White Paper: Fusion Simulation Program (FSP)

(July 26, 2012) – W. M. Tang (Princeton University, Plasma Physics Laboratory)

In view of the current ITER fiscal issues, it is particularly important to highlight validated simulation and modeling capabilities, enabled by modern high-performance computing, as key to mitigating costs by: (i) designing optimized scenarios and providing possible *in situ* guidance for the long pulse ITER experiments; (ii) efficient harvesting and dissemination of results from ITER; and (iii) risk mitigation by rapid proto-typing and exploring alternative designs and approaches. In particular, projections for plasma performance in the international burning plasma ITER experiment have been based on simplified computational models. However, reliable operation and efficient experimentation will demand careful planning based on more accurate modeling of the integrated physics in ITER as our knowledge continues to significantly improve. Compared to existing experiments, ITER represents a significant extrapolation in the duration/pulse length of each shot/discharge and in the energy exhausted to the periphery of the system. Since each shot is expected to cost over $1M, a strong well-planned simulation effort is needed to help optimize operation and data collection and analysis.

The mission of the Fusion Simulation Program (FSP) is to develop, validate, and apply state-of-the-art simulation models to address key scientific questions with urgent practical impact on the development of magnetically-confined plasmas as a clean and sustainable source of energy. Building the scientific foundations needed to do so requires the timely and cost-effective development of an integrated high-physics-fidelity predictive simulation capability for fusion reactors – from the core plasma to the associated engineering systems. The FSP will initially focus on producing: (i) validated comprehensive models of the plasma boundary and the interactions of the plasma with the surrounding wall – which will naturally complement new fusion materials science studies; and (ii) whole device models for the analysis, planning, and optimization of discharge scenarios *that are capable of avoiding disruptions* -- the large-scale macroscopic events leading to rapid termination of plasma discharges. Since the consequences of disruptions will be severe for ITER and reactor-scale devices, reliable prediction of high-performance plasma evolution and the margin for avoiding disruptions will be an indispensable part of discharge planning. Moreover, improved understanding will be needed to design operating scenarios capable of mitigating the impact of those disruptions that cannot be completely avoided. Overall, the nonlinear interaction of the plasma with control actuators are too complex to effectively investigate by empirical methods alone. Thus, modeling to guide exploration has proven to be an essential and successful strategy which promises to be greatly enhanced in an FSP activity that will feature a strong coupling to experimental validation. This is an aspect that distinguishes it from previous national and international efforts – a focused goal demanding close collaborations to validate the new codes against data from national and international magnetic fusion facilities. A successful FSP will enhance the return on investments in fusion experiments in general and help ensure the success of ITER by enabling the harvesting of scientific insights from a sustained burning plasma experiment. This in turn can enable discovery of new modes of operation with possible extensions of performance enhancements and improvements needed for possible future burning plasmas systems, such as FNSF and DEMO.

As the FSP demonstrates success, the effort can evolve and grow, enabling additional integration opportunities to be addressed, including (i) producing profile information in the plasma core region needed to optimize operational limits; and (ii) acquiring new insights into the interactions between energetic particles and electromagnetic waves that influence the efficacy of auxiliary heating of the plasma and the fast-particle confinement of fusion products. The FSP plans to collaborate strongly with the FES base Theory Program to carry out the basic research needed to provide the foundations for realistic integrated modeling and with DoE's Scientific Discovery through Advanced Computing (SciDAC) program. Possible associated alliance with DoE's Office of Advanced Scientific Computing Research (ASCR) would help ensure that modern applied mathematics & computer science technologies be ready for deployment with rapid sharing of new tools and approaches between applications – an advantageous aspect that would be featured in what promises to be a world-leading nationally coordinated program. In this regard, it is important to highlight the enthusiasm and interest received from the Applied Math and Computer Sciences communities at the FSP workshops – a fact that is highlighted in the FSP Plan as well as the workshop summaries described on the national FSP web-site [http://www.pppl.gov/fsp]. To enable greater scientific productivity through the delivery of more realistic robust codes, the FSP will include a coordinated national staff dedicated for software infrastructure, developer support, production computing, and user support - instead of the current practice of diffuse development and support of individual applications. The FSP will develop (i) high physics fidelity through the application of modern validation, verification and uncertainty quantification; (ii) efficient integration of the best physics components with common interfaces & data structures guided by an appropriate set of standards; and (iii) production of FSP-standardized, well-documented tool sets for data preparation, code input validation, data analysis, and visualization; and (iv) deployment of FSP tools in the research and engineering design communities. Moreover, a forward-looking FSP feature is the emphasis placed on the training of a new generation of "analysts" with a breadth of multi-disciplinary skills, which will involve strong university participation.

Over the past decade, the development and initiation of the FSP has been strongly supported by numerous major community workshops and strongly endorsed by FESAC and ASCAC panels. The problems now targeted by the FSP are entirely consistent with key priorities articulated by the ITER organization (IO), the FES community Research Needs Workshop (ReNeW) document, and the recent FESAC reports on international collaboration opportunities (e.g., in Asia with long pulse experimental capabilities not available in US facilities). A two-year DoE-funded FSP planning effort has produced a program plan in 2011 posted on the national FSP web-site and was achieved with strong community engagement via numerous national workshops and individual site visits to laboratories, universities, and industries. This major effort involved 6 national laboratories, 9 universities, and 2 companies that followed a set of prioritization criteria which included: (i) a clear need for multi-scale, multi-physics integration; (ii) importance and urgency; (iii) readiness and tractability; and (iv) opportunity to open up new lines of research and producing new insights/potential breakthroughs inaccessible by other means. Overall, the FSP will embody our state of knowledge in a suite of advanced codes under a unified framework and made widely available to the FES community. The funding needed to successfully launch the FSP is currently estimated to be ~ $12M/year – ramping up as the work-scope expands over the course of 5 years to a $22M/year effort. Details together with specific deliverables and timelines are specified in an Execution Plan posted on the national FSP web-site. Such an investment would deliver a cost-effective world-leading U.S. capability with focus on research that supports burning plasma science and addresses critical challenges for long-pulse/steady-state advanced tokamak operation. As such, the FSP should be among the highest priorities within the elements of the non-ITER part of the magnetic fusion portion of the FES program in virtually any budget scenario. It is relevant to recall here the US Senate Appropriations Subcommittee 2012 Report: (*page 97, Sept. 2012*): "The Committee encourages the fusion energy program take advantage of high performance computing to address scientific and technical challenges on the path to fusion energy. <u>The Committee supports the Fusion Simulation Program to provide experimentally validated predictive simulation capabilities that are critical for ITER and other current and planned toroidal fusion devices</u>. *Given current and future budget constraints, the Committee views this initiative as critical to maintain U.S. world leadership in fusion energy in a cost-effective manner."*

In closing, the distinguished FSP Program Advisory Committee (FSP PAC)* in their Report on May 8, 2011 strongly endorsed both the "concept and the potential of the FSP," and judged that "the FSP will:

(1) enable *significant advances in fusion science*;

(2) substantially *increase the value of ITER to the US*;

(3) make major contributions to build the *knowledge base required for DEMO*;

(4) provides one of the few opportunities available for the US to provide *recognized leadership in the international fusion science community*, and

(5) *provides the most credible path forward for the integrated whole device model that will be <u>highly important for the realization of fusion energy</u>.*"

** Allen Boozer (Columbia U), Leslie Greengard (NYU-Courant), Brian Gross (NOAA's GFDL), Gregory Hammett (PPPL), Wayne Houlberg (ITER), Earl Marmar (MIT), Daniel Meiron (CalTech), Jonathan Menard (PPPL), Michael Norman (UCSD), <u>Douglass Post, Chair</u> (DoD HPC Modernization Program), Rick Stevens (ANL & U.Chicago), Carl Sovinec (U.Wisconsin), Tony Taylor (GA), and James Van Dam (U.Texas, IFS).*