# SNOWMASS Report
# Section 3.1.3.1 Diagnostics

The success of any BPX will be dependent on the capability to make plasma measurements with sufficient quality of resolution and accuracy with sufficient reliability in a very hostile environment. These measurements will enable the development of understanding of the plasma behavior, provide the data necessary for achieving different operational modes and, finally, be used in the input for real-time control of the plasma behavior. All the proposed BPX devices will carry out physics studies needing very high quality information from diagnostics similar to those in present-day operation. However, there will be a major change in performance as new alpha-particle heating becomes significant and a relatively untested set of techniques for following the behavior of these particles will be introduced. Diagnosis of the confined alphas with sufficient detail represents a severe challenge in any BPX, requiring substantial development and improved assessment of measurement requirements. Many different diagnostic techniques will have to be integrated to provide the necessary operational guidance.

The design experience of CIT[1] and ITER[2] revealed the serious impact of the burning plasma environment on measurement capability. The need to maintain overall shielding integrity and the sensitivity of diagnostic components to prompt radiation effects (e.g. absorption and fluorescence in optical materials, induced conductivity in ceramic insulators and cables) leads to the location of components and their integration with shielding material which tends to limit spatial coverage. Reflecting optics must be used in the first shielding module, which means that the plasma-facing mirror is vulnerable to radiation effects as well as sputtering and deposition. Remote maintenance of the shield modules in the radial ports and of the divertor modules (if present) leads to careful, and costly, design at the tokamak boundary. Sensitive components will be housed in a distant shielded location. Carrying out, and then maintaining, calibration of many diagnostics will be a challenge, which largely has still to be addressed, bearing in mind the complexity of remote handling, shielding and access conditions.

Many person-years have been expended in planning the diagnostics for ITER. A carefully developed and evolving set of measurement requirements has been created for meeting the ultimate mission of a long controlled burn. The diagnostics to meet these requirements have been defined and many have undergone relatively detailed design studies. The integration of these systems into the available port space and shielding is well advanced, making use of the knowledge of the radiation shielding requirements that have evolved through the R&D studies of radiation effects. High priority has been given to measurements needed for control and machine protection. Detailed evaluations have been made of the ability of the various diagnostic techniques to provide the necessary temporal and spatial resolutions, coverage and accuracy to provide this information. At this time most of the measurements needed for control are assured, but a few, such as the measurement of current profile need further study.

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[1] S.S. Medley, K.M. Young and the CIT diagnostic team, "Plasma Diagnostics for the CIT", Rev. Sci. Instrum. **59**, 1745, (1988)

[2] ITER Physics Expert Group on Diagnostics *et al*., Nucl. Fusion **39**, 2541 (1999)

Much less time has been spent on preparing for FIRE diagnostics, though very much of the ITER experience can be applied to assessing the measurement capability. The mission of understanding and optimizing fusion-dominated plasmas in a smaller, higher density, RF-heated plasma leads to more extreme environmental conditions for some diagnostic components while simultaneously requiring better spatial resolutions. The same level of detailed evaluation as for ITER has not been completed, but most measurements appear possible with sufficient quality. Those diagnostic techniques, such as charge exchange spectroscopy and motional Stark effect (the technique most commonly used to measure the current density profile), dependent on a neutral beam's penetration for full spatial coverage, are problematic and beam development appears to be essential.

Preparation for the diagnostics for IGNITOR seems also to be less advanced, but the mission of achieving burn in short pulse plasmas without a divertor, and operating well away from stability limits for MHD modes, leads to a simpler set of measurements.

Diagnostic developments for tokamak BPXs are expected to be important eventually for Innovative Confinement Concepts.

## Section 3.3.3.1 Diagnostics

Assessing the planned set of plasma measurements for the different devices require a careful analysis of what actually drives the needs and requirements for a specific measurement. Different missions and different objectives set different requirements and thus an assessment should be made on the limits and constraints imposed on the future systems, not necessarily on individual diagnostics themselves.

While, in principle, given the appropriate resources, one can include any measuring technique in the diagnostic set, a few basic criteria would ultimately determine which ones can be effectively fielded in any given BPX experiment. Since the resources presently allocated to the design of the diagnostic set are vastly different between the three options, it is important not to focus too narrowly on any single diagnostic, but instead concentrate on the fundamental issues expected in a BPX.

**Access**
First and foremost is the basic and fundamental issue of access. The plasma measurements require a direct access to the discharge, and consequently the number of ports, their size, shape, location and view affect directly the diagnostics capability. In addition, in the presence of a divertor, additional measurements are required in an area, which is very restricted. Finally, many measurements benefit from a tangential view (looking in the toroidal direction), which, when absent, cannot always be compensated by the use of mirrors. Note that the ports must contain significant quantities of shielding to limit the neutron streaming.

**Radiation environment**

While one criterion of success is ultimately the realization of a large alpha particle production, the consequence is also a potentially very large neutron flux on the sensors with constraints not encountered in present-day experiments. The diagnostics would encounter an environment with very large neutron and gamma fluxes and fluences. Without mitigation, these are expected to produce effects such as Radiation Induced Conductivity (RIC), Radiation Induced EMF (RIEMF), nuclear heating, absorption, fluorescence and luminescence. Reflective optical components have to be used close to the plasma, rather than refractive lenses because of radiation effects.

**Erosion and deposition**

The large particle fluxes (e.g. neutral particles) found in a tokamak at or near the first wall mean that erosion and redeposition would be present as well in a BPX. This phenomenon, albeit not new, means that the performance and reliability of diagnostics can be significantly degraded. The extensive use of mirrors as the nearest plasma-facing component means that serious attention has to be given to calibration issues, potentially in real-time for long-pulse operation.

**Beam-based diagnostics**

Many measurements in present day tokamaks rely on the use of neutral beams to diagnose the plasma, even though beams may not be used as auxiliary heating. Many of these measurements do not have equivalent techniques, which do not rely on beams, and consequently a serious gap may exist if beam-based diagnostics cannot be fielded effectively. However, in general those techniques do not easily extrapolate to a BPX because of penetration issues and access, and consequently they require additional development as well.

**Cost**

Stringent measurement requirements, combined with the access limitations and harsh environment expected on a BPX, drive the implementation schedule and overall costs of diagnostic systems. In this context, it should be recognized that the implementation of diagnostics cannot simply be an "after-thought", as it has been traditionally. This will necessitate that the funding profile for the diagnostic set be accelerated compared to the historical record. This will allow adequate integration of the diagnostics into the machine design as well as permitting advanced development of currently unavailable or uncertain measurement capabilities.

# Assessment

As mentioned above, the conventional approach to diagnostic implementations has been traditionally to include them only after the design of the tokamak is largely completed. That is largely the case for FIRE and IGNITOR. However, since ITER went through a significant redesign (from ITER-98 to ITER-FEAT), the diagnostic features are better integrated into the overall scheme of the experiment at the design inception. Overall, the diagnostic set proposed by the ITER team appears to be feasible, sufficiently complete with a good probability of success, and the remaining issues are identified and subject to active R&D. The FIRE diagnostic set is plausible, but many issues remain, at least until a reasonable engineering feasibility study is undertaken. For IGNITOR, it has not been possible to fully evaluate this set. While the overall objectives of the 3 options are similar for physics evaluation, but not identical, the impact of access will be very important. ITER has certainly the largest port access, and consequently one of the most complete set planned yet, although some limit may ultimately exist for the physics evaluation set. FIRE has more ports assigned to diagnostics, even though they are smaller. FIRE retains basically the same measurement requirements, but adds the complexity of diagnosing a second divertor, a very demanding task. In the case of IGNITOR, the restriction in access is severe, but similar to that encountered on Alcator C-Mod, for example. Presently, with the available information, some concerns remain that some basic measurements can not be done effectively for physics evaluation, especially in regards to profile information. However, many details are not yet formalized in the design, and it should be noted that the lack of a divertor simplifies the requirements. In all three cases the access is also limited by the necessary shielding, which is required to limit the radiation dose to the field coils, the facility and at the site boundary.

Of particular concern is the lack of convincing alpha particle diagnostics planned for either experiment. Particular attention is required to properly measure the confined and escaping alphas, and appropriate diagnostic testing must be done prior to their integration into a BPX. In parallel, attention should be given to the development of measurement requirements for alphas in the context of difficulty in implementing the techniques.

The diagnostics will experience a harsh nuclear environment in all three options. Neutron and gamma fluxes will be about an order of magnitude larger for magnetic sensors and their cables for FIRE and IGNITOR than in ITER, and material selection and careful design will be more crucial. In all options, optical systems will require reflective optics close to the plasma to avoid absorption and fluorescence effects. Neutron streaming must be limited for FIRE and ITER, leading to the integration of the diagnostic components with shielding. While the fluence is much the highest in ITER with its long pulses, it is not likely to be a serious issue for diagnostics. Remote handling is a necessity for all three devices, and will feature strongly in design integration. All diagnostic systems should be installed and tested early, prior to any tritium operation.

The presence of erosion and deposition will be the most severe for ITER with its long pulse length although the lack of easy access would mean that all three options have to incorporate their effects on the long-term reliability and availability of diagnostic systems, including their effects on calibration.

Neutral beam based diagnostics are presently planned for ITER and FIRE. In the case of ITER, the feasibility study of these diagnostics is still ongoing, and will require more studies, but the outcome is promising. The beam pulse length may still be an issue however. The lack of beam penetration in FIRE will require the development of a new specialized beam, a planned activity. The feasibility study of these diagnostics has not been completed and remains an open issue. IGNITOR does not plan on a neutral beam, and many important parameters may not be measurable. Current profile, ion temperature profile, rotation will be thus be difficult to measure, if not impossible, using other techniques, if the physics mission requires such measurement.

In all cases, an aggressive and dedicated R&D program is required for full implementation of the necessary measurements in the three options. Research in radiation effects in materials must be pursued in a timely fashion, for the first components (such as magnetic loops) to be manufactured and tested. Many new diagnostic techniques require testing in existing experiments prior to their fielding in a BPX. Erosion and redeposition on first mirrors and other exposed components require serious attention as well, and the consequences on the performance and reliability of diagnostics, must be carefully addressed. These issues can influence, for example, the diagnostic calibration and consequently the ability of fulfilling the physics objectives. Finally, it is well known that the cost associated with a diagnostic set, for a similar coverage in plasma parameters is relatively independent of the size of the tokamak or experiment. Additional, specific details of the assessment can be found in the appendix.

**Contribution to ICC**

The development in plasma measuring techniques (diagnostics) has always been a discipline where the interaction between concepts has been most productive and direct. Diagnostics specific issues as encountered in tokamak BPXs can be expected to be most useful, if not critical, to the eventual development of Innovative Confinement Concepts. Although some techniques may not be directly applicable in another magnetic configuration, the wide majority of them are. Examples include measurement of alpha particle population, neutron flux and current profile. Issues of operation and survivability will be common to all BPX devices, including ICCs, although specific access solutions usually are not. The specific experience gained on a tokamak based BPX will also produce many benefits. For one, all the R&D required for mitigating radiation effects will apply to any ICC-based BPX diagnostics. New material or improved techniques for the first mirrors will be important as well. In addition, the development of reliable, simpler diagnostic techniques will be beneficial to any future reactor, be it a tokamak or not.