Measurement Requirements and the Diagnostic System on ITER: Modifications Following the Design Review.

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Abstract. The requirements for plasma and first wall measurements on ITER, and the planned ITER diagnostic system, have been reviewed as part of the ITER design review process by a panel of experts experienced in operating modern tokamaks. The review panel recommended some changes in both the measurement requirements and the diagnostic system. These changes have been largely adopted and a new baseline diagnostic system has been developed. In this paper we present the main changes and outline the new baseline diagnostic system.

1. Introduction

In the summer of 2007, the requirements for plasma and first wall measurements on ITER, and the components of the diagnostic system, were reviewed by a panel of experts experienced in operating modern tokamaks. The measurement requirements were reviewed in the light of the intended use of plasma measurements on ITER, and the diagnostic system was reviewed against the need for its integrated capability to meet those requirements. In addition to reviewing the diagnostic system, the panel also considered the impact on diagnostics of possible changes coming from the wider ITER Design Review. The panel made a number of recommendations for changes to both the measurement requirements and the system. Following the design review, a cross party group, the Diagnostic Working Group (DWG), was convened to develop a proposal that takes into account these changes. In common with other changes coming from the ITER Design review, effort was made to make the changes cost neutral. The proposal developed by the DWG was reviewed in the ITER Organization (IO) and accepted into the ITER Baseline in early 2008 and as a consequence there is now a new baseline for the ITER diagnostic system. In this paper we present the main changes arising from this process and we outline the new baseline diagnostic system.

2. Changes to the Requirements for Plasma and First Wall Measurements

The requirements for measurements of key aspects of the first wall and the main parameters of the plasma [1] have been developed over several years in a process involving many experts; in particular, the requirements have been reviewed by the members of the ITPA physics topical groups and by the staff of the IO. In total more than 100 diagnostic physicists and physicists experienced in operating tokamaks have reviewed the requirements. About 45 different physical parameters, such as plasma current, plasma shape and position, have to be measured and in total about 500 different measurement parameters (measurement ranges, temporal and spatial resolutions and target accuracies) are defined. The requirements act as the target for the detailed design and performance of the individual diagnostic systems that together make up the ITER diagnostic system.

The Review Panel recommended changes to the specifications of about 15 of the physical parameters. They also noted that there were areas where the requirements were not fully specified and they recommended that this should be rectified. Following the review, the DWG worked with members of the IO staff and developed improved requirements. Examples of the changes are:

1. The lower current for which we need to be able to measure the position and shape of the divertor channel (parameter #2) is now defined as 3 MA. Divertor operation is not expected below 3.5 MA.

2. The lower limit for measurements of radiated power (parameter #5) has been defined as 0.1 MW which should make possible measurements during initial plasma operation at low current. The upper limit remains at 1 GW which is expected to be the limit of the maximum stored energy during disruptions and a thermal quench time of 1 ms.

3. The upper limit of the measurement of the total fusion power (parameter #7) has been raised to 1.5 GW to give some margin over the maximum fusion power expected (about 1 GW).

4. The high temperature limit for the measurement of the surface temperature of the divertor plates (parameter #16) has been raised to 3,600 °C to cover the use of tungsten.

A significant change that affects the measurement of most of the profile parameters (electron density, electron temperature, ion temperature etc) is to the value of r/a that sets the boundary for the high spatial resolution measurements needed in the edge region and the moderate resolution measurements needed in the core. After a careful consideration of the various factors involved (expected pedestal width, decay lengths of electron density and temperature in the scrap off layer, need for proper experimental characterisation of edge profiles etc) it was decided to set the limit at $r/a = 0.85$. This is, of course, a compromise but it was felt that it would satisfy most of the measurement needs.

The total number of changes is about 100 which is too many to detail in the written version of the paper. However, all the changes are included in the poster and are also available on the web page of the ITPA Diagnostic Topical Group [2].

3. Changes to the ITER Diagnostic System

The ITER diagnostic system comprises about 40 individual measurement systems drawn from the full range of modern tokamak diagnostics. The selection, design and integration onto the tokamak of the individual systems is driven by the role of the measurements provided by the systems with priority being given to those that provide measurements for safety, machine protection and plasma control. The goal is to achieve an integrated measurement capability that, as far as possible, meets all the requirements for the measurements.

The diagnostic system was originally defined in 2001, designed in outline and documented in the ITER Final Design Report [3]. Since 2001 there have been changes in some of the requirements for measurements coming especially from the developing sophistication of plasma control and to support more advanced physics studies. Types of plasma operation are possible now, and have significant advantages as far as plasma performance is concerned, that were not in use in 2001. The Review Panel recommended some changes to the system in the light of these developments. The recommendations go mainly in the direction of requiring some additional systems, or at least the enabling interfaces of these, to be brought into the baseline. In one or two cases areas where systems could be removed, because of duplication in the measurement capability, or reduced in capability were identified.

Following the review, the DWG worked with members of the IO staff and developed specific improvements to the system. For example, the review panel recommended that provision should be made for the installation of a high resolution neutron spectrometer. This will be achieved by adding a collimator to the neutron camera on equatorial port 1 so that an instrument can be installed cost effectively after the initial plasma operation. In order to achieve the calibration of the array of detectors planned for making measurements of the neutron flux recent work has shown that it will be necessary to have a flux detector with a close coupling to the plasma. This will be achieved by adding a neutron flux detector below the divertor dome (Figure 1) to be installed at the same time as the other in-vessel systems. It is recommended that the temperature of the divertor target plates should be measured with good spatial and temporal resolution. This will be achieved by adding a dedicated thermography system operating in the infrared. It was also recommended that the X-ray measurements be enhanced. This will be achieved by installing an X-ray camera in the equatorial port 9 (Figure 2).

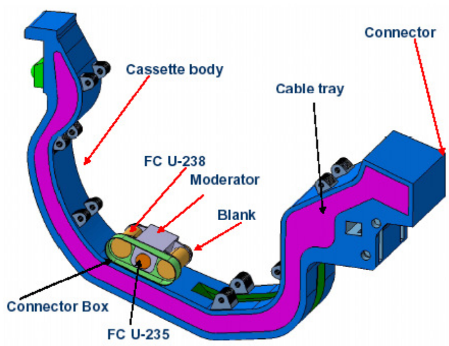

Figure 1. Divertor Neutron Flux Monitor integrated into divertor cassette

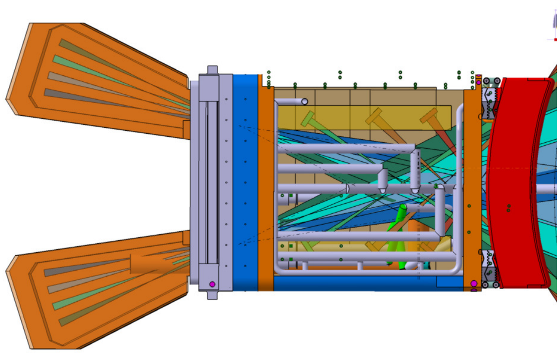

Figure 2. X-ray camera design concept integrated into an equatorial port (#9)

A shortfall in the measurement capability for the confined fast ions and especially alpha particles relative to the measurement requirements has been recognized for several years: a shortage of good measurement techniques has made it difficult to meet the requirement. The recent success of Collective Thomson Scattering (CTS) on TEXTOR [4] opens up the possibility of a system for ITER. In the changes following the design review, provision has been made for a cost effective subsequent installation of a system in equatorial port 12 (Figure 3).

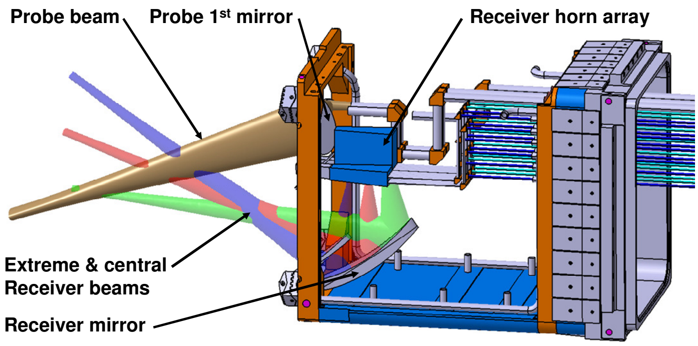

Figure 3. Low field side launch and receiver for CTS diagnostic integrated into an equatorial port (#12)

Careful review of the system showed that in some areas there was duplication of measurement capability. In one or two cases, inappropriate systems were included. For example, it was recognised that the visible continuum could be measured by adding dedicated detection channels to the passive spectroscopy systems thereby avoiding the need for a dedicated system. It was judged that it was not necessary to have a water neutron activation system in addition to the encapsulated foil system since the later would provide the needed measurements. In total about 15 different technical changes are being made in response to the design review and are summarised in Table 1. Table 2 summarises the revised Baseline Diagnostic System taking into account these changes.

In addition to dealing with the technical matters the DWG also worked to allocate the systems to the ITER Partners according to certain, agreed, credit targets. The result of this process is also shown in Table 2.

4. Dust and Tritium Control: New Measurements and Diagnostics

Two important areas highlighted by the review panel, and which were already under study, were the measurement of dust and retained tritium. The need for these measurements is driven by safety. To satisfy the safety requirements, an ITER dust and tritium control strategy [5] has been developed which comprises removal and measurement. According to the strategy, dust removal is conducted during scheduled divertor replacement shutdowns where the vessel floor is accessible for vacuum cleaning. The main tritium removal is conducted at the same time; tritium trapped in the divertor and the dust are carried out of the vessel. The most accurate assessment of dust and tritium inventory will be made during these shutdowns. However, the levels of dust and tritium must also be monitored during operation to prevent unacceptable inventories being reached before these shutdowns. Accurate measurement of the tritium deficit in the tritium plant provides monitoring of the tritium inventory during operation [6], but because of accumulated error in tritium burn-up estimates, direct measurement of the in-vessel inventory is required. The requirements for the measurements have been determined (Table 3).

Table 1. Summary of Main System Changes Arising From Design Review Recommendations

System	Design Review Report or DWG Recommendation	Technical change adopted
High Resolution Neutron Spectrometer	Provision for later installation of high res. neutron spectrometer	Add collimator into neutron camera on equatorial port 1 so that instrument can be installed cost effectively later.
Neutron Flux Monitor (Div)	The Divertor Neutron Flux Monitor should be included and installed for start up.	Install in VV below divertor. Must be installed for first plasma.
Gamma ray spectrometers	Provision for later installation of gamma ray spectrometers	Add interfaces so that gamma detectors can be installed behind the neutron detectors in Radial and Vertical Neutron Cameras
Collective Scattering System	Key alpha particle diagnostic systems need to be included. For confined alphas, Collective Thomson Scattering should be included.	Install low field side (LFS) collection waveguide and antenna for cost effective installation later.
X-ray cameras.	X-ray measurements should be enhanced.	Install camera in equatorial port 12.
IR thermography divertor	A dedicated divertor thermography system should be included.	Install optics in divertor port 16 and all necessary external parts. System to be available for start of operation.
Divertor VUV		Install mirror supports in divertor port and basic system
Hard X-ray measurements	The list of "first-plasma" diagnostics should include runaway electron/hard X-Ray measurements	Add hard X-ray detectors to diagnostic set for first plasma.
Beam Emission Spect.	Needed for calibration of CXRS measurements.	Add spectrometers and detectors for initial operation of CXRS.
Divertor Reflectometer	Consider relaxing the 3 mm spatial resolution requirement, and eliminating the divertor reflectometer system.	Drop the system
Electron Cyclotron Absorp.	Technically very difficult and no good experience base	Drop the system
Visible Continuum Array	Measurement can be made by other systems, eg CXRS.	Drop system. Measurement can be made by other systems, eg CXRS.
Edge Thomson Scattering	Concern over limited range of use	Move from upper port to equatorial port (#10). Spatial resolution is less but plasma coverage is better and measurements can be made for all scenarios of interest rather than just full bore plasmas. Integration of remaining systems in upper port also simplified.
Laser Induced Fluorescence		Integrate with Div. Thomson Scattering system. Include interfaces.
Water Neutron Activation system	Main benefit of system relative to foil system is time resolution but the flux monitors will provide better time resolution. Foil system judged to be adequate for role of neutron activation measurements.	Drop the system
Residual Gas Analysers		Formerly four. Reduce to two. Two were judged to be adequate to meet the measurement requirement.

Both tritium retention and dust production are linked to plasma facing component erosion. For this reason, measuring erosion is part of the dust and tritium monitoring strategy. According to this strategy, initially a conservative relation will be adopted, for example that all eroded material becomes dust. A more realistic relation will be used when it is supported by operational experience, such as early unscheduled shutdowns without divertor replacement.

To meet the new measurement requirements, it is proposed to add four new diagnostic systems to the ITER design:

1. Divertor erosion monitor. This is a system which can measure change in thickness of the inner and outer divertor target plates during operation. There are two techniques which are under consideration: i) a speckle interferometer [7] and ii) laser radar [8]. Either system will view the divertor targets through optics mount in the divertor dome (Figure 4).

2. Dust microbalance. This is a system for measuring local dust concentrations under the divertor targets during operation. As with the erosion measurement, operational experience will be required to learn how to scale the local measurements to a dust inventory. The preferred diagnostic technique is a capacitive diaphragm gauge [9], installed on divertor cassettes to sample the toroidal gap between cassettes.

3. Laser desorption. This is a system aimed at local measurement of surface concentration of tritium during shutdowns. A laser induced breakdown spectroscopy [10] system will be introduced by remote handling to make local measurements of the tritium trapped in the surfaces.

4. Removable samples. This is to provide local measurement of dust and tritium during shutdowns. Dust and deposit collectors in areas well shadowed from the plasma are recovered by remote handling for analysis.

This proposal has been accepted through the formal design change process in ITER and now forms part of the wider proposal for design enhancements arising from the ITER Design Review process.

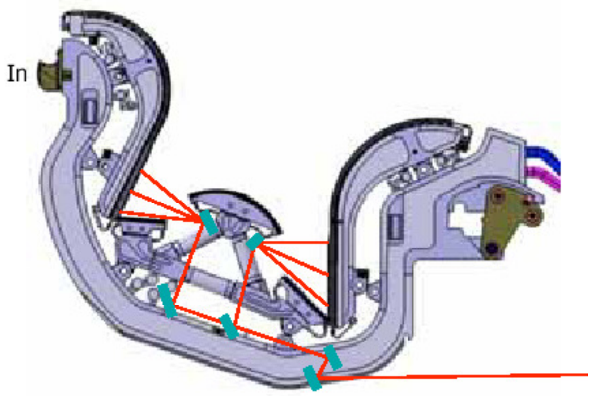

Figure 4. Configuration of the divertor erosion monitor. The laser path is implemented in the toroidal center of the divertor cassette, going through the pumping slot on the lower outer cassette body. Mirrors under the divertor dome allow viewing of the strikepoint regions of the vertical targets.

Table 2. Baseline ITER Diagnostic System and Party Allocations (Dust, Erosion and Tritium Monitors are not yet allocated)

Magnetic Diagnostics		**Spectroscopic and NPA Systems**	
Outer-Vessel Magnetics	EU	CXRS Active Spectr. (based on DNB)	EU/RF
In-Vessel Magnetics	EU	H Alpha Spectroscopy	RF
Divertor Magnetics	EU	VUV Imp Mon (Main Plas and Div)	KO
Continuous Rogowski Coils	EU	Visible & UV Imp Mon (Div)	JA
Diamagnetic Loop	EU	X-Ray Crystal Spectrometers	IN/US
Halo Current Sensors	EU	Radial X-Ray Camera	CN
Neutron and Fusion Product Diag.		Beam Emission Spectroscopy	IN
Radial Neutron Camera	EU	Neutral Particle Analysers	RF
Vertical Neutron Camera	RF	MSE (based on heating beam)	US
Microfission Chambers	JA	Hard X-ray Monitor	EU
Neutron Flux Monitors (Ex-Vessel)	CN	**Microwave Diagnostics**	
Neutron Flux Monitors (Divertor)	RF	ECE Diagnostics for Main Plasma	IN/US
Gamma-Ray Spect. (interfaces)	EU/RF	Reflectometers for Main Plasma	RF/US
Neutron Activation System	KO	Reflectometers for Plasma Posn	EU
High Res Neutron Spectr (interfaces)	EU	Divertor Interferometer	US
Optical Systems		**Plasma-Facing Comps and Operational Diagnostics**	
Thomson Scattering (Core)	EU	IR Cameras, visible/IR TV	EU/US
Thomson Scattering (Edge)	JA	Thermocouples	EU/JA
Thomson Scat/LIF Interfaces (Div. region)	RF	Pressure Gauges	EU
Toroidal Interferom./Polarim	US	Residual Gas Analyzers	US
Polarimetric Syst. (Pol. Field Meas)	JA	IR Thermography Divertor	JA
Collective Scatt. (LFS front end)	EU	Langmuir Probes	CN
Bolometric System		Dust and Erosion Monitors	tbd
Bolometric Array For Main Plasma	EU	Tritium Retention Monitors	tbd
Bolometric Array For Divertor	EU	**Diagnostic Neutral Beam**	IN

5. Summary

The requirements for plasma and first wall measurements on ITER, and the composition of the planned diagnostic system, have been reviewed by a panel of experts experienced in operating tokamaks. The requirements and systems were found to be 'reasonably optimal' but needing modification in some key areas. In response to the review, about 100 parameters of the 500 that make up the measurements requirements have been changed and in some cases defined for the first time, and about 16 significant changes have been made to the composition of the diagnostic system. The allocation of diagnostics to parties has been adjusted to take into account the system changes. Measurements of dust, erosion, and tritium retention have been handled separately as part of a coordinate approach to develop a strategy for dealing with dust and tritium retention [5]. This has led to the development of requirements for these measurements and the selection of techniques for making the measurements. It is believed that the new baseline for the diagnostic system, which includes

Table 3. Requirements for Erosion, Dust and Tritium Retention Measurements
Parameter Ranges, Target Measurement Resolutions and Accuracy

MEASUREMENT	PARAMETER	RANGE or COVERAGE	RESOLUTION Time or Freq.	RESOLUTION Spatial or Wave No.	ACCURACY
16. Divertor Operational Parameters	Erosion rate	1 – 10 x 10^{-6}m/s	2 s	10 mm	30 %
	Net erosion	0 – 3 mm	Per pulse	10 mm	12 x 10^{-6}m
46. Dust Monitoring	Dust accumulation rate	10^{-4}-10^{-2} kg/m^2/pulse	Per pulse	Several positions	50% abs 20% repr
	Dust concentration	10^{-2}–10 kg/m^2	Daily	Several positions	50% abs 20% repr
47.Tritium Monitoring	H,D,T accumulation rate	$2\cdot10^{19}$- $2\cdot10^{21}$ H,D,T/m^2/pulse	Per pulse	Several positions	50% abs 20% repr
	H,D,T concentration	10^{20}- $2\cdot10^{24}$ H,D,T/m^2	Daily	Several positions	50% abs 20% repr

all these modifications, represents a cost effective solution to the needs for plasma and first wall measurements on ITER. While good progress is being made with diagnostic design, some areas still require R&D. Progress with the highest priority topics are summarized in parallel papers at this conference [11,12].

Acknowledgement

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