Multi-Scale Validation of Nonlinear ELM Physics and Simulations

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B. Plasma boundary, including the pedestal, scrape off layer, and plasma-materials interactions

Motivation, Background, and Impact

Necessary elements for developing successful ELM mitigation or avoidance systems are experimentally validated models and understanding of the underlying physical mechanisms in the plasma edge region. Edge stability boundaries and their related pedestal structure must be identified to understand how ELM mitigation techniques function. ELM particle, current, and energy loss mechanisms critical to plasma-facing-component lifetime are poorly understood. Determining ELM trigger mechanisms or detectable precursors may be of importance to control. Future burning plasma devices such as ITER require validated models of ELM dynamics. They must strictly operate within ELM stability limits while maintaining core fusion performance in parameter regimes that cannot be attained in present-day research facilities. Open questions remain in this high-priority research area. The US fusion research program should emphasize and promote research efforts that target the fundamental physics governing ELM dynamics and the evolution of the plasma edge region.

There has been substantial progress in our understanding of ELM physics and control since ReNeW [1]. Predictive models of the H-mode pedestal structure were developed [2] and tested favorably [3] on several devices. Multi-machine tests of ELM mitigation/suppression techniques such as 3D field application and pellet pacing have led to their incorporation into ITER [4]. Others have been developed: vertical jogs of the plasma, supersonic molecular beam injection, edge RF heating and current drive schemes, and application of lithium and lithium wall coatings [5]. ELM-free regimes such as the QH and I-mode have been demonstrated on multiple machines [5]. Nonlinear codes such as BOUT++, JOREK, NIMROD, and M3D-C1 have been used to simulate ELMs, allowing estimates of ELM-induced heat loads, and investigating relevant physical effects during 3D field application [6]. These simulations are approaching experimentally-relevant parameters and phenomena, including that of nonlinearly-driven multi-ELM cycles [7].

The shortage of experimental science targeting nonlinear pedestal formation and ELM dynamics on Alfvénic timescales represents a critical research gap. ELMs are intrinsically nonlinear, being driven by multiple simultaneously unstable ideal MHD peeling-ballooning (P-B) modes. This complex phenomenon leads to rapid particle and energy transport on Alfvénic timescales, including generation and propagation of 3D filamentary structures [6, 8]. The pressure, current, and velocity fields all evolve temporally and spatially in different, but related, ways. Unraveling the interactions between these fields is a critical test of theoretical understanding of the dynamical evolution of ELMs. The evolution of the pedestal is also nonlinear. The EPED model posits a pressure gradient limit from kinetic ballooning modes (KBMs) evolving during the inter-ELM cycle, followed by an ELM triggered by crossing a P-B stability boundary [2]. Identifying and characterizing KBMs in experiment also requires nonlinear simulations [3, 9]. Also, measuring the temporal evolution of the edge current profile $J_{\mathrm{edge}}(R, t)$ and pressure $p_{\mathrm{edge}}(R, t)$ during the entire ELM cycle is required to understand the approach to, and crossing of, the stability boundary for P-B excitation [10]. This critical research gap should be addressed to test and eventually validate simulations of edge dynamics. Such simulations are needed to justify the design and expected efficacy of ELM control systems for future burning plasma devices.

The challenge is to measure all relevant fields—density, temperature, current, flows, etc.—throughout the ELM cycle with high spatial and Alfvén-scale temporal (~1 μs) resolution to compare to synthetic diagnostics and thereby test simulations of particular plasma configurations [6]. Further, simulations and multi-scale experimental tests across a variety of relevant physics parameters (aspect ratio, collisionality, Lundquist number, etc.), including both high- and low-performance plasmas, are needed.

Initiative Elements

We propose that existing and modestly upgraded experimental capabilities be employed to pursue an integrated experimental program that investigates the nonlinear properties of pedestal formation and ELM dynamics as part of the Integrated Simulations and Transients Initiatives under discussion at this Workshop series. The focus here is on the generally unexplored fast nonlinear dynamics involved in these processes. This effort will primarily integrate edge detailed observations of n_e, T_e, J, and v fields on the PEGASUS spherical tokamak [10] and high-speed pedestal density and flow field measurements on DIII-D and NSTX-U during ELMs. Such data can provide needed comparisons to integrated modeling employing synthetic diagnostics.

The deployment of 2-D BES imaging diagnostics at the edge of DIII-D and NSTX-U offers the capability of high speed $n_e(R, t)$ measurements across ELM cycles. In addition, new diagnostics will likely evolve to support measuring the evolution other plasma fields in that region. Nevertheless, the ability to measure all relevant fields over a wide range of parameters will remain limited in those high performance experiments. A second critical component of this program is the use of multi-field probe measurements in the mid-scale PEGASUS ST experiment at modest performance to test and validate the understanding of the interactions between the unstable edge plasma fields by benchmarking against simulations. The increased confidence in the modeling obtained there will then extend and support the interpretation of more limited data from high-performance DIII-D and NSTX-U experiments.

Fast-timescale nonlinear ELM phenomena have already been observed in all three of these facilities. Fig. 1 shows high-time resolution $J_{edge}(R, t)$ measured during a Type I ELM in PEGASUS. A complex, multimodal collapse of the edge current pedestal is observed, with "hole"-like perturbations preceding the ejection of a current-carrying filament. Similar density holes have been observed using BES during the ELM crash in experiments on NSTX and DIII-D (Fig. 2). Such n_e and J_{edge} dynamics are qualitatively similar to features in nonlinear simulations, such as shown in Fig. 3 [12]. However, more comprehensive diagnostic coverage to simultaneously sample several plasma fields at the same spatial locations is needed to test such models.

These proposed multi-machine experimental studies spanning multiple scales and parameter ranges will be employed to test and validate nonlinear ELM simulations. These experiments will be compared to theoretical and computational models of the nonlinear edge physics. Development of sophisticated synthetic diagnostics in simulation will be required to make scientifically meaningful comparisons to experimental measurements of complex nonlinear and transient ELM phenomena. Together, these efforts will build and validate the needed physics basis and predictive models for pedestal and ELM evolution and control in burning plasma devices.

Scope and Required Resources

Diagnostics with high spatial resolution and Alfvénic temporal resolution are required to measure fields of interest for validating ELM simulations. Examples satisfying these criteria include BES, UF-CHERS, ECEI, and multichannel probe arrays that measure J_{edge}, $n_{e,edge}$, $T_{e,edge}$, v_{edge}, and Φ_{edge}.

Investment in diagnostic innovation and/or upgrades is required to equip high-performance experiments with needed localized, Alfvén-timescale measurement capabilities. Near-term examples include: additional spatial resolution and coverage for the 2D BES systems on NSTX-U and DIII-D and enhancing the DIII-D UF-CHERS system for fast flow measurements. Innovative new edge diagnostics for measuring additional fields of interest at high performance are expected in the longer term. In addition, pulse length, diagnostic, and toroidal field system upgrades to the PEGASUS spherical tokamak can transform the facility into an ELM validation laboratory with robust, stable H-mode plasmas with more comprehensive edge diagnostic access. When integrated with the more limited measurements from DIII-D and NSTX-U, this will create unique opportunities for nonlinear pedestal and ELM physics research in support of this initiative. These upgrades to PEGASUS are discussed in more detail in a separate white paper [13].

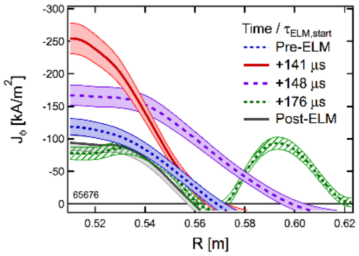

Fig. 1. Type I ELM $J_{edge}(R, t)$ in PEGASUS.

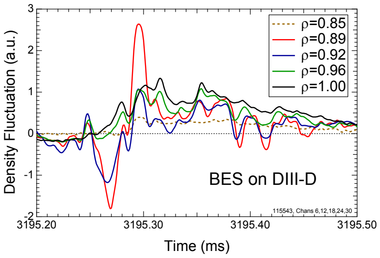

Fig. 2. ELM $n_e(R, t)$ on DIII-D via BES.

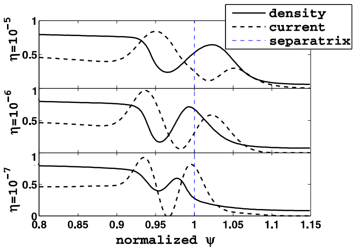

Fig. 3. JOREK-simulated $J_{edge}(R,t;\eta)$, $n_e(R,t;\eta)$ [12]

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