Progress in Experimental Validation Plan Development

by

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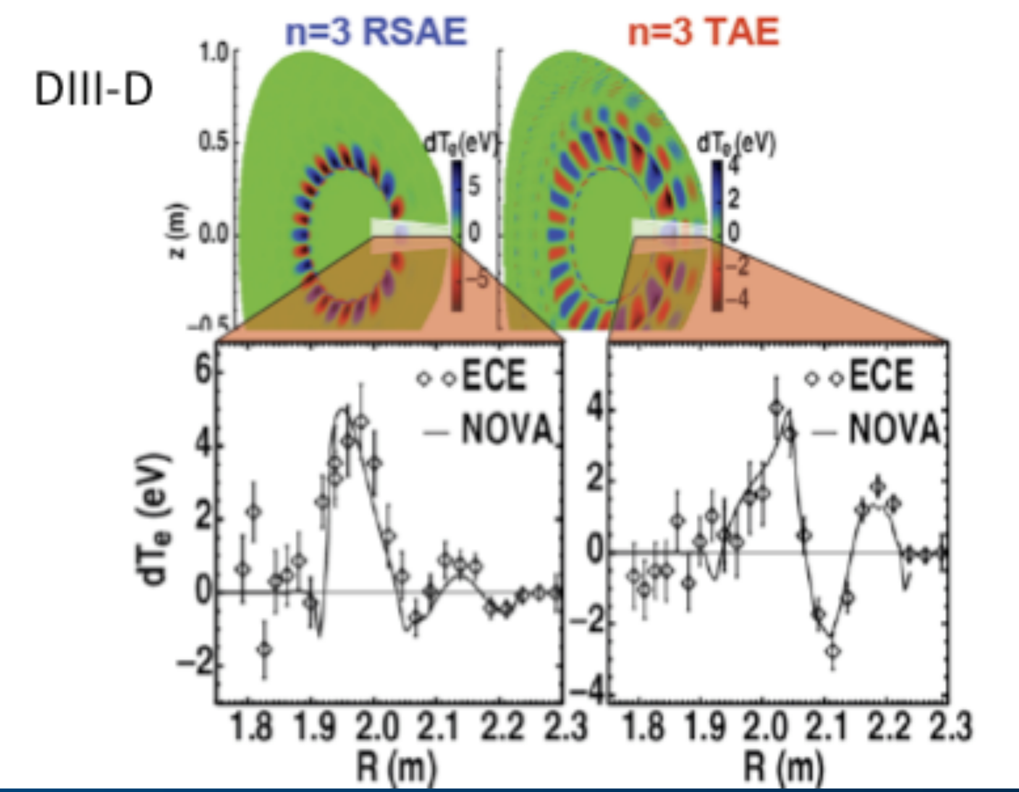
for FSP Team



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Three Out of Five Major Validation Tasks in Planning Phase have been Accomplished

1. Outreach: understand current practices in MFE and best practices in the wider scientific computing community ✔
2. Definition of the mechanisms for coordination with experimental groups ✔
3. Establishment of the requirements for data management and documentation ✔

In progress

1. Development of a best practices guide: including role of dedicated analysts
2. Gap analysis: identify critical missing elements, a strategy and resources to fill these gaps

➔ Proceed to development of validation plan for each science driver

Validation Best Practices Document Completed, Available on Validation Team Wiki

- **A detailed validation best practices document has been assembled to help guide FSP validation activities**

- **Key topics covered:**
  - Validation Workflow
  - Validation Metric Development
  - Defining the Roles and Responsibilities Analysts
  - Data management and documentation strategies

- **Document can be found on FSP validation team "notes" wiki (login required)**

http://www.psfc.mit.edu/FSP-Validation/index.php/Notes

Example of Best Practice: Developing a "Phenomena Identification and Ranking Table"

- **Oberkampf *et al* recommend developing "Phenomena Identification and Ranking Table" (PIRT) to efficiently prioritize validation activities in a proactive manner**

- **For the FSP, the PIRT would be a document which answers the following questions**
  1. Physical phenomena importance: What is the essential physics that must be input to, and described by, the application?
  2. Conceptual model adequacy: Are the underlying conceptual models adequate for describing the physical phenomena of interested identified in (1)?
  3. Code verification adequacy: Have the components and frameworks which represent the numerical implementation of the conceptual models identified in (2) undergone adequate verification testing?
  4. Experimental Adequacy: Is the existing experimental data adequate for desired level of model validation?
  5. Validation Metric Adequacy: What are the validation metrics to be used assessing the fidelity of the application?

Charge to FSP Integrated Planning Teams in Validation Plan Development

In support of validation, the plan should be specific on:

- The scientific issues and the regimes of validity covered by the simulation capability
- The suite of physics components (codes) to be used or developed
- Key physics for each component that should be confirmed by validation, especially areas of particular uncertainty in the underlying physical models
- Important multi-physics predictions that need to be confirmed by validation
- Key gaps in diagnostics or experimental capabilities
- The connection between near-term capabilities and outcomes
- Areas where iteration with validation would improve fidelity

Boundary Model Validation (T. Rognlien, D. Whyte): Physics, Measurements, and Gaps for Plasma/Neutral/Radiation

Issue	Critical physics	Measurements needed	Gaps
Cross-field plasma transp.	• Micro-turbulence/blobs • Meso-turbulence/ELMs • Coll. & turb. transport • Role of magnetic topology/ shear, X-point and wall/ divertor contact	• Time-average plasma profs/flows • Time-resolved fluctuation/ phase • Turb. mapped along B to wall	• T_i profiles • T_e, B fluct. • 2D coverage • Synth. diag. • Correlation along **B** • Kinetic data
Impurity gen. & transport	• Impurity (wall, volume) sources • Collision/turbulent transport including flows • Electron energy loss • Impurity sinks	• Location/properties of impurity sources • Impurity profiles/fluxes with charge-states • SOL impurity flows	• 2-3D profiles • Local sputtering coeff. • Temporal data • Atomic data • Hot wall data

Boundary Model Validation: Physics, Measurements, and Gaps for Wall Loads & Response

Issue	Critical physics	Measurements needed	Gaps
Heat & particle loads	• Surface fluxes from integrated plasma, atomic phys., neutrals, currents • Fueling, recycling, retention • Sheath physics • Radiation transport • Private-flux region transport	• Local profiles of plasma, fluctuations, neutrals, flows • Radiated power with spectral resolution • Temporal surface temp. • In situ fuel retention vs depth, temp. in material •Tile currents, B_{pol}	• 2-3 D profiles • Local recycling coeff. • Temporal data • Atomic data • Synth. Diag. • Kinetic data
Material surface evolution	• Plasma surface interaction & resulting evolution • Surface chemistry • Effect of coatings • Dust generation	• Net erosion/deposition rates • Off-line material analysis (all scales) • In situ analysis of surface stoichiometry, morphology, and dust	• In-situ diagnostics • Steady-state wall conditions • Hot wall conditions

Boundary Model Validation: Physics, Measurements, and Gaps for Interactions with RF

Issue	Critical physics	Measurements needed	Gaps
Effect of RF fields	• Properties of RF sheaths • Impurity generation • Power coupled to SOL & resulting modification • Impact of material launching structures	• RF sheath potentials • Ion/electron distribution functions • Impurity generation • Local T_e, n_e, & ioniz. rates in SOL • Characterization of launching structure surfaces	• 2-3 D plasma & field profiles • Plasma/field data in strong interaction zones • Kinetic data • Correlation along **B**

Pedestal Model Validation (P. Snyder, R. Maingi): Pedestal Evolution and Structure

General Approach:

- Envision phased development of increasingly sophisticated physics models
- Validation activities will begin on each model as it reaches some minimum level of maturity

	Critical Physics	Measurements Needed	Important Gaps
Pedestal Evolution and Structure	- Micro/meso stability - Quasi-linear and neoclassical transport - Nonlinear turbulent transport - Particle and energy sources	- Pedestal profiles as above - Pedestal fluctuations as above	- Fully resolved transient measurements - Other gaps as above - Synthetic diagnostics

Pedestal Model Validation : Transition Physics

	Critical Physics	Measurements Needed	Important Gaps
Transition Physics	- L-mode turbulence and transport - Turbulence suppression mechanisms - Feedback loops	- Edge profiles for ne, Te, Ti, Er, J(r) - Edge fluctuations for ne, Te, ϕ, B including amplitude, phase, cross-coherence - Near SOL profiles of ne, Te, Ti, perp. and parallel flows - Near SOL fluctuations for ne, Te, phi, B including amplitude, phase, cross-coherence	- J(r), magnetic shear - Resolution - 2D coverage - Non-Maxwellian ion temperatures - , Edge fluctuations for quantities other than n_e - Wave-number range and resolution - Synthetic diagnostics

Pedestal Model Validation : Steady-State Transport within Barrier

	Critical Physics	Measurements Needed	Important Gaps
Steady-State Transport within Barrier	- Quasi-linear and neoclassical transport - Nonlinear turbulence and transport - Sources and sinks - Neutral and atomic physics	- Pedestal profiles as above - Pedestal fluctuations as above - Neutral profiles - Impurity profiles	- J(r), magnetic shear - Resolution - 2D coverage - Pedestal fluctuations for quantities other than n_e - Synthetic diagnostics

Pedestal Model Validation : Relaxation Mechanisms

	Critical Physics	Measurements Needed	Important Gaps
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 B fields	- Fast evolution of profiles - Pedestal fluctuations for ne, Te, ϕ, B over wide range of frequencies and wave-numbers	- Fully time resolved transient measurements - 2D and 3D coverage - Synthetic diagnostics

Core Profile Validation Strategy (W. Nevins, S. Kaye): Summary

- **Key conceptual gap is developing a rigorous and computationally tractable framework for integrating MHD3D equilibrium effects with microturbulence**
  - Secondary challenge is MHD simulations with realistic resistivity for current high power or future burning plasma conditions

- **Strategy in "early" (first 10 years) focuses on parallel MHD-quiescent and MHD-dominated plasmas, with turbulence + MHD integration as long-time goal**
  - (3-5 years) slowly evolving, MHD quiescent plasmas, focusing on issues such as density peaking and intrinsic rotation
  - (5-10 years) rapidly evolving plasmas: internal transport barrier formation, core profiles changes in response to L-H transition. Possible integration with Alfven waves and fast particle transport
  - (> 10 years) self-consistent prediction of NTM formation and saturation in presence of microturbulence, simulation of full sawtooth cycle

Core Profiles Validation: Physics, Measurements, and Gaps for Transport in MHD-quiescent plasmas

(Non)locality of turbulence: key critical physics question to be addressed in both slowly and quickly evolving scenarios via comparisons of local and nonlocal models

Issues	Critical physics	Measurements Needed	Gaps
• electron transport • density peaking • intrinsic rotation • finite-β effects • EP-microturbulence interactions	• neoclassical transport • microturbulence • self-consistent coupling of both to equilibrium, sources, and EP	• magnetic equilibrium • profiles (n, T_i, T_e, V_{tor}) • fluctuations: δn (multiscale), δT_i, δT_e(multiscale), $\delta V_{\|\|}$, δE, δB • EP distribution in (x,v) • thermal neutrals?	• δTi (D & C) • high-*k* δT_e • $\delta V_{\|\|}$ • δE (HIBP only) • δB • neutrals
• ITB formation and hysteresis • heat pulse propagation • core response to L-H transition	?? (beyond above set)	• equilibrium profiles with high time resolution (to separate equilibrium from turbulence response)	• possibility of need for new transport formalism with faster equilibrium evolution

Core Profiles Validation: Physics, Measurements, and Gaps for Transport in 3D magnetic fields

Issues	Critical physics	Measurements Needed	Gaps
• error/external coil field effects on transport • evolution of profiles in presence of microturbulence, Alfven waves, and EP • saturation of NTM in presence of microturbulence (including feedback stabilization via ECH) • role of flow dynamics in MHD instabilities • sawtooth cycle (including heat pulse dynamics)	self-consistent & tractable model for coupling neoclassical, microturbulence, and MHD to 3D equilibirum + sources	full profile and fluctuation suite as for MHD-quiescent, plus additional magnetic diagnostics	a rigorous & tractable theory coupling MHD + turbulence

Wave-Particle Model Validation (P. Bonoli, R. Nazikian): Coupling of RF through SOL

	Critical Physics	Measurements Needed	Important Gaps
Coupling of ICRF and LHRF power through the SOL.	- Surface wave excitation - Power dissipation due to RF sheath formation. - Power dissipation due to nonlinear parametric decay instability. - Wave scattering from density fluctuations and / or blobs.	- SOL profiles for ambient ne, Te, and Ti - 2-D fluctuations (in R,z) for ne in the SOL. - Imaging of "hot spots" - B-dot probe measurements for surface wave detection.	- 2-D SOL profile information generally not available out to the vessel wall (or well beyond antenna strap). - Complete coupled edge-to-core simulation models not yet available to validate.

Wave-Particle Model Validation: Absorption of RF on Energetic Ions

	Critical Physics	Measurements Needed	Important Gaps
Absorption of ICRF power on energetic ions	- Importance of finite ion orbit width effects. - Effect of energetic ions on MHD stability of sawteeth, NTM's, etc. -	- Fast ion detection by FIDA or NPA diagnostics. - Other fast ion loss detectors ?	- Comparison between simulated and measured EP diagnostics (FIDA and NPA) still in its infancy (metrics, etc not well-established). - Energetic particle beta not yet included self-consistently in MHD equations, so that simulating EP stabilization still not possible without using reduced model (Porcelli model).

Wave-Particle Model Validation: Generation of Non-Thermal Electron Tails

	Critical Physics	Measurements Needed	Important Gaps
Generation of non-thermal electron tails by LHRF power	- Spatial diffusion of fast electrons. - Effect of energetic electron tail on sawteeth and NTM's	- Hard x-ray emissivity measurements (horizontally and vertically viewing). - Motional Stark Effect measurements of non-inductively driven currents.	- Complete coupled core to edge simulation models are not yet available to validate. - Better spatially and temporally resolved profiles of LHRF current density and hard x-ray emissivity are still needed.

Energetic Particle Model Validation: Mode Existence and Structure

	Critical Physics	Measurements Needed	Important Gaps
Mode Existence & Structure	- Role of thermal ions and acoustic coupling to shear Alfven wave - Nonperturbative effects of energetic particles on mode properties - Role of Kinetic Alfven Wave coupling on mode structure	- Profiles for ne, Te, Ti, Er, Z, J(r) - 2-D fluctuations (in R,z) for ne, Te, Ti - mode polarization: B_pol, B_tor, B_parallel, on toroidal, poloidal arrays - interferometry (radial, midplane, vertical) for global survey of MHD activity.	- 2-D internal ne, Ti not available. BES has the capability. - Mode polarization (B) not routinely measured. Key for mode identification.

Energetic Particle Model Validation: Linear Drive & Damping; Non-linear Saturation, Transport, particle Loss

	Critical Physics	Measurements Needed	Important Gaps
Linear Drive and Damping	- Coupling to Kinetic Alfven Waves - Continuum interception - Fast Ion pressure/energy distribution/isotropy	- All the above, plus - High radial resolution of density/temperature - Collective scattering, FIDA, …	- No method has yet shown to resolve KAWs
Non linear saturation, transport, particle loss	- Sources and sinks of energetic particles, effective collision rate - Resonance overlap - Particle trapping frequency	- All the above, plus - Fast scintillator detectors, multi-channel NPAs, …	Identification in progress

Disruption Model Validation (S. Kruger, J. Menard): Summary

- **Develop experimental database of disruptions organized by each type of disruption:**
  VDE, Fast MHD, slow MHD, disruption mitigation
  - Database needs to include control cases to adequately test the models
  - Experimental matching of cause of disruption to systematic understanding of consequences needs to improved
- **Overall goals:**
  - Test the extent to which we can predict disruption via WDM modeling. This should be done as a statistical measure rather than an expectation of 100% certainty
  - Understand ways of using feedback control to eliminate disruptions, especially those caused by slow MHD events
  - Have validated predictions for the consequences of disruptions: runaway electrons, effects on material walls, structures
  - Improve the use of disruption mitigation to ameliorate the consequences of disruptions

Disruption Model Validation: Fast MHD-Induced Disruptions

Issue	Critical Physics	Measurements Needed	Important Gaps
Fast MHD-induced disruptions (VDEs, ideal MHD)	-Stability of low-n modes -Non-linear VDE evolution -Uncertainty quantification of stability boundaries -Control of actuators for stable equilibria access -Thermal effects on walls including ablation, dust generation, … -Magnetic interactions with walls and subsequent evolution	•Fast measurements for mode structure identification & growth rate •Measurements for high quality equilibrium reconstruction •High-frequency plasma measurements near the wall as plasma scrapes off the wall •Identification of signatures of near-stability regimes •Measurements of heat and particle flux on walls (in situ measurements, IR measurements, …)	•Robust free-boundary equilibrium codes •Feedback control techniques have yet to be tested in a wide range of plasma conditions •Modeling of 3D effects of conducting structures and halo currents •Detailed physics models of PMI during disruptions •Development of reduced models for WDM analysis •Synthetic diagnostics for aid in determining experimental signatures of precursors •Modeling of controllability •Time-dependent measurements

Disruption Model Validation: Mitigation

Issue	Critical Physics	Measurements Needed	Important Gaps
Disruption mitigation (separate issues specific to this issue)	-Delivery of impurities into the impurities and their subsequent transport	•Detailed spectroscopy of impurity transport	•`Modeling of impurity injection systems •Impurity/radiation/ neutral transport •Synthetic diagnostics for aid in determining experimental signatures of precursors

Disruption Model Validation: Runaway Electron Dynamics

Issue	Critical Physics	Measurements Needed	Important Gaps
Runaway electron formation threshold and relativistic electron confinement	-Thermal energy and particle transport and RE formation during thermal quench -Role of velocity space instabilities driven by fast electrons in transport -RE confinement transport during current quench -Nonlinear evolution of magnetic topology when RE current is significant fraction of total	•Explore effects of 3D fields, MGI, pellets, etc. •Fast electron velocity measurements in configuration space •Parallel electric field measurements •Fluctuations during RE generation •3D magnetic field measurements and equilibrium reconstruction (?) •Fast electron interactions with first wall •EM forces on plasma fall	•`Ability to obtain plasma data approaching and during the quench phase •Rigorous models for self-consistent RE and plasma descriptions •Validation of reduced models •Correlation of RE deconfinement and 3D magnetic structure •Synthetic diagnostics for aid in determining experimental signatures of precursors •Modeling of controllability

Disruption Model Validation: Tearing Mode-Induced Disruption

Issue	Critical Physics	Measurements Needed	Important Gaps
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	•Highly localized diagnostics near the tearing layer during onset. •Measurements enabling 3D equilibrium reconstruction •Rotation measurements near the tearing layer •Identification of signatures of near-stability regimes	•`Validation of 3D equilibrium reconstruction •Modeling of controllability •Measurement of plasma modification due to 3D magnetic fields •Fidelity of NTV model and 3D field induced rotation •3D magnetic field effects on particle and heat transport •Synthetic diagnostics for aid in determining experimental signatures of precursors

Disruption Model Validation: Resistive Wall Mode-Induced Disruption

Issue	Critical Physics	Measurements Needed	Important Gaps
Resistive wall mode	-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	•Measurements enabling 3D equilibrium reconstruction •Measurements of mode structure •Identification of signatures of near-stability regimes	•`Validation of 3D equilibrium reconstruction •Modeling of controllability •Measurement of plasma modification due to 3D magnetic fields •Fidelity of NTV model and 3D field induced rotation •3D magnetic field effects on particle and heat transport •Synthetic diagnostics for aid in determining experimental signatures of precursors

Whole Device Model Validation: 2.5-3D Free-Boundary Equilibrium Generation and Discharge Evolution

Issue	Critical Physics	Measurements Needed	Important Gaps
2.5-3D free boundary equilibrium generation and discharge evolution	- Model field errors, magnetic islands, applied mag. Perturbations - Diagnostic location - Evolution of plasma and machine parameters - Breakdown processes - Dist. Functions in 3D space - Self-consistent treatment of EPs from NBI, ICRF, and fusion products	- 3D arrangement of magnetic probes; preferably also MSE points - Profile measurements	- Effective flexible fast 2.5-3D eq. code - Model for internal transport barriers and momentum transport - Mag. Islands consistent with diagnostics or MHD models - Source models in non-axisymmetric equilibria

Whole Device Model Validation: Evolution of Plasma Profiles from Boundary to Core

Issue	Critical Physics	Measurements Needed	Important Gaps
Evolution of plasma profiles from boundary to core	- Coupling of validated models for microturbulence, EP modes, MHD activities and their effects on transport	- Turbulence in density, Te, Ti, B - Profiles and gradients - EP sources and dist. Functions - Precise measurements of current density profiles	- Validated component models - Model for interactions between physics models - Synthetic diagnostics - Nonlinear saturation models for EP and MHD modes - Model linking MHD activity to flux evolution

Whole Device Model Validation: Prediction, Control and Mitigation of Instabilities

Issue	Critical Physics	Measurements Needed	Important Gaps
Prediction, control, and mitigation of instabilities	- Onset, growth rate, and nonlinear saturation for sawteeth, ELMs, RWMs, TMs, NTMs - How these modes affect plasma evolution – transport and poloidal flux	- Internal mag. Field fluctuations and structures - 3D arrangement of mag. probes	- Validated component models - Model for interactions between models - Effect on profiles and equilibrium - Effect on sources

Whole Device Model Validation: Interaction of Boundary with Plasma Core

Issue	Critical Physics	Measurements Needed	Important Gaps
Interaction of boundary with plasma core	- Effect of heat/particle flux on the boundary and of the boundary on the heat/particle flux	- Profiles and dist. fcns in the pedestal and SOL - Impurity generation at wall - 2D radiation profile - Radial elec. Field and bootstrap current in boundary region	- Validated reliable component models for SOL and PSI - Validated model for density transport in boundary and core - Effects on discharge and PSI of ELM control techniques - Impurity transport

Summary of Progress in Validation Planning

Good progress

- The scientific issues and the regimes of validity covered by (present) simulation capability
- The connection between near-term capabilities and outcomes
- The suite of physics components (codes) to be used or developed
- Key physics for each component that should be confirmed by validation, especially areas of particular uncertainty in the underlying physical models

Still work to be done

- **Important multi-physics predictions that need to be confirmed by validation**
- **Key gaps in diagnostics or experimental capabilities**
- **Areas where iteration with validation would improve fidelity**