + \vec{v}_{||}) = -\nabla (\rho T) + j \times \vec{B} + S_v - \vec{v} S_\rho + \mu \Delta \vec{v} - \nabla \cdot \vec{H}_{\text{neo}}
\]

**Momentum eqn.**

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

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

[Graph and legend explaining simulation conditions]
1. Simulation setup

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

3. RMP-induced ELM-crash suppression

4. Summary
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).
  - ✓ Edge localized perturbation.

- **Tearing**
  - ✓ $V_{\perp} = 0$ 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 $T$).
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.

![Graph showing Torque and NTV fluxes](image1)

![Graph showing Density degradation by NTV](image2)
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.
1. Simulation setup

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

3. RMP-induced ELM-crash suppression

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

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

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

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

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[1] M. Becoulet et al., NF (2017), 116059
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.
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  - 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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- **Suppression above RMP threshold**
  - Mitigated with small RMP amplitude.
  - Fully suppressed at $I_{RMP} > 3$ 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

[Diagram showing 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

  \[
  \text{Degraded pedestal} \quad + \quad \text{Broadened spectrum} \quad \text{Enhanced interaction}
  \]

  - 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) \(\rightarrow\) Localized to LCFS.
    - RMP-Tearing (island) \(\rightarrow\) 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 \(8/2 + 9/2\))
  \(\rightarrow\) 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 ($|V_{\theta,\text{ELM}} - V_{\theta,\text{RMP}}| \approx 0$).
    → **Stationary phase difference ($\delta$)** of RMP and ELM.
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    - Stationary phase difference ($\delta$) of RMP and ELM.
  - Static RMP, $V_{\theta,\text{RMP}} = 0$.
    - $V_{\theta,\text{ELM}} \approx 0$ to make stationary $\delta$. 
Slow poloidal rotation of ELM structure can be advantageous for enhancing the RMP-ELM interaction and achieving ELM suppression.

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  - Well sustained mode overlap: Favorable to coupling.
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    → Stationary phase difference ($δ$) of RMP and ELM.
  - Static RMP, $V_{θ,RMP} = 0$.
    → $V_{θ,ELM} \approx 0$ to make stationary $δ$.

- **Small $V_{θ,E×B}$ for RMP-ELM interaction**
  - $V_{θ,ELM} \approx V_{θ,E×B}$ [1, 2] at pedestal.
    → $V_{θ,E×B} \approx 0$ is favorable.
  - No suppression with large $V_{θ,E×B}$ at pedestal top.
    → Small $V_{θ,ELM}$ (or $V_{θ,E×B}$) 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. \(\rightarrow\) ELM driving source ↓
  - Enhanced interactions between ELM harmonics. \(\rightarrow\) 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 \(V_{\theta,EB} \approx 0\) at the pedestal.
Thank You
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, $\xi_{\perp n,m} - \delta T_{n,m}/\nabla T_{n,m}' = 0$

- 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

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

  $\rightarrow$ Spatial overlap between RMP-induced modes and ELM harmonics seems to be important.
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 $\rho, T, v_{\phi}$ profiles.
✓ x10 resistivity (x40 spitzer) and braginskii parallel conductivity are used.

\[
V_{\theta} = V_{\theta,E \times B} + V_{\theta,i^*} + V_{|l|,\theta}
\]
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 NTV particle and momentum fluxes and $\xi_\perp$ profile form JOREK](image-url)
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.
• 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.

• 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.

[Mode spectrum comparison and coupling analysis]
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 $\rightarrow$ Overlap is easy, but localized to LCFS.
  - Tearing $\rightarrow$ Wide radial range, but sufficient island width needed for overlap.

- Chiricov parameter (> 1) near the pedestal top ($S_{89}$).
  - $n = n_{RMP}$ island overlap to couple with higher $n'$s.
  - ELM suppression as island overlap occurs.

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

✓ Kink-peeling favorable MP configuration.

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

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

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