Integrated Simulation of Performance-limiting MHD and Energetic Particle Instabilities with Micro-turbulence

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An essential requirement of high fusion gain steady state burning plasma is control of performance-limiting MHD and energetic particle instabilities such as Neoclassical Tearing Mode (NTM), Resistive Wall Mode (RWM), Edge Localized Mode (ELM) and energetic particle-driven Alfven instabilities. These MHD instabilities can limit plasma beta value or lead to major disruption. Furthermore, energetic fusion alpha particles and beam ions can excite Alfven instabilities that in turn can lead to large energetic particle losses causing damage in the first wall. Therefore it is critical to build predictive simulation models in order to understand the physics of these instabilities and to avoid or control these modes. Here we show that an integrated first-principle-based multi-scale/multi-physics simulation model is needed to quantitatively predict the onset and the effects of these modes on plasma performance. Building such an integrated simulation model requires a substantial increase in resources above present level.

The excitation and evolution of macroscopic electromagnetic instabilities often depend on kinetic effects at microscopic scales as well as the nonlinear coupling of multiple physical processes (*e.g.*, turbulent and neoclassical transport, energetic particles, heating and current drive), which span disparate spatial and temporal scales. For example, NTM islands flatten the local pressure profile and modify plasma flow, thus affecting micro-turbulence and the neoclassical bootstrap current. On the other hand, micro-turbulence can impact island dynamics by regulating plasma current and electron heat transport along and across the magnetic field, and by driving sheared flows via Reynolds stress and Maxwell stress. A fully self-consistent NTM simulation must therefore incorporate nonlinear interactions between the resistive MHD tearing modes, neoclassical transport, and drift-Alfvenic microturbulence. First-principles kinetic-MHD simulation of burning plasmas with multi-physics and multi-scale dynamics is clearly a computational grand challenge problem. Specifically, important spatial scales for NTM physics range from the microscopic ion gyroradius (10^{-3}m) to the macroscopic MHD wavelength (10^{0}m). Key time scales include the micro-turbulence decorrelation time (10^{-4}s), the NTM dynamical time (10^{-2}s), and the energy confinement time (10^{0}s) – with a long-pulse ITER experiment expected to typically last ~ 10^{3}s.

A bold initiative is needed to meet this computational grand challenge of integrated simulation of MHD and energetic particle instabilities together with micro-turbulence. Methods need to be developed to integrate MHD and kinetic physics, to bridge the disparate temporal scales, and to efficiently utilize massively parallel computers at the peta-scale level and beyond. The goals are (1) to predict the impact of MHD and energetic particle instabilities on equilibrium and confinement; and (2) to predict disruption and its avoidance and control.