Key R&D activities for ITER Diagnostics

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Abstract. The design of diagnostic systems for ITER requires active R&D in many areas. This paper gives an overview of the progress in diagnostic R&D that has been made during the last two years, with emphasis on the various high priority topics (related to alpha particle measurements, neutron tomography, dust and erosion measurements). In addition, the progress that has been achieved in other diagnostic developments for ITER, for example in beam-aided spectroscopy, passive spectroscopy, neutron diagnostics, reflectometry and radiation effects are presented.

1. Introduction

The design of diagnostic systems for ITER requires active R&D in many areas [1]. The International Tokamak Physics Activity (ITPA) Topical Group (TG) on Diagnostics has identified various topics as 'high priority' (HP) and these form the focus of current work. This paper gives an overview of the progress in diagnostic R&D that has been made during the last two years, with emphasis on three of the ITPA High Priority topics:

- Development of methods of measuring the energy and density distribution of confined and escaping α-particles;
- Assessment of the various options for the Vertical Neutron Camera to measure the 2D n/α source profile and asymmetries in this quantity, and assessment of the calibration strategy and calibration source strength needed;
- Development of requirements for measurements of dust, and assessment of techniques for measurement of dust and erosion (with a special emphasis on dust measurements).

Additionally, also a number of other ITER-relevant diagnostic developments will be presented. The progress with the development of first mirrors that can survive the ITER environment (a fourth High Priority topic) is the subject of a separate paper [2]. The latest developments with the ITER measurement requirements and the diagnostic system are also presented in a separate paper [3].

2. High Priority Topics

2.1. Development of Methods of Measuring the Energy and Density Distribution of Confined and Escaping α-Particles.

Various techniques are being studied for their feasibility to measure the confined α-particles in ITER. These include: 1) Collective Thomson scattering; 2) charge exchange recombination spectroscopy on slowing down alpha particles in the energy range up to 0.5 MeV using the Diagnostic Neutral Beam, or from 0.5 to 1.5 MeV using one of the Heating Neutral Beams; 3) alpha knock-on neutron tail measurements; 4) alpha knock-on deuteron and triton NPA measurements; 5) passive flux of MeV He-atom NPA measurements; 6) Gamma-ray emission spectroscopy; and 7) a double charge exchange diagnostic based on a 10 mA, 1.7 MeV tangentially injected He-beam.

Potentially, the Collective Thomson Scattering (CTS) technique can enable a complete determination of the fast ion distribution function f(**v**,**r**,t) in burning plasmas. Prototype experiments at TEXTOR [4] have demonstrated the merits of CTS, and the practical requirements for making fast ion CTS measurements in burning plasmas are understood and tractable. The design and R&D on a 55 – 60 GHz CTS system for ITER [5] have continued (Fig. 1). As part of the changes arising from the design review process, the in-port components of this system are included in the revised ITER diagnostic system. Two options for the receiving system (with 1 and with 2 mirrors) are presently being explored. A mock-up of a candidate 4-mirror receiver system for the high field side (hfs) of ITER has been developed to demonstrate that there could be an engineering solution for such a system. However, the impact of the hfs system on other systems, for example, the blanket modules, and the enhanced, localised, nuclear heat load on the central solenoid have not yet been determined. Neutronics calculations have, however, been performed to study the heat loads on the first mirror. Simulation codes have been used to mimic the effect of beam misalignments. CTS in principle offers a number of potentially important additional measurements such as that of the fuel isotope ratio and of poloidal and toroidal plasma rotation. For these measurements much less power (~10 kW) than that required for the alpha measurements would be needed. Work on a 10 μm CTS system at JT-60U has largely concentrated on upgrading the CO_2 laser system.

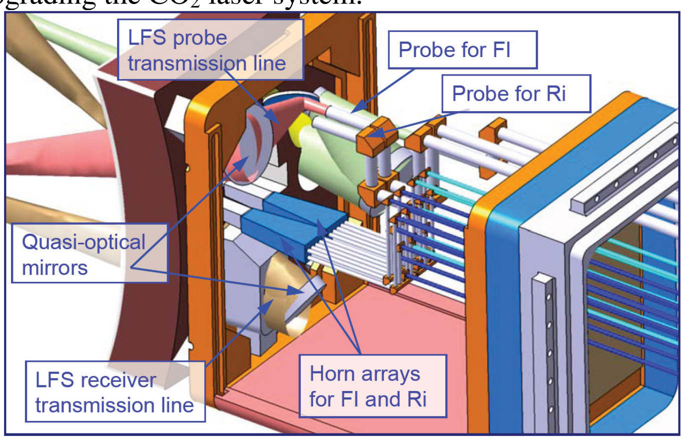

FIG. 1. Schematic view of the in-port components of the fast ion CTS system. Courtesy S. Korsholm.

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. Feasibility studies have indicated that such a system could satisfy the ITER measurement requirements for confined alpha particles in the plasma core. In Japan a full-size strongly focusing He^+-source has been developed for use in a proof-of-principle double charge-exchange diagnostic to demonstrate the principle [6]. A beam current of > 2 A was obtained at a beam energy of 20 keV. Additionally, a proof of principle lithium cell for production of a ground-state He^0 beam was constructed with an efficiency >1% for conversion of He^+ to He^-.

Charge Exchange Recombination Spectroscopy on Slowing-Down alpha particles also appears to be feasible in the energy range up to 0.5 MeV using the Diagnostic Neutral Beam or from 0.5 to 1.5MeV using one of the Heating Neutral Beams. A survey diagnostic for fast ions based on charge exchange recombination spectroscopy on the heating neutral beam has been proposed, with the aim to detect fast spatial redistributions of alpha particles due to interactions with Alfvén waves.

Measurements of the distortions in the neutron tail due to alpha knock-on interactions potentially provide information about the confinement and slowing down of the alpha particles. A potential new approach to the measurement is to use neutron activation techniques with energy thresholds between 15.5 and 20 MeV. It has been estimated that gaseous activation targets exposed to the high neutron flux (> 10^{13} $ncm^{-2}s^{-1}$) near the first wall will provide signals levels large enough to allow alpha particle physics studies. A gas activation target would have the advantage that there are no mechanical components near the plasma and that the signal level could be high. The drawback is that the system would only yield a time-integrated measurement.

In the gamma spectroscopy system at JET, a ^{6}LiH filter has been tested in one of the channels to study its usefulness for ITER [7]. The filter reduces the DD neutron background by two orders of magnitude, while it reduces the gamma signal by only a factor of two. Gamma-ray emission at 0.981 MeV from the $^{6}Li(t,p)^{8}Li^{*}$ reaction contains information about the presence of alpha-knock-on tritons with energies of 0.6-1.6 MeV, and alpha-particles with energies of 2.0-3.5 MeV. The measurement on ITER, however, would require a Li-content of about 1%.

The effect of RF and NB-driven fast ions on ITER plasmas, and the capability of various diagnostics (fast ion collective Thomson scattering, neutron cameras, gamma tomography and neutron spectroscopy) to measure those effects, has been studied with a package of simulation codes. The number of fast ions driven by RF and NBI is relatively small in ITER, compared to a machine such as JET. The difference between the thermal and total neutron emission for the scenarios studies is not more than 3% and at this level will not be noticeable in tomographic reconstructions using both the neutron cameras.

The detection of escaping alpha particles is not at all straightforward and currently this is an area of active research. Under standard operational conditions it is expected that the main losses will occur at the low field side, below the midplane (or above under reverse operation) where unfortunately it will be difficult to install detectors. For direct lost alpha detection, the detectors would need to be positioned in large cutouts in the blanket modules and it is not clear that such cut-outs can be made.

New Faraday cup (FC) detectors on JET, developed by the US have given excellent results and demonstrate that, in principle, they could meet the requirements for measurements (time and poloidal resolution) in ITER [8]. The data showed a very clear correlation between the fast ion losses and the occurrence of Edge Localized Modes (ELMs). The poloidal distribution of the losses has been observed to depend on the triangularity of the plasma and on the toroidal field ripple. The FC detectors are expected to be relatively insensitive to the harsh n/γ background, and a signal to noise ratio of about 2/1 is predicted for a 0.1% uniform lost alpha flux during 500 MW operation on ITER. Because of the excellent results obtained on JET a renewed effort on their possible integration in ITER is justified.

Infrared imaging video bolometers (IRVBs), can potentially operate in a reactor environment as has been demonstrated by the first bolometric images obtained from radiation in JT-60 [9]. The results are in reasonable agreement with those obtained from resistive bolometers. In addition to being potentially useful as a radiation hard bolometer for ITER, a stack of absorber foils of varying number of foils could possibly be applied in front of the IRVB to measure the energy distribution of escaping alphas.

New ceramic scintillators for lost alpha diagnosis have been developed: YAG:Ce stiffened by an Aron ceramic binder and YAG:Ce ceramics sintered at high temperature under pressure [10]. These scintillators have good linearity of light emission and they quench at relatively high temperatures. The scintillators have been tested under irradiation with a 3 MeV He^{+} beam. Another new type of scintillator material (TG-Green) for the diagnosis of escaping fast ions has been tested at ASDEX-UG [11]. Measurements with the new scintillator gave evidence that the fast ion losses from the tail of the ICRH particle distribution are related to MHD instabilities in the plasma core. However, neither the new European nor the Japanese scintillators would survive the neutron and gamma radiation in ITER environment for long enough a time.

An alternative approach to obtaining information on the lost alphas is by the observation of Ion Cyclotron Emission (ICE) (or in more general terms magneto-acoustic waves). ICE occurs in the scrape-off layer where electrons are slow and the phase velocity is high. ICE has been observed in tokamaks with fast ion losses [12]. Measurement is relatively straightforward (for example by magnetics or reflectometry) but the technique may only yield a qualitative indication of the lost alpha population.

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

The value of the Vertical Neutron Camera (VNC) for tomographic reconstruction of the neutron emission profile has been assessed by means of simulations, taking into account the background and the availability of the Radial Neutron Camera (RNC). The Lower VNC (Fig. 2) and Upper VNC are two implementation options for the VNC to provide these measurements; the first one views the plasma from below through the divertor port, while the other looks down from three upper ports. A comparison between the two options clearly demonstrated that the view through the divertor port yields the best performance.

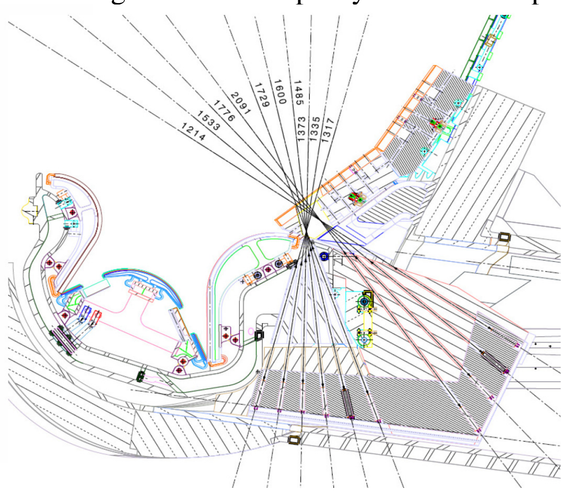

FIG. 2. Schematic layout of the Lower Vertical Neutron Camera. Courtesy Yu. Kaschuk.

After a thorough investigation of the possible options for the calibration of the neutron diagnostic system on ITER, it appears that the system could be calibrated using two sources in combination: a ^{252}Cf source and a 14 MeV neutron generator [13]. In order to obtain the necessary data, the sources would 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 is suggested to study, via detailed MCNP calculations, whether the total number of calibration points could be reduced without affecting the calibration accuracy and thereby reducing the time needed for calibration. The 14 MeV neutron generator will be a relatively large structure and it is not yet evident whether its deployment is practical. Also it needs to be assessed whether the effect of the generator and support structure can be deconvoluted from the calibration data. An important component for the calibration of the neutron systems is the availability of a Neutron Test Area [13]. Such a dedicated area is planned although its precise location is still under study.

2.3. Development of requirements for measurements of dust, and assessment of techniques for measurement of dust and erosion (with a special emphasis on dust measurements).

Recent studies and discussions within the ITER Organization reached the conclusion that the inventories for dust and tritium are expected to reach their maximum limits on a timescale comparable to the target erosion lifetime. The limit on hot dust is only 7 kg, compared to 1000 kg for cold dust. Based on this, a control strategy for dust and tritium has been formulated. Dust will be removed during the scheduled divertor replacements (approximately every 4 years). Additionally the dust will be monitored during and before shutdowns. Local measurements will be benchmarked versus the tritium and dust recovered during the replacement of the divertor cassettes. The first benchmarking will be done in the hydrogen phase.

A number of possible ways to measure dust and erosion have been identified. A specific retractable sample station could be mounted in a divertor cassette for routine dust measurements during maintenance periods. 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 where most dust is collected. Specific dust diagnostics could then be installed to target these areas in the DD and DT phases. An electrostatic dust detector has been developed [14]. The detectors have a very fine grid, which makes it possible to diagnose dust particles as small as 1-2 μm. The electrostatic dust detector not only measures the dust, but it also removes (displaces/evaporates) the dust impinging on it. A micro-balance using the principle of a capacitance manometer has also been developed [15]. The trajectories of incandescent dust particles have been measured in 3D in NSTX with two fast video cameras with a stereoscopic view [16]. Preliminary comparisons to the DUSTT code by Pigarov shows good agreement between model and observations. ELMs and disruptions are seen to generate dust particles that can pollute the plasma with impurities. The topic of dust cannot be separated from the topics of divertor erosion and tritium inventory. Techniques that could be applied for in-vessel tritium and material inventory measurements are: target erosion/deposition monitors, target ablators, and microbalance monitors in the divertor cassette.

Speckle interferometry can measure both the shape and the net erosion/deposition of the target area with a spatial resolution of ~100 μm and a depth resolution of ~10 μm. It is not clear whether the 10 μm resolution can be maintained for the depth of field required by the sloping ITER target and whether techniques exist to overcome this. Furthermore, the implementation proposed for ITER leads to views of the targets at shallow incidence. What is needed is a near normal view which is easiest to get from the divertor and will require a re-design of the optics very far from the laboratory versions [17]. Another system proposed to measure the erosion in real time is an optical radar system that could in principle meet the ITER measurement requirements [18]. The possibility of including one or more of these systems in the ITER diagnostic system is being considered as part of the on-going Design Change Requests that are dealing with the topics of dust and tritium retention.

The TEXTOR team is presently developing a multi-purpose Nd:YAG laser-based diagnostics system that combines laser-induced breakdown, ablation and desorption spectroscopy with Mie/Rayleigh scattering and quartz microbalances for measuring tritium retention, material deposition and dust. The system is aimed to be applicable to ITER conditions (Fig. 3).

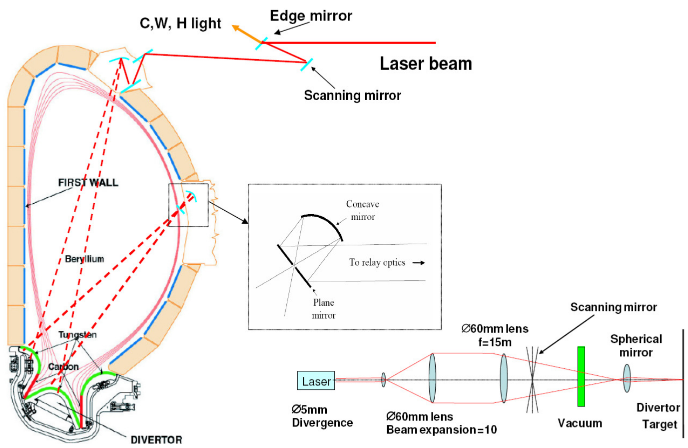

FIG. 3. Schematic layout of a multi-purpose laser diagnostic at ITER, combining laser-induced breakdown, ablation and desorption spectroscopy with Mie/Rayleigh scattering. Courtesy B. Schweer.

3. Progress in other related fields

The ITPA Diagnostics TG has worked on some additional High Priority (HP) Topics over the last two years. One of them, was the development of ITER-relevant diagnostic mirrors. Another was related to the development of the measurement requirements and an assessment of the capability of the ITER diagnostic system to meet them. The results of this work are presented in parallel papers [2, 3]. Much progress in the field of ITER diagnostics can be attributed to the Specialists Working Groups on (beam-aided spectroscopy, passive spectroscopy, neutron diagnostics (see Sec. 2.1 and 2.2), reflectometry, radiation effects, first mirrors [2] and Thomson scattering [19]). Some highlights of the work of these groups are presented below as far as they are not covered elsewhere in this paper or in these proceedings.

3.1. Reflectometry

First results from a 2D full-wave code for simulations of reflectometry at the lower X-mode cut-off from the HFS have been obtained at the Kurchatov Institute. The simulations using an ITER scenario-2 geometry show that the predicted high turbulence level may significantly distort the beam propagation. However, the lower X-mode looks good, compared to the O-mode or upper X-mode where turbulence effects are even worse. Refractometry simulations by Triniti concentrate on the dual or multi-frequency double-pass approach. UCLA has begun testing of ITER dimensioned corrugated waveguides, particularly they have measured beam radiation patterns. The need for density profile knowledge in front of the ICRH antennas has been identified. For this purpose a swept profile reflectometer is proposed, based either on the O-mode port plug system, or perhaps on the X-mode system in development for C-mod.

3.2. Beam-Aided Spectroscopy

In the field of Diagnostic Neutral Beam (DNB) related developments, the beam specifications have converged to values very close to the original target values: $I_{neutral}$ = 36A, E = 100keV/amu, div = 7mrad. The duty cycle and availability have been re-assessed as a result of a component stress study. Continuous operation of the DNB, with an optional 5 Hz modulation is recommended. The DNB duct aperture has increased to 350 x 450 mm^2. For the Charge eXchange Recombination Spectroscopy (CXRS) and Beam Emission Spectroscopy (BES) performance analysis a reassessment has been made of the continuum radiation level, the impurity composition (Tungsten, Beryllium Scenario) and the BES effective atomic rates and Motional Stark Effect multiplet structure. All three reassessments have led to enhanced performance expectations. Substantial progress has been made in the CXRS upper port-plug engineering encompassing: first-mirror risk minimization, shutter development, central tube design development, neutronics assessment and optimisation of periscope optics. An assessment was made of Fast Ion CXRS making use of DNB and HNB: The existing U-port and E-port periscopes may be potentially linked to broad-band instrumentation for the observation of slowing-down alphas in the range up to 0.7 MeV. A significantly higher energy range can be measured using the 1 MeV heating beam and the MSE E-port-3 periscope. An even more ambitious goal has been studied, that is to monitor fast alpha losses, triggered by Alfvén wave instabilities, by ultra broad instrumentation with high time resolution (5 ms) [20].

3.3. Passive Spectroscopy

Of particular note is that the imaging x-ray crystal spectroscopy has rapidly moved from demonstration to new and relevant measurement capability. A similar path can be expected for the energy-resolved x-ray imaging. Ray-tracing calculations for an x-ray crystal survey spectrometer have been done by the Indian Party Team together with the ITER IO. Toroidal bending of the crystal can reduce the height of the slit image, so that a single 2D detector can serve several crystals. Furthermore, an adequate spectral range and resolution can be obtained with candidate detectors such as Pilatus and Medipix. The effect of reflections on spectroscopic measurements is being modeled. The preliminary results are that the fraction of reflected light in the total intensity depends on the geometry of the source as well as the geometry of the wall. The values of the reflectivity found in the simulation are of the same order as the total reflectivity measured in the laboratory on sample tiles from JET which is reassuring (5-10% for CFC, 15-30% for Inconel). Preliminary ITER optics modelling uses an estimated reflectivity for Be and W, which indicates up to 60% reflected light.

3.4. Radiation Effects

The possibility of in-situ annealing of optical components (windows, lenses, fibres) depends on defect stability. Different silicas were irradiated to 12 MGy and E' centre (215 nm) thermal stability studied. KU1 and KS-4V are by far the best materials. Radioluminescence is a potentially powerful tool, with emission from oxygen (anion) vacancies and impurities giving much information, also differences in the matrix give large differences in light intensity. This has been illustrated for two lithium containing ceramics, of interest for the tritium breeding blanket module. However interpretation is not easy. The very low Thermal-Induced Electro-Motive Force observed for fibre glass insulated copper twisted pairs (so-called Sultzer cable) is promising. Full radiation testing still remains to be done. In-situ tests on MM 999 alumina have shown that this material is satisfactory at 120 ºC, but begins to degrade above 240 ºC. Japanese work on radioluminescence of lithium ceramics points out the potential of this technique, both for characterization and as a diagnostic component. Of particular note is the influence of the hydrogen content on the emission intensity. Different coatings on sapphire substrates have been examined following ion bombardment and neutron irradiation. The effect of 10 keV He ions at room temperature to doses of 10^{18}, 10^{19}, 10^{20} and 10^{21} He/m^2 have been examined, and shown no evidence for delamination or blistering of the coatings. Neutron irradiations were performed at the High Flux Isotope Reactor (HFIR) at ORNL up to 10^{18}, 10^{19} and 10^{20} n/cm^2, at 300ºC. The samples were then visually inspected, by the highest dose the sapphire substrate becomes black, however all surfaces remained smooth with no signs of cracking or delamination. There are still many open issues in the field of radiation effects and therefore there is a need to continue and even intensify the international ceramics irradiation testing programme.

4. 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 still a 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.

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