A Burning Plasma Diagnostic Initiative for the US Magnetic Fusion Energy Science Program

July 2007

White Paper presented to the
USDOE Office of Fusion Energy Science
by the US Burning Plasma Organization (USBPO)

Executive Summary

The US magnetic fusion energy science program needs an initiative for the development of innovative diagnostics for burning plasma experiments, such as the ITER device, now under construction, and a future demonstration facility (DEMO). Extensive diagnostic measurements of burning plasma behavior will be essential to optimize the US investment in ITER. Because the thermonuclear environment of burning plasmas will severely constrain the measurement capabilities of many present-day diagnostic systems, new methodologies need to be developed. In addition, several companion experimental facilities are being proposed, in the US and abroad, which will address key questions to be encountered in burning plasmas and which will also require innovative diagnostics.

At present, the US magnetic fusion energy science program does not support the development of innovative diagnostics for burning plasma experiments. The US ITER Project Office provides support for the construction of several US-credited ITER diagnostics. However, some critical measurement needs required for the success of ITER's mission are still unmet. The Office of Fusion Energy Sciences provides support for diagnostic development for existing experimental facilities; however, burning plasma diagnostics for upcoming experimental facilities are excluded due to lack of funds. We believe that this represents a serious gap in the US program, which would negatively impact US competitiveness both for planned and also for future burning plasma experiments, such as a demonstration facility (DEMO).

The purpose of this White Paper is to describe the components of a US initiative for the development of innovative diagnostics for burning plasma experiments as part of a comprehensive national diagnostic development program. Such an initiative would build on the traditional US strength in diagnostic innovation and would enhance the contributions of the U.S. magnetic fusion program.

The three main elements of this proposed new initiative are as follows:

1. Expansion of the present OFES diagnostic development program so as to provide support for short- and long-term development and implementation of new diagnostics needed for burning plasma research.
2. Integration of the capabilities of burning plasma diagnostics into existing analysis and simulation codes and, ultimately, into control systems
3. Provision of some modest funding with short time scales for the execution of specific tasks, such as modeling plasma/diagnostic interactions, reviewing designs of ITER diagnostic systems credited to other Parties, evaluating environmental issues for diagnostics, and coordinating this diagnostic initiative with the USBPO and the US ITER Project Office.

The inclusion of these three activities would represent roughly a doubling of the existing funding resources for OFES-sponsored diagnostic development work.

1. Introduction

Progress in fusion energy science relies strongly on the accurate comparison of detailed diagnostic measurements with theoretical predictions and computational simulations. Diagnostics thus constitute a vital "window" on the behavior and properties of plasmas and their interaction with the first wall. The US fusion program is recognized worldwide as a leader in improving the understanding and control of fusion plasmas, thanks to pioneering work on innovative diagnostics combined with recent rapid advances in computer simulation. The introduction of new diagnostics has often led to scientific breakthroughs. Hence it is vital for the US fusion program to maintain a strong effort in the development and utilization of new diagnostic systems.

The ITER mission—demonstrating the scientific and technological feasibility of fusion energy—will require a comprehensive set of diagnostics in order to assess the plasma and technological performance, as well as to provide many of the control tools necessary for attaining this performance. Arguably, measurements of burning plasmas (e.g., ITER and companion experiments) will require the best diagnostic systems ever to be implemented on any fusion device to date. Diagnostics that can be operated in a highly reliable manner in an extremely hostile radiation environment during long plasma pulses, that retain the precision and high resolution of present-day diagnostics, and whose alignment and calibration can be maintained, will be essential. Developing such diagnostics for burning plasmas will therefore require a concentrated and sustained R&D effort.

As the primary tools for accessing what can be learned in burning plasma experiments, diagnostics have a high-leverage impact on US participation in the planning and execution of the ITER scientific and technological program and, hence, on the US scientific productivity and competitiveness in the international fusion community.

The US program has historically been at the forefront of the development and implementation of new diagnostics for fusion research. Prime examples of such development include diagnostics for being able to measure the current profile with Motional Stark Effect (MSE), the ion temperature and velocity profiles with Charge Exchange Recombination Spectroscopy (CHERS) and high-resolution multi-chord X-ray spectroscopy, density fluctuations with Beam Emission Spectroscopy (BES) and reflectometry, and initial alpha-particle measurements with lost-alpha scintillators, pellet charge-exchange, and alpha-CHERS—as well as many others.

An important aspect of the US diagnostic program has been the highly successful integration of contributions from many institutions into experimental facilities such as TFTR, DIII-D, JET, Alcator C-Mod, NSTX, etc. Existing experimental facilities and well-connected teams of expert diagnostic scientists constitute a valuable infrastructure for prototyping innovative diagnostic concepts for burning plasmas. University groups—no less than those at national laboratories and industry—have been essential contributors, with their work extending from the construction and implementation of a diagnostic to its full scientific utilization. Training the next generation of scientists is also an important facet of this program.

2. Required ITER Diagnostics R&D

Earlier this year, the Diagnostics Topical Group of the US Burning Plasma Organization organized *The First Workshop on Diagnostic Development for Burning Plasmas* (held at General Atomics, February 6-8, 2007). Approximately 50 US researchers attended this workshop, while another 15 persons participated remotely via video-conferencing. Two notable guests were Dr. David Johnson, diagnostics WBS manager for the US ITER Project Office, and Dr. Alan Costley, diagnostics leader for the ITER Organization. Much of the information in the present White Paper derives from this workshop.

Although many of the diagnostic techniques planned for ITER are relatively well understood and developed, a significant number of issues remain to be addressed. These issues include the effects of *radiation* (induced EMF, induced conductivity, nuclear heating, photoluminescence), *long pulse* (stability, drifts), and *optics degradation* (erosion, re-deposition). A critical aspect of diagnostics for ITER is the development and testing of brand-new techniques, either to replace conventional techniques that are not expected to be functional on ITER or to measure previously undiagnosed parameters (such as tile erosion). Many of these important needs are related to un-credited ITER diagnostics, for which no funding is presently available. The expertise for addressing these needs can be found in many US groups.

The table below lists some of the important needs in burning plasma diagnostic R&D for which the US fusion community has expertise and could make contributions either through specific design activities or through tests in existing facilities. These needs are well aligned with high-priority activities developed by the ITPA topical group on diagnostics. Furthermore, these needs correspond to un-credited systems for ITER or to generic issues encountered in burning plasmas. They are not covered by the scope of diagnostic work supported by the US ITER Project Office.

Measurement	**Required R&D**	**Priority**
Confined alpha particles	New or very greatly evolved techniques	High
Lost alpha particles	New or very greatly evolved techniques	High
Magnetics	Radiation effects	High
Optical diagnostics	Erosion/redeposition, cleaning/restoring mirrors	High
Dust	New techniques	High
Tritium inventory and retention	New techniques	High
Optical diagnostics	New self-calibration techniques	Intermediate
Instability features (core and edge plasma regions	Soft X-ray	Intermediate
Fuel composition	Fast wave reflectometry	Intermediate
Tile erosion	New techniques	Intermediate
Impurities	New techniques	Intermediate
Core fluctuations	New techniques	Longer term

3. Proposed New Initiative

At present, the US magnetic fusion energy science program does not support the development of innovative diagnostics for burning plasma experiments. The US ITER Project Office provides support for the construction of several US-credited ITER diagnostics. However, some critical measurement needs required for the success of ITER's mission are still unmet. The Office of Fusion Energy Sciences provides good management of a program for diagnostic development for existing experimental facilities; however, burning plasma diagnostics for upcoming experimental facilities are specifically excluded due to lack of funds. We believe that this represents a serious gap in the US program, which would negatively impact US competitiveness both for planned and also for future burning plasma experiments, such as a demonstration facility (DEMO).

In this White Paper, we therefore propose an initiative for the development of innovative diagnostics for burning plasma experiments. The three main elements of this proposed new initiative would be as follows:

(1) Diagnostic development for burning plasmas

This would represent an expansion of the present OFES diagnostic development program so as to provide support for short- and long-term development and implementation of new diagnostics needed for burning plasma research. Examples of specific activities are to:

- Develop new techniques where serious gaps in the measurement capability exist.
- Develop instrumentation for un-credited ITER systems to a level where they could pass a Proof-of-Principle/Performance test.
- Seek alternate techniques to improve scientific output and productivity of a burning plasma experiment such as ITER and DEMO.
- Stimulate needed diagnostic specific development and understanding in technological areas such as:
    - mirrors/relaying optics
    - detectors
    - sources and lasers
    - radiation effects.

(2) Prediction and verification of burning plasma diagnostic performance

This would aim at integration of the capabilities of burning plasma diagnostics into existing analysis and simulation codes and, ultimately, into control systems. Examples of specific activities are to:

- Develop synthetic diagnostics.
- Develop new post-processors and other relevant hardware.
- Predict and verify expected performance of systems for ITER.
- Identify deficiencies in diagnostic coverage or operation.
- Prepare for full integration into a control system.

(3) Diagnostic program integration

This would make provision of some modest funding with shorter time scales for the execution of specific tasks, such as:

- Modeling plasma/diagnostic interactions.
- Provide opportunities through formal collaborations for US experts to participate in the design and construction of non-US ITER diagnostics assigned to other Parties.
- Reviewing designs of ITER diagnostic systems credited to other Parties or the ITER organization.
- Evaluating and addressing environmental issues for diagnostics.
- Initiate coordinated efforts in developing diagnostics for DEMO with international partners.
- Coordinating this diagnostic initiative with the USBPO and the US ITER Project Office.

The inclusion of these three activities would represent roughly a doubling of the existing funding resources for OFES-sponsored diagnostic development work.

4. Conclusion

The participation of the US fusion community in burning plasma experiments (such as ITER and companion projects) should involve a strong diagnostic development effort. This should include the design, development, construction, implementation, testing, and operation of diagnostic systems that would ensure long-term benefit to US scientific and technological capability and also increase US international competitiveness. We note that both Europe and Japan provide significant non-ITER project funding for burning plasma diagnostic development.

The scope of the diagnostic initiative proposed in this White Paper includes measurement needs for which established techniques either do not exist or have not been fully demonstrated. The long-term potential for burning plasma scientific research (for ITER and beyond) requires that, at some reasonable level, resources should be made available for the investigation and development of new, higher risk diagnostics. Historically, a development time of approximately five years is needed for a new diagnostic technique to mature from the conceptual level to the full demonstration level. The situation is rather critical in the US, where the serious reduction of resources for diagnostic development in the mid 1990's resulted in depleted support for new ideas and concepts. It is time to seriously support the long-term development of diagnostic in order to face current and future research needs in burning plasma science. We recall that a diagnostic initiative in connection with the formation of the US Transport Task Force in the late 1980s successfully led to the development, fielding, and utilization of many new diagnostics. We believe that the recent formation of the US Burning Plasma Organization creates a similar opportunity.

Development of and research in plasma diagnostics is also a key area for training the next generation of researchers, which will be important for the scientific exploitation of experiments such as ITER. A US burning plasma diagnostic initiative, as part of a strong and comprehensive diagnostic development program, would also strengthen the vital link among university, national laboratory, and industry groups in the US as they work together for ITER and other experiments.

In conclusion, a comprehensive initiative for the development of burning plasma diagnostics is needed to enhance the long-range contributions of the U.S. magnetic fusion program. Such an initiative is an essential component for progress in the understanding and control of burning plasma experiments, such as ITER, and eventually a fusion reactor, such as DEMO. We hope that the Department of Energy (OFES) can support such a proposal.