GA–A27232

FUSION SIMULATION PROGRAM

FINAL REPORT FOR THE PERIOD
SEPTEMBER 27, 2009 THROUGH JULY 31, 2011

by
PROJECT STAFF

Work supported by
the U.S. Department of Energy
under DE-SC0001266

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GENERAL ATOMICS

DISCLAIMER

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GENERAL ATOMICS

1. FINAL REPORT ON TASKS PERFORMED BY GENERAL ATOMICS FOR THE FSP PROGRAM PLANNING

Under this project, General Atomics (GA) was tasked to develop the experimental validation plans for two high priority ISAs, Boundary and Pedestal and Whole Device Modeling in collaboration with the theory, simulation and experimental communities. The following sections have been incorporated into the final FSP Program Plan (www.pppl.gov/fsp), which was delivered to the US Department of Energy (DOE). Additional deliverables by GA include guidance for validation, development of metrics to evaluate success and procedures for collaboration with experiments. These are also part of the final report.

1.1. Experimental Validation

1.1.1. Plan for ISA 1: boundary and pedestal

1.1.1.1. Goal and Focus. This ISA aims to develop the capabilities for modeling the outer region of the tokamak from the top of the edge pedestal to approximately a millimeter into the first wall with the goal of quantitatively predicting the density and temperature of the pedestal and the heat and particle loads leaving the plasma and impacting the plasma first wall and divertors. The model should cover phenomena over a wide range of timescales from the steady-state (time-averaged) heat and particle fluxes to larger transient fluxes induced by off-normal and loss of performance events such as disruptions and edge localized modes (ELM).

While a high pedestal is optimal for overall fusion performance, the free energy in the sharp gradients of the pedestal can also drive intermittent instabilities called ELMs. Though ELMs are generally benign on existing devices, they deposit heat loads on material surfaces, which could constrain material lifetimes on ITER, and operation with ELM control or in regimes with small or no ELMs is desired. Hence a validated understanding of the L-H transition, pedestal structure and ELM dynamics is crucial to the successful operation of ITER. Furthermore, ELM events, bursty transport and fuelling via neutrals couple the pedestal to the open field line scrape-off-layer (SOL) region and the material surfaces.

Normal operation of ITER and fusion reactors requires successful channeling of plasma heat flux from the core region to the SOL where the open magnetic field lines guide the heat and particles to the divertor. In the divertor, it is necessary that the heat be conducted away safely over a sufficiently large surface area or radiated in the presence of impurity ions to avoid material heat flux limits of ~10 MW/m^2. In the presence of off-normal events such as disruptions and ELMs, heat will escape across the magnetic field and impinge on highly localized spots, which gives rise to a limitation of approximately

$E_L \tau_A^{1/2} \sim 1$ MJ s$^{1/2}$, where E_L is the energy ejected into the SOL over a time scale of τ_A seconds. The large power deposited on the first wall will rapidly erode material facing the plasma resulting in significant shortening of the wall lifetime and thus potentially reducing availability of a fusion power plant. Avoidance or mitigation of disruptions and ELMs is essential for a fusion power plant. Because of the uncertainties of the physics in the tokamak boundary, it is likely any modeling of the boundary will be made up of a combination of first-principles and reduced (even empirical) models in the foreseeable future. A heavy burden will be put on experimental validation to quantify the fidelity of each component as well as the integrated model of this region. Fortunately a wide range of existing devices with pulse length ranging from a few seconds to hundreds of seconds, and operating with very different boundary conditions are available for this purpose.

1.1.1.2. Critical Issues. The critical issues that can impact the heat and particle loads as well the edge transport barrier and the maximum plasma pressure at the top of the pedestal include:

- Startup
- L-mode, H-mode, L-H transition
- Pedestal structure
- ELM avoidance and mitigation
- First wall (FW) and divertor PMI, loads on high heat flux plasma facing components (PFCs)
- Evolution of FW and divertor PFCs (material migration, mixed and redeposited materials, etc.)
- RF antenna/SOL interactions
- **Impurity generation and transport**
- **Steady-state operations with self-consistent plasma and wall modeling**
- Termination and shutdown.

The **green** highlighted issues are discussed in the pedestal science driver report, the **blue** highlighted issues are discussed in the boundary science driver report, and the **bold** highlighted issues straddle both areas. Each issue forms an extensive experimental validation campaign. Clearly, the boundary and the pedestal are closely coupled through many shared physics and code capabilities. They are also coupled to ISA 2: Whole Device Modeling (WDM) with focus on disruption avoidance, and other science drivers (Table 1).

The way these critical issues are structured, they are amenable to experimental validation in a multi-level approach as suggested in the validation best practices guidance (Section 3.5.4 of the FSP Program Plan submitted to DOE). In the pedestal area, the issue of L-H transition focuses on a one-time very rapid transition, the dynamics of which changes the character of the edge plasma completely and in fact establishes the edge pedestal. Key theoretical models to be validated would include the cause of the transition, and the behavior of the neoclassical and turbulent transport before and after. The pedestal structure issue centers on the time-averaged behavior of the pedestal in the H-mode. Prediction of stability boundary and transport evolution in a stable pedestal would be subjects for validation. ELMs are intermittent, performance degrading events. The physics to be validated describes the dynamics leading to the crossing of the pedestal stability boundary, the nonlinear consequence of the instability, and the mechanism resulting in the return to stability followed by repetition of the whole cycle. The time-averaged pedestal behavior is clearly dependent on the ELM dynamics and vice versa, which would be addressed by the next level validation (Fig. 1). This will have to be coupled to the L-H transition at yet another level of complexity to validate the evolution of the pedestal from startup.

Table 1
Shared Physics and Code Capabilities of ISA 1 and Other Science Drivers

Application Area	Capability Needed From ISA 1	Capability Provided to ISA 1	Capability Shared with ISA 1
ISA 1: Boundary and Pedestal	Boundary to Pedestal: Heat, particle, momentum fluxes Neutral and impurity fluxes	Pedestal to Boundary: Heat, particle, momentum fluxes	Boundary/Pedestal: Gyrokinetics Fokker-Planck collisions Kinetic neutral transport
Science Driver: Wave-Particle	Plasma profiles Fluctuation levels	Local heat deposition from fast particles and rf	Parasitic rf losses and impurity sources
ISA 2: Disruptions		Transient local heat and particle loads	Atomics and neutral physics, radiation transport
ISA 2: WDM	Reduced models for boundary, especially fueling, fuel retention, impurity sources		

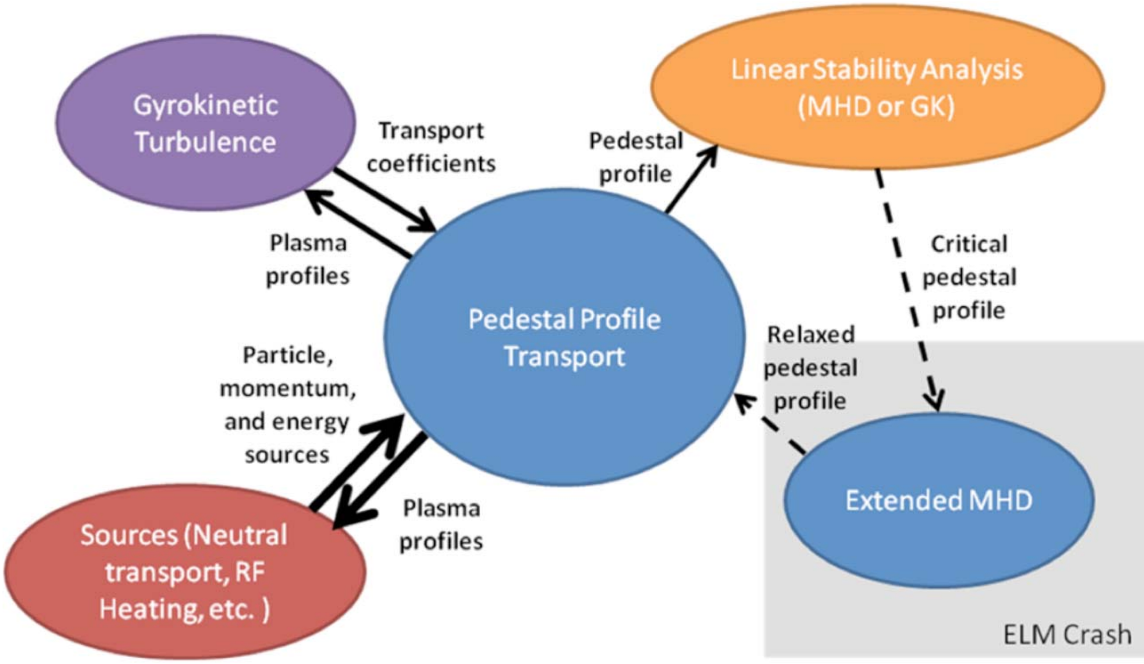

Fig. 1. Representative dynamics (Level 2) pedestal component configuration.

Analogously, in the boundary area, modeling the loads on high hear flux PFCs suggests validation of a short time scale phenomenon such as how the materials behave under a significant heat pulse from an ELM or a disruption. Conversely, modeling of material migration requires validation of long time cumulative effects. The two require very different designs of experimental campaign. One can also plan validation based on the separation in physics. An example is the rf antenna design that changes the sheath electric field, which impacts impurity production. Separately, the impurity transport can be examined under a fixed background. Keeping in mind the main focus of this ISA is to predict the impact of heat and particle loads on PMI, the code development plan has to eventually couple the heat and particle fluxes from the core and pedestal to the SOL and PFCs. The validation plan for this multi-physics coupling will have to be consistent with the code development timeline.

1.1.1.3. Validation Template. Borrowing from past experience in experimental validation, we can construct a template for testing and validating physics processes that reflects the hierarchical strategy. The template has five guiding principles with timescale indicated:

- Most processes have predicted implications for one or more profiles (1-3 years)
  - Make good, time-resolved measurements of profiles to see if predicted limits occur where predicted (e.g., critical gradients)
  - For most processes, we have some capacity to calculate these limits and capabilities are being improved

- Simultaneously, make measurements of phenomena which should appear when predicted limits are reached (e.g., rise in fluctuations with expected characteristics) (1-3 years)
  - For most processes, we can predict qualitative behavior of these phenomena
- Perform steps 1 and 2 over a wide range of plasma conditions, chosen to stress the important parameters of the processes (1-3 years)
  - If a process survives steps 1,2 and 3, we would have good confidence that it is important
- Longer term, need to make quantitative tests of the relevant phenomena (e.g., fluctuation amplitudes) (3-5 years)
  - This will generally require theoretical/modeling advances which are now underway
  - May require diagnostic advances
- For processes that survive steps 1-4, need development of integrated models (transport models or frameworks which incorporate important processes) (3-5 years or longer)
  - Determine how the processes interact
  - Validate integrated predictions against experiment.

1.1.1.4. Metrics. In order for this template to provide useful results, quantitative validation metrics will need to be developed for each model application of interest (i.e. different metrics will be needed for studies of L-H transition physics, pedestal structure, ELM dynamics, etc.). These metrics are needed to both establish the fidelity of current models (and thus the confidence that should be assigned to their predictions), and to track improvements in model fidelity as they (and available computing resources) improve. While the requirements for validation metrics is discussed in detail in the best practices section (Section 3.5.4 of the FSP Program Plan submitted to DOE), some key features of these metrics are that they should: incorporate an assessment of the numerical error in the model results, as well as both model and experimental uncertainties, and reflect the inherent key sensitivities of the models being considered. In general, a suite of "simple" metrics (which assess model fidelity for a single physical parameter) will be needed, with these simple metrics combined into composite metrics to provide more holistic assessments of model performance.

As an example of a possible metric suite, consider the case of the H-mode pedestal structure. The most basic metrics might be comparisons of the model-predicted pedestal height and width against experimental measurements, using a simple parameterization to characterize both model and experiment results. Here the experimental uncertainties are assessed based upon the fitting of the measured data points to the parameterization, and the model uncertainties via propagation of uncertainties in the experimental input parameters through the model. More advanced metrics might relax the assumption of a single pedestal width or height, and compare the predicted and measured structure of various profiles (e.g., n_e, T_i, T_e, E_r), or replace the use of parameterization comparisons with calculations of chi-squared "goodness of fits" for model predictions to measured data points. Additional constraints, such as predictions for turbulence statistics such as amplitudes, fluxes, and correlation lengths could be incorporated to supplement tests of the predictions of equilibrium pedestal profiles. The additional constraints added as the metrics are refined should be chosen with an aim of identifying key model strengths and weaknesses, thereby providing clear guidance for the theorists and modelers on which aspects of the model need the most improvement.

1.1.1.5. Readiness Assessment and Resources. To assist in the development of a validation schedule, we have tabularized (Tables 2 and 3) under each high priority issue, the critical physics that need to be evaluated, the readiness of the modeling/simulation capability and the experimental readiness in a self-consistent way. The green color in the tables indicates short-term (1-2 years) readiness, the blue color indicates medium-term (3-5 years) and the red color indicates long-term. Using these tables as guides, the next level details can be worked out by the validation team in the execution phase of the FSP.

For analyst manpower estimate, we summarize Tables 2 and 3 into several validation tasks.

- Validation of pedestal structure and dynamics
- Validation of pedestal relaxation and transients
- Validation of plasma-wall interaction
- Validation of coupled pedestal/boundary physics.

The manpower requirement and the validation tasks timeline are given in the WBS. Considerable basic research will be needed to develop more quantitative PMI models although reduced models might be tested early on. For this reason, validation of combined pedestal and wall-divertor interaction will be beyond five years.

Table 2
Boundary Physics Validation Assessment Table

Issue	Critical Physics	Model/Simulation Readiness*	Experimental Readiness
Cross-field plasma transport	• Micro-turbulence/ blobs; transport from strong, intermittent events • Mesoturbulence/ELMs • Coll. and turb. transport Role of magnetic topology/shear, X-point and wall/divertor contact	• Couple SOL fluid plasma transport/turbulence • Couple (2D, 2v) kinetic SOL plasma with nonlinear F-P collision model capable of full short-to-long mfp • Extend fluid turbulence to foot of pedestal • Fluid ELM simulation for SOL response • Couple evolving MHD equilibrium to account for shifting separatrix	• Fluctuations: reflectometry, probes, BES, gas-puff imaging • Profiles and flows: Thomson scattering, reflectometry, probes • Distribution functions: charge-exchange recombina-tion for ions and divertor Thomson for electrons
Heat and particle loads	• Surface fluxes from integrated plasma, atomics phys., neutrals, currents • Fueling, recycling, retention • Shear physics • Radiation transport • Private-flux region transport	• Couple neutral model, initially fluid • Develop and extend kinetic Monte Carlo neutral transport • Couple dynamic wall model for hydrogen wall uptake/ recycling with dynamic 2D SOL plasma model	• Particle fluxes: probes, D-alpha emission profiles • Heat fluxes: IRTV, thermocouples, probes • Near-surface tile analysis of hydrogen depth profiles • Radiation transport: spectroscopy • Private flux transport: probes, divertor Thomson
Material surface evolution	• Plasma surface interaction and resulting evolution • Surface chemistry • Effect of coatings • Dust generation	• Initiate full coupling between near-surface, particle-based sputter erosion/redeposition code for 2D impurities and SOL 2D fluid plasma model • Couple initial surface evolution model and near-surface plasma model	• Surface evolution, surface chemistry, and effect of coatings: DiMES/ MiMES-style probes; near-surface tile analysis of element depth profiles; scanning electron microscopy of surfaces; in-situ surface diagnostics (e.g., DIONISOS and MAPP)

Table 3
Pedestal Physics Validation Assessment Table

Issue	Critical Physics	Model/Simulation Readiness	Experimental Readiness
Pedestal structure and dynamics	• Micro-meso instability • Quasilinear and neoclassical transport • Nonlinear turbulent transport • Particle and energy sources and sinks • Neutral and atomics physics	• Linear peeling-ballooning stability analysis for static pedestal structure • Linear electromagnetic gyrokinetics (EM GK) • 2D neoclassical transport and flows • Static pedestal models based on coupled linear physics • Nonlinear EM GK turbulence simulations • 3D neoclassical transport including stochastic field and orbit loss • Reduced transport models based on nonlinear simulations • Couple to particle and energy sources	• Compare gradients within barrier to linear MHD and GK mode onset criteria • Measured edge current comparisons with neoclassical • Dynamic profile evolution • Turbulence comparisons with models
Relaxation mechanisms	• Nonlinear extended MHD and gyrokinetic models for ELM onset, nonlinear evolution and effects on plasma • Coherent mode stability, nonlinear evolution and effects on plasma • 3D equilibrium effects including non-axisymmetric magnetic fields • Pellet and other ELM triggering sources	• Linear onset from P-B calculations coupled to simple ELM crash models • Direct simulation of ELM dynamics using extended MHD, 2-fluid or kinetic-fluid codes	• Mode structure comparisons with linear calculations • ELM dynamics • Fast profile evolution • 3D equilibria • Multiscale and multi-channel fast dynamics
Transition physics	• L-mode turbulence and transport • Turbulence suppression mechanisms • Feedback loop • Transitions from low to high performance H-mode	• L-mode turbulence simulations with 3D codes • Couple linear or quasilinear gyrokinetic code with realistic geometry and ExB stabilization • Couple transport from core-pedestal • L-H Physics	• L-Mode turbulence characterization • Flow and E_r evolution • GAMs and zonal flow dynamics • Fast dynamics across transition • Fast evolution of flows and E_r across transition

1.1.2. Plan for ISA 2: whole device modeling (WDM)

1.1.2.1. Goals and Focus. The goal of this ISA is to build up capabilities for WDM, beginning with existing framework approaches and including components for profile evolution, stability assessment and nonlinear evolution (disruption prediction) including active control. This ISA would tackle the disruption prediction campaign outlined in the disruption science driver report. A key reason for the focus on disruption avoidance in the WDM development is because ITER can only withstand a few unmitigated disruptions a year. It needs WDM for plasma control development to achieve Q=10 while avoiding disruptions. It is envisioned that the WDM capability when developed to maturity will enable the ITER plasma control system (PCS) to meet the challenge of fusion burn control and event handling i.e. keep discharge available for physics exploitation and avoid disruptions and prolong discharges if possible. As an abstraction for the PCS, WDM will integrate all the necessary physics to simulate the plasma response to external influences. Magnetic field coils, heating and current drive sources, and plasma transport properties determine equilibrium shape and profiles. Pedestal/ELMs, fueling, and impurities strongly influence fusion performance. Heating, current drive, fueling, and 3D field actuators strongly influence plasma MHD stability and thus disruption avoidance. Disruption mitigation is required when disruption is unavoidable. Experimental validation will have to be planned to test the fidelity of each physics element, as well as binary and multiply coupled physics.

1.1.2.2. Critical Issues. Each box in this figure represents an extensive validation campaign. Following the best practices guidance described in Section 3.5.4 of the FSP Program Plan submitted to DOE, a hierarchical series of validation steps should be designed to evaluate the physics. Take for example the box: Compute set of nearby (equilibrium) states. One might start with validating an axisymmetric equilibrium and its sensitivity to measurements of $\langle J \cdot B \rangle$, q_{95}, l_i, etc. 3D effects are often important in tokamak equilibrium solutions. Next hierarchy up in validation will have to include error fields, TF ripples, RMP coils and magnetic islands. Effects of energetic particles on kinetic profiles will have to be accounted for. Further considerations will include the impacts of 3D fields on transport and equilibrium profile modifications. The edge pedestal has a profound contribution on the equilibrium. Both the edge bootstrap current and the pressure gradient can quantitatively alter the equilibrium hence the stability of the tokamak plasma. It is clear that diagnostics for measuring the current profile, the fast ion pressure profile, and the edge current and pressure are critical for the validation campaign. An essential list of diagnostics (including synthetic diagnostics) should be identified for the validation campaign designed for each box in Fig. 2.

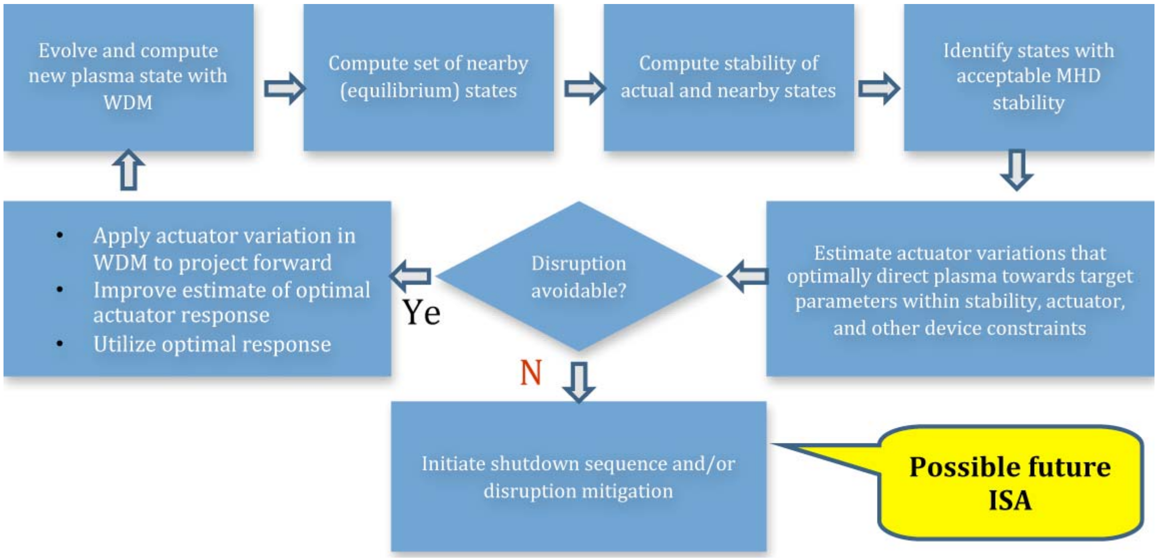

Fig. 2. Flowchart for WDM-based stability forecasting.

At the next level of complexity, validation will address the stability prediction capability, which will fully utilize the validated equilibrium models. The stabilities relevant to tokamak disruptions can be classified into six types (Fig. 3): external kink, vertical displacement event (VDE), internal kink (sawteeth), lock mode, tearing (TM) and neo-classical tearing (NTM) mode, and resistive wall mode (RWM).

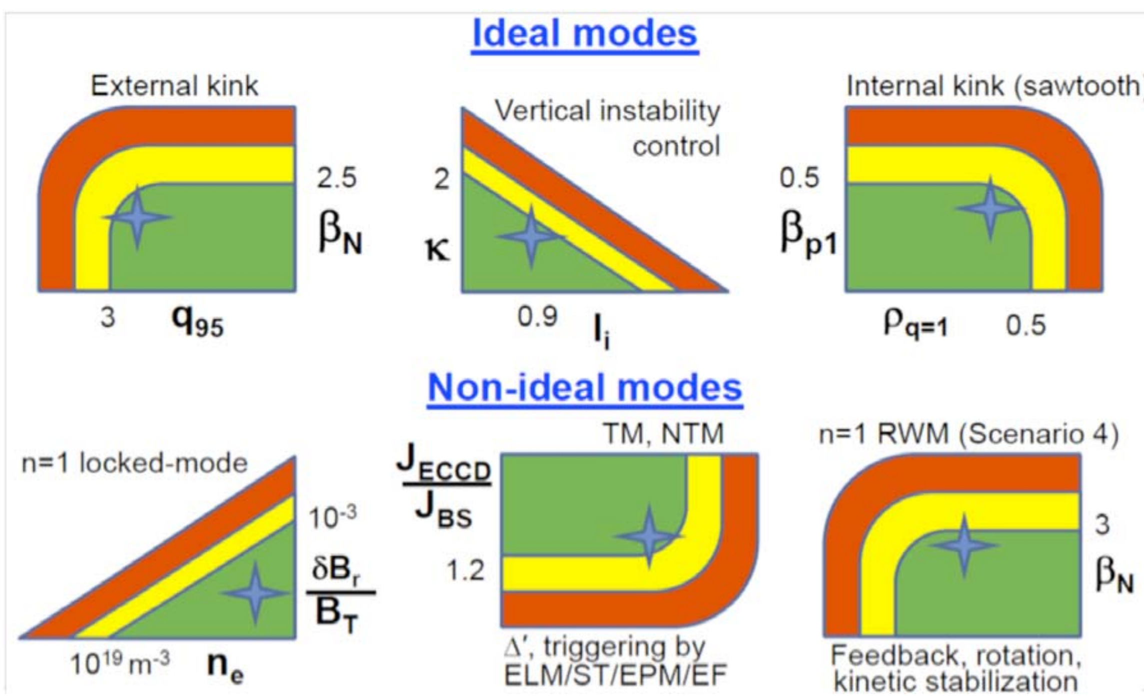

Fig. 3. Classification of instabilities responsible for tokamak disruptions.

Each of these instabilities requires validation of different critical physics issues. For the pressure and current-driven external kink modes, validation should focus on the WDM-experiment comparisons of disruption probability versus proximity to ideal limits. For VDE, the focus should be WDM-experiment comparisons of plasma response to varied κ, shape and l_i, also understanding of control noise, impact of disturbance and implications for ITER. For sawtooth instability and control, validation activities will evaluate 2D and 3D equilibrium and transport response to sawtooth, equilibrium and sawtooth control using validated actuators, and NTM triggering by sawteeth. Under locked-modes and error-field correction, the validation activities will include 3D (perturbed) equilibrium calculations needed in WDM for locked mode threshold, and establishing theoretical understanding of locked-mode threshold scaling. For NTM stability and control, the focus will be evaluating the fidelity of WDM combined with nonlinear extended MHD for understanding NTM stability/triggering thresholds, and WDM with 3D equilibrium for understanding transport response to NTM. RWM validation will continue to assess the validity of perturbative versus self-consistent RWM models, WDM-experiment comparisons of RWM stability thresholds, and the ability of actuators to modify equilibrium to optimize RWM stability. Since the proposed validation tasks are extensive, it is recommended that in case further prioritization is needed, the first focus should be on the VDE and NTM induced disruptions. These two are the most frequently observed causes for disruption reported on JET and other tokamaks.

Transport profile evolution governs the dynamics of a discharge leading to the eventuality of a stable plasma or a disruption. WDM is the tool used to simulate the profile evolution dynamics. Extensive experimental testing is needed to quantify the accuracy of the predicted profiles, which are essential for calculating stability thresholds. 3D magnetic fields play an important role in many disruption scenarios. 3D fields from MHD modes can damp rotation and induce disruption. The status of understanding of particle and momentum transport needs significant improvement. Fast ion transport by 3D magnetic perturbations can impact NBI deposition and alter the pressure profile. Applied 3D fields can provide useful control tools to improve stability and transport. Each effect depends on multi-physics, which in the near-term can only be modeled by WDM with reduced models. For this reason, it is important to quantify the impact of loss of fidelity in going from first principles to reduced components in WDM simulations. A plan to experimentally evaluate the fidelity of WDM in simulating multi-physics in the next five years is strategically reasonable and highly useful, for example in application to determine optimal actuator and transport response to avoid disruption.

1.1.2.3. Accuracy Requirements. “How accurate does a model have to be?” is a relevant question for FSP to consider. The need to avoid disruptions implies FSP components must be of sufficient accuracy to enable robust control and preserve sufficient distance from controllability boundaries. For example, to ensure reliable positional control in a vertically elongated tokamak plasma, the vertical instability growth rate must be monitored in real-time and kept below a critical value. Assuming Gaussian statistics, in order to achieve an incidence of disruption below one per year in DIII-D (in the absence of hardware or other system faults), this critical growth rate must be ~30% below the "moderate risk" growth rate for which the typical noise and disturbance environment produces ~5%-10% disruptivity. An FSP growth rate predictor with 5% accuracy would thus require the predicted growth rate to remain ~35% below the moderate risk growth rate. It is the size of the required margin from the controllability boundary (~30%) that typically determines the required accuracy for real-time monitoring. In contrast, the model accuracy required to ensure robust closed-loop stability characteristics is often much less stringent. For example, design of a robust linear control algorithm for vertical control typically requires no better than 20% error in predicted growth rate. The range of variation in accuracy required by these examples illustrates the importance of specifying a "target" uncertainty (TU) for a given FSP component such as the WDM.

1.1.2.4. Readiness Assessment and Resources. To assist in the development of a validation schedule, we have tabularized (Tables 4 and 5) under each high priority issue, the critical physics that need to be evaluated, the readiness of the modeling/simulation capability and the experimental readiness in a self-consistent way. The green color in the tables indicates short-term (1-2 years) readiness, the blue color indicates medium-term (3-5 years) and the red color indicates long-term. Using these tables as guides, the next level details can be worked out by the validation team in the execution phase of the FSP.

For analyst manpower estimate, we summarize Tables 4 and 5 into several validation tasks.

- Validation of plasma equilibrium states
- Validation of profile evolution from boundary to core
- Validation of fast MHD-induced disruptions
- Validation of slow MHD-induced disruptions
- Validation of transport-MHD coupled disruption simulations.

The manpower requirement and the validation tasks timeline are given in the WBS. The disruption validations will focus on identifying the disruption precursors and parametric disruption boundaries with high accuracy. Disruption dynamics and mitigation techniques will not be validated in the first five years with the prescribed funding constraints.

Table 4
Disruption Modeling Assessment Table

Issue	Critical Physics	Model/Simulation Readiness	Experimental Readiness
Fast MHD-induced disruptions (VDEs, ideal MHD)	• Stability of low-*n* modes • Nonlinear VDE evolution • Uncertainty quantification of stability boundaries • Control of actuators for stable equilibrium access	• Use WDM to simulate onset of VDE (force balance and control) • Extend MHD component capability to model impurities, radiation and wall (reduced model)	• VDE evolution: useful validation data available on many tokamaks – vertical position, halo/Hiro currents, heat flux patterns. • Low-n modes stability and uncertainly: analysis of closely spaced, high quality EFITs from existing or new experiments to test stability codes against data. • Dedicated experiments needed to test real time stability analysis and algorithms to avoid unstable state through profile control actuators in variety of operating scenarios.
Tearing mode-induced disruptions	• Accurate closures for MHD equations including energetic ions • Evolution of tearing modes on transport time scales including rotation dynamics and interaction with external structures • Threshold physics of neoclassical tearing modes	• Couple neoclassical gyrokinetic code to 3D equilibrium with magnetic islands • Develop 3D equilibrium solver that can handle islands and stochastic regions • Couple 3D equilibrium with 2.5D WDM code • Couple gyrokinetic turbulence code with 3D equilibrium	• Variety of existing data on NTM threshold and evolution
Resistive wall modes-induced disruption	• Accurate closures for MHD equations including energetic ions to accurately capture RWM stability • Evolution and control of RFA on transport time scales including rotation dynamics and interaction with external structures	• Incorporate kinetic effects in extended MHD • Couple self-consistent rotation with MHD and transport	• RWM stability: validate with closely spaced high quality kinetic EFIT reconstructions including fast ion pressure from existing or dedicated experiments

Table 5
WDM Validation Assessment Table

Issue	Critical Physics	Model/Simulation Readiness	Experimental Resources Needed
2.5 – 3D free boundary equilibrium generation and discharge evolution	• Model field errors, magnetic islands, applied mag. perturbations • Evolution of plasma and machine parameters • Dist. Functions in 3D space • Self-consistent treatment of EPs from NBI, ICRF, and fusion products	• Componentize 3D equilibrium with nested flux surfaces and prescribed boundary conditions • Couple flux surface averaged equilibrium quantities with 1D transport • Componentize 3D equilibrium with islands and prescribed boundary conditions • 2.5D reduced model transport simulation with island evolution	• Measurement of magnetic field at multiple toroidal locations external to the plasma
Evolution of plasma profiles from boundary to core	• Coupling of validated models for microturbulence and EP modes, and their effects on transport • Onset and evolution of internal transport barriers • Effect of large-scale instabilities on transport	• At least one componentized solver module with access to all reduced transport models embedded • Improve model for poloidal and toroidal momentum transport • Extend solver/transport component to include first principles transport models in both fluid-based and kinetic based reduced WDMs	• Fluctuation measurements of n, T_i, and T_e in kHz to MHz range in core and pedestal • Measurement of magnetic field fluctuations in kHz range in core and especially in pedestal
Prediction, control, and mitigation of instabilities	• Onset, growth rate, and nonlinear saturation for sawteeth, ELMs, RWMs, TMs, NTMs • How these modes affect plasma evolution e.g., transport and poloidal flux	See Disruption Section	• Measurement of magnetic field at multiple toroidal locations external to the plasma • Measurement of n_e, T_e, T_i profiles with high time resolution • Measurement of magnetic field fluctuations in kHz range in core and especially in pedestal
Interaction of boundary with plasma core	• Effect of heat/ particle flux on the boundary and of the boundary on the heat/particle flux • Effects of neutrals, large-scale instabilities, particle losses • Onset and dynamics of the H-mode pedestal; L-H transition	• Componentize reduced pedestal and edge models • Couple of 3D equilibrium, kinetic neoclassical and extended MHD codes	

2. ACKNOWLEDGMENT

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