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Seeing through the Gaps: AI-Supplemented Measurement in Fusion Devices and Beyond

Machine learning model uses data from a suite of sensors to reconstruct missing information and enhance plasma behavior monitoring.

LONG BEACH, Calif. — As technology advances, we can study increasingly extreme environments, from the bottom of the ocean to outer space, even working to bring the process that powers the stars to Earth with fusion energy. However, the ability to study the extreme environment of a fusion plasma is limited by the measurement tools available. To address challenges related to sensors being too slow or degrading in the harsh environment required for fusion, a team led by scientists from Princeton Plasma Physics Laboratory developed an artificial intelligence method to use available sensors at the DIII-D National Fusion Facility to monitor events otherwise missed by gaps in measurement systems.

Fusion research relies on the use of systems of sensors, called diagnostics, to monitor conditions during fusion reactions. This work used experimental data from the DIII-D tokamak, a device that "bottles" 100,000,000 C plasma with strong magnetic fields to conduct experimental fusion reactions. This data was used to train a machine learning model, called Diag2Diag, to provide detailed high-speed measurements of plasma behavior during fusion reactions.

In this study, the Thomson Scattering diagnostic, which measures electron temperature and density throughout the plasma, was the diagnostic chosen for enhancement with Diag2Diag. Thomson Scattering is an essential diagnostic, but the frequency of measurement is too slow to capture sudden bursts within the plasma called Edge Localized Modes (ELMs). ELMs occur at the plasma edge and can release intense bursts of heat with the potential to damage device walls.

To enhance the relatively slow Thomson Scattering diagnostic, Diag2Diag learned correlations among available faster diagnostics, such as magnetic probes, interferometers, and electron temperature sensors, and used them to reconstruct what Thomson Scattering would have seen if it could operate at a much faster speed. In effect, the AI model created a synthetic "super-resolution Thomson Scattering" running thousands of times faster than the actual system (Figure 1).

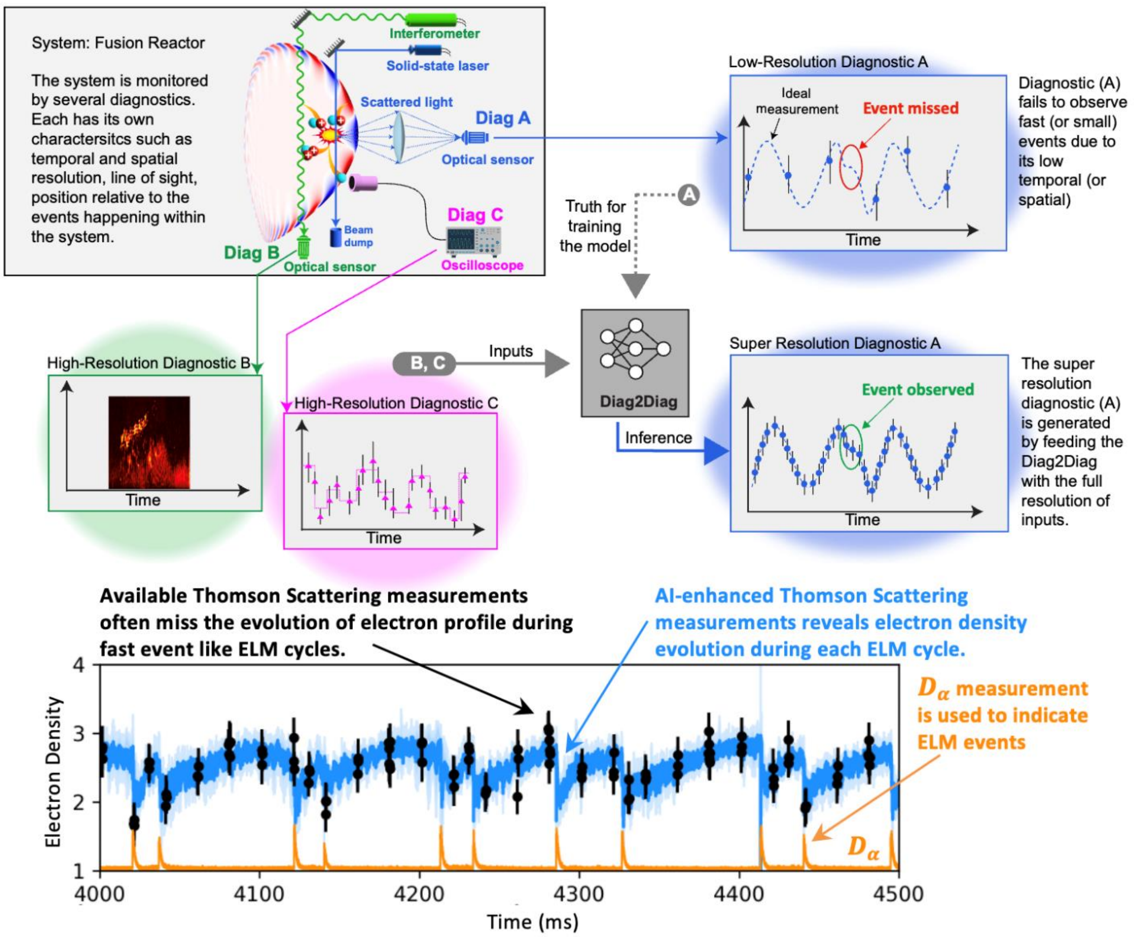

Figure 1: Diag2Diag can reconstruct and enhance Thomson Scattering measurements of electron temperature and density using other measurements on the DIII-D tokamak. (Top) Overview of the Diag2Diag multimodal super-resolution framework which generates a synthetic super-resolution of a diagnostic by learning the correlation between that and other diagnostic measurements with higher resolutions and better accuracy. (bottom) Reconstruction and enhancement of measured Thomson Scattering data (200 Hz measurement frequency) to super-resolution data (1MHz measurement frequency), revealing the electron profile evolution during ELM events.

Further evaluation showed that the high-speed measurements generated by Diag2Diag were reliable and useful. This new capability enabled researchers to capture the full life cycle of an ELM in a single experiment for the first time. Even more importantly, the AI model revealed new observations from experimental evidence supporting a long-standing theory: that special magnetic structures called magnetic islands, triggered by external magnetic fields, flatten the plasma profile at the edge and help suppress ELMs.

The Diag2Diag AI model is the first approach to provide reliable high-speed synthetic measurements of fast plasma behaviors from experimental data; previous studies all used computer simulations. Defining and applying these relationships among diagnostics ensures that fusion experiments do not lose valuable data if sensors underperform or are offline. It also helps scientists better understand and control critical plasma events, key steps toward practical fusion energy.

Moving forward, such an AI-enabled inter-diagnostic reconstruction approach could also guide the design of future reactors by identifying the minimum set of diagnostics needed, reducing costs while maintaining reliability. Beyond fusion, this approach could also have applications in other fields that rely on limited sensor data, from spacecraft operating millions of miles from Earth to medical imaging, letting scientists and engineers “see” more with AI.

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Abstract

PT04.3	Seeing Through the Gaps: AI for Super-Resolution and Diagnostic Recovery in Fusion Devices
Session	PT04: Tutorial/Invited Session: Plasma Diagnostics 2:00 PM–5:00 PM, Wednesday, November 19, 2025 Room: 104A/B