ARTIFICIAL INTELLIGENCE FOR TOKAMAK FUSION: ADVANCEMENTS IN DIAGNOSTICS, CONTROL, AND SCENARIO OPTIMIZATION

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Artificial intelligence (AI) techniques are transforming fusion energy research by enabling advanced diagnostics, real-time control, and scenario optimization. As fusion devices move toward reactor-scale implementation, AI provides a scalable and efficient approach to overcoming challenges in plasma diagnostics, instability suppression, and multi-objective control optimization in high-dimensional parameter spaces. This work presents key advancements [1] in AI-driven fusion research directly relevant to DIII-D and KSTAR for application in ITER and future Fusion Pilot Plants (FPPs).

One of the most impactful applications of AI is **enhancing the effective diagnostic resolution, quantity, and resilience** through super-resolution reconstruction and failure mitigation. Plasma diagnostics, such as Thomson Scattering (TS), Electron Cyclotron Emission (ECE), and Charge Exchange Recombination Spectroscopy (CER), suffer from limited resolution and operational constraints in ITER due to neutron damage and noise interference. To address these challenges, we have developed AI-based multimodal reconstruction techniques, including Diag2Diag [2] and RTCAKENN [3], which provide high-fidelity and super-resolution synthetic measurement predictions, including kinetic profiles and equilibria. At DIII-D, Diag2Diag has increased TS effective temporal resolution from ~50–200 Hz to 1 MHz using a novel method of Multimodal Super Resolution, enabling reconstrution of transient evolution of edge pedestal dynamics during a burst of edge-localized mode (ELM). Furthermore, it provides new evidence of the ELM suppression mechanism in the presence of the external 3D field. Similarly, RTCAKENN provides high-quality kinetic equilibria in real-time, which enables delicate profile tailoring and stability optimization. Notably, AI-driven predictive and failure compensation strategies lead to **cost-effective diagnostic reliability**, which is critical for long-pulse operation in ITER and reactor-scale devices.

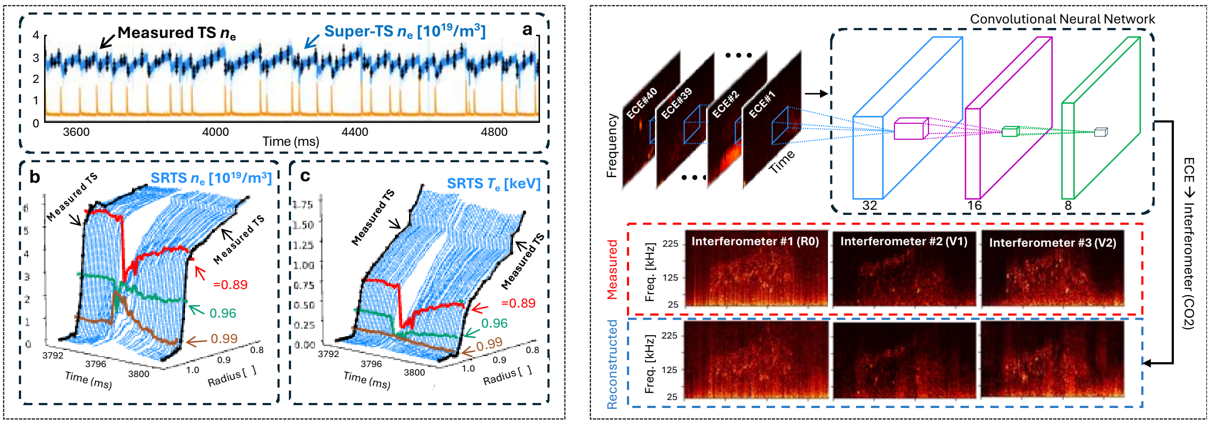

Figure 1. (Left) (a) Comparison of the electron density by the measured TS and the synthetic SRTS, for the DIII-D shot 153761 near the edge (ρ = 0.89). Dα with arbitrary units is plotted as an indicator of ELMs. (b-c) The evolution of SRTS between two consecutive measured TS near one ELM cycle across the plasma location for shot DIII-D 174823. **(Right)** Reconstructing Interferometer spectrograms from ECE spectrograms of DIII-D shot 170669 using convolutional neural networks, showing visual comparison of measured and reconstructed spectrograms.

Beyond diagnostics, AI brings new insight into real-time plasma control and instability suppression. High-performance plasmas exhibit non-monotonic and nonlinear behaviors, challenging traditional model-based controllers. AI-driven reinforcement learning (RL) and model predictive control (MPC) frameworks have been implemented on DIII-D, demonstrating active suppression of tearing modes by dynamically adjusting heating and shaping scenarios [1]. AI-based actuator optimization has also enabled flexible gyrotron power control, balancing tearing mode suppression, and scenario performance—an essential capability for ITER.

AI is also driving advances in ELM suppression control, **addressing the challenge of transient heat loads** on plasma-facing components [4]. AI-enhanced 3D field optimization schemes have enabled automatic 3D field real-time control (optimization) for robust and stable ELM suppression in both DIII-D and KSTAR while minimizing its adverse effects in core instability and confinement. These insights will be critical for ITER, where real-time

3D-driven ELM prediction and control will be necessary to maintain stable plasma performance while protecting reactor components.

In addition to plasma control, AI-driven scenario optimization shifts paradigms in experimental planning by replacing traditional trial-and-error approaches [5]. ML models trained on past experiments can identify optimal actuator configurations, accelerating scenario development while maintaining stability and confinement. This approach significantly reduces the time and resources needed for experimental exploration, supporting real-time adaptation of plasma scenarios in ITER and future reactors.

Future reactors will require **multi-objective optimization frameworks**, integrating diagnostics, predictive models, and real-time control feedback to optimize plasma conditions under evolving operational constraints, where AI provides key capabilities. Additionally, AI will accelerate scientific discovery by revealing previous physics challenges through large-scale fusion data analysis, directly contributing to ITER, FPPs, and future reactor-scale fusion devices. These AI advancements represent a significant step toward realizing practical, scalable, and commercially viable fusion energy, ensuring AI becomes a fundamental component of next-generation tokamak research.

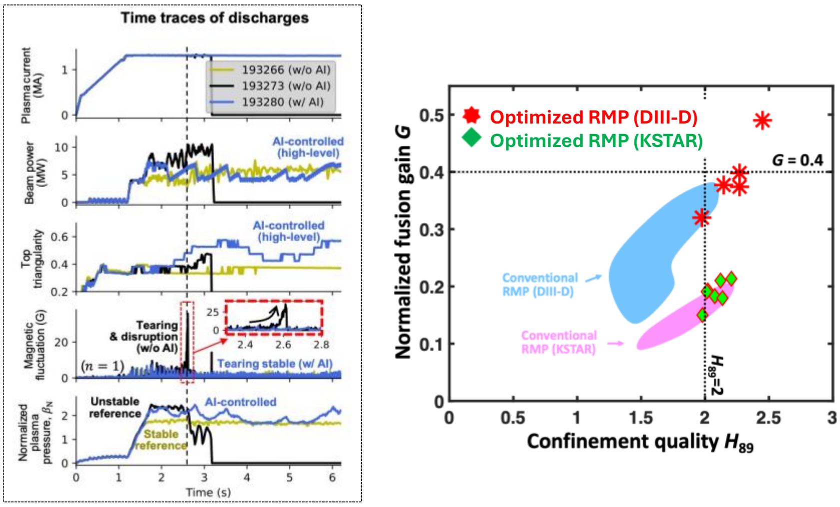

Figure 2. (Left) Time traces of various plasma parameters showing AI improvement (blue) over stable (green) and unstable (black) references. Beam power and top triangularity were the control actuators under feedback control. The magnetic fluctuations show there are no TMs in our controlled shot, and we see higher β_N than the stable reference shot. **(Right)** Improved figure of merit (G) and confinement quality (H_{89}) of ELM suppressed discharges with RMP optimization by controller.

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