Fusion Energy

WDMApp: High-Fidelity Whole Device Modeling of Magnetically Confined Fusion Plasmas

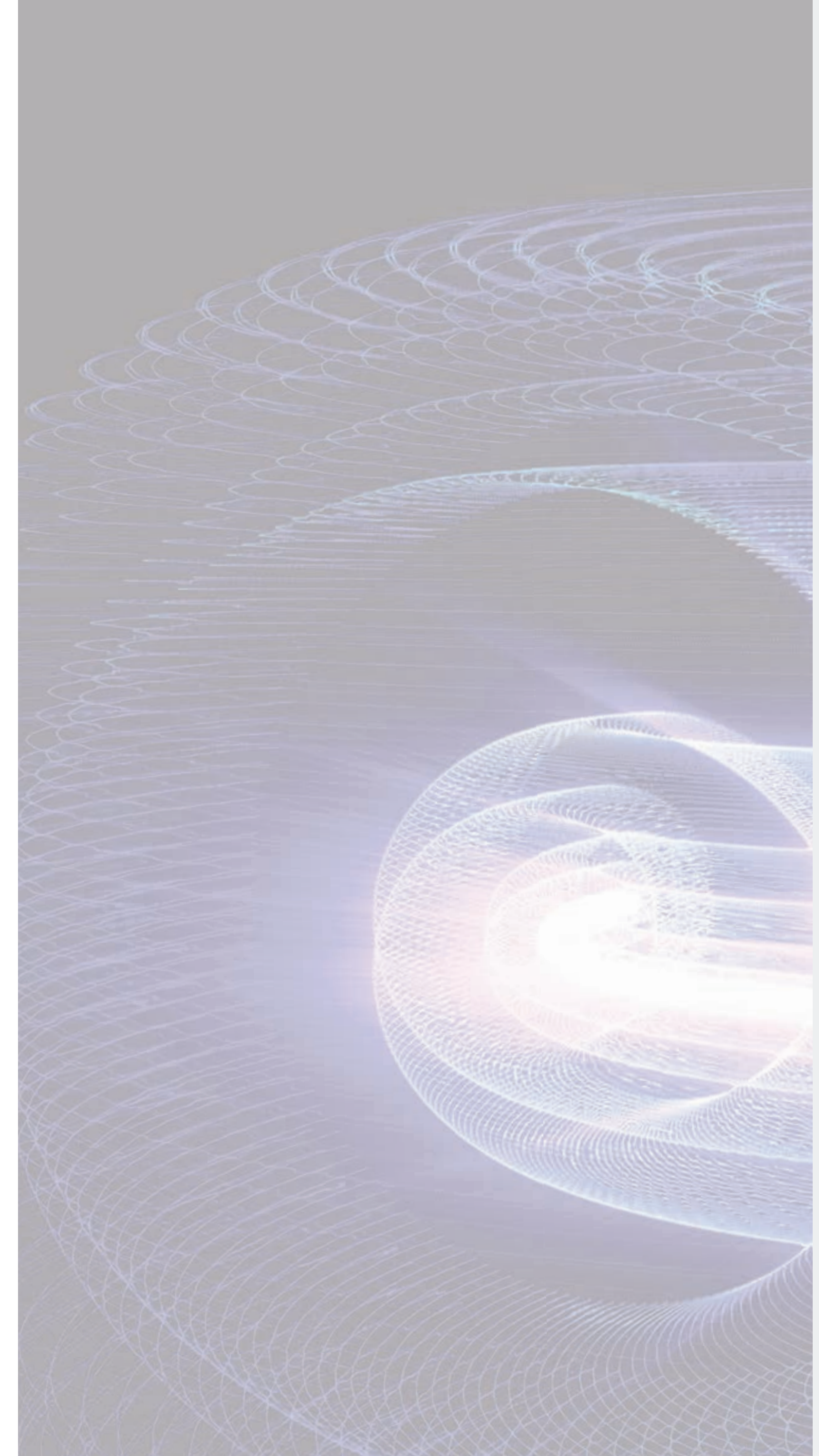
Magnetically confined fusion plasmas are being designed within the International Tokamak Experimental Reactor (ITER) and other projects that will operate in physics regimes never achieved through experiment. Accordingly, modeling and simulation activities that require exascale computational resources are required to design and optimize these new facilities. The WDMApp project is developing a whole device modeling approach that will provide predictive numerical simulations of the physics required for magnetically confined fusion plasmas to enable design optimization and fill in the experimental gaps for ITER and future fusion devices.

The Whole Device Model Application (WDMApp) project aims to develop a high-fidelity model of magnetically confined fusion plasmas, which is urgently needed to plan experiments on ITER and optimize the design of future next-step fusion facilities. These devices will operate in high-fusion-gain physics regimes not achieved by any current or past experiments, making advanced and predictive numerical simulation the best tool for the task. WDMApp is focused on building the main driver and coupling framework for the more complete Whole Device Model (WDM), with the ultimate goal of completing a comprehensive computational suite that includes all the physics components required to simulate a magnetically confined fusion reactor. The main driver for the WDM will be the coupling of two advanced and highly scalable gyrokinetic codes, XGC and GENE. The former is a particle-in-cell (PIC) code optimized for treating the edge plasma; the latter is a continuum code optimized for the core plasma. WDMApp takes advantage of the complementary nature of these two applications to build the most advanced and efficient whole device kinetic transport kernel for the WDM.

A major project thrust is the coupling framework EFFIS 2.0 (End-to-end Framework for Fusion Integrated Simulation 2.0), which will be further developed for operations exascale and optimized for coupling most of the physics modules that will be incorporated in the WDM. The current MPI+X implemented in the main GENE and XGC applications is to be enhanced with communication-avoiding methods, task-based parallelism, in situ analysis with resources for load optimization workflows, and deep memory hierarchy–aware algorithms.

The resulting exascale application will be unique in its computational capabilities and will have potentially transformational impact in fusion science, for example, by studying a much larger and more realistic range of dimensionless plasma parameters than ever before and by assessing the rich spectrum of kinetic microinstabilities that control the quality of energy confinement in a toroidal plasma (e.g., tokamaks, stellarators), with the core and the edge plasma strongly coupled at a fundamental kinetic level based on the gyrokinetic equations.

The exascale science challenge problem is the high-fidelity simulation of whole device burning plasmas applicable to a high-confinement (i.e., H-mode) advanced tokamak regime, specifically, an ITER steady-state plasma that aims to attain a tenfold energy gain. The physics objective is to predict one of the most important indicators for energy confinement in the H-mode—the plasma pressure "pedestal" height and shape. Realization of the H-mode with high-edge plasma pressure and mild pedestal gradient is critical to ITER's performance and success. Efficiency of the fusion burn is virtually determined by the height of the pressure pedestal at the edge. The strategy will involve using WDMApp, which is focused on coupling the continuum code GENE in the core region and the PIC code XGC at the edge.



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Progress to date

- Benchmarked linear and nonlinear instability calculations of ion temperature gradient–driven instability in cyclone base case between GENE and XGC to remarkable accuracy (~5%).
- Created core-edge coupling algorithms with minimum data movement between the codes that led to 10× performance improvement.
- Collaborated with the Co-Design Center for Particle Applications Codesign Project to develop and use the Cabana particle library for more stable execution of XGC on Summit without performance degradation.

WDMApp will use exascale computing to provide a whole device modeling capability for magnetically confined fusion plasmas that, due to sparse experimental data at proposed operating conditions, is required to design ITER and future fusion power reactors.