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

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Diagnostics Topical Group

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Executive Summary

The US magnetic fusion energy science program requires an initiative for development of the necessary diagnostics to support burning plasma experiments beyond ITER, such as a future FNSF, CTF and eventually DEMO facilities. Extensive diagnostic measurements of burning plasma behavior will be essential to optimize the US investment in ITER going forward. Because the steady-state thermonuclear environment of burning plasmas will severely constrain the measurement capabilities of many present-day diagnostic systems, new methodologies need to be developed and integrated into plasma control and operation/safety systems.

Many existing diagnostic systems, that support current facilities and are being adapted for ITER, will simply not work on high-duty-cycle burning plasma experiments beyond ITER. Providing diagnostic solutions for burning plasmas is critical as there are currently both measurement gaps (e.g., alpha particles, tile erosion, dust) and measurement extensions to long-pulse (steady-state), high-flux and high-fluence future burning plasma facilities that do not have viable solutions.[1]

At present, the US magnetic fusion energy science program does not support the development of innovative diagnostics for burning plasma experiments in general. The US ITER Project Office only provides support for the construction of ~7 US-credited ITER diagnostics. However, some critical measurements required for the success of ITER's mission are still unmet. Currently, the Office of Fusion Energy Sciences provides support for diagnostic development for existing domestic experimental facilities; however, burning plasma diagnostics for future burning plasma experimental facilities are excluded due to insufficient funds. This represents a serious gap in the US program, which will negatively impact the US leadership in future burning plasma experiments.

Development of and research in plasma diagnostics is also a key area for training the next generation of fusion plasma researchers. This will be critically important for the scientific exploitation of burning plasma experiments beyond 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 the development of fusion energy.

The components of a US initiative for the development of the necessary diagnostics for burning plasma experiments as part of a comprehensive national diagnostic development program are listed below. 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 main elements of the 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 diagnostic systems and extensions of existing diagnostic systems (where feasible) needed for burning plasma research.

2. Integration of the capabilities of burning plasma diagnostics into existing analysis and simulation codes and, ultimately, into plasma control systems.

1. Introduction:

Historically, progress in fusion energy science relied 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. However moving forward into the fusion era, this role will be significantly changed as plasma diagnostics serve as the primary sensors which will provide essential realtime information required for plasma control systems as they direct the actuators (fueling, heating. current drive and disruption mitigation systems) to maintain safe reliable performance of burning plasmas. The US fusion program is recognized worldwide as a leader in improving the understanding and control of fusion plasmas, largely due to pioneering work on innovative diagnostics combined with recent rapid advances in computer simulation. The introduction of new diagnostics leads to scientific breakthroughs and is necessary for operation of future burning plasmas. Hence it is vital for the US fusion program to maintain a strong effort in the development and utilization of new diagnostic systems.

Thrust 1 of the ReNeW Report[1] in 2009 emphasized the need to develop "diagnostics critical to the burning plasma research goals" to enable the understanding and control of burning plasmas for the fusion program. This is one of three issues that must be addressed in preparation of the instrumentation for a Demo-like device. These issues require specific attention over the next 10 years to provide input into the design, and hence anticipated performance, of a FNSF, CTF or Demo. The work must be done in parallel with the physics studies on current machines to establish the basis for the design of the burning plasma device.

Previous reports have defined the scope of work in preparation of measurement equipment for a Demo.[2,3] The difficulty of implementing the necessary plasma measurement capability on such a device has been shown in ref 4. It is important to note that the demands of plasma profile control set by advanced tokamak scenarios are very high, and it is not yet clear whether those of a stellarator are any less. These issues have been largely ignored in past design studies of Demo-like devices (e.g. Aries-AT[5]) which have oversimplified the integration of blankets and shielding with all auxiliary tokamak systems.

The three priorities to be addressed are:

1) Identify and develop the minimum plasma diagnostic requirements for control of steady-state burning plasmas; define the access required relative to blankets and other components surrounding the plasma such as heating and other ancillary equipment, define calibration requirements and engineer reliability into the systems.

2) Develop plasma diagnostics critical to the burning plasma research goals;

3) Define the necessary control data and develop control algorithms to help define

the control of a (limited) variety of long-pulse (steady-state) plasma scenarios.

These three priorities are very tightly coupled. They must be pursued urgently because it is probable that the measurement requirements will significantly affect the design of the future burning plasma device (CTF, FNSF, Demo). All of them will require coordination with materials studies and radiation testing being done elsewhere for the fusion program. These priorities are critical to the advancement of Burning Plasma Science Foundations (prediction and control) and Long Pulse (steady-state nuclear environment for CTF, FNSF, DEMO) identified by E. Synakowski in his *The Charge for Advice on Strategic Planning (9 April 2014).*

The steady-state burning plasma 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., CTF, FNSF, DEMO 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 steady-state operation, that retain the precision and high resolution of present-day diagnostics, and whose alignment and calibration can be maintained remotely, will be essential. Developing such diagnostics for burning plasmas will therefore require a concentrated and sustained R&D effort.

However, many existing diagnostic systems, that support current facilities and are being adapted for ITER, will simply not work on high-duty-cycle burning plasma experiments beyond ITER. Providing diagnostic solutions for burning plasmas is critical as there are currently both measurement gaps (e.g., alpha particles, tile erosion, dust) and measurement extensions to long-pulse (steady-state), high-flux and high-fluence future burning plasma facilities that do not have viable solutions.

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

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, and NSTX. 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. Priorities for Burning Plasma Diagnostic R&D

The most glaring gap in measurement capability for a future burning plasma device like FNSF, CTF, or Demo is that of the main source of heating, the α-particles. The measurements employed on TFTR[6] cannot be easily extrapolated to a burning plasma or a Demo and there is only a European development of collective scattering[7] currently in progress. Measurement of the escaping particles will be very problematic if determined to be necessary. The plasma size and temperature will limit the use of diagnostics dependent on neutral beams for their measurement source and detector sensitivity to neutron damage will affect many diagnostics. Thus new concepts for measurement of ion temperature, plasma rotation, current density distribution and relative fuel densities in the core should be considered.

Even diagnostics relatively simple in concept will have to be reappraised. Design of optical diagnostics dependent on mirrors close to the first wall to give spatial coverage will need to evolve for the very long pulses and the high level of wall-reflected light anticipated. Standard magnetic diagnostics, particularly those that have to be close to the plasma to allow for fast time-response for instability identification, may not be possible because of radiation-induced conductivity effects in their insulators and a rethinking of the measurement of plasma localization may be necessary. Sufficiently radiation-hardened bolometers and vacuum gauges might have to be developed. Development of measurements of dust and erosion of first wall materials is presently in its infancy[8], and techniques to provide sufficient spatial coverage will have to be studied.

Experience shows that for present-day tokamaks, it takes about 10 years to progress from concept to a fully developed plasma diagnostic with reliable control capability. For instruments to operate in, and provide control information for, a steady-state burning plasma like Demo, it could well take longer, since these have to contend with the steady-state hostile environment and severe restrictions on accessibility to the plasma. In ITER the engineering design phase (by itself) of existing, mature diagnostic concepts will occupy 5 to 7 years to meet technical and regulatory requirements.

Measurement	***Required R&D***
Confined alpha particles	New or very greatly evolved techniques
Lost alpha particles	New or very greatly evolved techniques
Magnetics (plasma shape)*	Radiation effects
Optical diagnostics (kinetic profiles)*	Erosion/redeposition, cleaning/restoring mirrors, self calibration techniques
Dust	New techniques
Tritium inventory and retention	New techniques
Core instabilities	New techniques
Instability features (core and edge plasma regions)	Soft X-ray
Fuel composition	Fast wave reflectometry
Tile erosion	New techniques
Impurities	New techniques
***alternate techniques may be required**	

Identification and development of diagnostic systems viable under steady-state burning plasma conditions 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.

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 steady-state burning plasmas. They are not covered by the scope of diagnostic work supported by the US ITER Project Office.

Measurement Priorities:

A process for assessing the measurement priorities for diagnostics on burning plasma devices was outlined in the ReNeW report in 2009, and vetted by the community at that time. The principles of that assessment process remain valid and are concisely repeated here.

There is a need to: *Identify sensors required and make advances in sensor hardware, procedures and algorithms for measurements of all necessary plasma quantities with sufficient coverage and accuracy needed for the scientific mission, especially plasma control.*

- Diagnostic Capability (identify and establish adequacy of measurements for achieving predictive understanding and plasma control; identify gaps where new measurement techniques are needed)

- Diagnostic compatibility with steady-state nuclear environment

- Interpretation and analysis: Coupling measurements more closely to validated predictive fusion science will enable a reduction in diagnostic coverage and analysis requirements. This is important given the likelihood for reduced diagnostic access in CTF, FNSF and Demo.

- ***Control:*** Develop and implement diagnostics required to *Investigate and establish schemes for maintaining high-performance, burning plasmas at a desired, multivariate operating point with a specified accuracy for long periods (steady-state) without disruption or other major excursions. Define the necessary control data and develop control algorithms to help define the control of a (limited) variety of long-pulse (steady-state) plasma scenarios. A staged development path where plasma control for long-pulse discharges on existing devices is established and then extended to (1) steady-state and (2) burning plasma environment required for future FNSF, CTF and DEMO facilities.*

3. Initiative for Burning Plasma 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 measurements needed 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 future experimental facilities are excluded due to insufficient resources. We believe that this represents a serious gap in the US program which will negatively impact the US competitiveness for future burning plasma experiments, such as CTF, FNSF, and eventually a demonstration facility (DEMO).

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

(1) Diagnostic development for burning plasmas beyond ITER

Examples of specific activities:

- Identify diagnostic set required to control, safely operate and achieve the goals for a steady-state burning plasma. Assess the environment under which these diagnostics must function.
- Develop new techniques where serious gaps in current measurement capability exist.
- Seek alternate techniques to improve scientific output and productivity of a burning plasma experiment.
- Stimulate needed diagnostic specific development and understanding in technological areas such as:
    - mirrors/relaying optics
    - detectors
    - sources and lasers
    - radiation effects.

Evolution required for diagnostics systems: An urgent task is to define what plasma diagnostics will be required for the control mission and to what quality, in amplitude, spatial and temporal resolution, they will have to perform. This definition will obviously evolve as the proposed operational plasma scenarios become better defined. Presently more and more diagnostic information is being fed into the control of tokamak plasmas but this growth may have to be reversed prior to a FNSF, CTF, or Demo. The access to the tokamak will be severely constrained by the need to generate tritium (and electrical power generation ability) in the blankets. Both diagnostic and blanket designers prefer to occupy the outer equatorial region (the neutron flux is highest there), and the possibility of putting diagnostic access off the midplane has to be considered. This type of consideration could strongly impact the design of the device, as well as the performance of the diagnostics.

Another significant issue is the robustness of the measurement equipment. Relative to the instrumentation in a fission reactor, the instrumentation (which has to be within the plasma device environment) is much more complex. A strong engineering effort must be set up to consider the issues of radiation effects on operation and lifetime of components, control and operation of movable components such as shutters, capability for maintaining calibration and redundancy. Obviously all systems will have to be maintained and replaced using remote-handling equipment, though this aspect will be prototyped on ITER.

There is an additional area of instrumental development which is less well defined. Up to now, measurement of the performance of the engineering systems in operating plasma devices has mostly made use of commercially available equipment with some care necessary because of the high magnetic fields. An initial attempt to assess the needs for evolutions of the instrumentation toward Demo was shown in ref. 2, section 9.3, but a much better assessment is necessary. A few examples of areas where design studies and development may be necessary are given below. The design studies would consider where the instrumentation would have to be placed relative to the very hostile radiation and temperature environment. They will also be affected by the particular solutions for heating, current-drive, and fuelling chosen for the plasma. Since the plasma in a CTF, FNSF, or Demo must survive through any transient "off-normal" events, such as disruptions, mitigation techniques will have to be considered, though the instrumentation will probably only require faster response times of injection and heating systems than would be necessary for the normal plasma control. Some potential examples of instrumentation for engineering systems are:

i) Gas injectors and their monitors;
ii) Temperature sensors of the first wall and vacuum vessel;
iii) Temperature sensors and neutron flux monitors for superconducting coils;
iv) Temperature distributions in RF launchers;
v) Internal measurements in neutral beam boxes, if NB heating is employed;
vi) Speed measurement and mass measurement at exit of pellet injectors;
vii) Neutron measurements, fluid temperatures and flow velocities in blanket modules;
viii) In-vessel inspection components (in a highly activated vacuum vessel);
ix) Instrumentation of versatile robotic equipment for remote maintenance.

(2) Prediction, verification and integration of burning plasma diagnostics

It is clear that the purpose of plasma diagnostics in a CTF, FNSF, Demo or fusion reactor will be the control of the plasma and for protection of the device (e.g. disruption avoidance). The plasma diagnostic systems will provide the data needed to control the plasma during all operational phases; start-up, development, burning phase and rampdown. Thus the equipment has to operate over a huge dynamic range of plasma properties. The information provided will probably be of lower quality than in present-day tokamaks because of the restricted access and the intense radiation environment.

Hence there is a definite need for the development and validation of interpretive and predictive modeling tools to be incorporated into the control systems. These will have to be tested on operating tokamaks, and also on ITER where the plasmas will be more representative of those expected in CTF, FNSF, or Demo. It has to be assumed that the principal operational regimes for future steady-state burning plasmas will have been demonstrated on ITER. It is felt that the computation capability will be easily able to handle a transport code such as TRANSP to allow profile fitting to a limited set of positional information within the necessary control time interval. The implementation of synthetic diagnostics to validate limited spatial data sets will also be necessary.

This initiative 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.

4. Conclusion

The participation of the US fusion community in burning plasma experiments beyond ITER (such as FNSF, CTF, and DEMO) must include a strong diagnostic development effort to ensure success. This will necessarily include the development, design, construction, implementation, testing, and operation of diagnostic systems that will promote a long-term benefit to US scientific and technological capability and also increase US international competitiveness. We note that both Europe and Japan currently 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 (beyond ITER) 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 10 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 from the mid 1990's resulted in depleted support for new ideas and concepts. It is time to seriously support the long-term development of diagnostics 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 diagnostic systems. We believe that future burning plasma experiments create 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 future burning plasma experiments beyond 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 devices beyond ITER.

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 CTF, FNSF and DEMO.

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