Advancing Multiscale Fluctuation Measurement Capability to Validate Integrated Simulations

G.R. McKee (mckee@fusion.gat.com), M.W. Bongard, R.J. Fonck, D.R. Smith, Z. Yan,
University of Wisconsin

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This proposed activity seeks to identify required measurement capability, develop and upgrade necessary diagnostic systems, and perform focused, theoretically motivated experiments to validate integrated simulations of fusion plasmas. Extrapolating the performance of modern fusion experiments to future burning plasma devices such as ITER will require a comprehensive and systematic endeavor to test, challenge, improve and ultimately validate simulations across relevant scales, parameters and operational scenarios. In addition, fully validated models will allow for optimization of performance and facilitate experiment design.

Motivation and Background: The process of experimentally validating simulations encompasses a range of metrics by which to judge model fidelity and accuracy [1]. Initial quantitative comparisons between simulation and experiment in the areas of turbulence and transport have yielded significant areas of agreement while also identifying important discrepancies [2-5], such as the L-mode Shortfall.

Specific phenomena for which validated models are required include L-H transition physics (transition trigger; relating scaling laws to local edge behavior); pedestal evolution (identifying and demonstrating gradient and height-limiting instabilities); multichannel transport (low to high-k turbulence; impacts on particle, heat, momentum channels); energetic particle-driven modes (spectral, magnetic and density eigenmode structure); neoclassical tearing modes; magnetic islands; and, importantly, interactions between these multiscale phenomena. As an example of the interaction of small and mesoscale phenomena (turbulence-zonal flow), Fig. 1 illustrates low-k density fluctuation imaging measurements and turbulent flow-field immediately preceding an L-H transition to discern L-H transition dynamics [6].

While numerous advanced fluctuation diagnostic systems have been deployed on various experimental facilities, key measurements are still missing, and application of these diagnostics to advanced scenarios is limited, where the strong interaction of transport, stability, current and pressure profiles make measurements particularly challenging. The edge and pedestal region establish a boundary condition that strongly impacts core performance and exhibits its own unique instabilities that limit gradients and height. This proposed activity will focus on fluctuation measurements of instabilities, but diagnostics for kinetic profiles, magnetic and other parameters are of course also highly relevant to the validation process.

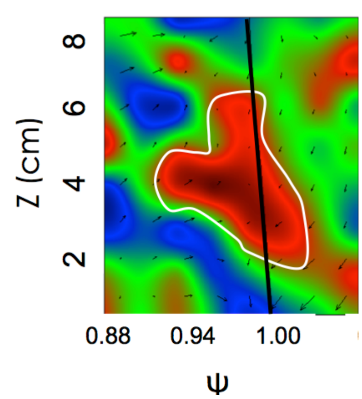

Figure 1. 2D turbulence image with superimposed eddy velocity map at L-H transition (BES on DIII-D) [6].

Proposed Activity: A comprehensive research plan to validate simulations will require comparing a range of measured parameters with simulation calculations. Comparisons of global parameters (τ_E, β_N, etc), kinetic profiles, and underlying small-scale instabilities will all be required. Each level of comparison provides increasing confidence that the simulations are accurately modeling experiments with the proper physical mechanisms. Research elements include:

- Identifying which physical parameters and fields are most important to clarifying underlying instability mechanisms, e.g.: potential, magnetic field, temperature, velocity
- Develop or expand new measurement capabilities via a reinvigorated and expanded FES diagnostic development program focusing on integrated simulation validation
    - o Examples may include low-voltage HIBP, Stark spectroscopy, magnetic sensor probes, Li-beam, HR-ECE, CECE, UF-CHERS, ECEI, VUV-BES
- Upgrade and expand existing diagnostic capability to a wider range of scenarios
    - o Improved spatial resolution, spatial extent, sensitivity (some pedestal localized)
- Executing focused experiments to vary high-leverage parameters and obtain required data

A range of scales and interacting instabilities will need to be considered, e.g., neoclassical tearing modes, energetic-particle-driven Alfvenic modes, low to high-k turbulence, and kinetic ballooning modes. This is necessary because any mode or instability can and will impact the driving or damping mechanisms for other instabilities as well as sources/profiles. Wide scale fast measurements can also provide disruption precursor detection. Fig. 2 shows an example comparison between measured density fluctuation spectra at two values of T_e/T_i in Advanced Inductive H-mode plasmas, and compares with TGLF calculations, illustrating the comparisons sought [9] via application of appropriate synthetic diagnostics.

While multiple density fluctuation diagnostics are available, new fluctuation measurement capability should include the following:

- High-k fluctuations in relevant wavenumber regions
- Electrostatic potential fluctuations over a wide k-range
- High-sensitivity ion & electron temperature fluctuations
- Magnetic field fluctuations (3D)
- Wide field measurements to simultaneously observe multiple scales and quantify nonlinear interactions
- Coupled measurements to directly determine fluxes

A comprehensive program will be conducted on multiple facilities over a range of size (ρ*), aspect ratio (A), and scenarios, e.g., L, H, I, EPH, QH-modes. The Transport Task Force is an appropriate vehicle for coordinating, guiding and assessing validation activities.

For new and untested diagnostic techniques, systems may initially be developed and deployed on modest scale and readily accessible experiments (e.g., Pegasus, MST, LAPD), and exported to larger experiments (e.g., DIII-D, NSTX-U) as appropriate. This will further enhance academic-laboratory collaborations and expose students to large-scale fusion facilities.

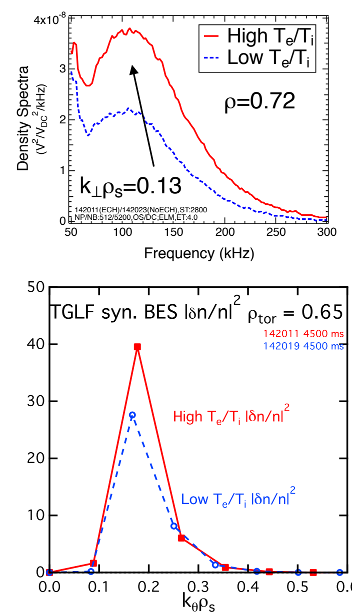

Figure 2. (a) low-k density fluctuation spectra (BES on DIII-D) at low and high Te/Ti, and (b) calculated spectra with TGLF and synthetic BES [9].

Impact: Successful experimental validation of integrated simulations will provide scientifically credible predictive capability for burning plasmas and greatly increase confidence that ITER and future burning plasmas can achieve their performance objectives. It will also provide critical tools for performance optimization and experiment design and execution, an important ITER need and an area of unique US expertise within the world fusion program.

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