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RECENT ADVANCES IN THE UNDERSTANDING AND OPTIMIZATION OF RMP ELM SUPPRESSION FOR ITER

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Recent Advances in the Understanding and Optimization of RMP ELM suppression for ITER

EX-D

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Recent experiments with applied resonant magnetic perturbations (RMPs) in low-collisionality ITER Similar Shape (ISS) plasmas on DIII-D have advanced the understanding of and increased confidence in obtaining edge localized mode (ELM) suppression in ITER. ELM suppression is obtained with a reduced number of I-coils (5 out of 12 coils) on DIII-D [Fig. 1(a,b)], demonstrating the effectiveness of mixed harmonics (n=1,2,3) for ELM suppression and hence mitigating against the risk of reduced coil availability on ITER. A consistent picture of the plasma response to RMPs is emerging from linear two-fluid resistive M3D-C1 simulations [1]. The M3D-C1 analysis reveals effective screening of n=3 resonant poloidal harmonics in the gradient region of the pedestal and amplified response with incomplete screening at the top of the pedestal [Fig. 1(c)]. X-ray imaging [2] is in good agreement with M3D-C1 simulations, consistent with a dominant edge kink response and strong screening in the gradient region of the pedestal [Fig. 1(d)]. The leading model of ELM suppression posits that the plasma response to RMPs creates a diffusivity hill that prevents the expansion of the pedestal to an unstable width [3]. The observation of effectual screening of resonant poloidal harmonics in the gradient region of the pedestal combined with the prediction of enhanced fields at the top of the H-mode pedestal is generally consistent with this picture. RMPs have the effect of generally lowering the density and pressure at the top of the pedestal in ISS plasmas. Pedestal analysis reveals a strong linear dependence of the pedestal

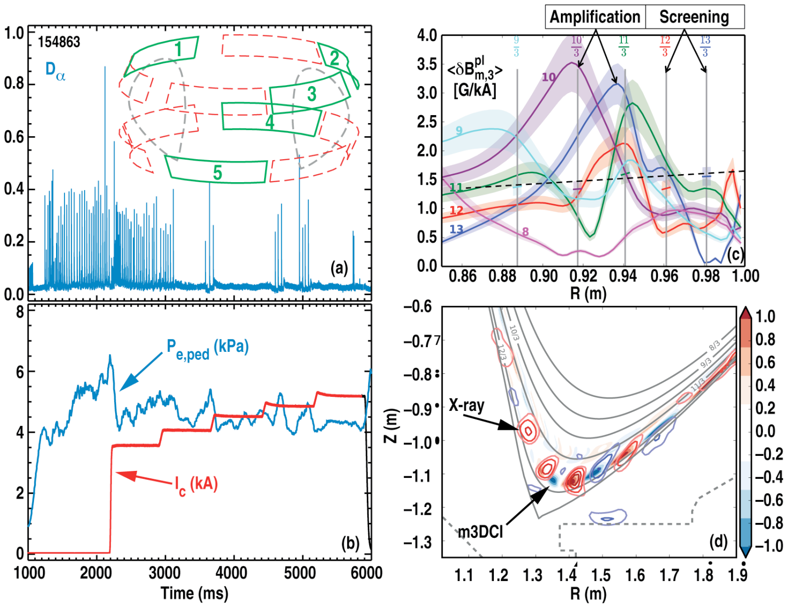

Fig. 1. (a) D_α signal for ELM suppression with 5 out of 12 I-coils and (b) the corresponding pedestal electron pressure P_e and I-coil current, (c) M3D-C1 simulation of amplification and screening of resonant poloidal harmonics (solid) compared to vacuum (dashed), (d) x-ray image of the perturbed emission (line contours) overlaid with M3D-C1 simulations of x-ray emission (filled contours).

pressure on the pedestal density in RMP plasmas (Fig. 2) and recent experiments indicate that the pedestal pressure can be raised by increasing the density.

The role of islands in the formation of the diffusivity hill at the top of the pedestal is a critical issue of current research. Figure 1(c) shows the radial profile of n=3 poloidal harmonics from M3D-C1 for a dominant n=3 RMP. A robust feature of the simulations is the amplification of the resonant fields at the 10/3 and 11/3 rational surfaces (suggestive of islands) and the screening of the resonant fields in the edge region at the 12/3 and 13/3 surface where steep pressure gradients occur. The perturbed emissivity from X-ray imaging [Fig. 1(d)] is obtained by differencing images with phase inverted n=3 RMP fields. The lines are the emissivity contours from X-ray imaging and the filled contours are simulated emissivity perturbations from M3D-C1. Good agreement is obtained, indicating strong screening of poloidal harmonics in the edge, however, resolution of structures at the top of the pedestal remain elusive. While there is no conclusive evidence for the formation of islands at the top of the pedestal, newly installed magnetic sensors and pedestal profile measurements indicate features suggestive of islands. However, the magnetic flutter model [4] also predicts a thermal diffusivity hill without the necessity of islands and quantitative predictions are consistent with experimental transport levels. While no one model encompasses the entirety of the observed phenomena in RMP plasmas, a consistent picture is emerging that enhanced fields at the top of the pedestal together with resonant field screening in the gradient region of the pedestal creates a diffusivity hill, either through flutter transport, islands or a combination of the two, that is responsible for limiting the expansion of the pedestal to an unstable width and suppressing ELMs. Susceptibility to locked modes is an important issue for RMP ELM suppression with a reduced coil set as the reduction in the number of coils introduced n=1,2 sidebands. ELM suppression with a reduced coil set is achieved at similar coil currents to the full coil set, demonstrating that increased n=1 and n=2 sidebands play an important role in maintaining ELM suppression as the magnitude of the n=3 sideband decreases. In order to avoid locked modes with the reduced coil set, optimal n=1 error field correction was applied from the outer C-coils to minimize the coupling of the I-coil field to the least stable n=1 kink. The resulting discharges were no more sensitive to locked modes than a dominant n=3 I-coil spectrum.

Analysis reveals a strong monotonic scaling of the pedestal pressure with the pedestal density that holds over a wide-range of q_{95} (=3.1–4.1), applied 3D spectrum (5–12 I-coils and mixed harmonics n=1–3) and varying I-coil current (Fig. 2). The pedestal model EPED predicts a linear scaling of the pedestal pressure with density due to the change in the electron collisionality and its effect on kink-peeling mode stability, however EPED overestimates the pedestal pressure in ELM mitigated plasmas at the lowest density range in the data. The data suggests that the pedestal pressure can be increased with density and recent experiments demonstrate improved pedestal pressure using density feedback in RMP ELM mitigated plasmas. Results suggest that the pedestal pressure in ELM suppressed plasmas may also be increased up to the EPED predicted value with careful control of the density and I-coil current.

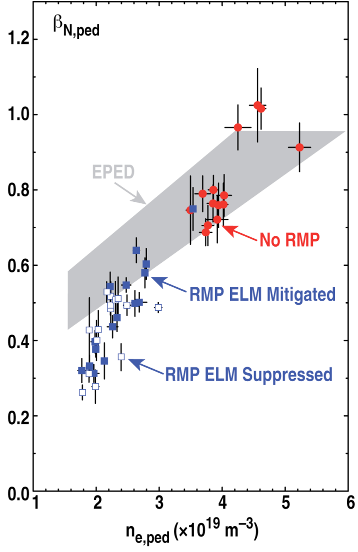

Fig. 2. Normalized pedestal beta $\beta_{n,ped}$ vs pedestal density $n_{e,ped}$ and comparison to EPED prediction.

Overall these advances in modeling and measurement have strengthened the physics basis for RMP ELM suppression and provide enhanced confidence in achieving robust ELM suppression with optimized pedestal performance in ITER.

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