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No Guesswork: Realistic Fusion Simulations Assist in Power Plant Design

Accurately predicting fusion power plant performance can potentially save billions of dollars and accelerate the path to clean energy.

LONG BEACH, Calif. — The quest to harness energy from fusion, the process that powers the sun and stars, has transitioned to an exciting phase: designing and building power plants that will demonstrate the feasibility of fusion as a practical, affordable, and abundant source of energy on Earth. Scientists need to predict how fusion devices will perform before building them to avoid costly mistakes and ensure optimal operation. These fusion power plants also produce fusion energy in extremely hot plasma (a collection of charged particles), with temperatures reaching ten times that of the sun's core. These conditions result in complicated new physics, which scientists must understand at the fundamental level to develop models and predictions for the fusion power plants.

Until now, simplified models have been used to design fusion research facilities, like ITER, the international fusion experiment under construction in France, and SPARC, a compact fusion device under construction in Massachusetts. These simplified models, however, have significant limitations in predicting how heat is confined within the fusion device — a key factor that determines overall performance.

To overcome these limitations, a team at the Princeton Plasma Physics Laboratory (PPPL) demonstrated that simulations solely based on the device design can accurately predict fusion power plant performance. By combining an ultra-realistic physical model with sophisticated numerical methods and high-performance computing, the researchers developed an open-source program called Gkeyll (pronounced as in "Dr. Jekyll and Mr. Hyde"). Gkeyll can simulate the complex turbulent phenomena that govern heat confinement in fusion devices using minimal engineering-relevant inputs, such as input power and the desired peak density of the plasma inside the device.

The team demonstrated this capability by simulating a specific experiment conducted on the Tokamak à Configuration Variable (TCV) fusion device in Switzerland, which is known for its ability to create a variety of plasma shapes. Just as the shape of an airplane's wings significantly affects its aerodynamic performance, the shape of the plasma in a fusion device has a major impact on its overall performance. As with the efficient wings that equip our modern aircraft, only a deep understanding of the relevant physics combined with accurate simulations can reveal the optimal plasma shape. The simulations performed with Gkeyll successfully reproduce the experimental measurements of plasma density and temperature profiles in the TCV fusion device.

Furthermore, the simulation offers new insights into the improved performance observed for some specific plasma shapes, such as the negative triangularity configuration shown in Figure 1.

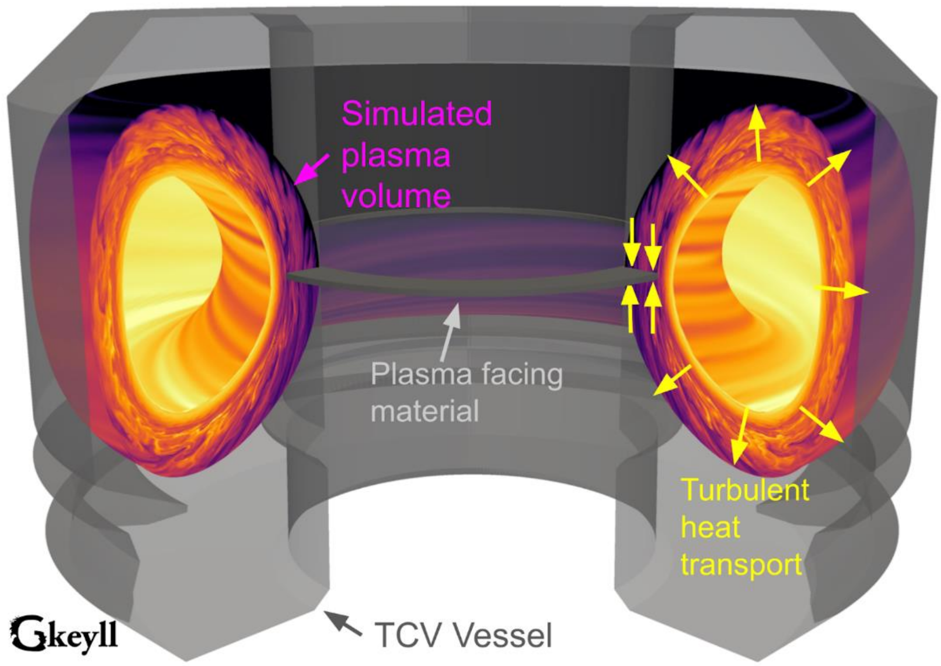

Figure 1: Open cut of Gkeyll simulation of TCV plasma. The temperature is shown in color scale, with hotter regions in yellow and cooler regions in purple. The turbulence here is transporting heat towards the vessel and must be controlled for optimal performance. The results of this simulation confirmed that the device's performance is improved when the plasma has this reversed "D" shape, called "negative triangularity."

By incorporating Gkeyll simulations directly into the design process of future fusion devices, like the successors of ITER and SPARC, researchers aim to help navigate the complex engineering challenges of building fusion reactors. Thanks to advanced mathematical methods, Gkeyll can balance precision against computing time, allowing researchers to run simulations at different levels of detail appropriate for the various design stages in the construction of a fusion power plant. The code can test whether the simplified formulas and models currently used to predict fusion device performance are actually reliable. Moreover, unlike these reduced models, Gkeyll can reveal detailed plasma dynamics, including identifying potentially problematic instabilities that could limit device performance. Finally, researchers also expect Gkeyll to play a role in developing digital twins of fusion reactors, virtual replicas that can simulate and monitor their physical counterparts, potentially offering real-time predictions of plasma behavior during actual power plant operations.

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References:
[1] A. C. D. Hoffmann et al., "Towards fully predictive gyrokinetic full-f simulations," arXiv:2510.11874 (2025).
[2] A. Hakim et al. "The Gkeyll code," https://gkeyll.readthedocs.io/en/latest/

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Abstract

PP13.15	Towards more predictive gyrokinetic turbulence simulations of the tokamak boundary region
Session	PP13: Poster Session VI: HED: Opacity, EOS, and WDM, ICF: LPI, Z-Pinch, Hydro, MFE: Analytical, computational, AI/ML techniques; Whole Device Modeling; Active Control; Diagnostics; Edge and Pedestal, Mini-Conference on the DOE Milestone Awardee Physics Basis. 2:00 PM–5:00 PM, Wednesday, November 19, 2025 Room: Hall B