Progress on [N]TM modelling and control in the ITER Plasma Control System design

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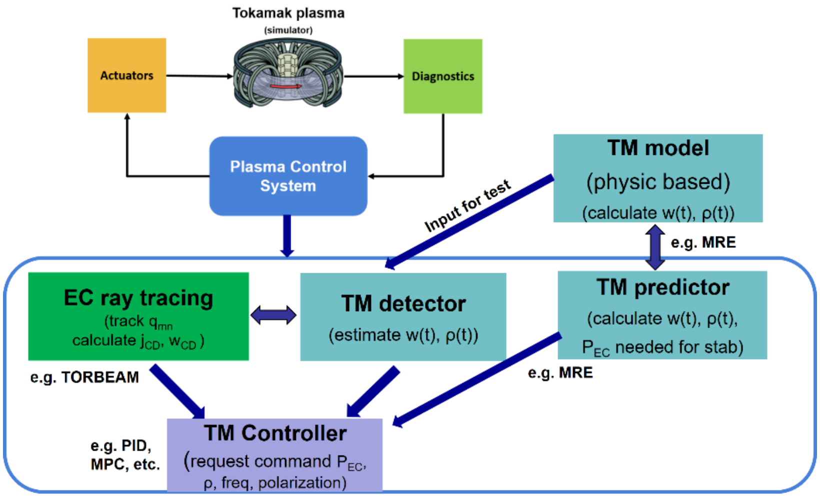
Abstract: [Neo-classical] Tearing Modes ([N]TMs) control is crucial in high-energy devices like ITER due to the disruptions that may cause potential machine damage. This work presents a real-time [N]TM control strategy for the ITER Plasma Control System (PCS), aiming to predict [N]TMs present and their characteristics, and apply stabilization using Electron Cyclotron Heating (ECH). Key components of the [N]TM control scheme are a predictor with extended co-MRE solver, coupled mode width and frequency dynamics, and a real-time [N]TM controller to track and suppress the instability. These components have demonstrated success on the TCV tokamak.

The [N]TM control strategy is implemented within the ITER Plasma Control System Simulation Platform (PCSSP), showcasing a closed-loop scenario. With ITER's upgraded ECH capacity in the new baseline, the feasibility of effective [N]TM control is significantly enhanced.

[N]TM real-time control scheme for ITER

[N]TMs are among the most critical MHD instabilities in tokamaks. They can degrade energy confinement and if they grow sufficiently large, may trigger disruption that potential cause damaging impact on ITER. Consequently, detecting and controlling [N]TMs are critical functions of the ITER PCS, which manages all aspects of the ITER plant to ensure the desired pulse scenario is achieved. The primary objective of this work is to develop a robust real-time [N]TM control for the PCS, which can identify and control this instability.



- [N]TM detector (magnetic and/or ECE based): detects [N]TMs as early as possible
- [N]TM predictor (co-MRE): identifies mode characteristics (size, growth rate, frequency, etc.)
- [N]TM controller: decides on the best strategy to suppress or stabilize [N]TMs, using predicted electron cyclotron (EC) power

Figure 1: [N]TM feedback control scheme

Co-MRE: [N]TM predictor with encouraging results on TCV

Recently, the extended co-MRE (comprehensive Modified Rutherford Equation) solver [1,2], which incorporates coupled width and frequency equations, has shown promising results both theoretically and experimentally on the TCV tokamak. This real-time module is routinely run on TCV experiments (Figure 2). These results were achieved using ECH to stabilize [N]TMs (Figure 3). An adapted version of this solver thus emerges as a strong candidate for an ITER [N]TM model to support the commissioning and operation of [N]TM control functions within the PCS.

The mode island width evolution is approximated by:

$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} \approx \bar{\rho}_{mn}(\Delta' + \Delta_{neo} + \Delta_{cd})$$

where w is the island width, $\bar{\rho}_{mn} = a\rho_{tor,mn}$ is island location in [m], τ_R is the resistive diffusion time, $\Delta', \Delta_{neo}, \Delta_{cd}$ are the classical, neoclassical (mainly bootstrap) and current drive contribution terms respectively.

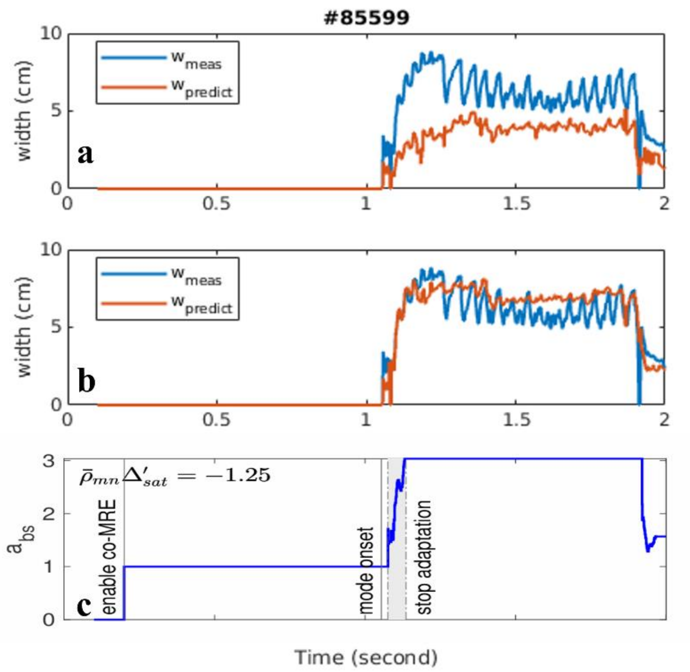


Figure 2: co-MRE outputs on TCV w/o coef. adaptation (a) and with coef. adaptation (b)

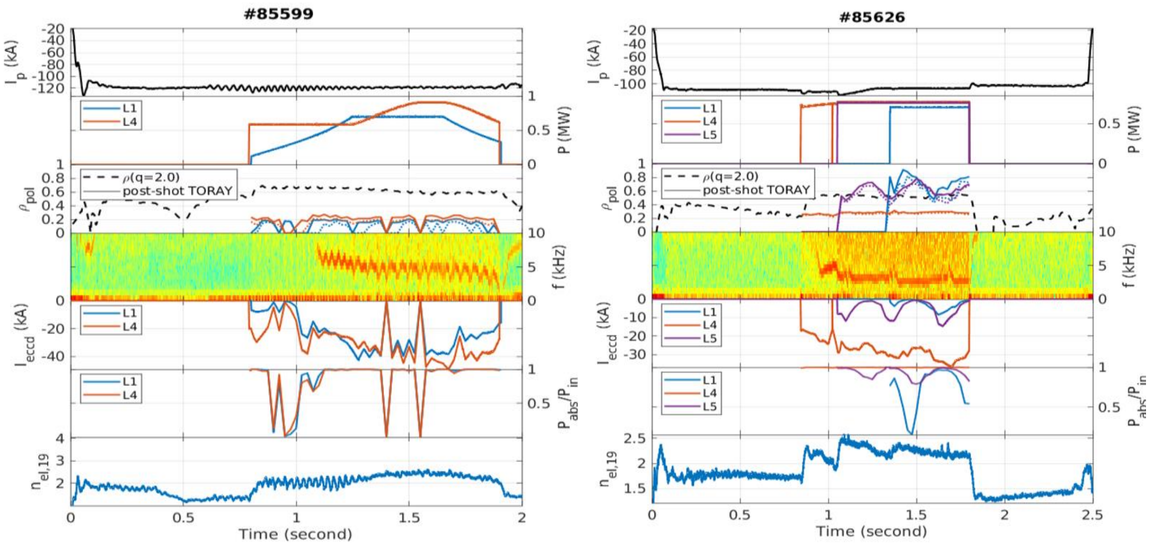


Figure 3: [N]TM control experiments on TCV

700-800kW power in the core is needed to trigger [N]TM (shot #85599). [N]TM controller did well (shot #85626) but stabilization is ineffective due to misalignment and low current drive.

Progress on ITER [N]TM control

ITER's new baseline includes enhanced ECH capabilities, boosting [N]TM control feasibility. ECH power increases from 20 MW to 40 MW on Start of Research Operations (SRO), and up to 67 MW during deuterium-tritium (DT) campaigns. [N]TM control relies on the Upper Launcher (UL), which has two mirrors – UL upper steering mirror and UL lower steering mirror - each of them can support up to four beams delivering 0.83 MW per beam to the plasma.

This work presents the 1st simulation result executed on the PCSSP with ITER scenario 130012/5 (METIS). The seed island width is set to 2 cm, without mode-locking and no plasma model is considered for feedback control effect. Figure 4 shows that the stabilization power P_{stab} predicted by co-MRE closely matches the results obtained using the GRAY code [3], including co-MRE and TORBEAM [4]. In closed-loop [N]TM stabilization tests (Figure 5), the [N]TM controller activated when the island width is around 20 cm shows effect on the island width. However, co-MRE actually identifies the minimum P_{stab} at the exact island location, whereas the sweeping method requires significantly more power to achieve stabilization (Figure 5). While some control components are still under development, this work demonstrates a promising foundation for robust [N]TM control in ITER operations.

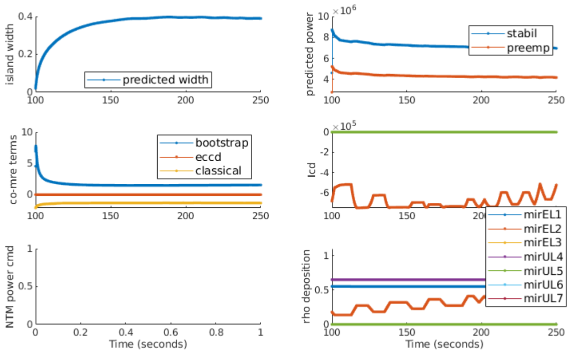


Figure 4: ITER [N]TM evolution without control

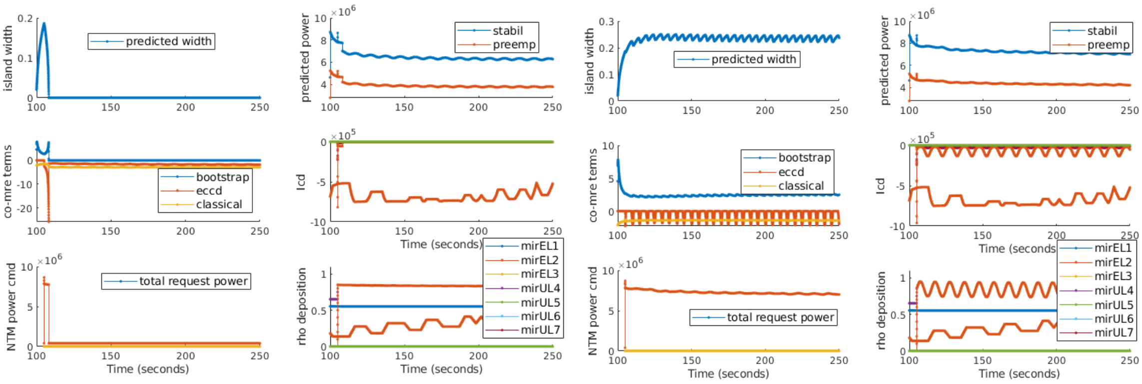


Figure 5: ITER [N]TM feedback control: (left) without sweeping, and (right) with sweeping

Conclusion and future work

While the closed-loop [N]TM control system shows promising results, several components—such as the EC ray tracing module, and the [N]TM detector—are still in early development. Ongoing and future work aims to enhance and complete these elements to ensure robust and reliable control. Planned improvements include integration of beam tracing in PCSSP, benchmarking with Pulse Design Simulator (which uses the same co-MRE solver), integration with Fenix/Metis for real-time plasma profile reconstruction and beam tracing, and validation against high-fidelity simulations using the EX-GRAY code. These efforts will further strengthen the foundation for effective [N]TM control in ITER operations.

References

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