MITIGATION OF ELM BY 3D MAGNETIC PERTURBATIONS IN HL-3/HL-2A TOKAMAKS

G.Z. Hao[1*], L.Wang[1], J. Huang[1], Y.Q. Liu[2], M. Becoulet[3],T.F. Sun[1], N. Zhang[1], G.Q. Dong[1]

[1]Southwestern Institute of Physics, Chengdu 610041, China
[2]General Atomics, San Diego,, USA
[3]CEA, Saint-Paul-Lez-Durance, France

Email: haogz2019@outlook.com

Key results: Externally applied Resonant Magnetic Perturbation (RMP) has been proven as an effective approach for edge localized mode (ELM) control. In this work, we report recent progress of ELM control with MP on the HL-3/HL-2A tokamaks. **The linear modeling results revealed that the formation of the periodic structure of equilibrium generated by RMPs is the mechanism for the transition of the dominant toroidal mode number of ELM. However, the nonlinear modeling indicates that the mode coupling is essential for the mitigation of ELMs for the studied case.**

Firstly, the three-dimensional (3D) magnetohydrodynamic (MHD) code JOREK was utilized to perform a linear study on the HL-2A device. Here, the linear study means that the n=0 component is fixed in the simulation. The primary objective of this investigation was to gain insights into how RMP affects plasma 3D equilibrium and, consequently, the behavior of ELM. The n=1 radial magnetic field perturbation induced by the applied RMP fields are plotted in Fig.1. A scan of the n=1 RMP coil current from 1 to 4.9 kAt revealed that the dominant toroidal mode number of mode transitions from the n=4 to n=3 when the RMP coil current exceeds a certain threshold. It was found that the n=1 periodic structure of equilibrium was numerically generated by the application of RMP fields as shown in Fig.2. Here, the periodic structure of equilibrium can be represented by the density distribution on a geometric surface. The linear modeling results revealed that the formation of the n=1 periodic structure of equilibrium is the mechanism for the transition of the dominant toroidal mode number of ELM.

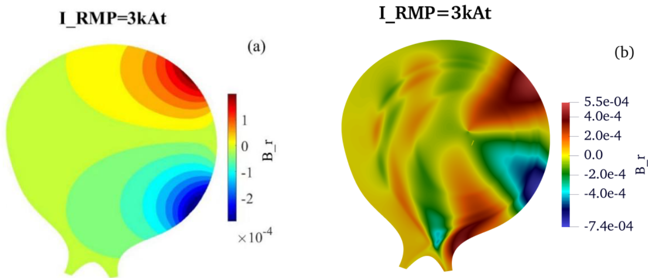

Fig.1. Amplitude of the n=1 radial magnetic field perturbation for (a) the vacuum field calculated by ERGOS, and (b) the total field perturbation including the plasma response. Contributions of other n-components (besides n=1) are not included in the plots here. A 3 kAt coil current is assumed.

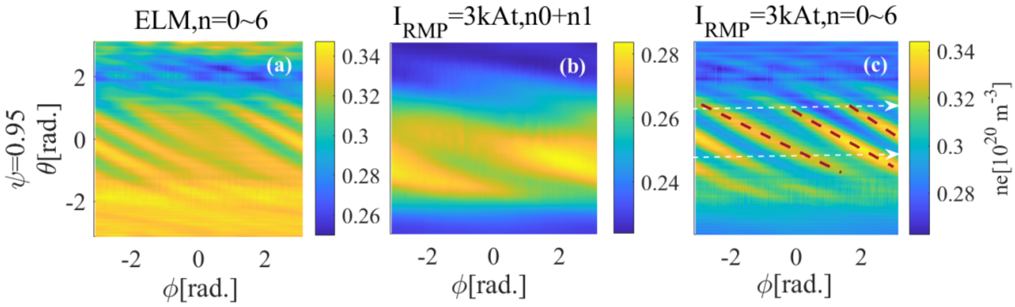

Fig.2. (a) The 2D plot of the total density of the natural ELMs, (b) 2D distribution of the (total) plasma density after reaching a 3D equilibrium (i.e. with the n=0 and n=1 components) assuming 3 kAt RMP coil current, (c) plasma density (with all the n components) at the surface in the 3D equilibrium, which the dominant n=3 pattern indicated by dashed lines. All results are shown at the radial location of ψ_n =0.95.

Furthermore, nonlinear modeling of mitigation of ELM with RMP for the case studied above. Based on the 3D equilibrium established after application of the $n = 1$ RMP at 4.9 kAt coil current with odd parity, ELM mitigation is successfully simulated consistent with the experimental result. Nonlinear simulations show strong mode coupling among toroidal Fourier harmonics, allowing redistribution of the magnetic energy such that the most unstable toroidal mode saturates at a lower level. This magnetic energy cascade offers an explanation of the RMP-induced ELM mitigation achieved in HL-2A. Detailed examination of the simulation results shows persistent resonant field screening even during the ELM mitigation phase. Finite plasma resistivity however does enable partial penetration of the resonant field thus modifying the edge magnetic topology and characteristics of the edge transport. Plasma radial profiles undergo pronounced changes around the pedestal region, when the magnetic energy of the most unstable toroidal mode reaches the maximum value. Systematic scans of the applied RMP coil current with the JOREK simulations find a threshold value of around 4.5 kAt resuired for achieving the ELM mitigation on HL-2A as shown in Fig.3. The detailed analysis suggests that 3D distortion of the magnetic surface alone is not sufficient to explain the onset of ELM mitigation. The process of mode coupling is also essential for energy redistribution and lower level of mode saturation. In addition, the non-linear modeling results from JOREK shows that the mode-coupling plays the dominant role in mitigating ELM for the studied case [Fig.4].

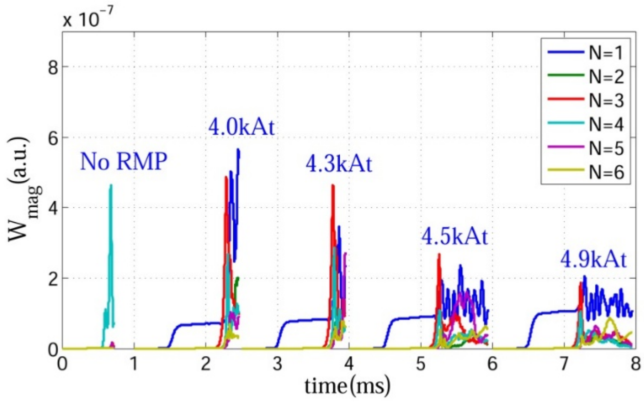

Figure 3. Time evolutions of the simulated magnetic energies for the $n = 1 - 6$ toroidal modes, assuming different levels of the RMP coil current. The case with no RMP corresponds to zero coil current. For better visualization, the start time is horizontally shifted for different cases.

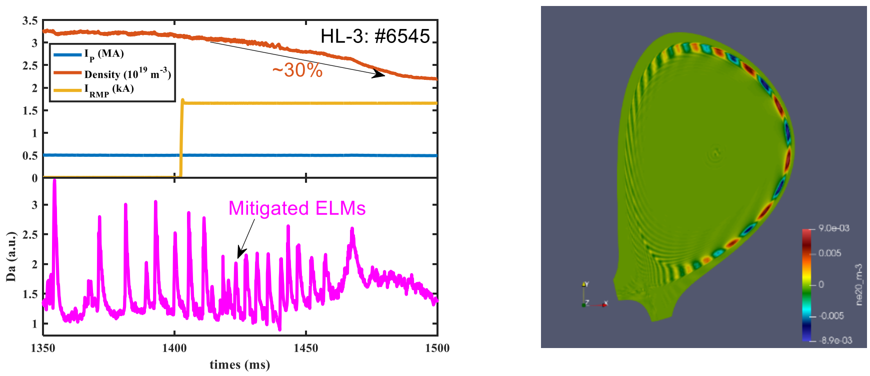

Figure 4 The time traces of plasma current, line-averaged density, RMP coil current and the D-alpha signal for the discharge of HL-3#6545(left). The perturbed density modeled by JOREK with assuming the odd parity configuration and 6.6 kAt current of RMP coil (right).

ACKNOWLEDGEMENTS

This work is supported by the National Magnetic Confinement Fusion Energy R&D Program (No. 2022YFE03060002), the Youth Science and Technology Innovation Team of Sichuan Province (No. 2022JDTD0003), the National Natural Science Foundation of China with Grant No. 12375214, the China National Nuclear Corporation Fundamental Research Program (No. CNNC-JCYJ-202236), the Innovation Program of Southwestern Institute of Physics with Grant No.202301XWCX006-04, and the National Natural Science Foundation of China with Grant No. 12105082. This work is also supported by the US DoE Office of Science under Contracts DE-FG02-95ER54309 and DE-FC02-04ER54698.