MACHINE LEARNING-BASED MULTIMODAL SUPER-RESOLUTION: EXPERIMENTAL EVIDENCE FOR ELM SUPPRESSION MECHANISM THROUGH RMP-INDUCED MAGNETIC ISLAND FORMATION

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We introduce Diag2Diag, a multimodal machine learning to achieve super-resolution from existing diagnostics at DIII-D. Leveraging such a novel technique, we have demonstrated groundbreaking physics insights into fusion plasmas, including experimental evidence of Edge Localized Mode (ELM) suppression through resonant magnetic perturbation (RMP)-induced magnetic island formation [1]. With Diag2Diag, we synthetically enhanced the temporal resolution of Thomson Scattering (TS) measurements from ~50–200 Hz to 1 MHz, enabling real-time, single-event observation of ELM dynamics and direct evidence of RMP-driven profile flattening at the pedestal boundary. **These advancements offer a solution to the limitations and uncertainties in plasma measurements, and paves the way for robust stability control and cost-effective operation in future fusion devices.**

ELMs are among the most critical and dynamic phenomena in magnetic confinement fusion, requiring fast diagnostics to capture their rapid onset, crash, and recovery cycles. Conventional TS diagnostics, limited to a few hundred hertz, hamper our ability to disentangle the underlying physics details of instabilities such as ELMs is vital for developing suppression strategies that protect plasma-facing components and sustain optimal confinement. Moreover, existing diagnostics often face reliability challenges; missing or low-fidelity measurements can derail high-stakes experiments aimed at controlling plasma instabilities.

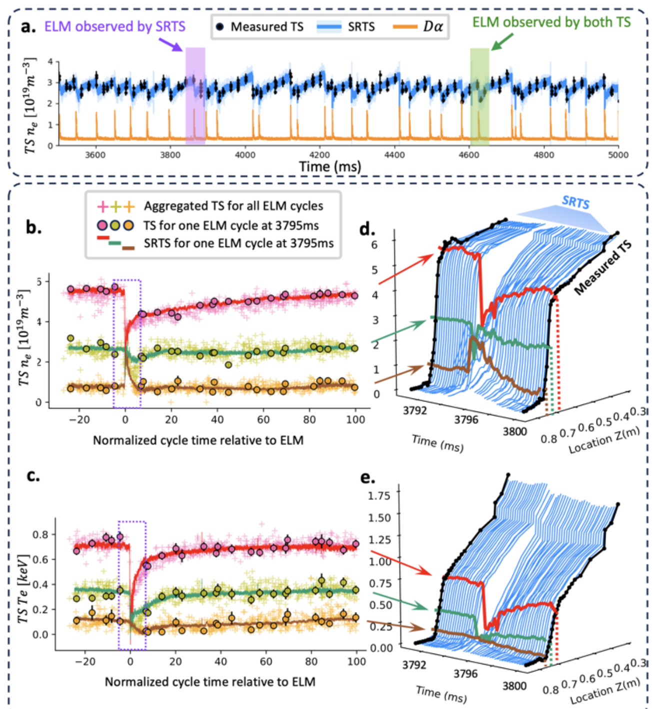

Figure 1: (a) Comparison of the electron density by the measured TS and the synthetic SRTS, for the DIII-D shot 153761 [2] near the edge. Dα with arbitrary units is plotted as an indicator of ELMs. An example of ELM event captured by both diagnostics, and another example only captured by SRTS are highlighted in green and purple, respectively. (b-c) Aggregating the measured TS density and temperature in three locations of plasma near the edge for several ELM cycles of the DIII-D shot 174832. The circles highlight the measures TS for one selected ELM cycle and the solid lines present the SRTS which agreeably match the measures TS. t = 0 represents the time when ELM is identified by Dα. (d-e) The evolution of SRTS between two consecutive measured TS near one ELM cycle across the plasma location.

To overcome these limitations, **Diag2Diag leverages machine learning to identify and exploit hidden correlations among different diagnostic systems, enabling it to generate high-resolution synthetic diagnostic from other available diagnostics.** By training on a set of high-resolution inputs including Electron Cyclotron Emission (ECE), interferometry, and magnetics, we construct super-resolution Thomson Scattering (SRTS) leading to super-resolution profiles of electron temperature and density, even when direct TS measurements are unavailable or degraded. This multimodal fusion not only addresses single-diagnostic failures but also recovers critical plasma parameters with fidelity sufficient for physics interpretation. By benchmarking the reconstructed data against independent measurements and theory-based models, we validated the accuracy and robustness of the technique [1].

With this enhanced diagnostic capability, we have resolved individual ELM events in unprecedented detail—no longer averaging over multiple discharges but directly observing the entire ELM cycle (See Figure 1). The super-resolved data reveal how ELM crashes propagate radially, shedding light on the interplay between localized instability triggers and pedestal recovery.

Moreover, by capturing temperature and density flattening at the plasma edge in real time, **we provide experimental confirmation of RMP-driven magnetic island formation** [3,4] (See Figure 2). Our results underscore the potential of targeted RMPs to mitigate ELMs by altering pedestal profiles, a strategy of particular relevance for ITER's high-performance scenarios.

Beyond immediate benefits to DIII-D operations, this work has broad implications for next-generation burning plasma devices. **Because Diag2Diag achieves its super-resolution through ML-based data fusion rather than hardware upgrades, it offers a cost-effective and flexible pathway to enhancing diagnostic performance under stringent engineering constraints.** High temporal resolution and reliable coverage of transient events will be increasingly essential as reactors like ITER push toward longer pulses and more demanding performance goals. Looking forward, the fusion community can leverage Diag2Diag to explore previously inaccessible fast physics regimes, refine control algorithms for edge instabilities, and accelerate the validation of theoretical models that underpin fusion reactor design.

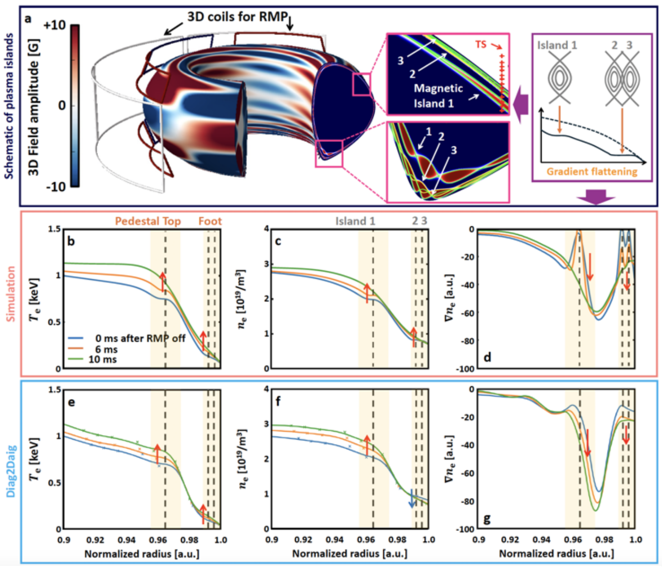

Figure 2: Structure of 3D coils and islands by perturbed field (a), and the evidence in the simulation (b-d) and the SRTS diagnostic (e-g) for RMP-induced island mechanism on the plasma boundary in DIII-D shot 157545.

In summary, our machine learning-driven diagnostic enhancement not only illuminates hidden plasma physics but also equips the community with a powerful tool for real-time, high-resolution analysis of ELMs and RMP effects. By providing richer, more accurate data, Diag2Diag paves the way for informed, data-driven solutions to the challenges of edge instability control, ultimately supporting the pursuit of sustained, high-gain fusion energy.

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