On Effect of n=2 RMP to Edge Pedestal in KSTAR with Nonlinear MHD Simulation
S.K. Kim1,2, S.J.P. Pamela3, M. Becoulet4, G. Huijsmans5, O. Kwon1, Y. In6, J. Lee7, M. Kim7, J.-K. Park8, S.M. Yang8, N. Logan9, M. Hoelzl10, E. Koleman10, Y.-S. Na2 and JOREK team11

1Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, U.S.A  
2Department of Nuclear Engineering, Seoul National University, Seoul, Korea  
3CEF, Culham Science Centre Abingdon, U.K  
4CEA, IFMn Saint-Paul-lès-Durance, France  
5Department of Physics, Daegu University, Daegu, Korea  
6Department of Physics, UNIST, Ulsan, Korea  
7Korea Institute of Fusion Energy, Daejeon, Korea  
8PPPL Princeton Plasma Physics Laboratory Princeton, Nj, U.S.A  
9KSTAR, Lawrence Livermore National Laboratory, Livermore, CA, U.S.A  
10Max Planck Institute for Plasma Physics, Garching, Germany  
11See M Hoelzl et al 2020 Nucl. Fusion sk42@princeton.edu

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 NTW

JOREK (3D Nonlinear MHD) [4].
• Realistic geometries with SOL.
• 5 fields reduced MHD equation.

PENTRC (NTW 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 (ϕ = 90°) RMPs.
• \( I_p = 690 \text{ kA}, \quad \psi_{Q5} = 4, \quad \beta_n = 3.3 \times 10^{19} \text{ m}^{-3} \)
• Stable ELM suppression entry by RMP ≥ 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 \( -p_{\text{B+}} \)\( \times\) convection (Mainly \( n_z \)).
• Island and stochastic layer (\( n_z \) and \( T \)).

NC toroidal viscosity (NTV).
• Edge localized NTV by displacement.
• NTV torque (\( \tau_{\text{NTV}} \)) and flux.

Net pedestal degradation.
• By KTM [6-8] and NTV [9].
  - net torque (40% of Exp.).
  - \( n_z \) pedestal (40% of Exp.).
  - P gradient (~ of Exp.).
  → Considerable effect of kink and NTV on pump-out.

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.

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.

Role of RMP coupling – Enhanced interactions between ELMs

Enhanced ELM harmonic interactions.
• Unlike ELMy, enhanced energy correlation among harmonics. [14]
• Broadened mode spectrum. [15]
• Prevented mode crash due to [1] + [2] [15].
• Nonlinearly saturated ELMs by
  - Degraded pedestal (Driving ↓)
  - Broadened spectrum (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 (\( s = 1 \)).

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 \( \psi_{\text{RMP}} \approx 0 \) at the pedestal.

This material was supported by the U.S. Department of Energy, under Awards DE-SC0020572. This research was also supported by R&D Program of "KSTAR Experimental Collaboration and Fusion Plasma Research (EURO21-127)" through the Korea Institute of Fusion Energy (KFE) funded by the Government of Korea (MOE, No. NRF-2019R1A2C1010757). Part of this work has been carried out within the framework of the EUFusion Consortium and has received funding from the Euratom research and training program 2014-2018 and 2019-2020 under grant agreement No 633053. This work was partly carried out the Marconi-Fusion supercomputer operated by CINECA.

References