Draft Final (13/6/01)

Summary of Diagnostics Break Out Session at BPS Workshop 2

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A next step burning plasma experiment (BPX) will require an extensive set of plasma and first wall measurements. In general, the requirements on the measurements (parameter ranges, spatial resolutions and accuracies etc) will be the same or more demanding than those on contemporary machines. The harsh radiation environment means that diagnostic system selection and design has to take into account a range of effects and phenomena not previously encountered: for example, Radiation Induced Conductivity and Radiation Induced EMF in cables and in magnetic sensors mounted in the vacuum vessel, radiation induced noise in diagnostic sensors, and erosion of diagnostic first mirrors due to energetic particle bombardment. The diagnostic designs also have to satisfy the stringent engineering requirements for vacuum integrity, tritium containment, remote handling maintainability etc. Access will be restricted and must maintain neutron streaming below allowable limits. The value of some key plasma parameters will be significantly different from current machines (higher temperatures, longer pulse length (possibly steady state), larger physical size etc) which can significantly influence diagnostic performance. Taken together these aspects mean that the implementation of diagnostic systems on a BPX will be a major challenge, arguably the most difficult challenge ever undertaken in plasma diagnostics

The challenge must be met effectively. Plasma measurements will play an important role in the safe and reliable operation of the BPX but also, and especially important in the context of this workshop, they will be the window to the detailed scientific knowledge that is a primary motivation for such an experiment. Development of BPX diagnostics is therefore an undertaking that should be pursued vigorously and closely integrated with the machine designs. Because of the time it takes to execute and analyze radiation tests on candidate materials and diagnostic components, and to develop new components and techniques where necessary, it is an undertaking that should be pursued now.

We interpreted our charge in terms of three questions: (i) what first wall and plasma measurements will be required to support a BPX; (ii) what is the status of diagnostic preparedness to meet this challenge; and (iii) what are the key areas where developments are needed? We concentrated on tokamaks but most of our findings would also apply to a BPX stellarator or possibly other large, long pulse, magnetic fusion device. The difficulties of implementation will be, to some extent, machine dependent and so we extended our study and looked briefly at the feasibility of implementing diagnostics on the different BPX contenders (ITER-FEAT, FIRE and IGNITOR).

(i) What first wall and plasma measurements will be required to support a burning plasma experiment?

As on existing machines, first wall and plasma measurements will be required for machine protection, plasma control and physics evaluation.

The plasma control must protect against contact of the plasma with the first wall, maintain the fusion power within allowed limits, minimize plasma disruptions, and, for machines with a divertor, maintain correct divertor operation (partial attachment). Hence key measurements which must be measured at a very high level of reliability for machine protection are the *separatrix/wall gap, first wall temperature, divertor plate surface temperature, fusion power,ELM type, line-average density, halo currents and disruption precursors (particularly the detection of locked modes).*

For plasma control, the principal measurements made on existing machines will also be needed on a BPX; *plasma shape and position, plasma current, and electron density*. But a burning plasma operating close to operational limits will require additional control measurements: for example, *plasma beta, radiated power, fuelling ratio* n_T/n_D*, plasma rotation and Helium ash concentration*. Key measurements in the divertor will also be needed – in particular *the position of the ionisation front* must be determined. It may be necessary to inject a controlled amount of a specific impurity or a combination of impurities (e.g. Ne, Ar) into the divertor and scrape-of-layer (SOL) plasma and so measurements of *impurity levels* in these regions will be required at the control level. The kinetic control must also keep the plasma away from the β and density limits and provide sufficient power flow through the separatrix to ensure H-mode plasma operation. This leads to requirements for a range of additional plasma measurements for control, including *radiative power loss from the plasma core, SOL, X-point region and from the divertor, plasma density profile, β,* n_T/n_D *ratio, rotating MHD modes and/or* T_e *and* n_e *at the divertor plate. It is clear that a* sophisticated multi-input, multi-actuator feedback control scheme is required for successful operation.

For operating scenarios exploiting advanced high confinement modes, for example reverse shear and optimised shear, control and hence measurement of the spatial profile of key parameters such as *q, pressure and rotation* are likely to be required. For sustained operation near the β limit, suppression of *neoclassical tearing modes (NTMs)* will probably be required. Similarly, for steady-state operation at high β levels stabilization of the *resistive wall modes (RWMs)* will be required. Measurements of the location and amplitude of these modes are therefore required.

The BPX plasma will be the first in which there is significant α-heating, so the experimental program will have an extensive explorative physics component. Key topics to be investigated include energetic alpha particle effects, confinement and transport, macrostability and MHD, and the physics of the divertor and the boundary. In each case there are specific issues that have to be studied and these studies will require particular measurements.

For the studies of energetic alpha particles, the key issues to be addressed include alpha driven instabilities, alpha particle redistribution due to MHD modes, the possible stabilization of MHD modes (‘sawteeth’), and alpha particle heating. In addition to the measurements required for plasma control and basic performance evaluation, important required measurements are the *energy and number density of confined alphas with space and time resolution, the energy and number density of escaping alphas and MHD modes.*

The issues to be addressed in confinement and transport studies include the scaling of the pedestal width and height with the normalized ion gyroradius $\rho_i^* = \rho_i/a$, ρ_i^* scaling of turbulence (scale length and transport), ITB control and formation, He transport and ash removal, and impurity accumulation. Key required measurements are the *electron temperature and density with high spatial resolution* in the edge and in the region of the ITB, and measurements of the *helium ash and other light impurities*. Measurements of the *amplitude and correlation length of fluctuations* are needed in tests of theories and models of transport.

Studies of the macroscopic stability of a burning plasma involve the investigation of the complex internal coupled processes which will determine *the profiles of the pressure, current density and rotation*. The stabilization of NTMs and RWMs will be required for the highest performance. Modes that lock can lead to a disruption and so should be measured preferably when they are small.

The global issue to be addressed in studies of the boundary is that of the burning core – plasma boundary interaction. Specific topics will include transport in the SOL, ELMs and edge stability, and the L – H threshold. In the divertor, key topics will be the ELM power handling capability, impurity screening, particle pumping, dissipation of core power efflux, erosion/redeposition and tritium retention. The generation of dust may also be important. Many measurements will be required to support the study of these topics including measurements of n_e *and* T_e *with high time and spatial resolution, radiated power, divertor helium density and impurities*. Measurements of the *temperature of the divertor plates* and, for long pulse operation, *erosion of the plates* will also be required. The *composition, quantity and location of dust* may also have to be determined.

(ii) What is the status of diagnostic preparedness for making measurements on a BPX?

An extensive range of established diagnostic techniques exists from which individual techniques can be selected for a BPX. Under the ITER framework a substantial database of radiation effects on candidate materials for diagnostic construction has been established. Candidate materials for cables, insulators, mirrors, windows, lenses and fibre optics have been irradiated with neutrons and gammas at relevant flux and dose levels and the effect on the key physical properties determined. In the case of mirrors, extensive tests have also been carried out with energetic ion beams to determine the effect of particle bombardment. Further, for ITER, representative systems have been designed in some cases to a high level of detail. The design work has identified the critical components and key factors which have to be properly handled in preparing diagnostic systems for a BPX. This experience and knowledge base are the main components of the currently available basis for the preparation of BPX diagnostics.

The detailed implementation of diagnostic systems on a BPX will depend on the precise details of the application: the measurement requirements, the actual levels of the radiation flux and fluence, the available access and the specific machine engineering considerations. It will therefore be machine dependent and hence only limited generic assessments of the diagnostic capability can be made.

The most advanced BPX diagnostic system design is that which has been prepared for ITER. For this system, designs of the diagnostics necessary for machine protection and basic plasma control have been prepared and it is believed that solutions have been found to most of the key implementation problems. The broad assessment is that, with the expected results in current design and R&D in progress, it is anticipated that most of the measurements required for machine protection and basic plasma control can be made at the required specification. Many of the measurements required for advanced control can also be made but in a few cases (for example the q profile) significant difficulties arise and it may not be possible to meet target requirements. The divertor appears to be an especially difficult region because of the limited access and the potential problem of erosion/deposition. The ultimate measurement capability at this level is not yet known.

Many of the measurements implemented for plasma control will also provide measurements for the physics exploratory studies but frequently higher specifications (resolutions and accuracies) are required in the latter case. In some cases, dedicated measurements are needed with high specifications and under BPX conditions will be very difficult to make. For example, for the studies of the energetic alpha particle effects a key measurement is the energy and number density of the confined alpha particles. The measurement needs to be made with good spatial and time resolution. Presently there is no developed technique which can meet the requirements although several possible techniques exist, for example collective scattering, alpha knock-on, pellet CX. The state of development of these techniques is at an early stage. Similarly, while the heating of the first wall of escaping alphas can be measured, there is no developed technique for measuring the energy and number density of the lost alphas which would be required for a detailed study. Again there are potential techniques - for example Faraday cup and scintillators - but major difficulties are foreseen in implementing such techniques on a BPX.

The high spatial resolution measurements of density and temperature required for the confinement and transport studies appear feasible in the edge region but such measurements in the region of the ITB look very difficult. The ITB will occur deep in the plasma and at a location dependent on the operating conditions which may vary substantially and on a BPX it will be very difficult to achieve high spatial resolution over a wide region of the plasma radius. High resolution rotation measurements also look difficult and direct measurements of the electric field with a HIBP are probably not possible because of access difficulties. He ash and other light impurity measurements may well require a dedicated diagnostic neutral beam which will be a high cost item.

Measurements of MHD modes look feasible but whether the required measurement specifications can be achieved is a matter for detailed study. In particular there is a potential issue on the maximum n number of the modes that should and can be measured. The detection of stationary (locked) modes, however, looks very difficult. The early detection of NTMs will be important and there is potentially a sensitivity question here. ECE can potentially measure NTMs but at the high temperatures of a BPX the minimum mode size that can be detected will probably be ≥ 5 cm. It should be possible to measure RWMs using special saddle loops.

The combination of limited access and potentially heavy erosion and deposition of divertor plate material give severe difficulties for measurements in the divertor region. Several key measurements appear very difficult: for example, the electron temperature both across and along the divertor legs, the ion temperature and plasma flows, and the identification, location and density of impurities. For some key impurities, VUV measurements are required and these look extremely difficult in the divertor since they require direct coupling of the measurement system to the tokamak vacuum. Measurements of the plate temperature are needed for the control and study of ELMs and while measurements of this parameter appear feasible it seems that it will be very difficult to achieve the high temporal resolution measurements that will be needed for detailed physics studies. Presently there is no developed technique for measuring in real time, or between pulses, target plate erosion that could be applied within the access constraints of a BPX divertor, although there are some potential techniques (speckle interferometry and laser microscope).

Measurements of other parameters such as dust, deposited layers and the amount of retained tritium are potentially very important but in this case the requirements are not yet clear. The development of possible measurement techniques is also at a very early stage of development.

(iii) What are the key areas where further developments are needed?

Clearly, further developments are needed in order to be able to bring the measurements to the point where the requirements can be met. Developments are needed in each of the three major components of BPX diagnostic R&D: irradiation tests on candidate materials and on prototype diagnostic components, development of new diagnostic components, and development of new or improved diagnostic techniques.

There are several key areas in the radiation effects work that need further development. An unexpectedly high asymmetric voltage was measured in tests with a prototype magnetic coil apparently due to the phenomenon RIEMF. However, a recent reexamination of the results suggests that there were problems with the long pulse integrator used in the tests, and/or other sources of voltage, for example thermoelectric effects, and further tests are required. The work on first mirrors has established several options (single crystal Mo, W and stainless steel) which could be used in situations where the dominant potentially damaging mechanism is erosion due to bombardment by energetic neutral particles. This is likely to be the situation for mirrors mounted close to the first wall in upper and mid-plane ports. However, for mirrors in the divertor region and possibly in ducts, deposition is likely to be the limiting mechanism and potential cleaning and mitigating methods (baffles and shutters) need to be developed. It is believed that there are window solutions for most diagnostics. However, for systems employing high power lasers, even a small amount of absorption can be serious and more accurate measurements of radiation induced prompt absorption are needed. Significant inconsistencies have been found in tests on optical fibres and need to be resolved.

Key sensors requiring development include compact steady state magnetic sensors, compact efficient neutron detector/spectrometers, and radiation hard bolometers and soft X-ray detectors. In each case candidate sensors exist but development work is required before devices suitable for installation on a BPX can be constructed.

To solve some of the measurement problems, new techniques are required. For example, techniques are needed to measure the confined and escaping alpha particles, divertor plate erosion, dust and re-deposited layers. In other cases existing techniques appear to be very difficult to implement under BPX conditions and new techniques are highly desirable. Examples are measurements of the plasma position and shape under long pulse (steady state conditions), measurements of the light impurities and especially the He ash, and measurements of the internal electric field. In yet other cases techniques have been identified which could make measurements of an important parameter simpler. A good example is Fast Wave Reflectometry which could make measurements of the fuel mix ratio, n_T/n_D, with spatial and temporal resolution but requires development. The hardware is very simple and application on a BPX can be easily envisaged.

Active charge exchange recombination spectroscopy for the measurement of light impurities, ion temperature and plasma rotation requires a conventional neutral beam but this is a high cost item and requires significant space and power. A short pulse intense beam would require less power and space and would give an improved diagnostic performance but requires development.

In parallel with the R&D, it is important that diagnostic designs are developed and that there is a close interaction between design and R&D. As mentioned above, the design work is machine specific and, because of the many interfaces between diagnostics and the machine, the diagnostic designs should be developed in conjunction with the development of the machine design. A fully integrated approach is required.

(iv) Comments on the feasibility of implementing diagnostics on the different BPX contenders (ITER, FIRE and IGNITOR).

The feasibility of implementing diagnostic systems on a BPX depends on several aspects but especially on the access and the environment. The BPX contenders discussed at the workshop (ITER, FIRE and IGNITOR) differ substantially in these two aspects.

All three have large ports at the mid-plane and so good diagnostic access can be expected at this level. However, ITER also has large ports at the upper level. This gives access for many diagnostics including views of the diagnostic neutral beam for CXRS, views of the divertor for spectroscopy, views of the first wall which combined with views from the midplane give a high surface coverage. Further, they give the possibility of installing diagnostics for edge measurements which can take account of the natural flux expansion at this level to achieve high spatial resolution. Both FIRE and IGNITOR have small diameter, long, vertical ports. On a BPX, optical systems have to use reflective optics close to the plasma (because there are no sufficiently rad. hard optical materials for refractive optics), and in narrow tubes it is not possible to achieve high optical throughput. If there is the additional requirement to include shielding in the tubes, the possible optical throughput will be very low. Hence, the vertical ports on FIRE and IGNITOR will be of limited use for viewing or collection systems but may be of use for input laser beams.

At the divertor level access is restricted and the lifetime of diagnostic components is potentially limited. Both FIRE and ITER have to provide diagnostics at this level. In the case of FIRE a duplicate set will be needed at both the upper and lower divertor levels. This requirement, combined with the absence of large upper ports, makes FIRE a relatively difficult machine for diagnostic implementation. Since IGNITOR does not have a divertor specific diagnostics are not required at this level.

The first wall neutron flux on both FIRE and IGNITOR is approximately five times higher than on ITER. Moreover neither of these machines has a blanket and so in-vessel diagnostic components and sensors will be subjected to the unattenuated first wall flux. On ITER, diagnostic components will be installed in the gaps between blanket shield modules or behind the modules giving an additional attenuation of a factor of 10 - 100. The prompt radiation effects will therefore be much higher on FIRE and IGNITOR. Nuclear heating will also be much higher leading to high operating temperatures of the diagnostic components and/or to a requirement for active cooling. The relative fluence at the diagnostic sensors per pulse will be FIRE : IGNITOR : ITER = 1 : 0.2 : 0.3 - 0.03. However, taking into account the anticipated number of pulses, the end of life fluence for diagnostic components will be several times higher on ITER than on FIRE, and several times less on IGNITOR.

The overall message of the BPX diagnostic breakout session, is that the preparation of diagnostic systems for a BPX is a major undertaking. There is a good basis of experience and knowledge but considerably more work needs to be done. The system design and supporting R&D need to be closely connected. The implementation is machine specific and so the diagnostic system design also needs to be developed in close connection with the development of the machine design. ITER has developed a fully integrated diagnostic set along these lines. FIRE and IGNITOR need to do so. Since diagnostics will play a critical role in providing the knowledge to be gained by a BPX claims for the benefit of such an experiment cannot be supported until the diagnostic problems have been solved.