The Design and Implementation of Diagnostic Systems on ITER*.

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Abstract. In order to meet the expected needs for first wall and plasma measurements, ITER will require about 40 different diagnostic systems drawn from all the main generic diagnostic groups – magnetics, neutron systems, optical and microwave systems, spectroscopic, bolometric, probes, pressure gauges and gas analysers. The design and implementation of the diagnostic systems is a major challenge because of the harsh environment in which many of the diagnostic components are located coupled with the restricted access and the need to meet stringent engineering requirements arising from the fact that ITER will be a nuclear device. It has stimulated an extensive design and R&D programme and the development of some novel approaches to diagnostic installation: for example, the use of plugs with custom modules at the upper and equatorial levels that serve both to support the diagnostic components and to provide the necessary shielding of the neutrons. In this paper, the difficulties of implementation are summarized and the novel solutions described. An assessment of the performance of the diagnostic system relative to the specified target measurement requirements is given.

1. Introduction

The implementation of diagnostics on ITER will be a major challenge, arguably the most difficult ever undertaken in plasma diagnostics. The number and type of plasma and first wall parameters that will have to be measured will be very similar to those measured on today's large devices, but the specification of some of the measurements, such as relative spatial resolution and accuracy, will be more demanding. More measurements will be used in active feedback control, and since the tokamak will be operating close to operational limits with very high levels of stored energy, high reliability in the diagnostic systems will be essential. On the other hand, the environment of ITER will be very harsh compared to those experienced on today's machines. In-vessel components will be exposed to high levels of neutron and gamma radiation, neutron heating and particle bombardment and, as a consequence, many phenomena that relate to the physical properties of materials, and how they are changed by irradiation, have to be taken into account in diagnostic design for the first time. Since the early days of ITER, these issues have been tackled in a co-ordinated programme involving all ITER partners and a comprehensive diagnostic system is being prepared [1]. There are many aspects to this topic. In this paper, we will concentrate on some of the novel implementation details and give an overall assessment of the expected performance of the system relative to the target - rather ambitious - measurement requirements [2]. Recent developments in the supporting R&D programme and are also reported at this conference [3].

2. ITER Environment and Potential Impact on Diagnostic Components

The highest levels of neutron and gamma radiation will be experienced by components near the first wall and in the divertor where the neutron flux levels will be up to $3x10^{18}$ n/m^{2}s, the dose rate up to $2x10^3$ Gy/s, and the plasma radiation up to 500 kW/m^2. The neutron and radiation dose levels will be typically 10 times higher than the maximum reached on present machines. The neutron heating will be typically 1 MW/m^3 compared to essentially zero on existing machines. Probably the most significant extrapolation is in the pulse length: these will be up to several thousand seconds, that is 100 times longer than that typical on present-day machines. Combined with the higher flux levels and planned high number of plasma pulses (30,000), this means that the end-of-life fluence levels will be more than 10^5 times higher.

The consequence of the higher flux and fluence levels is that many phenomena new to diagnostic design can occur and have to be taken into account. At least ten different such environmentally induced phenomena that can potentially play a role have been identified. These can have several deleterious effects: for example, they can change the physical properties of the material of the component/sensor and thereby change its performance; they can generate spurious signals, and they can cause damage that limits the lifetime. In some cases, the material can be changed permanently through transmutation. The effects may only exist during the plasma pulse (prompt), or they can be cumulative. For example, Radiation Induced Conductivity (RIC) and Radiation Induced EMF (RIEMF) in cables, and radiation induced absorption and luminescence in optical materials are prompt, whereas Radiation Induced Electrical Degradation (RIED) and Radiation Induced Thermoelectric Sensitivity (RITES) are cumulative. The environmental aspects, the effects on the specific diagnostic components, and the remedies that are being adopted to overcome them, are summarised in Table 1. More details can be found in [1].

Table 1: Summary of ITER Environmental Impact on Diagnostic Components

Environmental Aspect	Phenomena	Diagnostic Components Potentially Affected	Principal Effects	Adopted Remedy
High neutron and gamma fluxes	RIC, RIEMF, RIED, RITES, TIEMF (Thermally Induced EMF)	In-vessel wiring, magnetic coils and loops, microfission chambers, pressure gauges, bolometers, soft x-ray detectors, Langmuir probes	Changes in conductivity, degradation in insulator properties, induced currents and voltages leading to spurious signals	Shielding, careful choice of materials to minimize effects, compensation using dummy detectors, in-situ calibrations, generic redundancy and cross-checks
	Bulk heating	All in-vessel components	Temperature rise, possibly melting	Active cooling
	Radioluminescence Radiation induced absorption	Windows, fibre optics	Spurious optical signals, enhanced absorption	Shielding, careful choice of materials, in-situ calibrations
High neutron fluence	Material structural damage, activation, transmutation, swelling	All in-vessel components	Change in physical properties of material	Careful choice of materials, in-situ calibrations, remote handling design
Energetic neutral particle bombardment	Erosion, deposition	Plasma facing mirrors	Degradation in reflectivity	Careful choice of materials, shutters, baffles, in-situ cleaning and calibrations
High levels of EM radiation	Surface heating	All plasma facing components	Change in surface physical properties	Design for minimum exposure, in-situ calibration

3. The Implementation of Diagnostics on ITER

The diagnostic components are installed in multiple locations – within the vacuum vessel (VV), in equatorial and upper ports, divertor ducts, port cells, galleries, and the remote diagnostic building. The details of the implementation are different in each case.

In-vessel Installations. The principal diagnostic components mounted in the vacuum vessel are sensors for the magnetic diagnostics, bolometers, microfission chambers, soft X-ray and UV detectors, and waveguides for reflectometry. The magnetic diagnostics comprises sets of pick-up coils, saddle loops and voltage loops mounted on the inner wall of the vacuum vessel [4]. Pick-up coils are also mounted in some of the divertor cassettes. An additional set of coils will be mounted on the outside of the vacuum vessel to provide measurements in a lower radiation environment albeit with a lower frequency response. Sensors are mounted at sites where the maximum protection possible is sought from the blanket modules, with standard cut-outs provided if extra space is required (FIG 1). Where necessary the plasma is viewed through the gaps between blanket modules, which may have to be locally widened. Sensors and cabling are cooled by conduction to the vacuum vessel and thermal radiation to the blanket, and typically operate in the range 150-300°C.

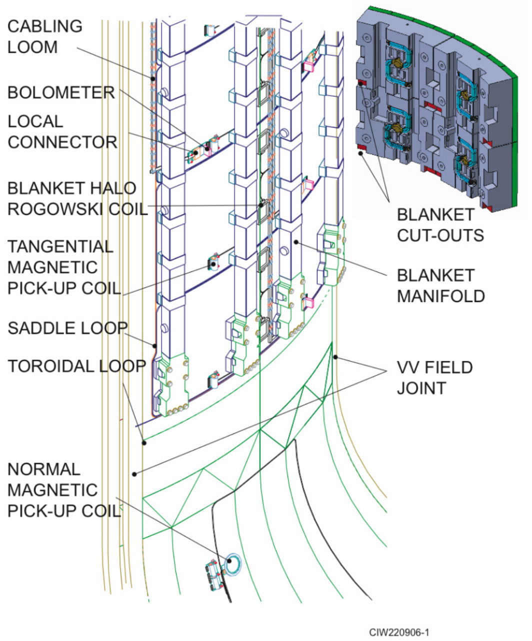


FIG. 1. Part of the inboard vacuum vessel with blanket and divertor removed, showing installed diagnostic sensors and cabling looms.

In upper and equatorial ports. A novel approach has been adopted for installing diagnostic components in the ports. Here the diagnostic components will be installed in port-plugs and these will contain modules, customized to the specific diagnostics in the port, to ease the construction and maintenance (FIG 2a and b). The port-plug provides the primary vacuum boundary at the port, as well as the feed-out for diagnostic transmission lines (windows for optical systems, waveguides for microwave systems and feedthroughs for electrical systems) and feed-in for control signals. Within the primary vacuum, the plugs provide the support for the diagnostic equipment, the shielding (equivalent to that lost accommodating the diagnostic channels), and the support for the blanket shield module with its first wall protection and shielding. First wall apertures are minimised by generally making use of common apertures. The blanket shield module performs the first wall function and provides shielding equivalent to blanket modules and the vacuum vessel at this location. Some diagnostics, for example, the VUV and X-ray crystal spectrometry, and NPA systems, require direct vacuum coupling and this is achieved through the use of welded vacuum extension(s) contained in dedicated shielded containment enclosures.

In order to achieve high optical throughput for the diagnostics and, at the same time, effective neutron shielding, the diagnostic optical and microwave transmission lines use folded labyrinths in neutron shielding blocks. The latter are a mixture of steel and water. The primary design requirements is to provide sufficient shielding, equivalent to that lost accommodating the diagnostic channels, to limit the nuclear heating of the cryogenic coils of the magnet system. This sets the limit to how many diagnostics can be installed in a port and unavoidably brings competition for space between the diagnostics. At the equatorial level typically no more than two systems with large labyrinths can be installed in one port, with large aperture systems placed near the port centres. At the upper level, the port dimensions are such that only one high neutron throughput (large viewing aperture) system per port is

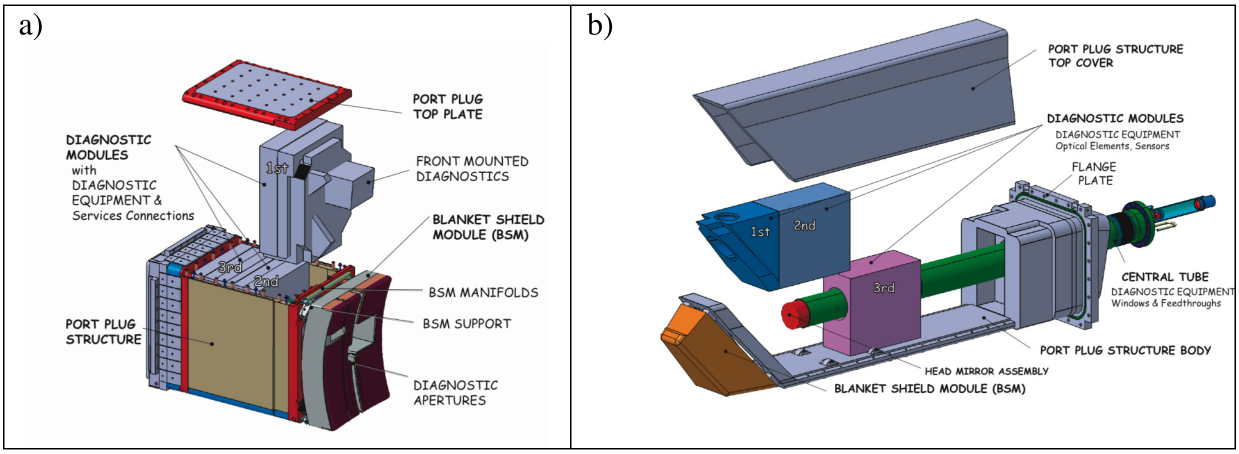


FIG. 2. Schematic of port-plugs for diagnostic installations in the equatorial (a) and upper (b) ports.

allowed. The shielding is also required to avoid activation of the reweldable flange components of the port duct.

Many factors have to be taken into account in optimising the distribution of diagnostics within the ports available and some guiding principles have been developed. Distributed systems are located uniformly toroidally, sometimes coordinated with the location of corresponding systems at different levels. Active spectroscopy systems have to view the dedicated diagnostic neutral beam or the heating neutral beams. Systems sensitive to gas and pellet injection must be positioned away from these systems. The reference port allocation that takes into account these requirements is shown in FIG 4.

Divertor diagnostic installations. In the divertor, diagnostic components are concentrated in the cassettes that can be accessed by the three remote handling ports and two diagnostic ports. Optical diagnostics make use of the central aperture of the cassette and the gaps between the cassettes. At the centre of each location for diagnostics there is a special diagnostic cassette. This is a standard divertor cassette modified to incorporate optical and microwave diagnostics while allowing remote maintenance in the same way as for standard cassettes. Either side of this there are two instrumented cassettes. These incorporate sensors, such as Langmuir probes, bolometers, and pressure gauges. Guiding principles have also been developed for the allocation of diagnostics to ports at this level. A schematic of some of the diagnostics installed in a divertor cassette is shown in FIG 3.

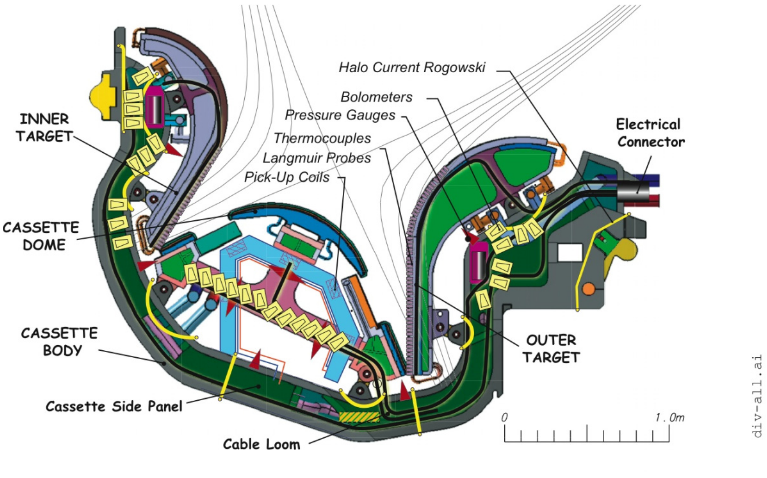
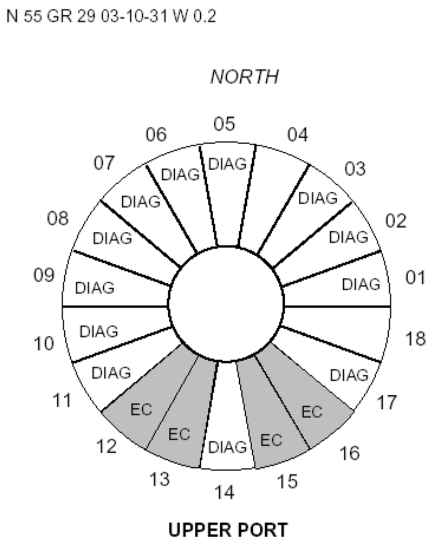


FIG. 3. Multiple diagnostic sensors installed in the divertor

Building diagnostic installations. Beyond the tokamak, diagnostic components are installed in the port cells, galleries and the diagnostic building. The optical and microwave transmission lines are typically several 10s of meters in length (similar to those used on JET).



01 Position Reflectometry (1 of 2)
Divertor Impurity Monitor
Activation System (16N, 1 of 2)

02 Vis. / IR TV (1 of 6)
Ha spectroscopy (divertor outer)
Ha spectroscopy (outer edge)

03 CXRS (on the DNB, core)
Vertical Neutron Camera (1 of 3)

05 Vis. / IR TV (2 of 6)
Activation System (16N, 2 of 2)
Vertical Neutron Camera (2 of 3)

06 VUV grazing image (x 2)
Activation System (foil, 1 of 2)

07 Ha spectroscopy (inner edge)
Ha spectroscopy (upper edge)
Vertical Neutron Camera (3 of 3)

08 Vis. / IR TV (3 of 6)
Main Reflectometry (1 of 3)
Bolometry

09 X-ray Crystal Spectrometry (imaging),
Main Reflectometry (2 of 3)

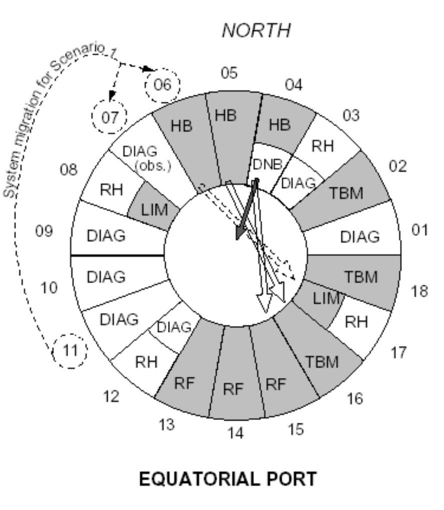
10 Polarimeter

11 Vis. / IR TV (4 of 6)
Edge Thomson Scattering
Activation System (foil, 2 of 2)

12 (EC), *CTS*

14 Vis. / IR TV (5 of 6)
X-ray Crystal Spectrometry (survey)
Position Reflectometry (2 of 2)

17 Vis. / IR TV (6 of 6)
Main Reflectometry (3 of 3)
X-ray Crystal Spectrometry (graphite)
Bolometry,
Soft X-ray Array



01 Vis. / IR TV (1 of 4)
Radial Neutron Camera
Bolometry, MSE (core, HB4)
Divertor Impurity Monitor
Gamma Ray Spectroscopy
High Resolution Neutron Spectrometer

03 Vis. / IR TV (2 of 4)
CXRS (on the DNB)
MSE (edge, HB5)
Ha Spectroscopy (divertor inner)

07 Activation System (16N, 1 of 2)
Activation System (foil, 1 of 2)
Neutron Flux Monitor (DD)

08 Neutron Flux Monitor (DT)

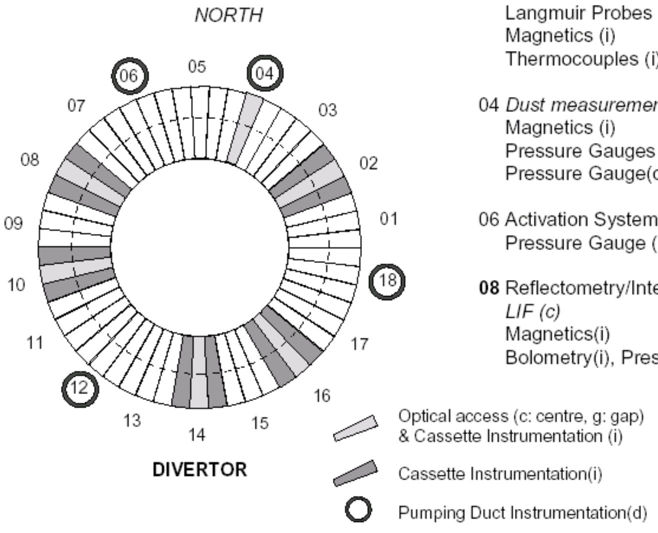
09 Vis. / IR TV (3 of 4)
Toroidal Interferometer/Polarimeter
ECE, X-ray Crystal Spectrometry (imaging)
Fast Wave Reflectometry
Soft X-ray Array

10 Thomson Scattering (main plasma)
Polarimeter
Thomson Scattering (inner divertor)

11 X-ray Crystal Spectrometry (survey)
VUV (main and divertor)
Reflectometry for the main plasma
NPA

12 Vis. / IR TV (4 of 4)
Ha Spectroscopy (upper edge)
Visible Continuum Array
CTS

17 Neutron Flux Monitor (DT)
Activation System (16N, 1 of 2)
Activation System (foil, 2 of 2)



02 Divertor Impurity Monitor (Visible, gcg)
Langmuir Probes (i)
Magnetics (i)
Thermocouples (i)

04 *Dust measurement (c)*
Magnetics (i)
Pressure Gauges (i)
Pressure Gauge(d), RGA (d)

06 Activation System (foil, 1/3)
Pressure Gauge (d), RGA (d)

08 Reflectometry/Interferometry (gg)
LIF (c)
Magnetics(i)
Bolometry(i), Pressure Gauges(i)

10 X-point Thomson Scattering (c)
Divertor Thomson Scattering (outer leg,g)
Ha Spectroscopy (g)
Langmuir Probes (i)
Magnetics (i)
Bolometry (i), Pressure Gauges (i)

12 Activation System (foil, 2/3)
Pressure Gauge (d), RGA (d)

14 Reflectometry/Interferometry (gg)
Plate Erosion (c)
Langmuir Probes (i)
Magnetics (i)
Thermocouples (i)

16 Divertor Impurity Monitor (VUV, gg)
IR thermography (c)
Magnetics (i)
Bolometry (i), Pressure Gauges (i)

18 Activation System (foil, 3/3)
Pressure Gauge (d), RGA (d)

FIG. 4. Distribution of diagnostics systems to the allocated ports on ITER. For one possible heating scenario upgrade (additional RF systems), the diagnostics in port 11 are relocated to ports 6 and 7.

The approach that has been adopted is, as far as possible, to remove from the tokamak area the sensitive, specialized, diagnostic equipment; the use of transmission lines being preferred over the difficulties of having specialised diagnostic equipment in areas with limited access. The basic approach in the optical transmission lines is to use optical fibres wherever possible; to use lenses where fibres cannot be used; and to use mirrors where lenses cannot be used. In some cases however, it is not possible to install the diagnostic equipment remotely and it has to be located near the tokamak because the loss in the transmission lines would be too great; for example, the UV spectrometers will be installed on removable trolleys in the port cells.

4. Assessment of Performance Relative to Target Requirements

The development of diagnostics for ITER is still in progress and, in some cases, more design and R&D are needed before the diagnostics can be implemented. However, it is useful to try to assess where the development stands at this stage relative to the defined measurement requirements [2] as a guide to where future work should be focussed.

The approaches being adopted for the installation of the diagnostic components, as outlined in section 2, are expected to be successful and the components can be installed and will meet the ITER general engineering requirements. The diagnostics that have been selected are, in general, diagnostics that are well established on existing machines. The actual performance on ITER, therefore, will depend mainly on the extent to which the special measures taken to overcome the environmental factors are successful.

For the magnetic diagnostics, simulation work has shown that the chosen configuration of sensors will, in principle, meet the measurement requirements [4]. The actual performance will depend on the extent to which the radiation effects have been handled. Extensive in-situ irradiation tests of magnetic coils have been carried out in the supporting R&D programme, and have shown that multiple effects, in particular, RIC, RIEMF and RITES, can occur simultaneously. In application on ITER, they could lead to spurious voltages and loads that would pollute or change the signal voltages. Although there are still aspects of the results not fully understood, the results show that it is probable that coils can be developed for ITER in which the combined action of these effects is tolerable and enable the basic requirement for pulse length to be met (< 400 s burn), and it may be possible to use the coils for measurements on long (> 1000 s) pulses. The development of steady state sensors and long pulse integrators also shows good progress and it is likely that Hall sensors can be developed for applications outside the ITER vacuum vessel. There is redundancy in the measurement capability of the diagnostic, and for the measurement of key control gaps, a dedicated reflectometer system is also being implemented. This is one example, where a novel approach is being planned for ITER to overcome the special environmental factors to meet the enhanced measurement requirements (in this case for long pulse lengths).

No insurmountable difficulties are expected for the implementation of the neutron flux monitors and activation systems. However, the ability of the neutron cameras to provide the measurements for which they are intended, for example the total fusion power and the neutron source profile, is directly linked to the available access. No particular difficulties are foreseen for the radial viewing camera but there are significant interface difficulties for the vertical viewing camera that have not yet been solved. If these are not solved, then the measurement of the spatial profile of the neutron source strength will be limited to cases where the neutron emission is constant on a magnetic flux contour. Compact neutron spectrometers exist and it is feasible to install them in the radial neutron camera. However, high resolution spectrometers are needed for some measurements and these tend to be large and/or require a close coupling to the plasma, and implementation on ITER is problematic.

The calibration of the neutron diagnostics is another difficult area under ITER conditions.

The most critical and potentially performance limiting component of all the optical/IR, spectroscopic and microwave systems is the first mirror. This is the subject of extensive R&D. On the basis of the results obtained thus far, it is believed that solutions for the first mirrors exist where the dominant potentially damaging mechanism is erosion due to the bombardment of high energy neutral particles. This may be the case for most systems installed in the equatorial and upper ports. However, it is possible that deposition of eroded first wall material or viewing duct material will also occur, leading to a degradation of optical performance. Mitigating methods in this case would be baffles in the duct, cleaning techniques, and/or shutters in front of the mirror. Shutters are highly desirable and will be incorporated. Their engineering design still requires detailed study.

For diagnostic components in the divertor, it is probable that deposition of eroded material will be the dominant potentially damaging mechanism. At this stage, only limited information is available on this process. More investigations and developments are required before the actual extent of the problem is known and the most effective countermeasures can be selected. Alternative views from the equatorial and upper ports are provided where possible.

A bolometer that is believed to be sufficiently radiation-hard for use during the initial DT operation exists, but a device with enhanced radiation hardness may be required for the anticipated end-of-life fluence level of the machine. Potentially suitable devices are being investigated.

For microwave systems, no insurmountable installation difficulties are expected and the lifetime of the in-vessel and plasma facing components is expected to be sufficiently long that no replacements will be needed in the life of the machine, except for upgrade. However, in a few cases, the diagnostics will have to perform in untried regions, for example, measurement of the central plasma density by using the X-mode lower cut off from the high field side, and tests and developments are needed on existing machines. In other cases, there are technology limits, for example, divertor reflectometry needs to operate at frequencies up to about 300 GHz but tunable, powerful, sources do not yet exist at these frequencies.

No insurmountable difficulties are foreseen with the basic operational diagnostics such as pressure gauges and gas analyzers and there is a high probability of meeting the measurements requirements of the parameters to be measured by these systems.

It is convenient to group the parameters that have to be measured them into three basic groups: those required for basic machine protection and basic plasma control (group 1a); and additional measurements needed for control in specific scenarios (usually profile measurements) (group 1b). All the measurements will be used in studies of the physics of the plasma but some additional dedicated measurements will be needed (group 2). The design and R&D work carried out to date has shown that it should be possible to measure many of the parameters at the specified level. The assessed situation relative to the defined measurement requirements for each parameter is shown in Table 2.

5. Conclusions

The environmental aspects of ITER, especially the relatively high levels of neutron and gamma radiation, combined with long pulse operation and demanding measurement requirements, mean that the implementation of diagnostics will be a major challenge and arguably the most difficult ever undertaken in plasma diagnostics. The challenge is being met

Table 2: Assessment of Measurement Capability

GROUP 1a Measurements For Machine Protection and Basic Control	GROUP 1b Additional Measurements for Control in Specific Scenarios	GROUP 2 Additional Measurements for Performance Eval. and Physics
Plasma shape and position, separatrix-wall gaps, gap between separatrixes Plasma current, q(a), q(95%) Loop voltage Fusion power $\beta_N = \beta_{tor}(aB/I)$ Line-averaged electron density Impurity and D,T influx (divertor, & main plasma) Surface temp. (div. & upper plates) Surface temperature (first wall) Runaway electrons 'Halo' currents Radiated power (main pla, X-pt & div). Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate) Disruption precursors (locked modes m=2) H/L mode indicator Z_{eff} (line-averaged) n_T/n_D in plasma core ELMs Gas pressure (divertor & duct) Gas composition (divertor & duct) Dust	Neutron and a-source profile Helium density profile (core) Plasma rot. (tor and pol) Current density profile (q-profile) Electron temperature profile (core) Electron den profile (core and edge) Ion temperature profile (core) Radiation power profile (core, X-point & divertor) Z_{eff} profile Helium density (divertor) Heat deposition profile (divertor) Ionization front position in divertor Impurity density profiles Neutral density between plasma and first wall n_e of divertor plasma T_e of divertor plasma Alpha-particle loss Low m/n MHD activity Sawteeth Net erosion (divertor plate) Neutron fluence	Confined a-particles TAE Modes, fishbones T_e profile (edge) n_e, T_e profiles (X-point) T_i in divertor Plasma flow (divertor) $n_T/n_D/n_H$ (edge) $n_T/n_D/n_H$ (divertor) T_e fluctuations n_e fluctuations Radial electric field and field fluctuations Edge turbulence MHD activity in plasma core

Expect to meet measurement requirements; performance not yet known; expect not to meet requirements

through a combined, integrated design and R&D programme involving all the ITER partners and guided and coordinated by the ITER International Team. Considerable progress has been made and a diagnostic system which, in principle, should meet most of the measurements requirements is in preparation. The actual performance will depend on the extent to which the special provisions adopted to deal with the environmental factors of ITER are successful. On the basis of the design and R&D carried out thus far, it is expected that most of the measurements needed for machine protection and basic control will be measured at the required level. There are difficulties with some of the measurements necessary for advanced control, for example the escaping alphas, and there may ultimately be consequential effects on the operation of the tokamak, but more work is required before these can be determined. Some of the measurement systems that are intended solely for physics purposes also have implementation difficulties. Current work is focused on these areas.

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