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Developing physics basis to optimize 3D-edge long-pulse tokamak scenarios

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Small non-axisymmetric (3D) magnetic fields can provide robust ways to control transport and instabilities in tokamaks when optimally used, as has been highlighted by the edge-localized mode (ELM) suppression using resonant magnetic perturbation (RMP). Despite significant progress on RMP ELM control since its first discovery in DIII-D [1], still a number of seemingly inconsistent results are indicating research needs to identify the common physics basis that unifies observations across the world program. Recent progress in KSTAR is potentially providing a resolution on the complexity involved in generating 3D fields (Fig. 1), by demonstrating a possibility to predict entire 3D field spectral windows for ELM suppression [2]. A key

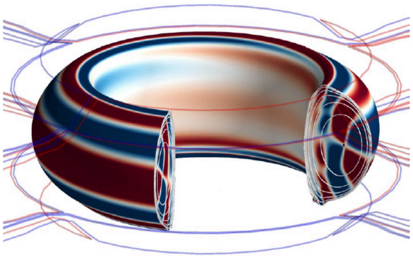

Figure 1. Perturbed KSTAR tokamak by resonant magnetic perturbation coils (field and current distributions in colors) that safely suppressed edge-localized MHD instabilities [2].

hypothesis is that the inner-layer local bifurcation process required for ELM suppression is well separable from the outer-layer 3D response, motivating the metric matching approaches between the inner and outer regions. Non-linear TM1 [3] simulations have been successfully used to predict the layer bifurcation process called resonant field penetration, with the GPEC calculations [4] to match the field penetration thresholds to outer-layer 3D responses. These approaches have been successfully adopted for error field correction (EFC) criteria against the resonant field penetration in the core [5], which are also important for low-n RMP applications to avoid a disruptive MHD. Strong similarities are expected between the RMP and EFC problems in terms of local parametric scaling, but 3D-edge physics is apparently richer than the core, as exemplified by the accessibility condition in shaping, q_{95}, or rotation, beyond which RMP ELM suppression appears to be almost forbidden. Recent TM1 simulations indeed show the steep variation of RMP response across edge q-profiles, reproducing the favorable q_{95} windows (Fig. 2)

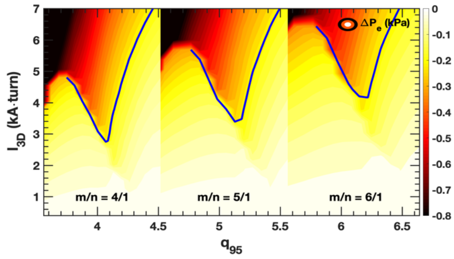

Figure 2. TM1 prediction for variation in the pedestal pressure (Pe) by n=1 RMP as a function of q_{95} in a KSTAR plasma (from #18730).

observed in KSTAR (q_{95}~4.0,5.0,6.0 [6]). Plasma shaping is also critical, challenging RMP applications in high or low triangularities as indicated by EAST and KSTAR observations. Successful RMPs are non-disruptive with stable edge islands, across which transport processes can keep modifying the profiles and instabilities. The advanced ECEI and other diagnostics in KSTAR are revealing coherent fluctuations across islands, which are being used for GTC to validate turbulent transport physics under RMPs. Demonstrating RMP ELM suppression in long-pulse advanced scenarios is also a unique area where KSTAR can contribute. One approach relies on the optimization of 3D heat flux to mitigate the excessive heating and changes of the PFC conditions, with the predictive EMC3-EIRENE modeling coupled with response simulations such as GPEC, MARS or M3D-C1. Another approach is empirically developing an adaptive RMP controller, as an initial PCS implement based on the real-time D_α in KSTAR is already promising. In parallel, the acquired understanding and predictive capabilities are being incorporated into the task to improve and possibly design new 3D coils in future KSTAR or next-step devices [7]. All the elements above including accessibility, scaling, transport, heat flux optimization, control, and designs are being integrated around KSTAR through a collaborative research program.

References

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