Predictive Simulations of Drift Wave Turbulence, Extended MHD, and Heating and Current Drive

Peter J. Catto and Paul T. Bonoli
MIT Plasma Fusion and Science Center

Overview: Predictive modeling of the ITER pedestal and scrape-off layer (SOL) are key challenges to the theory and computational community as it makes steady progress in simulating drift wave turbulence, extended MHD effects, and heating and current drive in the core of tokamak plasmas. Key issues in the edge are the physics underlying the transitions (the "trigger") between low or L, high or H and/or improved or I mode confinement profiles, evolution of the pedestal (including its width and height), flows (retaining radial momentum transport) and their impact on fluctuations, pedestal and SOL coupling, the density limit, radio frequency (RF) wave propagation and heating, and effects of a 3D magnetic field. To gain insight into the difficulties we give background, discuss progress, and highlight innovative and promising procedures being developed for the core. Wise funding decisions by DOE are required to maintain a respectable theory program at an FY12 funding level. An FY13 funding level further marginalizes the effort.

Core turbulence: Gyrokinetic (and gyrofluid) simulations have highlighted the extreme sensitivity of ion temperature gradient and other turbulent transport to local temperature and density gradients, finding that tokamaks tend to operate near the nonlinear marginal stability threshold. Typically codes find that core density and temperature profiles (and thus device performance) can be estimated if the parameters at the top of the pedestal are known. As a result, the physics of what establishes the pedestal width and height are a key issue. The computed turbulent fluxes are highly sensitive to changes in the gradients of the mean plasma profiles ("stiff"). As experimental measurements of these gradients have significant uncertainties, it is difficult to quantify the uncertainty in turbulent fluxes computed using these gradients as fixed inputs. However, the inverse problem of finding the mean profiles from given fluxes is not stiff. This problem is also the one of far greater importance, as the fluxes are set by externally applied and typically better known, particle, momentum, and heat sources. The challenge is then to evaluate the global profile evolution by treating the wide range of space-time scales spanned by the turbulent fluctuations. It is impractical to predict profile evolution by global gyrokinetic plus Maxwell equation solvers. To correctly address this problem, a multiscale numerical approach is required that couples gyrokinetic equations and conservation of number, momentum, and energy equations to the requisite order. This multiscale coupling of the gyrokinetic codes GS2 and GENE to the fluid code TRINITY in the subsonic or diamagnetic drift limit is appropriate for ITER and Alcator C-Mod. TRINITY evolves the density, temperature, and potential profiles on the confinement time scale. GS2 or GENE need only be run until turbulent saturation to calculate the turbulent fluxes for TRINITY. In this ITER relevant limit symmetries must be properly accounted for when the cross section is up-down symmetric to ensure vanishing momentum transport without flow, making higher order terms are responsible for intrinsic rotation. These predictive profile-evolving simulations will become key tools in roughly five years at an FY12 funding level once the essential higher order features are added. The FY13 funding level has already delayed this effort. Progress predicting the ITER edge profile evolution requires a 50% funding increase and the training of a new generation of superb plasma theorists.

Extended MHD: The majority of MHD problems relevant to fusion involve multi-fluid and kinetic effects. These include sawtooth oscillations and other reconnection processes such as neoclassical tearing modes, edge localized phenomena, and resistive wall modes. Other physical effects that must often be retained are diamagnetic effects including gyroviscosity, a generalized Ohm's law, and weakly coupled ion and electron flows and temperatures. Kinetic closures are required since the core plasmas are weakly collisional. They are being developed for M3D-C1 and some progress is being made on NIMROD. These hybrid core kinetic-fluid descriptions may provide insight into magnetic island evolution. First results are anticipated in approximately five years at FY12 funding.

RF: RF waves are used for heating, current drive, and pressure and current profile control. Predictive simulations are critical to optimize operation in existing tokamaks and burning plasmas such as ITER. Full wave, Fokker-Planck and Monte Carlo codes for simulating non-thermal distributions in the lower hybrid range of frequencies (LHRF) and ion cyclotron range of frequencies (ICRF) are available and validation activities are testing their predictive capabilities. Within a few years core comparisons allowing prescribed profile evolution should be feasible. Other challenges are evaluating the importance of finite ion orbit effects on the interaction of ICRF waves with fusion alphas, and neutral beam or ICRF generated energetic ions. The assessment of these interactions on stability and the impact on fusion is likely to require 5-10 years at FY12 funding.

Quantitative understanding of the coupling of ICRF and LHRF power in the edge including the 3D geometry of the RF launcher is only now starting to be possible. These models not only have to accurately predict the linear coupling characteristics of RF launchers (expected within 5 years), but they also have to account for nonlinear processes, such as parametric decay instabilities and RF sheath formation, that result in parasitic losses observed almost ubiquitously in RF experiments (anticipated within 5-10 years). In addition, theoretical investigations of scattering of RF waves from edge density fluctuations and blobs in the SOL are underway and may be possible within 10 years.

Key recommendation: Extending turbulence descriptions into the pedestal requires coupling to the open field lines of the SOL, treating strong spatial gradients including the large radial electric field, and perhaps retaining non-Maxwellian ion features. Correctly evolving the pedestal profile requires determining the physics responsible for robust behavior observed such as the L-H transition and Greenwald density limit. Theoretical understanding of the mechanisms is required rather than complex and computationally costly gyrokinetic codes trying to include more physics. New numerical algorithms are needed for these codes making it unlikely that they will yield useful results in the next 5-10 years. Concurrently, it is necessary to develop theoretical understanding of the edge that can be used to simplify the codes or at the very least help interpret the simulations. The robust phenomena observed cannot depend on the delicate interplay of a myriad of physical processes. The strong numerical program that is already underway needs to be supported by a similarly strong theory effort to develop a truly predictive edge capability.