ITER Diagnostics: Design Choices and Solutions*

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Abstract. An extensive diagnostic system will be installed on ITER to provide the measurements necessary to control, evaluate and optimise the plasma performance and to study burning plasma physics. Because of the harsh environment, diagnostic system selection and design has to cope with a range of phenomena not previously encountered in diagnostic implementation. In this paper, we describe the key problems encountered and give examples of the solutions that have been developed. A brief description of the scheme developed for integrating multiple systems into individual ports is also included. We conclude with an assessment of overall system performance.

1. Introduction

ITER will require an extensive diagnostic system to make the measurements necessary [1,2] for the control, evaluation and optimisation of plasma performance. While there is a substantial base of experience and knowledge gained on existing and earlier machines, especially tokamaks, the implementation of diagnostics on ITER represents a major challenge. The relatively high levels of potentially damaging fluxes at the first wall – neutrons, γs, energetic particles, visible and UV – mean that diagnostic system selection and design has to cope with a range of phenomena not previously encountered in diagnostic implementation. The diagnostic designs also have to satisfy stringent engineering requirements on T and Be containment, neutron shielding, vacuum integrity, remote handling, maintainability and reliability. Further, the value of some key 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.

Since 1992 these issues have been tackled in a co-ordinated programme involving all ITER partners, and a comprehensive diagnostic system which will meet the needs for measurements has been designed. The system comprises about 40 individual measurement systems drawn from the full range of modern plasma diagnostic techniques - magnetic, neutronic, optical, bolometric, spectroscopic, microwave, probes, gauges etc. In the selection of the systems several factors have to be taken into account such as the measurement requirements, the diagnostic needs for access to the plasma, the anticipated sensitivity of any in-vessel components to radiation, capability for integration with other systems etc. Also, because the extrapolation to ITER conditions is substantial, wherever possible systems are selected from those already highly developed and well established on existing machines and known to be reliable both in terms of the hardware and the measurement. This is not possible in all cases and for some measurements new concept (N/C) techniques have had to be selected. It also has to be kept in mind that ITER will lay the foundations for a demonstration fusion plant and so the experience necessary to prepare diagnostics for the core of such a plant must be gained The list of selected systems is shown in Table I along with the physical parameters to be measured.

TABLE I. SELECTED SYSTEMS AND PARAMETERS TO BE MEASURED.

Selected Diagnostic System	**Parameters Measured**
Magnetic Diagnostics	
Coils and loops mounted on the interior surface of the vacuum vessel. Halo current sensors mounted on the blanket shield module supports. *Coils mounted between the vacuum vessel skins.* Rogowski coils and *loops* mounted on the exterior surface of the vacuum vessel. Coils mounted in the divertor.	Plasma Current, Plasma Position and Shape, Loop Voltage, Plasma Energy, Locked-modes Low (m,n) MHD Modes, Sawteeth, Disruption Precursors, Halo Currents, Toroidal Magnetic Field, Static error field of PF and TF, High Frequency macro instabilities (Fishbones, TAE Modes)
Fusion Product Diagnostics	
Radial Neutron Camera, *Vertical Neutron Camera*, Micro-fission Chambers (N/C) Neutron Flux Monitors (Ex-Vessel) Gamma-Ray Spectrometer Activation System, *Lost Alpha Detectors (N/C) Knock-on Tail Neutron Spectrometer (N/C)*	Total Neutron source strength, *Neutron/Alpha source profile*, Fusion Power, Fusion power density, Ion temperature profile, Neutron fluence on the first wall, nT/nD in plasma core, *Confined alpha particles, Energy and Density of escaping alphas*
Optical/IR(Infra-Red) Systems	
Core Thomson Scattering Edge Thomson Scattering , X-Point Thomson Scattering, *Divertor Thomson Scattering* Toroidal Interferometer/ Polarimeter, *Polarimeter (Poloidal Field Measurement) Collective Scattering System*	Line-Averaged Electron Density Electron Temperature Profile (Core and Edge) Electron Density Profile (Core and Edge) *Current profile Divertor Electron Parameters Confined alpha particles.*
Bolometric Systems	
Bolometer arrays mounted in the ports, in the divertor and *in the vacuum vessel.*	Total Radiated power, Divertor radiated power *Radiation profile (core and divertor)*
Spectroscopic and Neutral Particle Analyser Systems	
H Alpha Spectroscopy, Visible Continuum Array Main Plasma and *Divertor Impurity Monitors,* X-Ray Crystal Spectrometers, Charge eXchange Recombination Spectroscopy (CXRS) based on DNB, *Motional Stark Effect (MSE) based on heating beam, Soft X-Ray Array (N/C),* Neutral Particle Analysers (NPA), *Laser Induced Fluorescence (N/C)*	Ion temperature profile, Core He density, Impurity density profile, Plasma rotation, ELMs, L/H mode indicator, nT/nD & nH/nD in the core, edge and divertor, Impurity species identification, Impurity influx, *Divertor He density*, Ionisation front position, Zeff profile, Line averaged electron density, *Confined alphas, Current density profile*.
Microwave Diagnostics	
Electron Cyclotron Emission (ECE) Main Plasma Reflectometer Plasma Position Reflectometer, Divertor Interferometer/*Reflectometer*, *Divertor EC absorption (ECA)*, Main Plasma Microwave Scattering, *Fast Wave Reflectometry (N/C)*	Plasma position and shape, Locked Modes Low (m,n) MHD Modes, Sawteeth, Disruption Precursors, Plasma Rotation, H-mode indicator Runaway electrons, Electron Temperature Profile, Electron Density Profile, High Frequency micro-instabilities, *Divertor electron parameters.*
Plasma-Facing Components and Operational Diagnostics	
IR/Visible Cameras, Thermocouples, Pressure Gauges, Residual Gas Analysers, *IR Thermography (Divertor), Langmuir Probes*	Runaway electrons: energy and current Gas pressure and composition in divertor Image and temperature of first wall Gas pressure and composition in main chamber and duct, *Escaping alphas*, Ion flux, ne and Te at divertor plates, *Surface temperature and power load in divertor.*

Systems with implementation difficulties, and the physical parameters that currently have an uncertain measurement capability, are shown in italics. N/C: new concept technique.

4) Magnetics

The magnetics diagnostic system [3] comprises numerous types of sensors mounted in several locations (Table I). Sensors are mounted on the inner wall of the vacuum vessel behind the blanket shield modules (FIG. 1), and on the outside of the vessel. It is also proposed to mount coils between the skins of the vacuum vessel but it is not yet clear whether these can be accommodated. Because of the uncertainty these coils are shown in italics in Table I. The required magnetic fluxes and fields are obtained after integration.

The step to ITER requires that proper account is taken in the design for (i) nuclear heating, (ii) long pulse operation, and (iii) radiation effects that might lead to spurious signals and/or sensor damage. Installation and maintenance of the sensors are also key design considerations. Nuclear heating of the sensors is taking into account by thermally anchoring the sensors to the vacuum vessel For long-pulse operation, integration with compensation for long-term drift to 3,600 s is needed. R&D on such integrators is in progress and already the performance available is close to that required for ITER suggesting that the ITER requirements can be achieved [3]. Non-inductive methods and hybrid magnetic sensors are also envisaged as a backup system for long pulses.

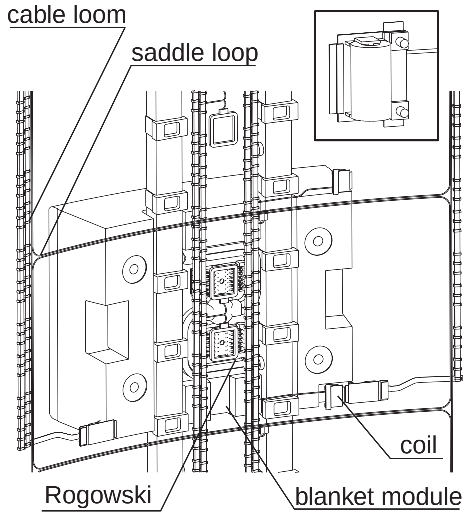


FIG. 1. Coils and loops mounted behind the blanket modules. Inset: details of sensor coil viewed from the plasma.

There are two radiation effects that can influence the signals – Radiation Induced Conductivity (RIC) and Radiation Induced EMF (RIEMF). A third radiation effect – Radiation Induced Electrical Degradation – can lead to permanently reduced insulation strength after long exposure. However, the conditions (temperature, radiation level, and electric field strength) when this effect occurs have been established by R&D and are avoided in the ITER design. The affect of RIC is to load the sensor during the pulse. A limit on the acceptable conductivity σ_c is set so that the error does not exceed 0.2% of the signal. RIC on candidate insulators has been investigated during the ITER R&D framework and it appears that a margin of one order of magnitude on this effect can be readily achieved (FIG. 2). Both neutrons and γs induce current between the sensor and its surroundings and if there are asymmetries in the radiation field and/or sensor load a small EMF can be generated. Several measures can minimise this: (i) increasing the ratio of effective sensor area to cable length, (ii) reducing the temperature and radiation field asymmetries by adopting an even layer coil structure and

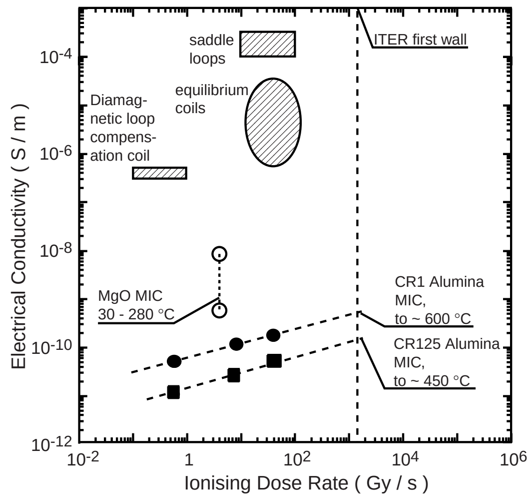


FIG. 2. RIC limits on ITER sensors. After [3].

choosing areas of expected uniform radiation level, (iii) lowering the coil resistance and hence reducing the differential voltage, and (iv) reducing the integrator sensitivity to common mode voltage by lowering the balanced impedance to ground at the input. Most of these measures have been adopted in the ITER design. Tests with prototype coils are in progress and, on the basis of the tests carried out so far, it is expected that measurements for pulse lengths of at least several hundred seconds will be possible without significant limitation due to this effect. Further tests are required to determine the precise limitation and these tests will be carried out later this year.

5) Fusion Product Diagnostics

An extensive array of fusion product diagnostics is planned (Table I). The principal difficulties in implementing these diagnostics on ITER are (i) providing sufficient plasma coverage for the lines of sight in the neutron cameras, (ii) providing the capability to make measurements over a very wide dynamic range (up to seven orders of magnitude), and (iii) executing and maintaining the calibration of the different systems.

For the radial camera, the plasma is viewed through a fan-shaped array of flight tubes formed in a vertical slot in the blanket shield module of an equatorial port plug. The sight lines intersect at a common aperture defined by the port plug and penetrate the vacuum vessel, cryostat, and biological shield through stainless steel windows. Each flight tube culminates in a set of detectors chosen to provide the required range of sensitivity and temporal and spectral resolution. High resolution neutron spectrometers, on selected chords provide emissivity-weighted, chord-averaged measurements of ion temperature. Calibration of the detectors requires a moveable neutron source inside the vacuum vessel. To obtain the neutron source profile, observations in the vertical direction are also required and so a second camera is proposed. This would have sight-lines viewing the plasma downwards through long narrow tubes in the upper port plug, vacuum vessel and cryostat. However, there are difficult interface issues and it is not clear whether this camera can be realised.

Fission chambers containing ^{235}U or other isotopes, will be situated at different locations within ports and outside the vacuum vessel. In addition, micro-fission chambers will be deployed behind the blanket in poloidal arrays at two toroidal locations. These are miniature fission detectors of the type commonly used for in-core neutron flux measurements in fission reactors. The use of multiple locations allows compensation of effects due to changes in plasma position or shape and provides redundancy in case of detector failure By using detectors containing different quantities of fissionable material, different sensitivities are obtained and the wide dynamic range will be achieved.

Two types of activation systems are planned. One type uses pneumatic transfer to place a sample of material close to the plasma for irradiation. This will give an accurate but relatively slow measurement. The second system measures the gamma-rays from the decay of ^{16}N produced in flowing water. This system will be faster (a few seconds) but less accurate. Taken together these systems will provide a robust, independently calibrated, measure of fusion power.

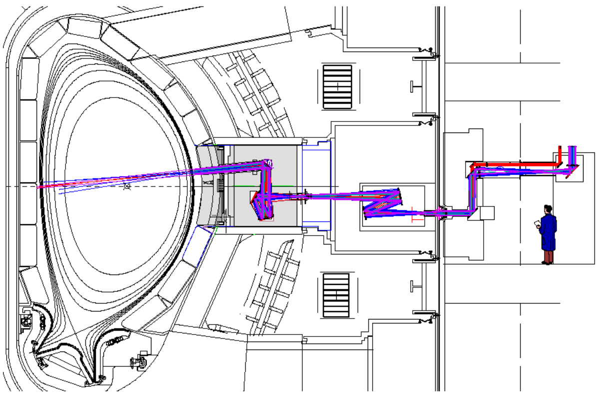
A possible detector for measuring the escaping alphas is the Faraday cup [4]. These are still under development (N/C device). The best location would be at a poloidal position below the mid-plane where the maximum loss is expected to occur. Installation at this position is problematic because of the modifications required to the blanket shield.

Information on the confined alphas can be obtained from measuring the 'tail' on the neutron spectrum caused by knock-on collisions between the fast alphas and the fusion ions. Threshold bubble detectors are a possible detector for this measurement and would be relative easy to include.

6) Optical Systems

The principal optical systems are shown in Table I. The key issue in applying optical systems to ITER is to provide good optical throughput at the same time as effective neutron shielding. Labyrinthine transmission lines with two or more near-90° bends embedded in shielding blocks in the ITER ports provide the necessary shielding. Calculations have shown that attenuation factors of several orders of magnitude can be readily achieved [5].

Additional important design considerations are assuring the lifetime of any in-vessel components, coping with nuclear heating and hence distortion, differential movements between parts of the systems, and ensuring the systems can be calibrated. R&D has shown that the optical properties of refractive materials deteriorate rapidly in high neutron irradiation and so the plasma facing element has to be a mirror. Mirrors will be subject to all the first wall fluxes**.** In addition, they may also be subject to the deposition of material eroded from the divertor and first wall and from the duct in which they are mounted. By locating the mirrors at the bottom of a duct, it is possible to reduce the flux of energetic particles by up to two orders of magnitude. Furthermore, extensive R&D has shown that mirrors made from low sputtering coefficient materials deposited on a high thermal conductivity substrate are robust against erosion [6]. More R&D is required on the mechanisms and extent of deposition, but baffles, cleaning techniques, and/or shutters are possible mitigating methods. The mirrors are actively cooled to deal with nuclear heating. Active alignment systems are employed to compensate for differential movements. An example of a system employing these measures is the core Thomson scattering system which operates on the time-of-flight (LIDAR) principle (FIG. 3).



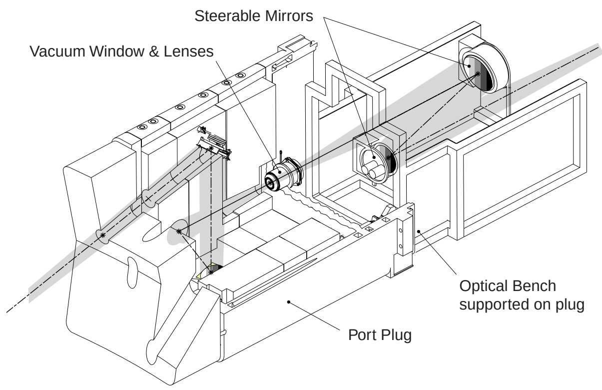


FIG. 3. LIDAR system in a mid-plane port, and close up of the components in the port. Movements of the components that are attached to the vacuum vessel relative to those attached to the building (transmission line) are compensated by a pair of mirrors adjustable in real time.

To make the most efficient use of the port space multiple diagnostics have to be installed in each port. The installations have to provide the individual diagnostics with the required plasma access but must also satisfy the stringent engineering requirements (outlined in section 1), in particular on remote handling capability and maintainability. A modular approach has been adopted: an example is shown in FIG. 4. The shielding, cooling and support structures typically take about 75% of the volume of the port structures leaving about 25% available for diagnostic components.

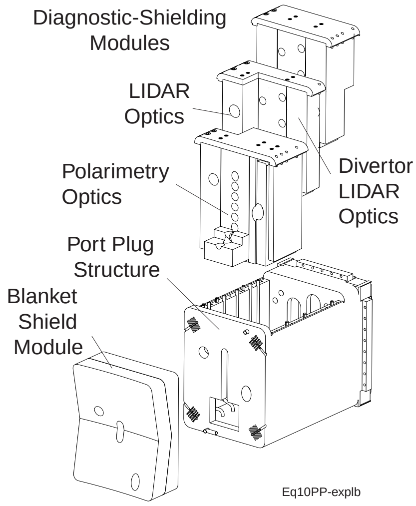


FIG. 4. Multiple diagnostics installed in one port.

7) Spectroscopic systems

An extensive array of spectroscopic instrumentation will be installed covering the X-ray to visible wavelength range (Table I). Both passive and active measurement techniques will be employed. The four main regions of the plasma - the core, the edge, the scrape-off layer (SOL), and the divertor - will be probed.

Those systems that make measurements in the wavelength range $\lambda > 200$ nm share many of the same problems as the optical systems and can utilise the same solutions. However, systems that operate in the VUV and X-ray regions must be directly coupled and require an extension of the primary vacuum outside the bioshield (FIG. 5). The primary vacuum extension is enclosed in a secondary vacuum chamber. Neutral Particle Analysers also require direct coupling and are similarly mounted.

Measurements of the light ion impurities in the plasma core, and in particular the Helium ash arising from the fusion process, cannot be made by passive techniques because of the high temperatures. For these measurements active techniques using neutral beams will be

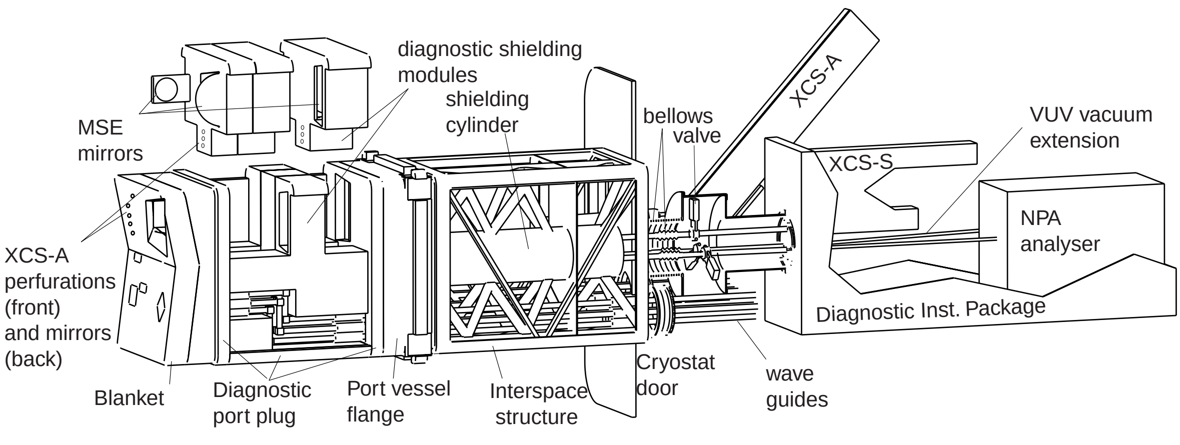


FIG. 5. Direct coupled systems installed in a mid-plane port including X-ray crystal spectrometer array (XCS-A) and survey instrument (XCS-S), VUV spectrometer and Neutral Particle Analyser.

employed. The optimum beam energy is ~ 100 keV/amu, well below the energy of the heating beams (1 MeV). A dedicated diagnostic neutral beam (DNB) is provided for these measurements. The beam is viewed from the upper port above the DNB and an equatorial port. Calculations for standard conditions show that a good signal-to-noise ratio can be achieved in the measurement of the He ash in the core region [7]. In order to achieve beam penetration to the core for Motional Stark Effect (MSE) measurements, a beam energy > 500 keV/amu is necessary. One of the heating beams will be used for this measurement [8].

6. Bolometry

Bolometer arrays will be installed in certain equatorial and upper ports, in specially instrumented diagnostic divertor cassettes and, possibly, at selected locations on the VV, to provide the spatial distribution of the radiated power in the main plasma and divertor region through sparse-data tomography. From each location several lines of sight observe the plasma in fan shaped array(s) in the poloidal plane. Bolometers on the VV would view the plasma through the gaps between adjacent blanket/shield modules. This provides some protection while allowing a wide field of view.

The key step in the application to ITER is the development of a radiation-hardened bolometer. A bolometer that is believed to be sufficiently robust for use during the initial DT operation exists, but a device with enhanced resistance may be required for the anticipated end-of-life fluence level of the machine. Potentially suitable devices are being investigated in a supporting R&D programme and promising results have been obtained [9].

7. Microwave systems

The principal microwave diagnostics are shown in Table I. The main implementation difficulties are the provision of the in-vessel antennas and waveguides, and the hardware necessary for in-situ calibration and alignment.

For the ECE system two collection antennas in an equatorial port plug, a transmission line set, and spectrometers for analysing the emission are employed. The antennas (Gaussian beam periscopes with cooled first mirror) are staggered vertically to give access to the core for a variety of plasma heights near the nominal plasma centre height. For each antenna, there are built-in calibration hot sources at the front end. The sources can be intermittently viewed through an un-cooled mirror that can be inserted in the viewing line. The radiation is coupled to wide-band corrugated waveguide with passive mechanisms to take up machine movements.

The main plasma reflectometer has three sub-systems in order to cover the needed frequency ranges. It includes antennas and waveguides on the inboard side in order to probe the plasma centre. In order to give back-up to the magnetics for very long pulse operation the position of a fixed density layer is measured at four points in the poloidal plane using independent reflectometers. The waveguides for this Plasma Position Reflectometer are routed in the vacuum vessel along the similar paths to the in-vessel diagnostic wiring, and then onwards through an upper port to the remote sources and detectors.

7. Operational Systems

Several diagnostics will be used to aid the operation of the tokamak and, in some cases, to protect the internal structures. Viewing systems will be used to survey the first wall and divertor plates during a pulse, and the temperature of the divertor plates will be measured by infrared thermography. These and additional systems are shown in Table I.

For the viewing systems, the problems are essentially the same as those of the optical systems and the same solutions can be applied. The established method of monitoring the presence of runaway electrons is to measure the hard X-ray emission but this will be difficult to apply on ITER because of the high gamma background. Measurements of synchrotron emission at infrared wavelengths have been used successfully on TEXTOR [10] and this method is being considered for ITER. Existing pressure gauges and gas analysers are applicable to ITER with minimal development.

8. Conclusions: Assessment of Overall System Performance

Although the step to ITER diagnostics is substantial and many details are not yet developed, it is believed that the measurements required for plasma control and machine protection for basic operation scenarios can be made to the required specification. Most of the parameters needed for the control of plasmas operating in possible "advanced" modes can also be provided although in a few cases, for example the current profile, the specifications are not yet fully met. The measurements will also provide much important information needed in physics studies of unique phenomena which may occur in burning plasmas, for example alpha-induced Alfvén waves.

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