High Priority R&D Topics in Support of ITER Diagnostic Development

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Abstract. The development of diagnostics for ITER is a major challenge because of the harsh environment, strict engineering requirements and the need for high reliability in the measurements.. A number of R&D tasks have been identified by the International Tokamak Physics Activity (ITPA) as 'high priority' and form the focus of current work: 1) Review the requirements for measurements of the neutron/α particle source profile and assess possible methods of measurement; 2) Development of methods to measure the energy and density distribution of confined and escaping α-particles; 3) Determine any additional tests and measurements needed of the irradiation effects on candidate materials and sensors used for diagnostic construction; 4) Determine the life-time of plasma facing mirrors used in optical systems; 5) Develop the requirements for measurements of dust, and assess candidate techniques for the measurement of dust and erosion; 6) Assess the effects of radiation on magnetic coils used for measurements of the plasma equilibrium and support the development of new methods to measure steady state magnetic fields accurately in a nuclear environment. This paper will report on recent achievements in these tasks.

1. Introduction

The harsh environment on ITER arising from the high levels of neutron, gamma and electromagnetic radiation, particle bombardment and nuclear heating, means that a range of phenomena new to diagnostic design have to be considered in the implementation of the diagnostic systems [1]. R&D is required in many areas to provide the necessary knowledge base for the design. The International Tokamak Physics Activity Topical Group (TG) on Diagnostics has identified a number of topics as 'high priority' and these form the focus of the on-going work of the TG. This paper reports on recent progress in the various 'high priority' topics.

2. High Priority Topics

2.1. Assessment of the various options for the Vertical and Radial Neutron Cameras to measure the 2D n/α source profile and asymmetries in this quantity, and assessment of the calibration strategy and calibration source strength needed.

An instrument which measures the neutron emission along multiple lines of sight in the poloidal plane through a mid-plane port is included in the ITER diagnostic set, and is known as the Radial Neutron Camera (RNC). The camera measures the total neutron emission and, assuming the neutron emission to be a constant on a magnetic flux contour, the spatial profile of the neutron emission can be deduced by combining the neutron measurements with magnetic measurements. The central question is, therefore: Can the neutron emission profile be expected to be constant on a flux contour in ITER? If this is not the case, then measurements with a Vertical Neutron Camera (VNC) will also be needed so that a tomographic inversion can be carried out. An investigation is therefore in progress to determine if asymmetries will occur in ITER and if it is important that they should be measured. Part of the investigation involves studying the asymmetries on existing machines.

Examples of asymmetries in the neutron emission profiles in JET [2,3] and JT-60U have been found. Following tritium pellet injection in JET, a large peak in the neutron emission is observed near the plasma edge [4]. The condition is transient with a duration of about 50-150 ms. Abrupt Large Amplitude Events occur in JT-60U and give rise to asymmetric neutron emission [5]. While the observed event on JET is transient it could be sustained on ITER in case it will have continuous T fuelling. Instabilities on D-IIID have been found to give rise to asymmetric fast ion profiles and calculations suggest that a similar phenomenon may occur on ITER [6]. Additional to these examples from present devices, it still needs to be demonstrated via dedicated modelling studies whether asymmetric neutron profiles will occur on ITER under any of the planned operating scenarios. If the answer is positive, it will be necessary to demonstrate that the asymmetric profiles can indeed be measured with the proposed combination of RNC and VNC.

The design of the RNC is well advanced [7]. The system is a combination of an ex-vessel neutron camera with a number of in-vessel chords, such that the full plasma cross section can be measured (see Fig. 1).

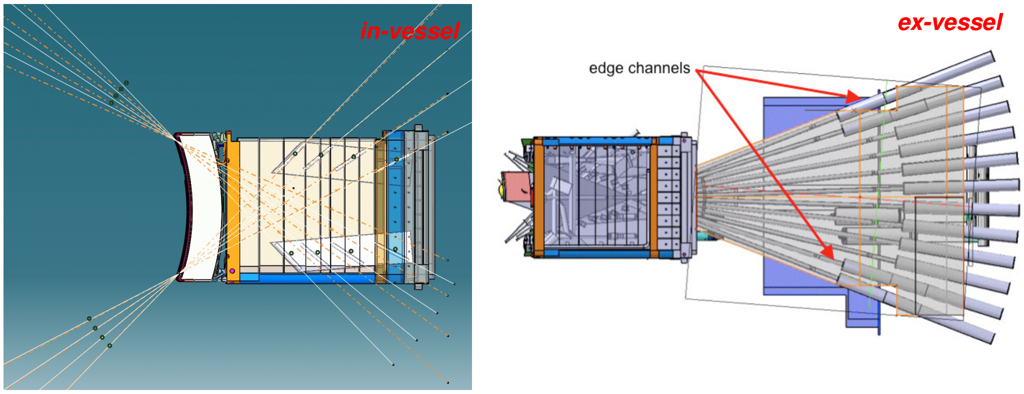

FIG. 1. The Radial Neutron Camera is composed of in-vessel (left) and ex-vessel chords (right). Courtesy B. Esposito

The most promising option for a VNC has the collimators and detectors installed in a divertor port, and views the plasma through (enlarged) gaps between the divertor cassettes and the blanket modules. The integration issues of the divertor VNC are thought to be manageable, but the system has a relatively low signal-to-noise (s/n) ratio for the channel monitoring closest to the low field side. Future work will be focussed on solving the integration issues and finding an alternative option for the chord which has a low s/n value. When combined with the measurements from the RNC, it should be possible to determine the neutron source profile as required.

A central issue in the discussion of the neutron diagnostics is the calibration strategy and the strength of the neutron calibration source that will have to be mounted temporarily in the ITER vacuum vessel for the in-situ calibration. It is important to establish the relationship between the costs of the various calibration method options (source strength and deployment method) and the total time required for the calibration. The latter will be on the critical path to ITER operation since the calibration will be one of the last activities before the closure of the vacuum vessel.

It is proposed that the neutron diagnostics are calibrated using two sources in combination: a ^{252}Cf source (with 10^{10} n/s) and a 14 MeV neutron generator (with 10^{11} n/s). In order to obtain the necessary calibration data, the sources will need to be located at many different positions (current estimate is 92) in the ITER vessel and the total time needed for calibration is estimated to be of the order of 5-6 weeks. It needs to be studied, via Monte-Carlo Neutron Particle (MCNP) transport calculations, whether the total number of calibration points can be reduced without affecting the calibration accuracy and thereby reducing the time needed for calibration. An important component for the calibration of the neutron systems is the availability of a neutron test area [8]. Such a dedicated area is included in the plans for the hot cell building at ITER.

2.2. Development of methods of measuring the energy and density distribution of confined and escaping α-particles.

In order to understand the behaviour of the dominant heating particles in the burning plasma, and to support the physics studies leading to optimal performance, it will be necessary to measure the number density and energy of the confined energetic alphas and the flux of escaping alphas. Since high energy α-particles are not common in present-day devices (apart from some limited experiments in TFTR and JET), systems that could diagnose the α-particle population are still in the development phase. Various systems have been proposed, but most of them need to be further developed and tested at present devices (e.g. in alpha-particle simulation experiments).

With respect to the *confined α-particles*, a 60 GHz microwave collective Thomson scattering (CTS) system for ITER [9], aimed specifically at measuring the confined alphas and other fast ions, has been further developed. In principle the system could meet most of the ITER measurement requirements at different radial locations simultaneously, and a conceptual design is available. The system is able to distinguish the alphas from the deuterium ions in the heating beams [10] (see FIG. 2). A CO_2-laser system for CTS measurements at JT-60U has been upgraded to higher power and higher repetition rate [11]. First measurements with this system should give an indication of the value of such a system for ITER.

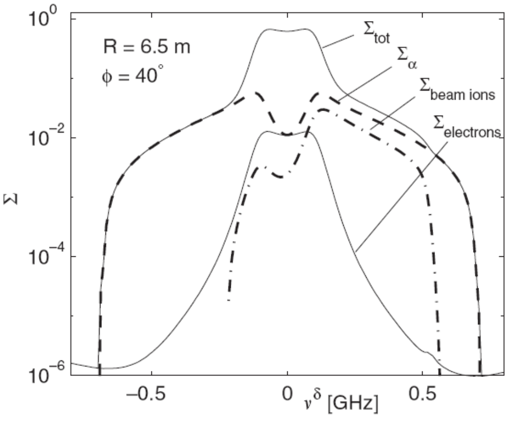

FIG. 2. Normalized theoretical CTS spectrum for a scattering angle $\theta = 20°$, orientation $\varphi = 40°$ and 60 GHz probe frequency. The figure illustrates the total power density Σ_{tot} as well as the separate contributions from the α-particles, the beam ions and the electrons. Figure taken from [10].

Recent experience at JET has demonstrated that γ-ray measurements can give important new insights in α-particle physics and could be of high interest for ITER [12]. The γ-ray emission provides information on the distribution function of charged fast particles. The γ-ray system on JET is being upgraded so that it will be compatible with DT operation.

Confined alpha particles in the energy range 1 – 3 MeV could, in principle, be measured by a double charge exchange diagnostic, utilizing a 1.7 MeV, 10 mA tangentially injected He-beam [13]. Feasibility studies have indicated that such a system could satisfy the ITER measurement requirements for confined alpha particles in the plasma core. Present work concentrates on development of suitable He-beams [14] and on the possible integration of such a system on ITER.

New, high efficiency, bubble detectors have become available and may enhance the prospects for knock-on neutron measurements with these compact devices. Neutron emission spectroscopy (NES) has the potential to provide some information on the knock-on neutron population. To resolve the alpha particle population under various ITER heating scenarios, different views would be needed. In total, three different NES systems (viewing radial, co- and counter-tangential) would be required to cover all scenarios, but implementation of multiple instruments on ITER is unlikely because of the large aperture and direct coupling needed [15].

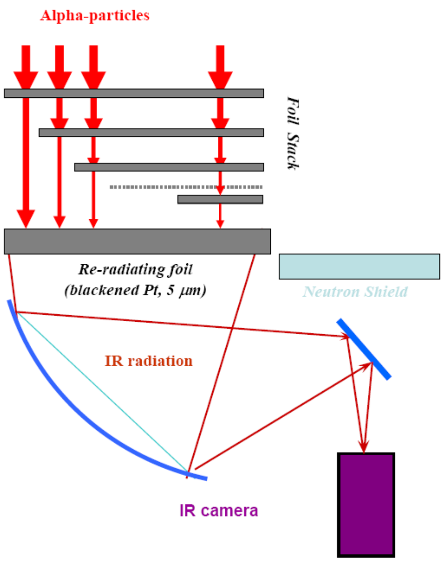

FIG. 3. Principle of the infrared viewing bolometer (IRVB) for detection of escaping alpha particles. Figure courtesy of B. J. Peterson.

The prospects for diagnosing *escaping alpha-particles* are more pessimistic compared to those for confined α-particles. Systems such as scintillators and Faraday-cups will probably be subject to failure in the high radiation fields at ITER. Recently proposed techniques still need to be demonstrated in an environment that resembles ITER. One of these techniques utilizes ceramic scintillators mounted in special cut-outs on the sides of the blanket modules. The scintillators would be observed in the visible region through a diagnostic port. New ceramic scintillators with good linearity of light emission and that quench only at relatively high temperatures have been developed [16]: YAG:Ce stiffened by a ceramic binder and YAG:Ce ceramics sintered at high temperature under pressure. These scintillators have been tested under irradiation with a 3 MeV He^+ beam. Reactor tests are planned to test the sensitivity of the system to neutrons and gammas. It is still unclear, however, how these could be installed on ITER.

An infrared imaging video bolometer (IRVB) combined with an energy discriminator using a varying number of layers of absorber foils (see FIG. 3) is also proposed to measure the intensity and energy distribution of escaping α-particles and a prototype has been tested on an ion accelerator [17]. A prototype IRVB has been successfully operated at JT-60U for measurements of radiated power [18]. The first images from the IRVB are reasonably consistent with data obtained with resistive bolometers. The IRVBs can operate in a reactor environment and prospects for their utilization on ITER are optimistic.

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

Long-time integrators that are compatible with >1000 s operation have been recently developed for various fusion devices. Integrators for JT-60U are designed such that saturation, caused by excessively high voltage during MHD instabilities including disruptions, is avoided [19]. For KSTAR new integrators are being developed that are compatible with long pulse operation. Integrators developed for W7X have also been developed to the required standard and, in addition, appear to be able to cope with the typical level of Radiation-Induced Electro-Motive Force (RIEMF) common mode currents expected in ITER [20]. The understanding of RIEMF, Thermally-Induced EMF (TIEMF) and Radiation-Induced Thermo-Electric Sensitivity (RITES) is gradually increasing. Processes leading to a pure RIEMF contribution in the core-to-sheath current/voltage in mineral insulated cables are well understood and the modelling results are in good agreement with observed data. For ITER conditions the prediction for RIEMF is ~100 nA/m for Cu core and ~3 nA/m for Stainless Steel (SS). The TIEMF contribution of virgin cable appears to depend on changes in its physical state during manufacturing and are more pronounced for pure Cu than for SS. RITES during irradiation is probably caused by transmutation for Cu and by lattice damage in SS; this means that the prediction of the effect for ITER has to rely on simulations to account for the difference in spectra between fission and ITER. Tests are underway to understand the detailed causes of TIEMF and aid conductor selection for signal cables and coils. In parallel, the design of the coils is being improved to reduce the thermal variation within the winding pack.

Radiation-hard Hall probes (see FIG. 4) have been developed and tested under irradiation conditions [21]. The Hall probes are presently being tested at JET, Tore Supra and TEXTOR and could be used outside the ITER vacuum vessel, provided they would be able to work at higher ambient temperatures. The change of the Hall probe sensitivity at this location in ITER is predicted to be ~7% during the full life time. An in-situ self-calibration technique that compensates for this change has been developed [21]. Preliminary work is underway to assess the possibilities for other in-vessel and ex-vessel steady state techniques, based on thin metal film Hall probes.

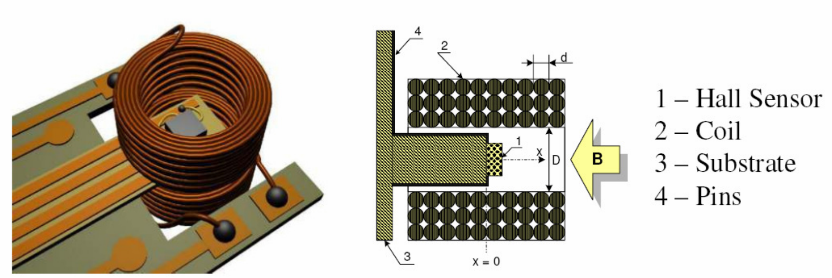

FIG. 4. 3D model of a Hall probe with in-situ self-calibration mechanism. Figure taken from [22].

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

Because of the need to prevent neutrons streaming to the ITER structures, direct lines of sight for diagnostics are in general not possible especially for optical systems that requiring optical high throughput (large apertures). In these cases the plasma is viewed by labyrinthine optical systems employing mirrors. The first mirrors are positioned in an extremely vulnerable environment and are subject to erosion and deposition by particle bombardment, nuclear heating, swelling, etc. Despite this, they should maintain their optical properties over the full ITER life time. Therefore, much attention is devoted to R&D aimed at developing mirrors that can survive in this harsh environment and to methods to protect the mirrors [23].

Detailed experiments on the effects of erosion and deposition on mirrors have been performed in several fusion devices. The experiments have shown that, if the materials are chosen carefully (low sputtering rate single crystals or metal film on metal substrate), erosion should not have a significant effect on the reflectivity of the mirrors in a wide wavelength range. On the other hand, deposition rapidly deteriorates the reflectivity as well as the polarization characteristics of the reflected radiation. Deposition patterns on mirrors have been measured in several machines. Encouraging results have been achieved in dedicated experiments at DIII-D (see FIG. 5). Molybdenum mirrors exposed at moderately increased temperature of ~125°C-180°C in DIII-D divertor, did not suffer from carbon deposition despite significant exposure time in the deposition-dominated conditions [24]. Dedicated tests on current machines (Globus-M and T-10 tokamaks) and in laboratory facilities (Ioffe and Kurchatov Institutes) have shown that by operating the mirror at elevated temperatures the deposition is significantly reduced, but the mitigation process is complex and strongly depends on exposure conditions. It has also been found that the choice of the substrate (mirror) material strongly influences the deposition efficiency (TEXTOR, Tore Supra and TCV tokamaks and in laboratory tests). Several new experiments have recently been started or are planned in the immediate future, addressing a number of key issues: deposition mitigation (DIII-D, TEXTOR), material choice (University of Basel, TEXTOR, Kurchatov Institute, ENEA), shutters/protection (HL-2A), techniques for in-situ control of mirror performance (IPP Kharkov), development of methods for in-situ cleaning of deposited films by laser ablation and the exposure of mirrors to low temperature plasma (Kurchatov and Ioffe Institutes). Relatively recent developments are Rh-coated mirrors and nanostructure mirrors, which are being tested now for their potential application in ITER.

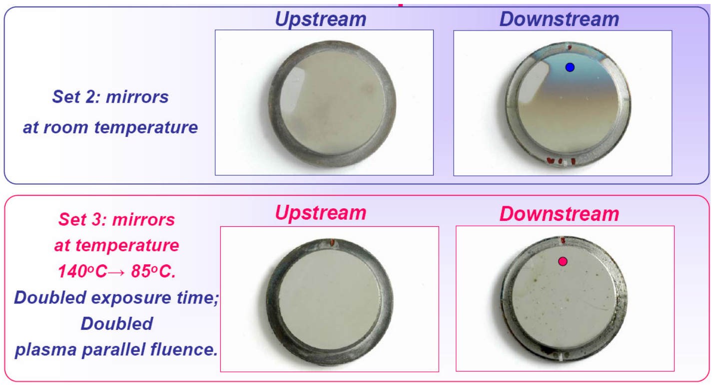

FIG. 5. Photographs of mirrors that have been exposed to the DIII-D divertor plasma. The mirrors that were heated clearly show less deposits than mirrors that were at room temperature. Other condition were identical. Figure courtesy of A. Litnovsky.

The effect of erosion on the reflectivity of retro-reflectors to be employed in the poloidal polarimeter (118 or 50 μm) and the tangential interferometer/ polarimeter (10.6 μm) systems at ITER has been studied [25]. Both theoretical calculations as well as test bench experiments with mirrors that were eroded by deuterium ions from a plasma source have indicated that for retro-reflectors employed at a wavelength of 118 μm the reflectivity is not seriously affected, provided the reflectors are manufactured from Mo or W. At 10.6 μm the effect of erosion may lead to a degradation of the reflective properties.

Work with polycrystalline W and Mo mirrors that were exposed to bombardment with He^+ ions from a source showed that the reflectivity can be strongly reduced in the wavelength range 190-900 nm due to formation of bubbles, blisters and holes [26]. The reflectivity decreases with increasing ion energy, irradiation temperature and dose of He ions. Recent calculations of the He fluence and the corresponding energy spectra during the full ITER life time at the various mirror locations in ITER are comparable in magnitude to the threshold where bubble formation might start to occur. Since these effects occur over such a long time it is thought that they can probably be ignored in ITER. Nevertheless, since the modelling calculations are based on numerous assumptions, it is felt that these should be checked independently before conclusions are reached.

A predictive capability is required in order to be able to design mirrors which will have a long lifetime in the ITER environment. Dedicated models should be developed to predict the effect of deposition and erosion on the optical properties (reflectivity, polarization characteristics) of the mirrors. These models should be benchmarked by comparison to practical situations in present devices. Modelling of the mirror lifetime in realistic situations has been initiated but much more needs to be done in this area.

2.5. Development of measurement requirements for measurements of dust, and assessment of techniques for measurement of dust and erosion.

Measurements of dust are required to ensure that excessive radioactive dust has not accumulated and become a potential safety hazard. Measurements can only be made of the dust in specific locations but the safety inventory limits are set on the total amount of dust on the hot and cold surfaces. It is expected that a significant amount of tritium will be retained in co-deposits of Be and C which distribute as dust and hard films. The topic of dust cannot be separated from the topics of first wall (blanket and divertor) erosion/deposition and tritium inventory, and they are therefore combined into a single high priority issue.

The work on dust measurements is still very much hampered by the fact that there are not yet any clear requirements for the measurement that can realistically be achieved. A number of possible methodologies to address the combined issue, as well as techniques for the measurement of dust have been identified. For example, during the regular maintenance periods of ITER, dust samples could be taken from various locations (target plates, blanket tiles) and detailed material and tritium analysis could provide the overview to the combined issue. Moreover, a specific retractable sample station [27] could be mounted in a divertor cassette for routine measurements of C co-deposits (see FIG. 6). This system could be used during ITER operation to take samples on a regular basis, which could be locked, transported to, and analysed in a remote station. One possible strategy would be to take samples from various locations during the ITER hydrogen phase so as to determine the locations were most dust is collected. Specific dust diagnostics could then be installed to target these areas in the DD and DT phases.

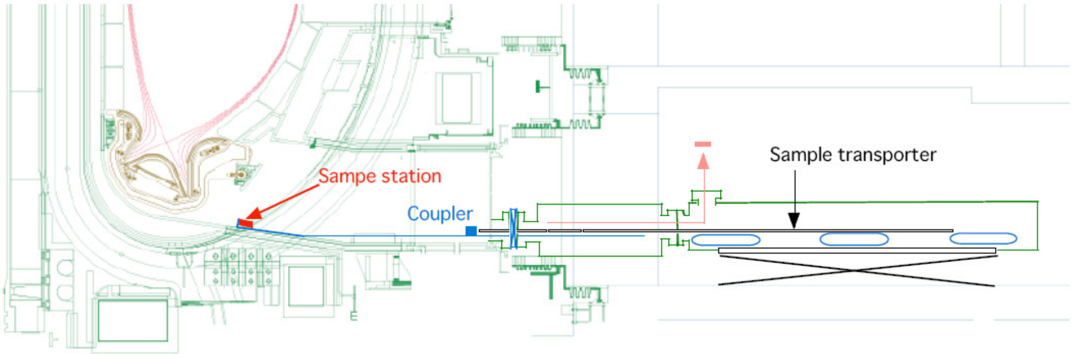

FIG. 6. Retractable sample station for measurement of dust underneath the ITER divertor. Figure courtesy of K. Itami.

Various in-vessel dust diagnostics have been proposed including dust detection grids [28], capacitive diaphragm microbalances [29], and laser ablation techniques. It is yet to be determined whether these techniques can be applied in ITER. In DIII-D dust is observed as a parasitic signal in many of the Thomson scattering data [30]. The basic particle/radiation interaction is Mie scattering. It is possible to determine the number density of dust particles from the data, but it is not clear if the dust thus measured can be used to predict the amount of dust that can become a safety hazard.

2.6. Determine any additional tests and measurements needed of the irradiation effects on candidate materials and sensors used for diagnostic construction.

The harsh radiation environment expected in ITER has led to an ever increasing activity on specific radiation effects of concern for diagnostic components [31,32]. The radiation induced modification/degradation of some of the physical properties, has to be taken into account in diagnostic design and for this to be done accurate data on these effects is required. As the design of ITER diagnostic systems has matured, radiation work has changed from a more general assessment of potential problems, to one where specific components are being examined. In addition, new potential radiation related issues have been identified, such as TIEMF (Thermal Induced EMF) and RITES (Radiation Induced Thermoelectric Sensitivity). The outstanding needs of the diagnostic systems in terms of radiation tolerance, as well as significant gaps in the current radiation effects knowledge base for components are now being identified. Examples of radiation tolerance testing which is on-going, planned, or still to be considered include: selected cables and complete coil assemblies for in-vessel magnetic sensors, optical fibres, complete window assemblies, bolometers, Hall probes, qualification for in-vessel use of neutron flux detectors and compact spectrometers for the RNC, and microfission chamber survival to ITER end of life. It is clear that much dedicated work and reactor time is needed in this area.

3. Concluding remarks

Significant progress has been made with the high priority topics and in several areas the needs of diagnostic design are satisfied. However, further work is required in some areas and this has been specified and in many cases is underway. There is a still the need for the development of new diagnostic techniques and instruments that will be rugged in the ITER environment There are many other diagnostic issues that are of similar importance, but somewhat less urgent. The progress on several diagnostic topics is presented in a number of separate papers in these proceedings. An overview of the design and implementation of diagnostics systems for ITER is given in [1]. Ref. [23] gives an overview on the work on first mirrors. The progress in the field of Thomson scattering and Beam-Aided Spectroscopy for ITER are presented in refs. [33] and [34]. The measurement requirements and the diagnostics for fast particle measurements are reviewed in [35]. A comprehensive overview of the diagnostics R&D work in the field of ITER diagnostics will be published in April 2007 in the 'Progress in the ITER Physics Basis' [36].

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