Progress with High Priority R&D Topics in Support of ITER/BPX Diagnostic Development

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Abstract. The development of diagnostic systems for next step Burning Plasma experiments (BPX) such as ITER requires R&D in some key areas. The International Tokamak Physics Activity (ITPA) Topical Group (TG) on Diagnostics has identified five topics as 'high priority' and these form the focus of the current work of the TG: (i) development of methods of measuring the energy and density distribution of confined and escaping α-particles; (ii) review of the requirements for measurements of the neutron/α source profile and assessment of possible methods of measurement; (iii) determination of the life-time of plasma facing mirrors used in optical systems; (iv) assessment of radiation effects on coils used for measuring the plasma equilibrium and development of new methods to measure steady state magnetic fields accurately in a nuclear environment; and (v) Development of measurement requirements and assessment of techniques for measurement of dust and erosion. This paper presents the recent progress in these areas.

Introduction

In order to prepare the diagnostics for ITER substantial diagnostic development is necessary. Many specific issues have been identified by the ITPA Topical Group on Diagnostics as high priority, intermediate and long term. In this paper, the emphasis will be put on the present set of five high priority issues. For a more complete coverage of the other issues the reader is referred to [1,2].

High Priority Issues

1. *Development of methods of measuring the energy and density distribution of confined and escaping alpha particles*

The measurement of the energy and density distribution of confined alpha particles will be important on ITER. The distribution function should be measured as a function of pitch angle in order to separate the physics of passing and trapped ions. Techniques to make these measurements are in the infancy and the experience on existing devices is limited. One possible technique is Collective Thomson Scattering. There are two possible implementations:

CO_2 (10 μm) extreme forward scattering [3] and scattering at mm wavelengths with simultaneous forward and back scattering to resolve the velocity distribution near parallel and near perpendicular to the magnetic field [4]. A study has been completed in Europe [5] on the various collective Thomson scattering options to measure alphas and fast ions in ITER (60 GHz, 170 GHz, 3 THz and 28 THz). The 60 GHz option is the most attractive, because it combines a good s/n ratio with minimum required technological developments. It can provide good resolution in space, velocity and time, and meet the ITER measurement requirements. The system is rather robust against density variations and mechanical disturbances. However, this approach does have a magnetic field limitation ($B > 3$ T). A collective Thomson scattering system for measuring confined fast alpha particles on ITER based on the 60 GHz option has been designed [4]. Implementation of the system appears feasible although some key interface details need to be worked through. Detailed calculations have demonstrated that the system can in principle separate the isotropic alpha population from the energetic ions originating from the deuterium beams (see Fig. 1). [6].

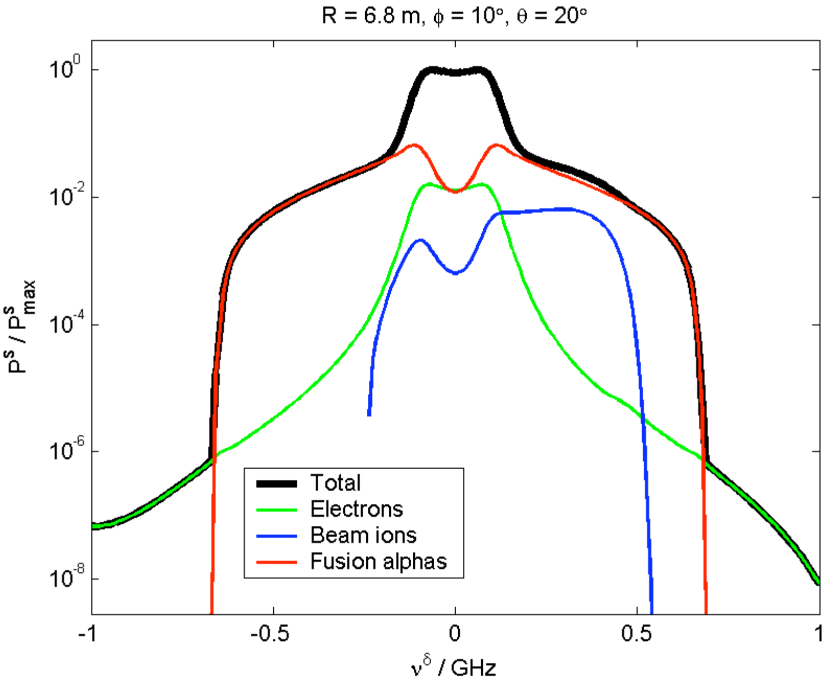

Figure 1. Spectral power density for a 60 GHz CTS in an ITER deuterium-beam heated reference H-mode plasma [6].

Another possible approach is based on the measurement of the alpha knock-on tail. This is an indirect method that is based on the elastic scattering between alpha particles and fuel ions, which produces energetic deuterons or tritons. One proposal, which has been successfully tested on JET [7], is to measure the high-energy neutron tail produced by alpha knock-on energetic ions. The high-energy neutron tail can potentially be measured using a neutron spectrometer, such as a Magnetic Proton Recoil (MPR) spectrometer, a bubble detector [8,9] or a nuclear emulsion track detector [10]. The discrimination of the alpha knock-on neutrons from beam particle knock-on neutrons is a potential problem that needs to be addressed. Another possible approach is to measure knock-on ions neutralised by the 1 MeV D^0 heating beams or by electron capture from intrinsic impurities [11]. In these cases, fast neutrals would be analysed by a Neutral Particle Analyser (NPA). Stripping foils can be used to separate energetic D^+ from He^{2+}-ions. Calculations for ITER predict NPA count rates up to 10^4/sec for deuterons of $E > 1$ MeV [11].

With regard to the measurement of escaping alpha particles, it is important not only to monitor the bombardment location (loss imaging) for machine protection, but also to measure the pitch-angle and energy distribution of the escaping alpha particles as well as their temporal behaviour during MHD to understand the underlying physics of the loss mechanism. The loss location is predicted to be at about 200° in poloidal angle with a toroidal enhancement between adjacent toroidal field (TF) coils. An infrared camera can be used for loss imaging. Candidate diagnostics for time-resolved pitch-angle and energy measurement of escaping alphas include Faraday-cup and scintillator probes. Their application to ITER is not straightforward because the diagnostics need to be installed near the first wall where the radiation conditions are the most severe. In this location the scintillators need to be actively cooled since they will be exposed to temperatures above 300 °C. Radiation induced effects such as Radiation Induced Conductivity (RIC) and Radiation-Induced Electro-Motive Force (RIEMF) may generate spurious signals in the measurements with the Faraday-cup detectors.

2. *Review requirements for measurements of neutron/alpha source profile and the assessment of possible methods of measurement*

One of the outstanding questions connected to the measurement of the alpha/neutron source profile is whether the neutron emission profile can be expected to be a constant on a magnetic flux surface. If so, the need for a Vertical Neutron Camera (VNC) on ITER is much reduced because it would be possible to obtain the profile of the neutron emission from measurements with the radial camera (RNC) and magnetics. In some conditions in JET, for example under conditions where non-isotropic fast ions are present (ICRH, NBI and conditions with strong negative shear), the neutron source profile is not a constant on a flux contour [12]. The non-uniformity of the neutron source on magnetic surfaces at JET was also measured during sawtooth crashes and is expected during Alfvén eigenmode activity. Under these conditions both a RNC and a VNC are needed to reliably measure the neutron source profile in JET. In ITER the alpha heating is expected to be dominant and isotropic and so the neutron emission should be nearly constant on a flux surface. It is necessary to model the plasma with the expected anisotropic fast ion content from ICRH, etc. and to establish if significant asymmetries in the neutron source profile will occur and if they can be measured.

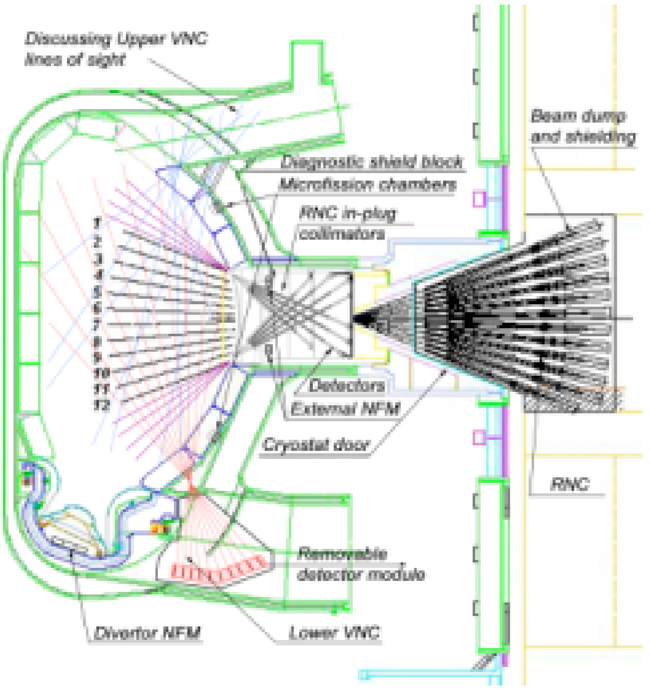

Figure 2. Radial Neutron Camera and recent proposal for a Vertical Neutron Camera.

Various designs for installing a VNC on ITER have been studied. Since ITER is not equipped with vertical ports a VNC looking down from the top is not feasible. The design currently under investigation has 11 viewing chords looking upwards through gaps between adjacent blanket modules with the collimators installed in a shielding block in a divertor port [13]. The design (see Fig. 2) appears to be feasible but further study of the concept is needed.

The various neutron diagnostics for ITER are presented in more detail in another paper at this conference [13].

3. *Determination of life-time of plasma facing mirrors used in optical systems*

The plasma-facing component of all optical systems needs to be a mirror because refractive components suffer from Radiation Induced Absorption and Radioluminescence. The plasma facing mirrors will be subject to erosion and deposition. Systematic measurements of the effect on reflectivity and on mirror lifetime of potentially damaging effects are required, especially erosion due to sputtering by Charge Exchange (CX) atoms and deposition due to erosion of first wall and divertor target plates. Lifetime studies of laser mirrors for large numbers of pulses are also required.

Significant progress has been achieved in understanding the effects of long-term bombardment of mirrors by CX atoms [14]. An important conclusion from simulation experiments, in which mirror samples are subject to bombardment by deuterium ions from a plasma source, is that in cases where sputtering is the main deteriorating effect, it is necessary to manufacture the mirrors from single crystalline materials or as metal film on metal substrate (see Fig. 3). Moreover, it was concluded from these simulation experiments on single crystal Mo and W mirrors, that mirrors fabricated with a higher degree of mechanical treatment, i.e., with higher level of strain in the outermost surface layers, degrade significantly faster than mirrors made with special precaution (i.e. by electric cutting followed by very careful polishing with a gradual decrease of the grain size). For Cu and Mo mirrors it was found that the reflectivity of mirrors with a large grain size, exhibits a much smaller decrease than that of mirrors with small grain size for the same amount of erosion, again indicating the importance of the manufacturing process of the mirrors.

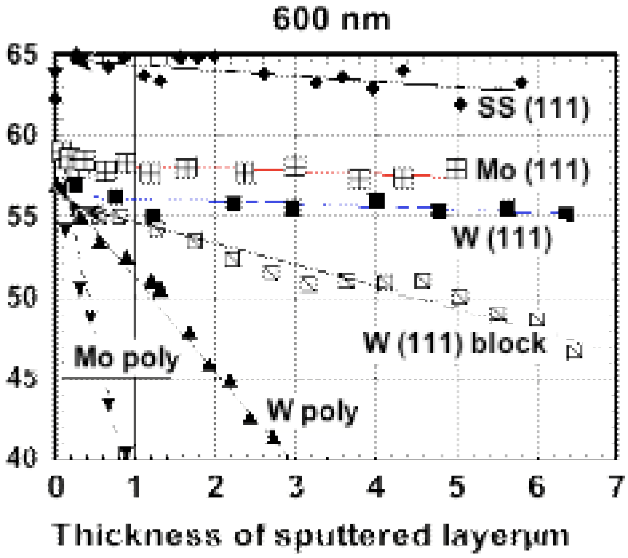

Figure 3. Effect of sputtering on the reflectance of various types of mirrors at 600 nm [15].

In contrast to the effect of sputtering, which is reasonably well understood and can be overcome by an appropriate choice of mirror material, there is presently no good model to describe the mass transport of the eroded materials in the tokamak, which can then be used as input in calculations to predict the deposition rate of these contaminants on the surface of plasma facing mirrors located at different positions. Dedicated experiments on operating plasma confinement devices aimed at understanding and quantifying the effect of deposition on the characteristics of mirrors have only recently been started and any definite conclusion cannot be made yet. However, it was observed that even a quite thin (≥10 nm) contaminant layer, e.g. of C-H or Be film, can strongly modify the total reflectance of the mirror as well as its polarization characteristics [15]. The effects of deposition need to be actively studied and mitigation methods (e.g. shutters, baffles) and cleaning methods developed.

4. *Assessment of radiation effects on coils used for measuring the plasma equilibrium and development of new methods to measure steady state magnetic fields accurately in a nuclear environment*

Radiation affects the design of magnetic coils in several ways: (I) In the selection of coil parameters to avoid prompt effects on the signal due to RIC, RIEMF and Radiation Induced Thermo-Electric Sensitivity (RITES). (II) In the choice of materials to avoid mechanical damage (cracking, swelling) and electrical damage (Radiation Induced Electrical Degradation – RIED). (III) In the design of suitable cooling mechanisms to take away the generated heat.

For RIC, the insulator materials and thickness has to be chosen so that the corresponding loading error is negligible. Due to space constraints, coils are affected more than loops. RIED is the degradation of insulating properties in the presence of radiation. This occurs for significant electric field (> 200 kV/m), at elevated temperature (> 200 °C), exposed to significant radiation level (> 100 Gy/s) and kept in this condition for significant time (> 1000 s). The insulator material, including impurity content, is important and even different samples of the same material can behave differently.

RIEMF is generated as the radiation (neutrons and gammas) induces currents between the sensor wire and its surroundings. The dominant mechanism depends on the materials of the sensor and on the radiation spectrum. It is already well documented for cable used in specific applications in fission reactors. This *current*, depending on RIC and external loads, will cause the winding to float at some *potential* with respect to the instrumentation ground. This is the so-called RIEMF. Some fraction of the RIEMF current can generate a differential voltage (along the wire) through asymmetries in the radiation field and loading, whether these are internal (due to RIC) or external. Some fraction of the RIEMF voltage can also appear in the signal through an inadequate Common Mode Rejection Ratio (CMRR) of the integrator.

RITES is a recently isolated effect which was originally invoked to explain the appearance of larger than expected (several μV) signals across the terminals of ITER-like test coils exposed to ITER-like radiation levels in fission reactors [16]. In RITES, the thermal gradients are supplied by nuclear heating and gradients in thermoelectric properties are generated by transmutation and/or lattice damage. The present experimental results [17] suggest that RITES in fact dominates over RIEMF and that the thermoelectric sensitivity of un-irradiated coils (due to manufacturing non-uniformities in the conductor) can exceed the predicted RIEMF.

The design of the ITER magnetic diagnostic has been evolving for some time. All the above issues affecting the magnetic coil design and performance have had to be considered, and, through ITER-specific R&D, some of the key issues have been identified for the first time. Throughout, the aim of the design activity has been to provide a design that meets a demanding specification and is qualified for the machine lifetime despite the identified constraints.

For RIEMF, conductor and sheath materials, radiation field uniformity and integrator specification are the important parameters. From the currents observed in ITER-like coils in fission reactors [18], the maximum RIEMF current is about 1 μA and this, into a load resistance of 1 kΩ, would generate a common mode voltage of 1 mV and require a Common-Mode Rejection Ratio (CMRR) of 2000 or better for the integrator. Integrators that can meet the ITER pulse length requirements are available [18] but need further development to achieve the required CMRR. The resulting RIEMF voltage would be about 100 nV for the expected asymmetry of order 10%. This is tolerable, so it appears that an acceptable design can be found for the ITER coils for long-pulse applications.

For RITES, conductor material, radiation field uniformity and temperature control all play a role. For the equilibrium coils already designed for ITER it is expected that RITES will contribute ~1 μV to the coil output and therefore be the dominant source of error at the coil and in the flux measurements for timescales in excess of a few hundred seconds. More R&D is required on cable performance under irradiation, but on present results it appears that specialised coils for long pulses with better cooling characteristics and, almost certainly, poorer frequency response will have to be added to the design. It may also prove necessary to relocate these coils near the middle of the blanket module from the present location near the edge.

Although there are still aspects of the results not fully understood, on the basis of the work carried out, it is probable that coils can be developed for ITER in which the combined action of RIEMF, RITES and other related effects is tolerable, and it may be possible to use the coils for measurements on long (> 1000 s) pulses.

In parallel the development of steady state sensors also shows progress and it is likely that Hall sensors can be developed for applications outside the ITER vacuum vessel [19]

5. Development of measurement requirements and assessment of techniques for measurement of dust and erosion

In a DT-fuelled tokamak, the dust normally generated by various mechanisms can potentially become a serious safety issue if it reaches significant quantities in mobile form. For a machine the size of ITER, 1 μm removed from the first wall corresponds to several kg of potentially hazardous material, and so significant quantities of dust might be generated. Several techniques are under investigation to provide spot measurements of the amount of dust collected in key areas in the machine (for example below the divertor) in order to estimate the total amount and, potentially, determine the need for preventative cleaning. Techniques for measuring dust that can be implemented on a BPX such as ITER are required along with a method for extrapolating the local measurements to give estimates of the required global quantities. The progress in the area of dust diagnostics and real-time erosion monitoring has been slow and therefore this issue has recently (June 2004) been promoted to high a priority issue.

A novel device to detect dust particles settling on remote surfaces has been developed and tested [20]. This detection device consists of two interlocking combs of closely spaced conductive traces on a Teflon circuit board. When a direct current bias is applied, impinging dust creates a transient short circuit between the traces. The increase in bias current generates a signal pulse that is counted by standard nuclear counting electronics. The device has been tested in air and in vacuum and its sensitivity to carbon particles determined. The detection threshold was 50 μg/cm^2 for the finest (127 μm) grid spacing. Other candidate *dust monitors* include modified capacitive pressure gauges, modified quartz microbalances, optical fibre endoscopes inserted between pulses, and optical collection trays.

Mitigation and protection methods have been developed for optical components of a possible Thomson scattering system for measurements in the divertor region [21]. A deuterium gas flow in front of the mirror is included to prevent dust from settling on top of the mirror. Bench tests indicate that for an efficient dust removal a gas-fuelling rate is required of about 1 Pa m^3/s.

6. Establishment of a Radiation Effects Database.

Before June 2004 the establishment of a Radiation Effects Database was a High Priority item. It was replaced with the Dust and Erosion Measurements (see 5.), which had previously been an intermediate priority item.

During the ITER EDA many measurements were made of the change of relevant physical properties of candidate materials for diagnostic components (windows, optical fibres, ceramics, etc) that can occur due to irradiation. Further measurements are ongoing. The results of this worldwide effort are presently described in numerous separate reports and publications. To make the information better accessible to the diagnostic community and to irradiation experts an electronic Radiation Effects Database is being developed.

Conclusion

While good progress has been made more is needed on all the high priority topics. Moreover, there are also many intermediate and long-term issues that need to be addressed. It is expected that co-ordinated work in all the ITER parties will continue. The recent addition of China and Korea to the ITPA process should increase the resources available to work on these topics.

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