# THE UNITED STATES MUST MAINTAIN A WORLD-CLASS DOMESTIC TOKAMAK PROGRAM TO SUPPORT BURNING PLASMA SCIENCE DEVELOPMENT

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**WHITE PAPER**

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GENERAL ATOMICS

# The United States Must Maintain a World-Class Domestic Tokamak Program to Support Burning Plasma Science Development

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The NAS Committee Interim Report[1] states that, "burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components." Further, the report states that "any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER."

Active participation in the ITER project is necessary for the US to derive full benefit from the ITER project in its quest for a domestic fusion power plant. With ITER's first plasma being only 7-8 years away, there is no credible alternative that might achieve burning plasma conditions sooner. Effective participation in ITER requires that the US continue to invest in domestic tokamak facilities and research to address operational issues for ITER and prepare the physics and fusion technology needed to enable next step devices. Such an active domestic experimental program would ensure that the US gains maximum benefit from a successful ITER project along with a strong R&D program that:

1. Provides solutions and technical support for successful preparation and operation of the ITER facility. In some areas the US is world-leading and is providing essential information.
2. Prepares and provides a team of talented and experienced scientists and technologists to participate in the ITER research program and bring its results back to the domestic program.
3. Develops the physics basis and tools to take ITER's results and make use of them to move to the next steps on the path to a cost-effective DEMO.

By supporting strong participation in ITER, including continued strength in these three areas, the US will be positioned to build on ITER's accomplishments to move toward the ultimate goal. The purpose of this white paper is to argue that these points are best addressed by continued operation of state-of-the-art domestic tokamak facilities in the time leading up to and during ITER operation.

A strategic plan leading all the way to DEMO[2] is beyond the scope of this white paper, but the leading candidate for its configuration remains the Advanced Tokamak[3]. Devices that contribute most strongly to ITER's success clearly must be tokamaks; it is assumed here that subsequent devices addressing DEMO preparation, as well as DEMO itself, will also be tokamaks (for any

[1] https://www.nap.edu/download/24971 (downloaded January 18, 2018).
[2] M. Wade, et al., white paper submitted to Committee on a Strategic Plan for US Burning Plasma Research.
[3] R. Buttery, et al., white paper submitted to Committee on a Strategic Plan for US Burning Plasma Research.

plausible configuration the missions are largely configuration independent and could be addressed with a tokamak).

## Providing technical support for a successful ITER research program

The US Fusion Energy Sciences program is a leader in establishing the basis for successful design and operation of ITER in several different areas, largely based on experiments carried out in US tokamak facilities[4]. Although the ITER design is largely finalized, the need for "satellite" tokamaks will continue. ITER, of course, includes seven international partners, but the US has to date made crucial scientific contributions well beyond its 1/11 share of the construction costs by applying its strengths in areas such as transient control and the flexibility to design, simulate (both through experiment and theory-based modeling), and characterize operating scenarios for ITER.

Even at this late stage of ITER preparation, US tokamaks continue to provide essential knowledge for finalizing the designs of ancillary systems such as ELM coils, error field correction coils, the disruption mitigation system, and more. Later, during ITER operations, there are likely to be opportunities for upgrades in transient control and heating and current drive systems, but these can only be considered if a firm basis is developed elsewhere. Also, there will be a continuing need during ITER operation to qualify operating scenarios in a lower risk setting, positioning US scientists to play key roles in ITER experiments.

While existing fusion facilities will not create burning plasmas, they can nonetheless access and simulate conditions that are highly relevant to burning plasmas. Moreover, our present facilities can be used to address major challenges before confronting them in a burning plasma device, accelerating the progress on new facilities while minimizing risk.

Research must be targeted to resolve issues related to transients. ELM control is essential, and ITER plans have been informed through extensive study of ELM suppression using 3D fields, ELM mitigation techniques such as pellet-pacing, and naturally ELM-stable regimes such as QH-mode. A hierarchical approach is needed for meeting the disruption challenge, including design of scenarios that are naturally disruption resistant, predictive algorithms for assessing the plasma stability, control tools for stabilizing large scale MHD, recovery modes for dealing with off-normal faults and reliable mitigation tools when a disruption cannot be avoided. NSTX-U and DIII-D are already well-poised to address these issues, and future funding should support further enhancement in capabilities (such as additional heating and current drive tools, as well as new 3D coil sets and diagnostic improvements for disruption studies).

Supporting these considerations suggests the need to operate flexible domestic facilities with the ability to rapidly deploy and test new tools and the measurement capabilities to fully characterize their impact. One or more such devices in the US would be complementary to devices in Europe, Japan, Korea, and elsewhere that have more ITER-like plasma-facing components and/or longer

[4] http://www.burningplasma.org/resources/ref/fspp/whitepapers/GACP%2020006244R2_USBPO%20FESAC%20SP%20white%20paper_2014-08-19.pdf (downloaded January 18, 2018)

pulse lengths, but with less operational flexibility. The US already has two such flexible and well-diagnosed facilities in DIII-D and NSTX-U.

DIII-D has been undergoing, and will continue, a progression of upgrades that allow it to operate under increasingly reactor-relevant conditions including strong electron heating (as expected from alphas in a burning plasma) and low rotation. Future funding could significantly augment these capabilities with additional electron heating and more flexible low torque heating, providing access to new parameters of high beta at low rotation, and enabling stronger tests of the underlying physics, which in turn will spur the development of increasingly sophisticated and complete models.

To fulfill a role as an ITER satellite tokamak, facility upgrades to DIII-D should be considered including:

- New and novel disruption mitigators for evaluation prior to possible deployment on ITER prior to the second pre-fusion-power operation (PFPO-2) phase in the early 2030s.
- Increased pulse length, input power and energy for heating and current drive, and increased heat-handling capabilities.
- Additional flexibility in 3D fields motivated by improved physics understanding and numerous applications including error field control, ELM control, scenario development, and stability control. A more fully developed scientific basis for these affects continues to be a long-term need.
- Heating upgrades to facilitate operation under increasingly reactor-like conditions, namely low input torque (balanced NBI) and electron heating (additional ECH).
- Novel heating and current drive systems for consideration as candidates for ITER upgrades to support steady-state operation. For example, DIII-D has begun studies of Helicon current drive, which may provide several advantages over present-day current drive actuators.

**Effective leadership and participation in the ITER research program**

ITER will provide the first laboratory for studies of the behavior of a burning plasma, and as such will offer an unprecedented opportunity to the US Fusion Energy Science community to move into what we all acknowledge as the next frontier in our field. <u>We must be prepared to fully embrace that opportunity</u>.

Maintaining technical leadership is essential for that readiness, but it is just as important to optimize the organization of the ITER research program to facilitate that participation. This will eventually be decided in negotiation between the Domestic Agencies and the ITER Organization Central Team, but a US Burning Plasma Organization Task Group has already prepared a set of "Recommendations for ITER Experimental Operation, US Team Formation and Participation" to help guide the process[5].

Also, an ITER Research Plan has been developed and revised[6] in cooperation between the ITER Central Team and the community to guide the research program from first plasma all the way

[5] R. Maingi, et al., https://www.burningplasma.org/resources/PDFS/taskgroups/BPO_ITER_Participation_FullReport_Final_23June2015.pdf (downloaded Feb 13, 2018)

[6] Public release currently in preparation by the ITER Central Team

through the first DT research phase in the mid 2030s. US scientists have been heavily involved in all phases of developing this plan, and we anticipate it will undergo further revision based on progress at the ITER site and in the Domestic Agencies' facilities.

To be prepared to play a leading role in the ITER research program, the US needs to recruit, train, and motivate a talented and vibrant technical workforce. In training such a workforce, there is no substitute for the kind of hands-on training that can only happen on a major experiment. This alone should be enough to justify maintaining a leadership-class domestic tokamak facility in the United States.

**Maintaining readiness to move to next steps after ITER**

Although the US does not have an "official" roadmap leading to a magnetic fusion DEMO, the major elements are well known. ITER fulfills an essential niche in that roadmap, providing the first data on a high-gain burning plasma and the technical elements supporting it. Moving toward a DEMO will require that the lessons learned on ITER be absorbed into a vibrant domestic community able to apply the results toward a DEMO as well as to address the other roadmap elements. The technical workforce mentioned above is crucial, but continued research – eventually requiring new facilities – will be essential as well.

The US has not constructed a large facility since the 1980s, when TFTR and Doublet III/DIII-D came into operation. Several of our international partners in ITER are in the midst of a long period without a major domestic tokamak facility, and much of their expertise developed in the past has been lost through attrition. If we want to be serious about producing a fusion DEMO, we need to maintain the skills to design, construct, and operate a world-class facility without long temporal gaps in our program.

**Recommendations**

Scientific or technical leadership requires two things: Acknowledged expertise, and resources to develop and instantiate that expertise. Although the US FES program does not presently have the resources to ensure leadership in all areas of fusion development, we are leaders in several areas critical for progress in burning plasmas, including transient control, general plasma control, operating scenarios, energetic particle physics, and integrated modeling, to name a few. There is a common theme in that our position in all of these areas relies on a strong scientific approach that includes sophisticated measurement (a US leadership area in its own right) and model validation. That theme is a recognized hallmark of US fusion research.

Continued progress toward fusion requires that we take a bold burning plasma step and maintain a domestic program that is able to both support and take advantage of that step. Such a step has several benefits: It pushes progress toward fusion energy, maintains US leadership in at least some areas, and provides exciting new opportunities for discovery science. The alternative is to cede leadership to our international partners, and eventually allow them to become the world's suppliers of fusion energy technology.

Ultimately, the physics understanding obtained from the research performed in our domestic facilities, coupled with the major advances enabled by the burning plasma of ITER, will empower the US to maintain and strengthen leadership in fusion energy development.