Key Priorities for the U.S. Program in Support of ITER

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"The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science. The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research." - *2002 Fusion Summer Study Report*

In 2003, the U.S. fusion research community committed to the ITER project, seeking to leverage a modest U.S. investment to gain access to a highly capable, burning plasma device. ITER is a critical element in the U.S. Magnetic Fusion Energy (MFE) strategy. Most fundamentally it will validate tokamak physics at the reactor scale and in burning plasma conditions, providing vital understanding for future steps along the path to fusion energy. Secondly it provides a unique opportunity for the US to develop leading expertise in areas critical to the success of fusion. To capitalize on these benefits, a vigorous U.S. research program in support of ITER is essential. This research should leverage the U.S.'s unique capabilities in resolving remaining design issues and addressing physics challenges that are crucial to ITER's success. In addition, we must establish the experience and expertise necessary to play leading roles in ITER operation and to prepare the U.S. to obtain the full benefit of the knowledge gained from ITER.

The time is now for the U.S. program to commit fully to ITER. ITER construction has started, and the realization of ITER plasmas is less than a decade away. To be best prepared for this eventuality, the U.S. program should focus on three major goals: 1) ensure that ITER achieves its objective of Q=10 for 300 s; 2) establish the physics basis for extending the technical reach of ITER; and 3) prepare a workforce capable of efficiently exploiting ITER in resolving burning plasma physics issues of importance to fusion energy development. Each of these priorities require a significant, vibrant research program that effectively utilizes the most compelling assets of the U.S program (people, facilities, measurements, theory-experiment coupling) to establish and maintain U.S. leadership into and beyond the ITER era.

Priority #1 — Ensure that ITER Achieves Its Objective of Q=10 for 300 s. The achievement of this performance goal will be a transformational event in fusion energy development, marking the transition from a scientific endeavor to fusion energy technology development. As such, this goal should be the highest priority in the U.S. program with the U.S. base research program mobilized and prioritized to ensure that this objective is secured. There are two primary activities within this priority: 1) provide the physics basis for resolving remaining design choices for ITER; and 2) develop the physics basis and qualify control capabilities that will expedite Q=10 operation within the ITER Research Plan. The first of these is time urgent (requires resolution by ~2016) and therefore should receive the highest near-term priority. While the latter does not have this level of urgency, research should begin now and continue through the beginning of ITER operations to be prepared to actively address the challenges of ITER operation when this starts.

Several design decisions, which dramatically affect ITER capabilities, still remain. Arguably, the three most critical decisions are the specification of an ITER disruption mitigation system (ITER DMS), finalizing the choice of the built-in control actuators for edge localized modes (ELMs), and the choice of divertor plasma facing material. In each of these areas, the U.S. has world-leading capabilities to provide the physics basis for adequately informing a final decision on these systems.

- *Disruption Mitigation.* Disruptions pose the single biggest risk to timely achievement of Q=10 operation in ITER. Research is urgently needed to determine the most effective technique of safely terminating high-current ITER plasmas that have reached an unrecoverable status. Such a technique must simultaneously meet the challenging demands of local thermal heat load limits, acceptable electromagnetic forces, and preventing/dissipating runaway electrons. The recent

decision by the U.S. to accept responsibility for the ITER DMS further elevates the priority of this research.

- *Edge Localized Modes.* A second risk to timely Q=10 operation in ITER arises from rapid material erosion due to uncontrolled ELMs. The U.S. is a world leader in developing the ELM-mitigation techniques being considered for use in ITER. These include the use of external actuators such as pellet injection and non-axisymmetric coils as well as operation in regimes that obtain H-mode-like performance without ELMs (e.g., QH-mode, I-mode). High priority should be placed on leveraging U.S. capabilities in this area to provide timely information on decisions affecting the choices of ELM control actuators on ITER.
- *Divertor Facing Material.* ITER is still debating the use of carbon vs tungsten as the divertor plasma-facing material. Based on experience worldwide, this choice will have a significant impact on the available operating space in ITER, potentially limiting the operating space available for physics studies. For this reason, it is critical that the U.S. continue to engage in this discussion bringing to bear its unique capability of operating on a carbon first wall.

We must also develop understanding of how to utilize ITER's tools to achieve its primary objectives. Developing the necessary control methodology and appropriate operational scenarios on existing devices will significantly accelerate the research program on ITER while minimizing loss of control and potential component damage, thus reducing overall cost and risk. Furthermore, exploration on present experiments has provided insight into new operational regimes with potential for improved performance and physics understanding on ITER. A key challenge is developing the necessary physics understanding to extrapolate from present experiments to ITER conditions.

- *Plasma Operating Scenarios.* There are a number of operational issues on ITER that can be evaluated on present devices. Present facilities have full diagnostic capabilities and control capability to develop and evaluate the fully-integrated scenarios in ITER relevant conditions and to understand the discharge evolution that is governed by transport, current drive, and stability.
- *Control.* The U.S. program is a world-leader in developing and implementing plasma control for tokamaks worldwide, and is already playing a leading role in specifying the approach for ITER. Key U.S. capabilities include versatile digital control systems, control simulation capability, actuators for instability control, 3D field control, and the ability to simulate burn control.

Priority #2 — Establish the Physics Basis for Extending the Technical Reach of ITER. Research opportunities and the future progress of the U.S. fusion program would be enhanced significantly if methods can be developed that expand the performance envelope of ITER. Priority should be placed within the U.S. program on developing and qualifying regimes consistent with ITER constraints that could potentially provide significant advances in the performance capabilities of ITER. At a minimum, these advances will expand the operating space available for physics studies in ITER. In addition, such advances could significantly increase the impact of ITER operation with potential of achieving Q>10 operation (with the possibility of ignition), Q>5 steady-state operation (providing a basis for DEMO), and Q=10 operation at lower plasma current (reduced risk to device).

It is critical that this development be done with ITER operating conditions in mind (e.g., strong electron heating, low levels of applied neutral beam torque, low collisionality). The U.S. fusion program is the world leader in scenario research, enabled by highly capable devices with sufficient flexibility to mimic the heating and current drive systems of ITER. These capabilities uniquely position the U.S. program for providing a compelling basis for enhanced operation in ITER. Increasing the confidence that such scenarios can be realized in ITER will also require advances in both the basic understanding of fusion plasmas in the burning plasma regime (e.g., transport in electron dominated regimes, stability at modest rotation) and the control of phenomena important to performance (e.g., instability control, ExB shear).

Priority #3 — Prepare a Workforce Capable of Efficiently Exploiting ITER. The influence that the U.S. program can exert on the ITER Research Plan and ultimately the knowledge gained from ITER for future fusion energy development will be determined by the quality of research staff that the U.S. delivers for ITER operations. These scientists will be tasked with confronting a new set of physics challenges that are beyond the reach of present-day devices.

Training a new generation of scientists with the experience and expertise needed to impact the ITER scientific program, requires a compelling U.S. program with high priority on (1) facilities that can address ITER-relevant plasma conditions, (2) extensive measurement systems capable of elucidating key physics phenomena, (3) and strong coupling between theory and experiment to validate physics-based models. Such a program will prepare the U.S. to play a significant role in ITER and prepare the U.S. to gain full benefit from the knowledge gained in ITER and move forward in the development path for fusion energy.

There are a number of areas important to the science of burning plasmas (ITER) and fusion energy, where the U.S. program has demonstrated leadership and could have a significant impact on ITER. These include:

- Energetic particle physics,
- Developing operational scenarios in ITER relevant conditions,
- Developing the physics basis for steady-state tokamak operation,
- ELM control and ELM-free operational regimes,
- Robust plasma control,
- Plasma termination; disruption control, mitigation techniques, runaway electron control.

To conclude, ITER represents the centerpiece of the U.S. program: its success is critical to U.S. strategic interests in magnetic fusion research. The highest priority of the U.S. domestic magnetic fusion energy program should be to conduct research to ensure ITER's success, to prepare a well-trained staff that will provide scientific leadership for ITER, and to position the U.S. to gain maximum benefit from the knowledge gained from ITER.