Positioning the U.S. to Play a Leading Role in and Benefit from a Successful ITER Research Program

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At its Snowmass Fusion Summer Study in 2002, the US Fusion Energy Science (FES) community reached a consensus that "*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… ITER offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations for long durations with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology*." In the ensuing 12 years, nothing has occurred that contradicts these statements. In fact, several Fusion Energy Sciences Advisory Committee (FESAC) panels have reiterated this position.

Much has happened since we reached that consensus. The ITER Organization (IO) was formed, representing over half of the world population, including the United States. A site was chosen, near Cadarache, France. The overall design was finalized. Construction is underway of a device that we believe is capable of meeting ITER's specific technical objectives to achieve fusion gain $Q \geq 10$ for hundreds of seconds, and $Q \geq 5$ for thousands of seconds in a steady-state operating scenario, as well as a more general objective of providing a unique laboratory to study the physics and technology of burning plasmas.

There is some frustration within the FES community and in government regarding the cost and pacing of this construction. Other than stating that the vast majority of the issues in this area are non-technical in nature, addressing this is beyond the scope of this white paper.

In recognition of the fact that ITER is moving ahead, the FESAC Strategic Priorities Panel was instructed to assume participation in ITER. However, it is not good enough for ITER to *just happen*. We want to make sure ITER is a success in that (a) ITER meets its technical objectives, and (b) its results inform and benefit US efforts toward the eventual construction and operation of a demonstration power plant.

This implies the need for effort in three broad areas. First, continuing support is needed for ongoing ITER design decisions. Examples include hardware and techniques for controlling the repetitive heat pulses from Edge Located Modes (ELMs), the disruption mitigation system, and mass-limit definition for ferromagnetic materials contained in the test blanket modules. Second, we must be preparing for leading roles in the ITER research program. This includes addressing technical issues, such as qualification of operating scenarios, and non-technical issues, such as the preparation of a talented and effective US research team. Third, the US must be positioned to benefit from the output of the ITER research program. This includes maintaining a healthy domestic research program, specifically, one that addresses issues that are complementary and distinct from those emphasized in ITER. These areas will include a continued emphasis on confinement physics, but additional and increased emphases on materials, fusion nuclear science, and technology.

The US is already a clear leader in many of the areas critical for the success of ITER, and is currently well positioned to be influential throughout the research program, even given the relatively small contribution (approx. 9%, which is the same as all of the ITER partners with the exception of Europe) we are making toward construction. In this white paper, we describe in more detail some of the US efforts that are assuring and will assure ITER's success both in absolute terms and for a future US program moving toward fusion as an energy source.

The objective of this white paper is to endorse efforts that are currently being given high priority in our tokamak research programs utilizing the C-Mod, DIII-D, and NSTX-U devices. These tokamaks, with a total replacement value well in excess of $1B (money that has already been spent), are important assets that have world leading capabilities in their abilities to simulate many features of burning plasmas, and each of these devices is among the most well diagnosed fusion experiments in the world, consistent with our emphasis on developing a scientific basis for extrapolation to future devices such as ITER. Successful preparation for ITER will require that significant run time continue to be available.

Since we are not proposing new investments, we are submitting only this single white paper concentrating on status and priorities. However, we note that all three major US devices have proposed ambitious upgrade programs. Many of these upgrades will improve the fidelity with which we can perform experimental simulations of burning plasma conditions, and we believe they should be supported.

1. Efforts needed to support a successful ITER research program

The US is participating and, in many ways, leading (denoted by check marks) in many areas where work is needed to support the success of ITER.

1.1. Inform ITER design decisions

The ITER design is sufficiently advanced that construction is underway, but there are technical issues that must be addressed to reduce risk and accelerate experimental programs when ITER is operational.

√ *Develop and qualify disruption prediction, avoidance, and mitigation techniques.*
The US is responsible for building ITER's Disruption Mitigation System (DMS), but the ITER Organization is responsible for the design and technology selection. That having been said, DIII-D and C-Mod have been the most active tokamaks in the world in carrying out relevant research. DIII-D, in particular, is the only tokamak that has implemented both of the leading technologies anticipated for deployment in ITER's DMS: massive gas and shattered pellet injection. C-Mod, with multiple MGI valves and diagnostic arrays, has pioneered the study of local asymmetries in radiation. JET's routine use of its DMS to protect its "ITER-like wall" is providing an invaluable database. However, the fragility of that wall limits their ability to carry out dedicated disruption mitigation experiments. The US has also taken a lead in disruption prediction and avoidance, although this is currently at an earlier level of development. In particular, work on NSTX and NSTX-U is providing a basis for a sophisticated empirical prediction system.

√ *Prepare a physics basis for ELM control and ELM-free operating scenarios that can be extrapolated to ITER.*
ELMs cause repetitive heat pulses to plasma facing surfaces that can potentially cause significant damage. The US has been a pioneer in developing techniques to mitigate this danger. Resonant Magnetic Perturbation (RMP) ELM suppression was discovered and first demonstrated on DIII-D, and it provided the basis for ITER's In-Vessel Coil system. Pellet pacing of ELMs was developed first on ASDEX-U, but recent work by the ORNL Team on

DIII-D has demonstrated most of the characteristics needed for ITER. Finally, C-Mod (I-mode) and DIII-D (QH-mode) have taken the lead on developing high performance operating scenarios that are naturally free of ELMs.

√ *Extend current plasma control techniques to be effective in the burning plasma environment.*
The DIII-D Plasma Control System has been implemented on many devices around the world, including NSTX-U, KSTAR, and EAST. Researchers from DIII-D, NSTX-U, and elsewhere have been working together to extend these capabilities to increasingly ITER-relevant conditions.

√ *Develop standards for acceptable error fields and techniques to measure and correct them.*
This includes efforts to measure and control error fields, which is ongoing in all three US tokamaks. Also, the DIII-D Test Blanket Module mockup is a unique tool for experimentally simulating the effect of localized magnetic perturbations as expected in ITER.

- *Qualify candidate heating and current drive upgrades for ITER steady-state scenarios.*
  LHCD in C-Mod and ECH in DIII-D provide opportunities for direct tests of the actuators planned for ITER; Off-axis NBI in DIII-D and NSTX-U provide immediate capabilities to test scenarios with copious off-axis current drive.

- *Be prepared to take up other issues as they arise during construction and planning for operation.*
  New issues continue to arise that require further study for the ITER design. As construction progresses, the issues generally become smaller, but the capabilities to address them will continue to be essential. Our facilities continue to receive frequent requests for experiments and tests – for example, several experiments were proposed and led on DIII-D and C-Mod by ITER Organization physicists during the past month.

1.2. Prepare for leading roles in a successful ITER research program

Plasmas produced in ITER will differ in important ways from those we can produce today. Improved understanding of how to extrapolate from current research will be important for reducing risk in the ITER research program.

√ *Advance the capability to simulate ITER plasmas using validated models.*
Need to simulate each condition before attempting it in ITER.

√ *Understand energetic particles and energetic particle driven instabilities.*
Today's fast ions from neutral beam heating are a proxy for alpha particles in ITER.

√ *Develop plasma-based solutions for controlling heat flux on ITER's divertor.*
Geometric variation (within constraints of ITER design) and divertor seeding for detachment.

√ *Develop and qualify ITER inductive and noninductive operating scenarios.*
Scenarios must integrate core and edge solutions including high-Z materials and without large ELMs.

- Develop techniques to understand and mitigate damage to tungsten surfaces from helium plasmas in the non-nuclear phase and helium ash in the DT phase.

1.3. Prepare the US to make use of the results of the ITER research program

- Maintain strong domestic programs in tokamak physics, materials, technology, and fusion nuclear science throughout and in parallel with ITER research program.
- The consequences of allowing the domestic program to shrink significantly in favor of ITER would be crippling to the post-ITER development of fusion as an energy source.

2. The US has world-leading assets already in place

2.1. The US suite of major tokamaks

All three major US facilities have extensive diagnostic suites and work closely with the theory and modeling community emphasizing the development of physics understanding leading to the validated models needed for ITER.

The following three tables highlight some of the capabilities of these facilities and identify planned upgrades that will support preparations for a successful ITER research program.

Table 1. The Alcator C-Mod Tokamak at MIT

Area	Present capabilities	Planned upgrades
Boundary	▪ Record heat flux with ITER B_{pol} and λ_Q ▪ Metal plasma facing components ▪ Unique scrapeoff layer and surface diagnostics	▪ Advanced tungsten divertor ▪ Extended in-situ surface analysis (AIMS)
Equilibrium and transient control	▪ MGI, runaways, asymmetries ▪ ELM-free operation with I-mode	
H&CD capabilities	▪ Unique tests at ITER B, n_e ▪ High power density ICRF ▪ Understand and mitigate high-Z sources ▪ LHCD informs ITER steady-state upgrade	▪ Second field aligned ICRF antenna ▪ New off-midplane LHCD antenna to test efficiency with higher single pass absorption
Transport, EP, Diagnostics	▪ Heat, high-Z particle and momentum flux and turbulence studies ▪ Electron-dominant heating, no core torque or fueling	▪ Extended turbulence, x-ray diagnostics ▪ Improved MSE q(r) diagnostic

Table 2. The DIII-D Tokamak at General Atomics

Area	Present capabilities	Planned upgrades
Boundary	▪ Extensive diagnostics (Divertor Thomson scattering, etc.) ▪ Geometry variation	▪ Diagnostics
Equilibrium and transient control	▪ DIII-D Plasma Control System in widespread use ▪ Disruptions - Testing both leading ITER DMS actuators, RE control, active avoidance ▪ ELM control - Qualifying both ITER techniques: RMP, pellet pacing ▪ ELM avoidance: QH-mode	▪ Heating and current drive improvements (see below) ▪ Additional 3D coils
H&CD capabilities	▪ On- and off-axis NBI; co-/counter-NBI ▪ ECH for direct electron heating and OACD ▪ ITER baseline/hybrid/SS qualification under increasingly relevant conditions	▪ Additional ECH to simulate fusion α heating and provide off-axis CD for steady-state scenarios ▪ Additional balanced NBI for torque-free heating ▪ Additional off-axis NBI for steady-state scenarios
Transport, EP, Diagnostics	▪ Too many actuators and measurements to list	▪ More in development

Table 3. The NSTX-U Spherical Tokamak at PPPL

Area	Present capabilities	Planned upgrades
Boundary	▪ Detachment threshold studies ▪ Laser blow-off for high-Z impurity transport ▪ Divertor magnetic configuration variation	▪ W divertor tiles ▪ Full metal 1st wall ▪ Divertor cryo-pump
Equilibrium and transient control	▪ Advanced disruption warning + MGI ▪ ELM pacing with granule injector, 3D fields	▪ Off-midplane 3D field coils

Area	Present capabilities	Planned upgrades
H&CD capabilities	▪ Understand fast-wave edge losses, optimize coupling and core heating ▪ High power NBI (on- and off-axis)	
Transport, EP, Diagnostics	▪ Access non-linear Alfvén Eigenmodes, vary distribution with full diagnostics + modeling ▪ Thermal, momentum, particle transport vs. beta and collisionality ▪ MSE-LIF: measure q(r) and p(r) without heating beam	▪ Electromagnetic turbulence diagnostics

2.2. The role of international collaboration in US research

These devices provide the US FES program with the assets needed to make leading contributions to the preparation for burning plasmas. It has been suggested that some US efforts could be replaced by international collaboration. However, it is important to realize that international collaborations will have the largest impact and benefit when leveraged from a position of strength provided by our domestic research program. Also, the capabilities of the foreign devices tend to be complementary rather than competitive with our own suite of tokamaks. US facilities each provide distinct and important capabilities that are unique in the world program, which is why the IO proposes so many experiments here. The US has been, and should continue to be, an effective partner.

The physics program contributing to ITER is coordinated by the International Tokamak Physics Activity (ITPA), which in turn is under the auspices of the IO. The US has been a major participant in the ITPA and its activities, with all three facilities placing high priority on ITPA joint research activities and with the US currently providing the leaders of two of the seven topical groups and one deputy. Also, the US Burning Plasma Organization (USBPO) acts as an interface between the ITPA and the US community at large.

The US is actively collaborating with EAST (China) and KSTAR (Korea). These are superconducting devices, with potentially long pulse lengths, but are somewhat less flexible and less mature than our devices. The combined capabilities of the US and Asian devices allow for joint teams of researchers to utilize the long-pulse devices and the more flexible and better diagnosed shorter pulse devices together with the aim of developing and qualifying long-pulse operating scenarios. Note that the approach here is *not* to develop a scenario in the US and export it to Asia. Rather, these collaborations benefit from being able to move in both directions.

We also collaborate actively with JET (England) and ASDEX-U (Germany). These devices have metal walls and have a long history of joint experiments with DIII-D and C-Mod. One area where international facilities may provide opportunities to extend beyond US capabilities is the upcoming DT campaign planning in JET, which will provide the world's only opportunity to study a burning (albeit at low gain) plasma prior to ITER.

2.3. Modeling and simulation

One of the hallmarks of US research is the emphasis on developing validated models for plasma behavior. The simulation and modeling needs for ITER, and burning plasma devices in general, are different than for current tokamak experiments. The safety of a burning plasma class machine requires prediction of stability limits and transport prior to running a discharge. Simulations and modeling predictions become an essential part of planning experiments. The ITER organization has recognized this need and defined an Integrated Tokamak Modeling (ITM) framework for the integration of models and sharing of data. A major effort developing integration tools in support of ITER is underway in Europe.

The US is a world leader in high-performance computing, and has developed first principles codes to predict MHD and gyrokinetic stability and transport in realistic flux surface geometry. The US has also developed state-of-the-art heating and current drive codes. There is already a focused effort in the US, and worldwide, to validate the simulation and modeling codes with experimental data at all levels of the hierarchy, from turbulence characteristics and linear stability thresholds, to plasma profile predictions. Some codes have demonstrated sufficiently accurate validation with experiment to trust the reliability of their predictions prior to experiments.

In preparation for ITER, the US Fusion program should continue to take a leadership role in developing simulation and modeling codes for their predictive capability. This capability must be employed in present experiments so that it can be refined and expanded to gradually achieve the level of confidence required to provide timely input to the ITER Research program and a robust basis for ensuring proposed scenarios do not pose risk to critical ITER components. An essential requirement for achieving integrated modeling prediction is a framework that manages the flow of data and calculation results. The framework should be designed to be useful at each stage of its development so it can be engineered based on experience. For the framework to be useful, it needs to focus on more efficient workflows for the modeling and simulation of data using existing codes. Prototype frameworks that can form the foundation of this broader initiative have already been developed in the US.

Routinely using model predictions in the planning of experiments and the analysis of data will require training and support of staff dedicated to these tasks. In order to expand the use of predictive modeling, additional modeling and analysis specialists (“analysts”) are needed to collaborate with experiments.

3. Summary

ITER will provide the first opportunity for the FES community to study a high gain burning plasma. Although the FESAC Strategic Priorities Panel has been instructed to take our participation as a given, it is important for us to step back and think about what that means. Especially given the high cost of ITER, it is critically important that we be prepared to reap the maximum benefit from this investment.

The US does not need new facilities to make ITER a success. We have already made cumulative investments in excess of $1B on DIII-D, NSTX-U, and C-Mod, and each of these is capable of being extremely productive for ITER along other paths to fusion power. When the panel is considering new US facilities that can broaden our experience and knowledge base, it will need to be very careful that we do not give up critically important capabilities that we already have.

To best ensure ITER’s success, the US tokamak program will need to maintain its world-leading capabilities in these areas until approximately the time ITER starts up. There is likely additional value in having one or more of our facilities continuing to run in parallel with ITER to help qualify operating scenarios, but this is outside of the time frame being considered here.

Many of the upgrades proposed for the US tokamaks will improve our capabilities to perform research with increasing fidelity to ITER conditions, and so we strongly endorse those (see Tables 1-3). In addition, a continued emphasis on developing and using validated models will require continued investment in our diagnostics suites and in computational capabilities (both hardware and analyst). Also, increased investment in technology during the coming years may both contribute to ITER’s success and better position the US to learn from ITER.

Finally, we must continue to leverage – not replace – our unique capabilities by collaborating with international experiments that have complementary capabilities.