Physics R&D in Support of ITER/BPX Diagnostic Development

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Abstract. The development of diagnostics for a next step burning plasma experiment (BPX) is a major challenge [1]. Within the International Tokamak Physics Activity (ITPA), one Topical Group (TG) specialises in diagnostics and aims to support the development and design of the needed systems. Several diagnostics issues have been identified as 'high priority' and form the focus of current work of the TG. The core of this paper is a presentation and discussion of recent progress in the field of these high priority research topics. Moreover, the status of the recently initiated International Diagnostic Database will be briefly described.

1. Introduction

The development of diagnostics for a next step Burning Plasma eXperiment (BPX) is a major challenge [1]. Implementation of existing diagnostic techniques requires substantial design and in some cases dedicated R&D. Moreover, some plasma parameters cannot be measured by existing techniques under BPX conditions and new techniques are required. Within the International Tokamak Physics Activity (ITPA), one Topical Group (TG) specialises in diagnostics and aims to support the development and design of the needed systems. The principal activities of the group are to (i) identify and develop the requirements for the large range of measurements, (ii) identify research and development needs in the area of BPX diagnostics, (iii) advise on the selection of diagnostic techniques, on the design of the diagnostic systems, and on their implementation on BPXs, including integration with other components, (iv) develop appropriate databases, and (v) facilitate good communication within the area of diagnostics and specifically on BPX diagnostic issues.

The requirements for measurements are determined from a careful analysis of the role the measurements will play in the control and evaluation of the plasma performance and in attempts to understand the physical phenomena that limit the performance. Detailed specifications and the justification for all the required measurements have been developed for ITER [2,3], and more recently also for FIRE. The requirements for the various BPX's, and in particular ITER, are continuously being updated, in close collaboration with the other ITPA TG's, to take account of the newest experimental and theoretical findings at the various magnetic confinement devices around the world.

2. High Priority Research Tasks

The ITPA TG on Diagnostics is co-ordinating many voluntary physics tasks. In total five of these tasks have been identified as 'high priority' and form the focus of current paper.

2.1. Current Density Measurements (Requirements and Methods)

Task 1 is the *"Determination of requirements for the measurement of q(r) and assessment of possible methods that can be applied to a BPX"*. In general, the measurement of q(r) on a BPX is a very difficult but important task that is presently not well covered and so the development of new techniques that would demand less access and be more rugged in a reactor environment is encouraged. Different requirements are imposed on q(r) by the various operational scenarios (see Table I). Given the fact that the implementation of the diagnostics is very difficult, the continuous aim of the discussion is to derive the minimum requirements that are needed to support the physics programme. In a recent interaction with the Transport and ITB TG with the specific aim to assess the measurement requirements for advanced tokamak scenarios, it was suggested that it is desirable to have a higher spatial resolution in q(r) in the vicinity of internal transport barriers.

TABLE I: MEASUREMENT REQUIREMENTS FOR THE CURRENT DENSITY IN ITER

Parameter	Physics aim	Range	Resolution		Accuracy
q(r)	Physics study	0.5 - 5	10 ms	a/20	10 %
		5 - TBD	10 ms	a/20	0.5
r(q=1.5,2)/a	NTM feedback	0.3 – 0.9	10 ms	–	5 cm / a
$r(q_{min})/a$	Reverse shear control	0.3 – 0.7	1 s	–	5 cm / a

The main systems that are being designed for measuring q(r) in ITER have difficult implementation issues. For the Poloidal Field Polarimeter these are the installation and lifetime of the retro-reflectors mounted on the high field side. In the Motional Stark Effect (MSE) system, the viewing beam will have to be reflected off several mirrors (at least four) before detection, which could lead to impurity coatings and accompanying depolarisation effects.

Although polarimetry and MSE are the prime candidates for measuring the current density profile in the plasma core of a BPX, other diagnostics such as ECE and reflectometry can yield additional constraints for equilibrium solvers. In ASDEX-UG it has been demonstrated that sharp peaks occur in the density fluctuation level measured by reflectometry when rational q-surfaces are crossed during density ramp down experiments [5]. No dear peaks were observed during density ramp up. The measurements indicate that under some conditions the reflectometric measurements might be used to give one or more constraints on the q-profile.

2.2. Divertor Measurements (Requirements and Methods)

Task 2 is the *"Determination of measurement requirements in the divertor region and recommendation of diagnostic techniques"*. Ideally measurements of the main plasma parameters (n_e, T_e, etc.) would be made with good time and spatial resolution along and across both divertor legs, but this is not feasible because of access difficulties. Therefore, in this case also, it is essential to determine the minimum requirements for measurements. By working closely with the ITPA

Scrape Off Layer and Divertor TG, the requirements have been developed for ITER. System designs have also advanced and there is now a closer match between requirements and anticipated measurement capability for a number of divertor parameters although some significant discrepancies still remain. In particular, the measurement of the electron temperature at high spatial resolution along the divertor leg - as required for spectroscopic analysis - is difficult and it is unlikely that these requirements can be fully met. Measurements along the inner divertor leg look particularly difficult.

2.3. Radiation Induced Electro-Motive Force

Task 3 is *"Assessment of the impact of Radiation Induced Electro-Motive Force (RIEMF) on magnetic measurements and perform improved measurements on prototype coils".* A small EMF can be caused in mineral insulated cables by asymmetries in the radiation field and/or sensor load. The data on Radiation Induced Electro-Motive Force (RIEMF) in cables has recently been reviewed. Extrapolations to ITER conditions based on this data suggest that it should be possible to design magnetic coils for ITER which can operate satisfactorily even in the presence of this effect. However, results obtained in earlier radiation tests with prototype magnetic coils apparently showed a much higher RIEMF. A re-analysis of these results was undertaken and suggests that either a systematic error was present in the measurement of the drift (the integrator is the most likely cause of the difficulty), or that another voltage source was present in the measurement. Recent measurements of RIEMF in coils under γ-irradiation [6] also indicate a manageable effect in ITER (*see FIG. 1*) but the key test in a reactor (neutrons and gammas) remains outstanding. The Japanese Participating Team plans to carry out these tests in the course of 2002. The plain cable results suggest that RIEMF will not be a concern for large coils (e.g. saddle loops).

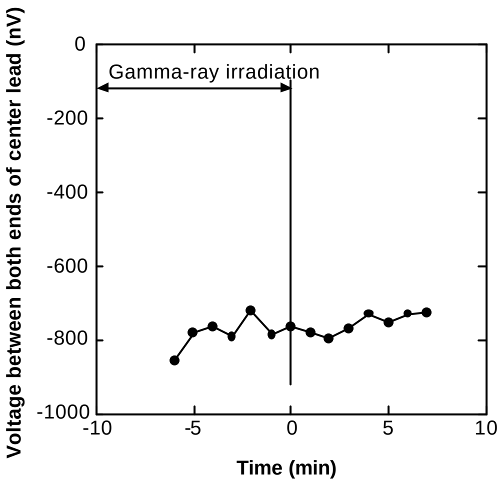

FIG.1. Time evolution of the voltage across a coil measured in a test rig (^{60}Co, 4 Gy/s). The upper limit of 50 nV of differential voltage change at the transition translates to > 800 s of pulse length under ITER conditions for this (smaller than planned) test coil. More sensitive tests are planned. (Adapted from [6]).

2.4. Life-Time Issues of Plasma Facing Mirrors

Task 4 is the *"Determination of life-time of plasma facing mirrors used in optical systems".* The plasma facing components of many diagnostic systems will be a mirror, that will be subject to intense neutron, gamma and ultra violet radiation, neutron heating, particle fluxes arising from charge exchange (CX) atoms (typically $2\cdot 10^{19}$ particles$\cdot$ $m^{-2}s^{-1}$ with energies up to several keV), and to the deposition of material eroded from the divertor, first wall and shield structure. Systematic measurements of the effect on reflectivity and on mirror lifetime of potentially damaging effects are required; especially erosion due to CX sputtering and deposition due to evaporation of first wall and divertor target plates. Lifetime studies of laser mirrors for large numbers of pulses are also required. Extensive tests in which candidate mirror materials have been subject to different types and levels of radiation have been carried out. Dedicated experiments have shown that single crystal mirrors (made of Mo, W and stainless steel) are very resistant to erosion caused by sputtering (*see FIG. 2*) [7]. The mono-crystalline mirrors can be made in large sizes (up to 12 cm). Good results have also been reported for mirrors made with metallic coatings such as Mo and Rh. Recent calculations of the eroded layer thickness due to the flux of charge exchange atoms have indicated that all of the above mentioned first mirrors will survive if sputtering is the dominant effect. The deposition of contaminants on mirror surfaces in the divertor region is expected to exceed the erosion by sputtering. However, the role of deposition on windows and mirrors for the core plasma is less clear and dedicated studies are needed at present day large-scale fusion devices. A mirror test will be implemented in the divertor and in the core plasma duct of JET. There are no major problems expected with second mirrors fabricated as metal film on metal substrate except for possible deposition of eroded first wall and/or duct material, the effects of which can be minimized by mitigating and protective methods (e.g. laser cleaning, baffles, shutters).

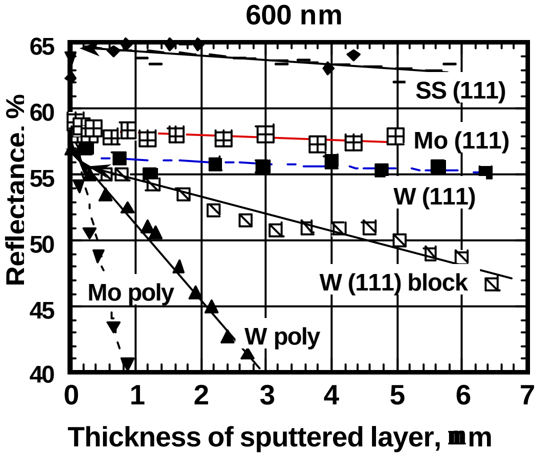

FIG.2. Reflectance of SS single crystal, W and Mo mirrors of different structure (polycrystal, block single crystal and single crystals with (111) planes of orientation) at 600 nm depending on the thickness of the layer eroded due to bombardment by ions of deuterium plasma.

2.5. Diagnostics for Confined and Escaping Alpha Particles.

Task 5 is the "*Development of diagnostic techniques for the measurement of confined and escaping alpha particles*". The measurement of alpha particles (confined and escaping) is important for a BPX, but existing candidate techniques have significant implementation and/or interpretational difficulties under BPX conditions. Fast-ion collective Thomson scattering has become a routine diagnostic on TEXTOR to study the fast ion velocity distribution [8], but the application of this technique to the diagnosis of confined alpha-particles has not yet been demonstrated. A technique that has demonstrated that it can yield information on the alpha-particles is Alpha Knock-On Tail Neutron Emission Spectroscopy [9] but requires a close coupling to the plasma and this leads to significant shielding and activation problems. On ITER both of these techniques will encounter severe difficulties to distinguish the alpha particles in the presence of a relatively intense background of fast ions from the 1 MeV neutral heating beams. Development of new techniques is therefore encouraged. The techniques that are proposed for escaping alpha particles are based on detectors (Faraday cups, scintillators, etc.) that are positioned at, or shortly behind, the first wall. These techniques also have implementation difficulties.

3. Intermediate and Long Term Issues

Additional to the high priority issues, the ITPA focusses also on a number of intermediate and long term issues including the assessment of methods to diagnose the fuel ratio n_D/n_T, to measure steady-state magnetic fields, to study the erosion of divertor tiles in real-time, to measure the occurrence and quantity of dust. Much of the work on these issues is done by six Specialists Working Group that work under the coordination of the ITPA Topical Group on Diagnostics. Two of these Working Groups are of a more general nature (First Mirrors and Radiation Effects), while the others focus on specific diagnostic methods and systems (Neutron Diagnostics, Thomson Scattering, Reflectometry, and Spectroscopy and NPA).

4. International Diagnostics Database

An International Database on the Reliability and Availability of Diagnostic Systems in use of present machines has been developed and is presently accessible via the internet (www.rijnh.nl/IDD). Information that is contained in the IDD is a general description of each diagnostic (e.g. number of channels, spatial and temporal resolution, accuracy, plasma parameters that measured), details on problems that are encountered in the hardware and in the analysis/interpretation of the data (if applicable with their remedies), calibration issues, etc. The database is relevant for anyone working in the field of diagnostics and encountering specific problems in the hardware and/or analysis as well to guide the selection and design of the diagnostic systems for present and future magnetic confinement devices. Currently the IDD contains data on 120 diagnostics from 15 different machines (most of them tokamaks, but including also stellarators, pinches and spheromaks).

5. Concluding Remarks

It should be noted that many of the above issues are of a rather urgent nature. Although the first BPX, including its diagnostic systems, is not expected to come into operation during this decade, many parts of the instrumentation issues will be ‘frozen’ in an early phase of the design. This will be especially the case for diagnostic components that are mounted in the vacuum vessel. This calls for an intense research programme on several issues including first mirror issues and radiation effects, and for an early definition of the diagnostics to be implemented and the establishment of their feasibility under ITER/BPX conditions.

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