Rapid, Robust, Real-Time AI-Based Plasma Equilibrium Profile Reconstruction and Control on DIII-D

TEC-CTL

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We have developed and deployed a new real-time AI-based model, RTCAKENN[1] (Fig. 1), that reconstructs the equilibrium internally and outputs seven key kinetic profiles on DIII-D with sub-4 ms latency, and maintains high accuracy even when critical diagnostics (e.g., Thomson Scattering and/or Charge Exchange Recombination Spectroscopy and/or Motional Stark Effect) are absent. This addresses a major challenge in future fusion devices such as ITER and beyond, which will operate with limited or degraded diagnostics over time. RTCAKENN has been running by default in the DIII-D Plasma Control System (PCS) in over 100 discharges, demonstrating its reliability. Furthermore, RTCAKENN has been integrated with both a model predictive controller (MPC) and a reinforcement learning (RL) controller–which are poised for experimental validations. This represents a significant step toward robust profile control under diagnostic gaps, paving the way for more reliable plasma operation on next-step fusion devices.

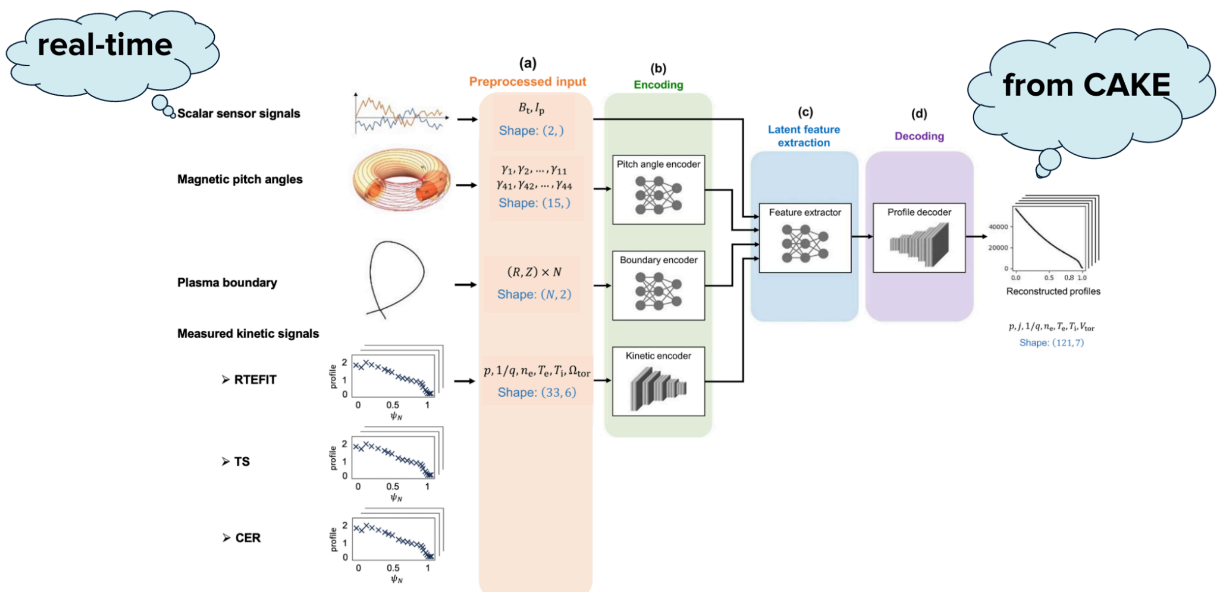

Fig 1: simplified depiction of the RTCAKENN architecture, which uses real-time data to internally reconstruct the plasma equilibrium such that it can generate all profiles of interest for real-time control

Recent DIII-D experiments confirm RTCAKENNs ability to provide accurate pressure, current density, safety factor, pressure, electron density, electron temperature, ion temperature and ion rotation profiles in real-time, even as diagnostics are intentionally withheld. Figure 2(a-b) show RTCAKENN's reconstructed electron density and temperature profiles when TS data is withheld (and similarly for CER), while panel (c) shows a comparison from an experimental discharge between RTCAKENN and the well-established CAKE[2] code, illustrating not only close agreement but also robustness when TS/CER data is removed, when keeping the total pressure from RTEFIT. The reconstructed equilibrium data fall within the error bars of the offline tools. These results address a key operational scenario for ITER and beyond, where diagnostics may become intermittent or unavailable, yet precise profile control is essential to maintain performance, stability and safety.

RTCAKENN itself–even without the demonstration including the controllers–represents a substantial advance, greatly enhancing operational flexibility and resilience. This higher level of diagnostic-independence provides immediate value for real-time plasma monitoring and enhances future experiments aimed at integrating AI-driven control.

With RTCAKENN fully integrated into the PCS, the next step is leveraging its real-time predictions for active profile control. Two complementary controllers have been developed and readied for experiment:

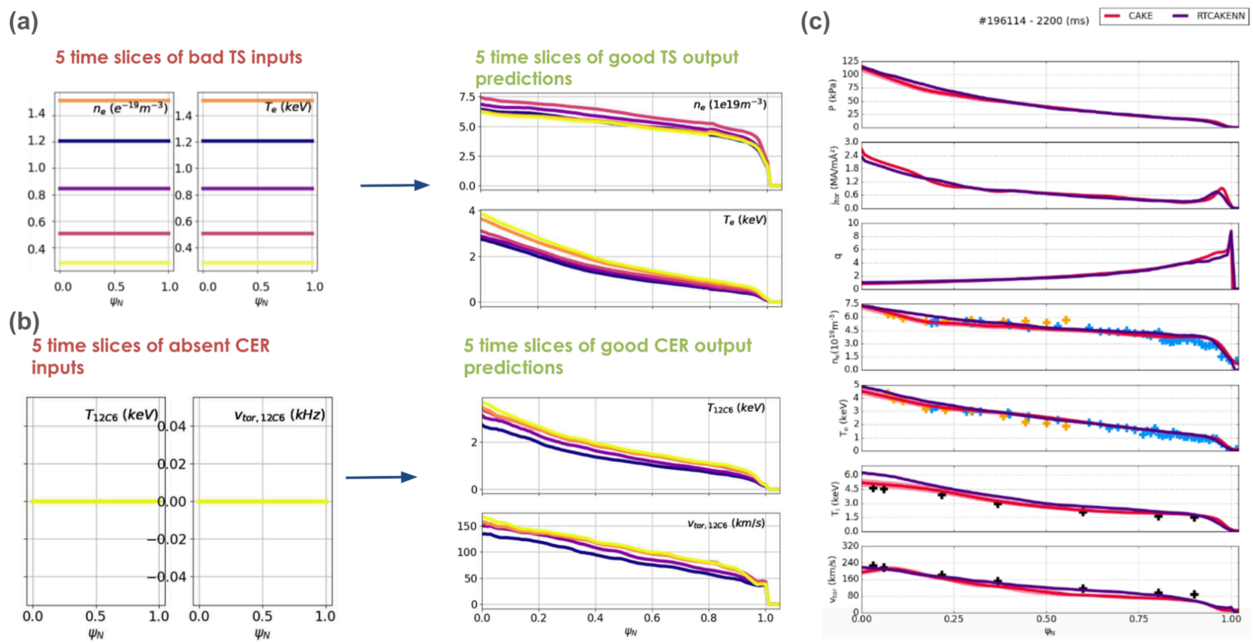

Fig 2: Example of RTCAKENN robustness in absence of TS and CER data (a-b), and accuracy when experimental RTCAKENN data (purple) is compared against the well established CAKE code (red) (c).

(1) Model Predictive Controller: Built upon a linear latent-space representation of the plasma state, the MPC anticipates the plasma's response to actuator inputs, and adjusts these actuators to achieve the desired profile targets.
(2) Reinforcement Learning Controller: Trained on a predictive environment, the RL controller autonomously discovers control policies to optimize plasma conditions, continuously adapting to changing states in the pursuit of profile control.

A dedicated experiment is scheduled for April 23, 2025 to verify that these controllers, guided by RTCAKENN's robust predictions, can maintain or steer targeted plasma conditions when certain diagnostics are intentionally withheld. Several other experiments will rely on RTCAKENN as well. This demonstration would mark a major milestone toward handling diagnostic attrition in ITER and future long-pulse or steady-state devices.

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