Automatic Between-shot Kinetic Equilibria and Neutral Beam-Heat Load on DIII-D Using Supercomputers

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A new computational paradigm for fusion facilities, recently put into production, leverages remote Leadership Compute Facilities (LCFs) with on-demand queuing, direct support for ongoing experiments, and failover to ensure availability despite maintenance or downtime. Providing kinetic equilibrium and neutral beam heat-load analysis in a timely fashion is only possible through access to large-scale resources, with various architectures (CPUs vs GPUs), that exceed the capability on-premises at the experimental facility. This shift in the utilization of high-performance computing (HPC) resources is pivotal for the future of fusion energy, particularly with the increasing data demands of ITER coupled with growing simulation sophistication.

For the first time, high-fidelity kinetic equilibria and neutral beam heat-load deposition are automatically generated between plasma discharges on DIII-D, improving experimental decision making in the control room and advancing towards a digital twin of the tokamak. In the past year, approximately 150,000 kinetic equilibria (see Fig. 1) have been generated, compared to only 4,000 manually produced over the previous 35 years [Smith2024]. This marks a transition from a labor-intensive process with ad hoc availability to providing timely, routine and consistent results.

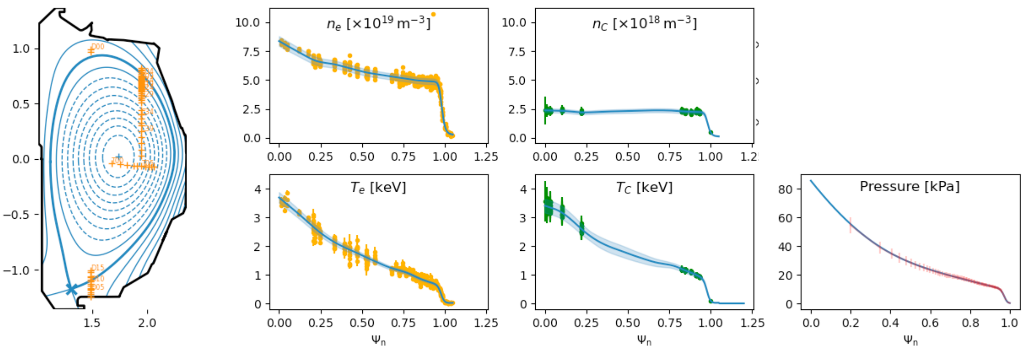

Fig. 1. Kinetic equilibria are now automatically generated for every plasma discharge by the CAKE workflow, which self-consistently calculates the magnetic flux surfaces and the temperature, density and pressure profiles.

Additionally, thousands of individual heat-load simulations now track injected particles from each of DIII-D's eight neutral beams over hundreds of time points per discharge, connecting strike locations and total energy deposition with the injector(s) responsible. This is crucial for preventing facility damage and guiding complicated scenario design, which are important considerations for current devices, ITER and future reactors.

First pioneered by DIII-D and Argonne Leadership Compute Facility (ALCF) a few years ago, automated remote access to on-demand HPC resources was difficult to maintain in production at that time due to the queuing requirements and lack of consistent interface infrastructure [Kostuk2018]. Now, these hurdles have been overcome for these two workflows and it is also easier for additional plasma modeling simulations to benefit from inclusion into this paradigm. Indeed, The U.S. Department of Energy, Advanced Scientific Computing Research (ASCR) is beginning a new program called the Integrated Research Infrastructure (IRI) to facilitate and expand this transition.

A few hundred kinetic equilibria (every 20 ms over a 5-10 second discharge) are completed in about 10 minutes by CAKE using National Energy Research Scientific Computing (NERSC) HPC resources, fast enough to inform control room decisions for the next discharge [Xing2021]. Turbulent transport calculations, stability analysis and reduced-order neural network surrogate models are now generated as a result of the regular availability of kinetic equilibria [Bechtel Amara2024]. Kinetic equilibria provide a more detailed and accurate description of the plasma's internal dynamics than equilibria based off of magnetic data alone. Kinetic equilibria are a self-consistent result using input from magnetic sensors, motional stark effect, Thomson scattering, charge-exchange recombination spectroscopy and auxiliary heating.

Between-shot monitoring of in-vessel strike locations from individual neutral beams is made possible by utilizing ALCF HPC resources, enabling timely identification of potential hot spot hazards and impurity creation. This information allows operators to take corrective action and prevent costly downtime on current and future devices from compromised vacuum vessel integrity or damage to diagnostics. The IonOrb code has verified a significant strike point responsible for a DIII-D vacuum leak and two weeks of unexpected downtime. It is also used to calculate the spatial distribution of power deposited onto a newly installed antenna. Neutral beams are important for heating and current drive, allowing experiments to achieve a wide variety of plasma scenarios, yet with total power from all 8 beams approaching 20MW on DIII-D, predicting the heat load deposition on the walls is crucial for protecting diagnostics, eliminating hot spots, and reducing impurities from carbon wall ablation.

Progress towards a complete digital twin of the DIII-D tokamak is advancing through the integration and acceleration of these increased fidelity models. Rapid kinetic equilibria provided by CAKE are essential for accurate scenario design and for training fast predictive surrogates. The IonOrb simulations required extending the available plasma equilibrium and toroidal field outside of the typical limiter region, as well as integrating it directly with as-built laser scan data of the vessel. Together, these improved simulation workflows utilizing ASCR resources provide researchers with access to actionable information in the control room during experiments, allowing them to adjust strategies and optimize results. This ensures the safety and efficiency of experiments, driving new scientific discoveries and advancing the field of fusion energy research.

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