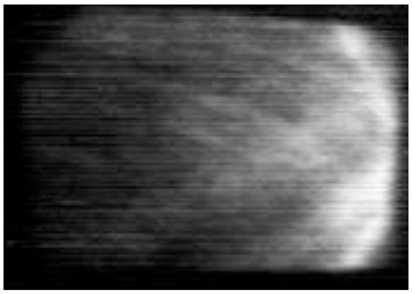
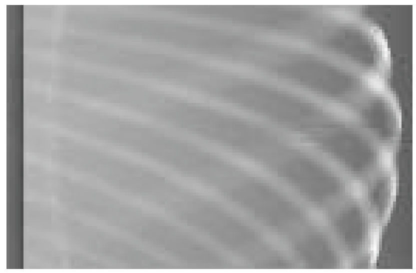
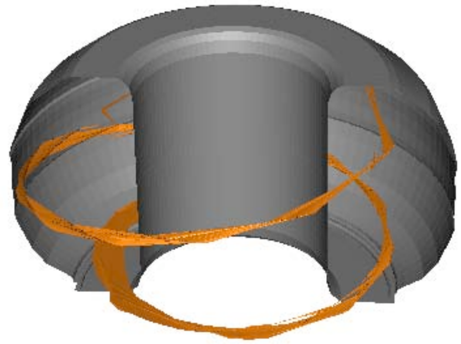
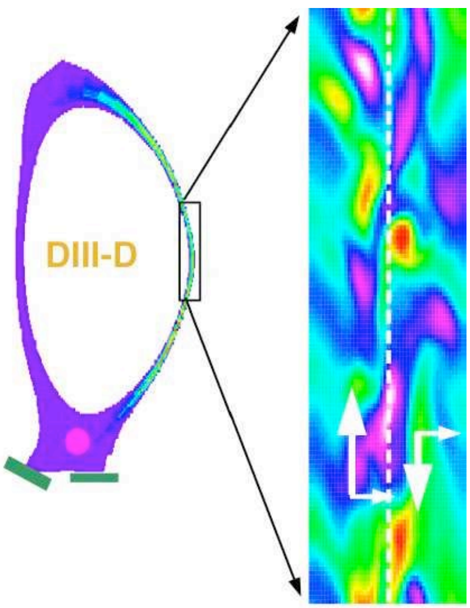
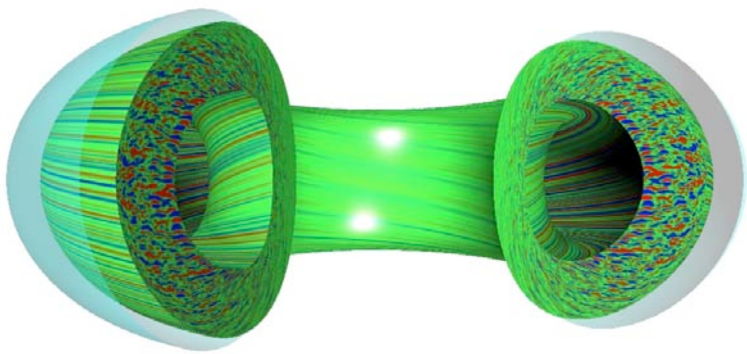
Proposal for a Fusion Simulation Prototype Center For Edge Plasmas











Principal Investigator: R. H. Cohen, Lawrence Livermore National Laboratory

Co-Principal Investigators:

P. J. Catto, MIT
P. Colella, LBNL
M. R. Dorr, LLNL
A. H. Glasser, LANL
G. W. Hammett, PPPL
S. I. Krasheninnikov, UCSD
J. R. Myra, Lodestar
B. N. Rogers, Dartmouth
P. B. Snyder, GA

1. ABSTRACT

This center will develop the capability necessary for direct numerical simulation of the H-mode pedestal and ELM cycles in tokamak fusion devices including transient plasma transport to divertors and walls. Our deliverable is a 5D (3 in configuration, 2 in velocity) continuum gyrokinetic code solved on a field-line-aligned computational grid, and fluid equations solved on the same grid. The gyrokinetic formalism will be extended to allow steep equilibrium plasma gradients found in the edge region; this has begun and will be completed under this proposal. The project will build upon a basic edge gyrokinetic code being developed at LLNL, adding the additional physics (electromagnetic field solve, coupling to impurities, neutrals) necessary to properly simulate pedestal and ELM phenomena, and further improving the code structure and numerical methods. Multiple-timescale techniques will be applied to bridge the gap between fluctuation timescales and the transport timescales of scrape-off layer response and pedestal re-formation. The code is built upon a set of data structures that allow field-line connectivity of the various regions of a diverted tokamak; these are in turn built upon an adaptive-mesh-refinement framework that provides parallelism and will provide grid adaptivity. A "spiral approach" to software construction will be employed, whereby successive refinements to the code will be made to increase robustness, interoperability, accuracy, and performance, while accommodating increasing physics complexity. The code will be applied to a sequence of applications with comparisons to other codes, theory, and experiments, including DIII-D, C-Mod and NSTX.

2. EXECUTIVE SUMMARY

The tokamak edge plasma can develop steep gradients of temperature, density and rotation velocity (the "edge pedestal") that strongly (favorably) influence core plasma fusion performance. The pedestal can be periodically interrupted by magnetohydrodynamic events (edge-localized modes, or ELMs), which rapidly remove stored energy and particles from this region resulting in intense heat pulses to divertors/walls. Thus understanding the edge pedestal structure, particularly the temperature and density at the top of the pedestal ("pedestal height"), and its periodic destruction and re-formation during an ELM cycle, is critically important for prediction of overall plasma performance.

Predictive simulation of an ELM cycle divides into at least three substantial, semi-independent challenges: (1) calculation of pedestal structure and its build-up between ELM events, (2) simulation of the ELM crash through to its nonlinear conclusion; and (3) following the ELM heat pulse into the scrape-off layer (SOL) and through the divertor-leg plasma. These challenges have been only incompletely addressed. The presence of large collisional mean free paths and particle drift orbit widths make kinetic simulation essential for quantitative prediction of pedestal structure and ELM heat pulse dynamics; this has not been done, and is complicated by the high initial collisionality of the divertor leg. Furthermore the disparity of timescales between the turbulence that gives rise to much of the transport in the pedestal region, and the pedestal build-up, means that direct simulation of turbulence-timescale equations to follow pedestal evolution requires very long simulations. Simulations of ELM crashes tend to fail with the timestep collapsing partway through, accompanied by significant magnetic perturbations and structure on the scale of the computational grid. The proposal will address the first challenge by developing an edge gyrokinetic code to incorporate the necessary kinetic effects and by deploying multiple timescale techniques to enable efficient simulation of pedestal build-up and quasi-steady-state structure. The second challenge will be met by computing on a grid that is aligned with the magnetic field and remains approximately so throughout the calculation, to accommodate changing directions of anisotropic flows, and by refining the mesh if necessary to ensure adequate resolution. The third challenge will be met through the approach outlined below. The substantial algorithmic expertise on the project team and a layered code design will ensure that algorithmic improvements motivated by experience with the simulations will be implemented.

The fundamental approach is a continuum gyrokinetic code, coupled to a fluid-equation plasma model solved on the same field-line-aligned computational grid and in the same computational environment. *Kinetic simulation* is necessary because particle drift orbit widths can become comparable to equilibrium radial gradient scale lengths and because mean free paths can exceed parallel gradient scale lengths. *Fluid components* are desirable (and perhaps necessary) for various reasons: to handle highly collisional impurities and high-density, low-temperature limits and regions, to provide a fast option for electron dynamics (fluid electrons with kinetic ions), to provide a vehicle for kinetic-code verification in the high-collisionality limit, and to provide a faster-running vehicle to explore qualitative issues and to do quantitative simulations with kinetic-effect models developed via the kinetic code. *A continuum representation* of kinetics is highly advantageous because of the wide range of collisionalities in the edge and because of noise associated with particle-based methods, a problem that is especially severe given the inapplicability of δf methods to the edge and the low noise required to see H-mode transport barriers. Also continuum gyrokinetics has been found to be very robust and successful for core microturbulence. The *gyrokinetic equations must be modified* to accurately handle the steep equilibrium plasma gradients found in the edge region; the necessary formalism extensions have begun and will be completed under this proposal. It also requires coding strategies that accommodate the large equilibrium potential variations along field lines characteristic of edge plasmas as well as the geometric complications of open field lines adjacent to closed flux surfaces; this necessity leads to the choice of a *code developed for the edge*, rather than the extension of a core gyrokinetic code. *Multiple-timescale techniques* (*e.g.,* relaxed iterative coupling and projective integration) will be tested for their ability to accurately calculate edge turbulence effects on long time scales, such as the time over which the pedestal (re)forms.

The code so constructed will have applicability to a wide range of important edge physics problems beyond pedestal physics and ELMs. These include the observed transition between "L" (low) and "H" confinement modes, L-mode turbulent transport, intermittent transport, density limits, power and particle exhaust, and impurity sources and transport.

The project will build upon a basic edge gyrokinetic code being developed under Lawrence Livermore National Laboratory LDRD funds, adding the additional physics (electromagnetic field solve, coupling to impurities, neutrals) necessary to properly simulate pedestal and ELM phenomena. The code is built upon a set of data structures that handle the field-line connectivity of the various regions of a diverted tokamak; these are in turn built on top of an adaptive-mesh-refinement framework that provides the parallelism and will provide grid adaptivity.

The project will add capability in three phases, with distinct physics targets. In phase 1, the physics mentioned above (with a simple fluid neutrals model) will be added to the LLNL code, along with implementation of fluid component options, while retaining the choice of a static grid aligned with an initial magnetic field. This will enable simulation of linear and early-nonlinear phases of the ELM crash, and simulation of edge turbulence in low ("L") and high ("H") confinement performance modes of a tokamak, and in particular during the pedestal build-up. In phase 2, techniques will be deployed for (a), grid re-alignment to better follow large-amplitude magnetic perturbations, (b), a full gyrokinetic collision operator, and (c), if needed, an intra-species kinetic-fluid hybrid strategy to enable simulations that encompass the full range of collisionality and more faithfully capture neoclassical effects. These enhancements are targeted at enabling simulation of a full ELM crash, as well as strongly collisional and/or weakly turbulent plasmas. In the final phase, 3, we will add multiple timescale techniques to efficiently calculate the pedestal build-up and steady states consistent with the underlying turbulence, and a kinetic neutrals model to provide a more quantitative treatment of neutral-gas fueling. This phase targets simulation of full ELM cycles and more accurate treatment of recycling effects. Also in this phase we will develop reduced models of kinetic effects from experience with the kinetic code, for incorporation in the fluid code. Long-lead-time code development and theory needed in phases 2 and 3 will be initiated during earlier phases.

A "spiral approach" to software construction will be employed, whereby successive refinements to the code will be made to increase robustness, interoperability, accuracy and performance, while accommodating increasing physics complexity. As the code system grows in capability, advanced numerical algorithms will be developed and applied to address the severe computational challenges posed by the high dimensionality, strong anisotropy, skewed geometry and multiple scales of a gyrokinetic edge model. These algorithms will be made scalable to take advantage of ultrascale computing platforms. Also, software infrastructure will be developed to assist in the analysis of the data that the code will produce. To accomplish these goals, the current investments in the SciDAC APDEC and TOPS ISICs will be significantly leveraged, and that leverage will be combined with many years of participants' experience developing fluid edge and core gyrokinetic codes.

The code will be applied to a sequence of applications with comparisons to theory, other codes and experiments as capability evolves: fluctuation-timescale edge turbulence; ELM crash (linear phase); ELM crash (nonlinear phase); SOL/divertor response; pedestal build-up; full ELM cycle. The project will work with experimentalists from each of the major facilities who will assist in the experimental comparisons and provide advice on development priorities. R. Groebner from DIII-D, S. Zweben from NSTX, and B. LaBombard from C-MOD have agreed to be our primary experimental contacts.