Advanced plasma diagnostics for validation in high-performance toroidal confinement experiments

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Predicting the performance of existing and future devices, including ITER and beyond, is of central importance to the development of magnetic fusion energy. The process[1] of systematically performing experiments in high-performance magnetic confinement devices, exploiting advanced diagnostics, and making detailed comparisons with state-of-the-art models and simulations has become known as "validation". There is a great deal of work on validation being done presently, and within a ten-year strategic plan for fusion, investment in validation and *validation infrastructure* should be increased. By *validation infrastructure* we mean a coordinated investment in hardware/diagnostics, theory/simulation and manpower needed to validate predictive models for tokamak performance. Validation infrastructure is more than investment in hardware and codes; it involves establishing resources at labs and universities to better allow scientists to cut across traditional group boundaries, e.g. coordinating seamlessly between simulation vs. theory vs. experiment. Opportunities exist for universities via PhD training on validation projects, which challenge and excite students, to make connections between experiment and theory.

We present in this talk an argument for the highest priority areas where validation efforts are needed to prepare for DEMO, including open physics questions that must be answered before a tokamak-based DEMO is deemed feasible. We present a prioritization of the required advanced plasma diagnostics[5] necessary to close the top priority gaps and present guidance on how to build a validation infrastructure that includes hardware/diagnostics and theory/modeling/simulation by leveraging an enhanced role of universities and student participation at major US fusion facilities. We estimate the anticipated costs[6] of such efforts, and provide mapping into the proposed FES funding structure.

Assuming success at ITER, there remain major gaps in plasma physics understanding and in the engineering and technology needed to build DEMO. Open physics questions that must be answered before DEMO are summarized within the fifteen gaps[2] identified by the 2007 FESAC report. Three of the most important gaps are G-9, G-5, and G-7[3], which cover the areas plasma-wall interactions and plasma facing components, avoidance/detection/mitigation of disruptions, and an integrated understanding of RF launching structures/RF physics/wave coupling for current drive, respectively. If no suitable answers to physics questions within these gaps are identified, then fusion energy production with the tokamak concept *may not be feasible*[4]. Closing these gaps in the next ten years can be done using existing and proposed US tokamak facilities, contingent upon investment in expanded validation infrastructure.

Expanded validation infrastructure means a strong and ramped-up investment in new, advanced diagnostics and modeling/theory efforts in boundary physics, disruption physics, and RF physics. This white paper will cover what diagnostics and modeling are needed to predict boundary conditions dictated by plasma wall interactions and plasma facing components (which requires knowledge of both plasma physics and material science). In addition, the kind of measurements needed to diagnose and interpret small, rapid changes in plasma parameters that precede disruptions will be discussed. Concepts for how best to diagnose / assess new RF heating and RF current drive techniques, including new options for antenna designs and antenna placement, will be presented.

The talk will limit discussion to tokamaks, because ITER is a tokamak and at the present time, DEMO and FNSF are envisioned as tokamaks. The reason to limit the discussion to US facilities is that validation is an area where the US can take a world-leadership role, hence a targeted investment strategy is crucial to keep costs as low as possible. Brief commentary on validation at international tokamaks, and discussion of complementary roles of test-stands vs. holistic devices validation activities, are presented.

References and Footnotes:

1. See for example S. Schlesinger, Simualtion 32 (1979) and as defined by Paul Terry et al in Phys. Plasmas 16, 062503, (2008): "Validation is the process by which it is determined that the mathematical model faithfully represents stipulated physical processes, again within prescribed limits."

2. See the 2007 FESAC Gap report, Section 4.d. pages 188-193. "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy". A Report to the Fusion Energy Sciences Advisory Committee 2007.

3. Addressing Gaps G-9, G-5 and G-7 in the next ten years involves a strong and ramped-up investment in new, advanced diagnostics and modeling/theory efforts in these areas. Note that from the 2007 FESAC report, G-1 "Sufficient understanding of all areas of the underlying plasma physics to predict the performance and optimize the design and operation of future devices", which encompasses the efforts needed to address G-9, G-5 and G-7.

> G-9 "Sufficient understanding of plasma-wall interactions to predict the environment for and behavior of plasma facing and other internal components for Demo conditions."
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> G-5 "Ability to predict and avoid or detect and mitigate off-normal events that could challenge the integrity of fusion devices."
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> G-7 "Integrated understanding of RF launching structures and wave coupling for scenarios suitable for Demo and compatible with the nuclear and plasma environment."

4. If we do not identify viable solutions to the plasma wall, PFC, boundary and divertor problems, then we cannot proceed to develop high-performance core plasma scenarios (like H-mode or I-mode) using validated models. If we do not solve the problem of predicting and mitigating disruptions be developing validated models, then the tokamak is not a feasible path. If we do not develop viable methods of current drive via validated models for antenna design, location, plasma interactions then a steady-state tokamak reactor is not feasible. These three Gaps, G-9, G-5, G-7, encompass seven of the fourteen priority issues that must be addressed in existing large-scale tokamaks before FNSF will be designed and built: Plasma facing Components (#1), Materials (#2), Off-Normal Events (#3), Plasma Wall Interactions (#5), Theory and Predictive Modeling (#8), Measurement (#9) and RF Launchers and other internal components (#10). We note that there are other priority issues that could be addressed in test-stands or will be addressed by FNSF and ITER ahead of DEMO.

5. Advanced plasma diagnostics are those that are to be deployed at existing or proposed major tokamak facilities (e.g. facilities like Alcator C-Mod, DIII-D, and NSTX-U). Diagnostics at test-stands or other types of plasma facilities (which need not be tokamaks, or even confinement experiments) are not covered in this talk.

6. Presentation at FESAC, by E. Synakowski, Assoc Director, FES. April 10, 2014, http://fire.pppl.gov/FESAC_Strategic_Charge_041814.pdf