

ITER DIAGNOSTICS: A SUCCESSFUL EXPERIENCE IN INTERNATIONAL COLLABORATION

A. E. COSTLEY AND THE ITER JCT AND HOME TEAMS

ITER Naka Joint Work Site, 801-1 Mukouyama, Naka-machi, Ibaraki-ken 311-0193, Japan

The physical environment in which ITER diagnostic components have to operate is outlined, and the general design requirements, which they must satisfy, are summarised. The designs of three representative diagnostic systems are described to illustrate the solutions that have been developed. The changes arising from the move to a Reduced Technical Objective/Reduced Cost ITER, are summarised. Some key outstanding issues are identified. The work is an ongoing collaborative venture between diagnostic specialists and engineers in the four ITER partners and this unique aspect of the work is highlighted.

1 Introduction

The International Thermonuclear Experimental Reactor (ITER) requires an extensive plasma measurement system for the purposes of machine protection, plasma control and physics studies. The measurement system comprises about 40 individual diagnostic systems. The development of the designs of the diagnostic systems is a substantial technical challenge because of the combination of the harsh environment of ITER with the demanding measurement requirements. This challenge is being met by a coordinated design and R&D effort of the four ITER partners – Europe, Japan, the Russian Federation and the United States of America. In this paper, we outline the design challenge and we show how it has been met by describing a few representative examples. Not all of the requirements have been satisfied and ITER itself is undergoing change, so the work is ongoing. The new developments are summarised and some key unresolved issues are identified. We concentrate mainly on optical and microwave systems consistent with the theme of the Laser Aided Plasma Diagnostic Meeting.

Naturally, the starting point is to define the measurement requirements. This has been done through an iterative process involving the relevant physics and engineering groups in the ITER Joint Central Team (JCT) and the ITER Diagnostics Expert Group. The latter group consists of two or three diagnostics specialists from each ITER partner plus some members of the JCT. Detailed measurement requirements are drawn up by the Diagnostic Expert Group on the basis of the anticipated needs for the measurements and supplemented by modelling

calculations whenever possible. Expert groups exist on other topics, for example confinement, and the members of these groups are included in the review process. The output is a set of detailed measurement requirements, which are used in the selection of the individual diagnostic systems and act as a target for the diagnostic design.

The activity has been ongoing since the beginning of the ITER Engineering Design Activities (EDA) in 1992. During this period the measurement requirements have been specified,¹ diagnostic systems have been selected,² and the designs of many of the systems that will be used to make the most important plasma measurements have been developed.³ Recently, the required detailed technical performance of ITER has been revised and a Reduced Technical Objectives/Reduced Cost (RTO/RC) ITER is now under design. The RTO/RC-ITER will be significantly smaller than ITER(98)⁴ but will maintain the programmatic objective. However, the main factors which drive the diagnostic design - required measurement capability, reliability, maintainability, environment of key components, shielding requirements, vacuum requirements and tritium containment – remain approximately the same. The discussions in this paper focus mainly on the designs developed for the ITER(98) but the expected changes for the RTO/RC-ITER are summarised.

The paper is organised in five main sections. In section 2, the environment in which ITER diagnostics will have to operate is described and the general requirements that the designs have to satisfy are summarised. The designs of three representative systems are presented in section 3. The changes for the RTO/RC-ITER are summarised in section 4 and the key outstanding issues are given in section 5. A summary is presented in section 6. A unique feature is the international aspect of the undertaking and this is highlighted where appropriate.

2 Environment and General Design Requirements

Diagnostic components will be installed in many regions of the machine – inside the vacuum vessel, in the diagnostic ports, in the inter-space between the vacuum vessel and the cryostat, outside the biological shield and in the remote diagnostic areas – but it is those installed in the vacuum vessel close to the first wall that will be in the harshest environment. Here there are high neutron and gamma radiation fluxes, substantial heat loads from plasma radiation, and high neutral particle fluxes from charge exchange processes in the edge regions of the plasma. The background temperature is elevated to about 350 °C at all times. The PF coil system produces a large poloidal magnetic field which is about 1 T at the first wall, 0.2 T at the cryostat wall and 0.01 T 100 m from the machine centre. An additional hazard for components in the vacuum

vessel is material evaporated from the divertor and first wall which will be re-deposited on plasma facing surfaces. This could be particularly severe during disruptions.

It is not just the intensity of these hazardous conditions that is significant but also the longevity. ITER pulses are typically several thousand seconds in duration with steady state operation as an ultimate goal. Relative to the harshest conditions experienced on existing machines the particle fluxes are about 5 times higher, the neutron flux levels are about 10 times higher, the neutron fluence is about 10,000 times higher, and the pulse lengths are about 100 times longer. The environmental conditions are summarised in Table 1.

Table 1: Environmental conditions in key locations for diagnostic components.

Location Typical diag. component	Neutrons		Heating rate (ss) W/cm ³	Fluence > 0.1 MeV n/m ²	Particle flux atoms /m ² s	Plasma radiation (peak) kW/m ²	Ambient temp °C
	> 0.1 MeV n/m ² s	< 0.1 MeV n/m ² s					
First Wall	3x10 ¹⁸	8x10 ¹⁷	12	3x10 ²⁵	~ 5x10 ¹⁹	500	350
Back- plate/between shield modules <i>Mag. coils</i> <i>Bolometers</i> <i>Retroreflectors</i>	3x10 ¹⁶	2x10 ¹⁶	0.5	3x10 ²³	~ 10 ¹⁸	10	350
Back- plate/behind shield modules <i>Mag. loops</i>	1.9x10 ¹⁶	1.4x10 ¹⁶	0.25	1.9x10 ²³	~ 0	~ 0	350
Diagnostic block <i>First mirrors</i>	1.3x10 ¹⁶	9x10 ¹⁵	0.1	1.3x10 ²³	~ 10 ¹⁷	~ 1.5	~ 120
Labyrinth <i>Second mirrors</i>	2.3x10 ¹³	3x10 ¹³	3x10 ⁻⁴	2.3x10 ²⁰	~ 0	~ 0	~ 120
Tor. field coil case <i>First windows</i>	10 ¹² – 10 ¹³ total		3x10 ⁻⁶	~ 10 ¹⁹	~ 0	~ 0	~ 120
Divertor Cassette <i>First mirrors</i>	2x10 ¹⁴ – 1.3x10 ¹⁶	4x10 ¹⁴ – 3x10 ¹⁶	10 ⁻³ – 10 ⁻¹	~ 10 ²⁴	10 ¹⁷ – 10 ¹⁹	1 – 100	~ 140
Divertor Cassette <i>Second mirrors</i>	2x10 ¹⁴ – 6x10 ¹⁵	6x10 ¹⁴ – 1x10 ¹⁶	4x10 ⁻³ – 4x10 ⁻²	~ 10 ²⁴	To be determd.	To be determd.	~ 140

Many consequences follow from these harsh conditions. The neutron/gamma radiation and plasma radiation lead to substantial heating of all plasma facing components (up to 12 Wcm⁻³) and so all such components have to be actively cooled. Physical damage can occur and so the materials have to be carefully chosen. The electrical properties of insulators can be altered by

the radiation and so again materials have to be carefully chosen. Optical properties of potential lens and window materials can be affected and the radiation can induce radio-luminescence. The effects are so substantial that no refractive optical components can be plasma facing. Instead, actively cooled metal mirrors are used as the first optical element. However, for such mirrors care must be taken to minimise the potential change to the reflectivity and possible physical damage due to the bombardment by neutral particles.

The information on which to base the choice of materials in the different applications has come from an extensive irradiation effect R&D programme that has been ongoing since the beginning of the EDA. A wide range of materials have been investigated and their mechanical, electrical and optical properties have been documented.⁵ This has been a four party undertaking with sharing of results and sometimes joint investigations. The work has established a substantial database, which is used in material selection for diagnostic components.

The environmental conditions effectively establish a set of general design requirements for diagnostic components: such as active cooling for plasma facing components; no refractive optical components in the vacuum vessel; first mirrors made of metal; careful choice of insulators etc. But the diagnostic components have also to satisfy another set of general design requirements: these are the requirements for all components mounted in the tokamak. They are the stringent requirements for the vacuum integrity of the machine; for containment of tritium; for maintainability with the remote handling tools; and for a reliable performance and a long lifetime. For some components, for example magnetic loops mounted on the vacuum vessel, the required lifetime is the same as that as other semi-permanent machine components, that is many years. Finally, diagnostic penetrations through the shield wall represent a potential reduction in the shielding and could lead to an enhancement of the radiation levels in the cryostat. All diagnostic penetrations have to be designed so that the shielding is not reduced. In practice, this is achieved by using folded transmission lines mounted in effective shielding material.

3 Some Representative Systems

3.1 Edge Thomson scattering

An important parameter for understanding and controlling high performance plasmas, especially H mode plasmas, is the edge temperature profile. Projections from current experiments indicate that the width of the electron pressure pedestal will be in the range 0.1 – 0.2 m at the mid-plane and the pedestal height will be of 4 – 8 keV. Gradient scale lengths in the scrape-off layer are expected to be only 0.01 – 0.02 m. Measurements over a limited spatial extent (about 0.3 m) at

high resolution (~ 5 mm) are therefore required. In the ITER environment this is a difficult measurement challenge. A dedicated edge Thomson scattering system, which largely meets these requirements, has been designed by a team in the United States.⁶

Access through a top port allows the measurement to be made in a region where the physical size of the edge is expanded by about a factor of three due to the flux expansion (figure 1). This leads to enhanced signal/noise in the measurement for two reasons: the scattering length is increased for the same effective spatial resolution, and the collection system does not view the hot plasma core thereby reducing the bremsstrahlung background.

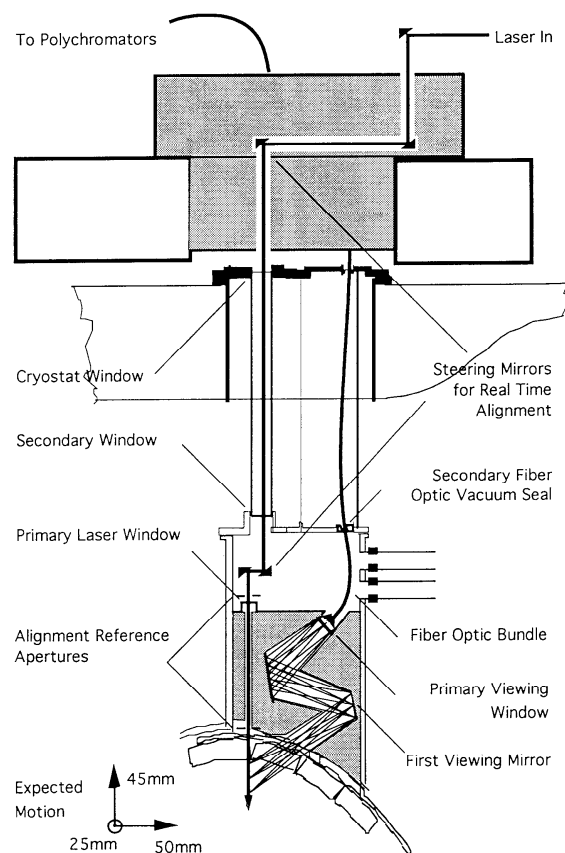


Figure 1. Proposed installation of Edge Thomson Scattering system in an early version of the top port.

The laser beam is introduced through a labyrinth and passes through a gap ~ 100 mm in the toroidal direction between two blanket modules. The scattered radiation is collected through a second labyrinth and transmitted to the remote spectrometers. Mirrors are used in the labyrinths.

Extensive work undertaken in Europe in support of the design of the main core Thomson scattering system (a LIDAR system), has shown that a metal mirror coated with rhodium should have the necessary combined properties of high reflectivity, low sputtering coefficient and high thermal conductivity.⁷ On the shielded side of the labyrinth, optical fibres are used in the collection system and should deal effectively with the differential movement of the optics attached to the vacuum vessel and the optics attached to the bioshield. The working wavelength range is 800 – 1200 nm where luminescence and darkening due to nuclear radiation are known to be low. Active alignment will be required for the input laser beam.

The proposed design meets the target measurement requirements for temperature range, density range, spatial resolution and precision, but is marginal for the spatial range that can be examined. To permit the investigation of a range of plasma scenarios a range of 0.6 m is desirable but the present design only meets the measurement requirements within a range of about 0.4 m. A re-design of this system for the new ITER port configuration (section 4) is required.

3.2 Microwave reflectometry

Many diagnostics will be installed in the equatorial ports: a typical system is the Main Plasma Reflectometer.⁸ This system will be used to provide essential information on the density profile and density perturbations due to plasma modes. It will also supply valuable information on plasma turbulence in all regions of the plasma. In order to provide coverage of the full profile, three sub-systems are necessary. An extraordinary mode (X-mode) launch system, reflecting off the upper cutoff plasma layer is used on the low-field side to provide measurements of the scrape-off layer (SOL) profile. An ordinary mode system is used to provide the inboard and outboard density profile in the gradient region. Finally an X-mode system reflecting off the lower cutoff plasma layer and launched from the high field side provides the core profile. The operating frequency ranges of the sub-systems are respectively 84 – 220 GHz, 20 – 155 GHz and 10 – 110 GHz. The design of this system is a collaborative effort between the European and the Russian Federation parties.

The low field side systems share an array of broad-band antennas of typical diameter 100 mm mounted on a diagnostic block in an equatorial port and viewing the plasma through apertures in the blanket/shield (figure 2). The antennas do not protrude in front of the diagnostic block. As a result, the front ends of the antennas are at least 0.8 m away from the plasma during operation, with the first mirror (mitre bend) at least 1 m away from the first wall. Broadband

overmoded corrugated circular transmission lines couple the front ends to the system electronics which are placed several tens of meters away in the pit. Components such as swivelling mitre bends, expansion joints and long elastic sections are used to accommodate vessel movement with respect to the bioshield whilst preserving millimetre-wave performance.

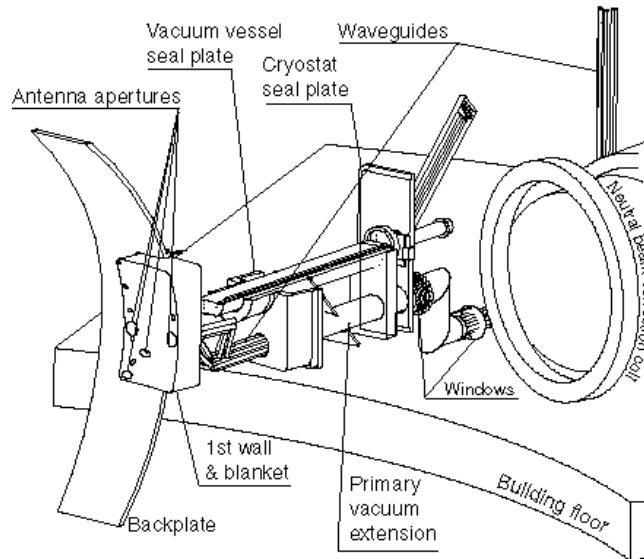


Figure 2. Low field side antenna and waveguide for the Main Plasma Reflectometer.

The high field side systems consist of four antenna pairs, mounted on the backplate and viewing the plasma between blanket modules. Radiation is routed to these systems using small bore waveguide. This waveguide resides in the space allocated on the backplate and blanket structure for the diagnostic conduit. The waveguides are brought out through three of the vertical ports to electronics residing in the bioshield interspace. Expansion joints and elastic sections are used to accommodate the vacuum vessel movement.

For all systems, labyrinths in the transmission lines reduce neutron streaming outside the vacuum vessel and bioshield. Vacuum windows of fused quartz, directly bonded to metal structures and inclined at the Brewster angle for the appropriate polarisation, provide robust, low millimeter-wave loss, pressure boundaries.

It is expected that the combined performance of these three sub-systems will match or exceed the performance target set for the measurement of the density profile with respect to time and space resolutions.

3.3 *Divertor impurity monitor.*

A key to achieving high fusion performance in ITER will be the proper operation of the divertor. The divertor is required to remove power and particles from the plasma and to ensure minimum contamination of the core plasma by impurities. A key diagnostic in the understanding and operation of the divertor is the Divertor Impurity Monitor (DIM).⁹ This system is being designed by Japan.

The principal functions of the DIM are to identify impurity species, to measure concentrations and influxes of impurities, deuterium and tritium, and to provide information on the ion temperature and the position of the ionisation front. The expected impurities are carbon, tungsten, beryllium and copper originating from the divertor target plate and from the surface of the first wall in the main chamber. Neon and other impurity gases injected into the plasma for radiation cooling in the divertor are also to be observed. In order to carry out these functions, measurements with spectral, temporal and spatial resolution of the relevant spectral lines from the plasma in the divertor region are required. The measurements have to be made in the uv and vuv regions.

The multiple sightlines are achieved using mirrors mounted in a special divertor cassette (figure 3). Each divertor leg is probed by two overlapping viewing fans and each viewing fan comprises 100 sightlines. A mirror optical relay system passes the radiation to windows mounted on the vacuum vessel flange. Additional viewing fans probe the X-point region. A dog-leg in the transmission line in the bio-shield provides the necessary shielding. Beyond the bio-shield, the spectrometers which probe the short wavelength region ($\lambda < 450$ nm) are located. These are mounted on a moveable trolley so that they can be readily withdrawn for divertor maintenance. For longer wavelengths, low loss optical fibre is available and so the spectrometers can be located remotely.

The front end mirrors are the most critical components. They will be exposed to energetic charge exchange neutral particles and potentially to material eroded from the divertor. During disruptions the erosion could be very severe. The mirrors will be made from a low sputtering coefficient metal (Mo or Rh). Baffles will protect against the deposition of eroded material. It is not known at this stage whether these measures are sufficient and this is a subject of ongoing investigation.

Relative movement of the vacuum vessel and the spectrometers during a plasma pulse is another important design consideration. An active alignment system using a probing laser is under design.⁹

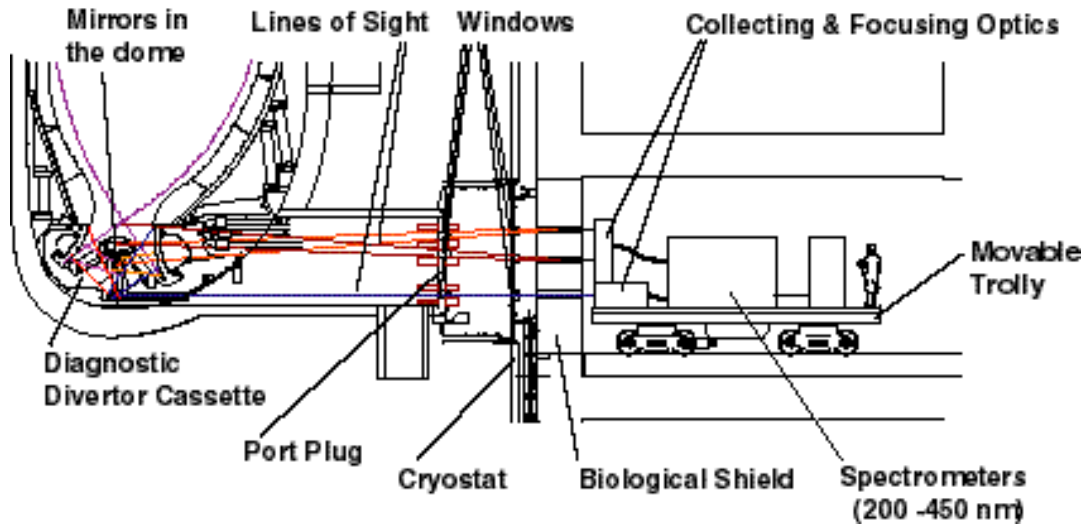


Figure 3. Divertor Impurity Monitor (visible and UV) installed in a divertor port.

For the vuv region ($10 < \lambda < 200$ nm), absorption in the windows is high and so direct coupling of the spectrometer is necessary. Several possible schemes to make the measurements have been investigated but the arrangement with the spectrometers and detectors mounted inside the divertor port is thought to be the most practical.¹⁰

3.3 Integration

The individual diagnostic systems have to be installed on the tokamak in a manner that makes the best possible use of the limited port space. This is a substantial task and has to be carried out in conjunction with the installation of other tokamak systems. Unavoidably, priorities have to be set and for diagnostics this is done according to the expected role of the measurements provided by the diagnostics. Those which provide measurements for machine protection and basic plasma control, are given the highest priority. The allocation of space to diagnostics at the different levels - upper ports, equatorial ports and in the divertor - has to be done in coordinated way: for example, to achieve the required coverage the Plasma and First Wall Viewing system requires coordinated views from both upper and equatorial ports. This process of integration is carried out by the Joint Central Team at the two ITER Joint Work sites.¹¹

4 Changes for the RTO/RC – ITER

Recently the detailed technical performance required of ITER has been revised. The ITER activities are now focussed on designing a device which will achieve $Q = 10$ in long pulse, inductively driven plasmas and which aims to demonstrate steady-state operation at $Q = 5$ using non-inductive current drive. The device will have substantial operational flexibility in plasma equilibrium and operating scenarios, and it is intended that the possibility of ignition should not be excluded. While the values of the main parameters of the device have not yet been finalised, it is already known that they will be approximately: major radius ~ 6 m, minor radius ~ 2 m, elongation ~ 1.8 , plasma current ~ 15 MA, toroidal field ~ 5 T and burn duration ~ 400 s. The fusion power output will be reduced relative to ITER (98) but the neutron wall loading will still be 60 – 80 % of the former value.

The role of plasma measurements is unchanged. There will be detailed changes in the measurement specifications arising principally from the change in the plasma size and shape, and some adjustments in the priorities amongst the different measurements because of the enhanced emphasis of ‘advanced’ modes of operation. The main factors which drive the design of the diagnostics, however remain unchanged. The principal changes come in the implementation of the diagnostic systems.

At the equatorial level the changes are likely to be minimal because the ports will have the same basic configuration although they will be smaller. On the other hand, the changes for diagnostics installed in top ports will be substantial and generally beneficial. The RTO/RC – ITER will most likely have relatively large horizontal, or near horizontal, ports at the top and for most diagnostic systems this should lead to an improved installation. For the Edge Thomson Scattering for example, it should be possible to install a system with an enhanced f-number and more secure alignment between the input and collection optics. At the divertor level, detail changes will be necessary because of the revised divertor configuration – mainly a reduction in the size of the cassettes and an enhanced tilt in the poloidal plane. Measurements on the inner divertor leg are likely to be degraded because of these changes. Diagnostic systems with the sensors mounted in-vessel, for example magnetics, will have minimal changes. Many details of the installations have yet to be determined and this will be a principal activity during the EDA extension phase, which will continue until mid 2001.

5 Outstanding Issues

The development of the designs of the diagnostic systems and the integration of the systems onto the tokamak, are substantial tasks and are, at this stage, only partly completed. However, sufficient work has been done to be able to identify the critical design issues.¹² For most optical and microwave systems, the key issues are associated with in-vessel components and particularly the front end components.

For most of the optical systems, the critical design issue is the lifetime of the first mirror. As outlined in section 3, by setting the mirror back from the plasma down a viewing duct and by using a coating of a low sputtering coefficient metal on an actively cooled metallic base, it is expected that the required performance and lifetime can be achieved. There is still some uncertainty arising from the potential hazard of re-deposited first wall and divertor material. The installation of shutters in the optical chain is a possible protective measure. For systems installed in top and equatorial ports, however, re-deposited material is not expected to be a problem. It is believed, therefore, that the first mirror issue is basically solved for systems such as the Core Thomson Scattering (LIDAR) system, Edge Thomson Scattering, Plasma and First Wall Viewing, and Visible and UV Spectroscopy.

Some systems, however, presently require a large aperture mirror relatively close to the plasma to achieve the required signal levels. Active Charge Exchange Recombination Spectroscopy and Motional Stark Effect are two such systems. Significant design changes will probably be required to reduce this requirement.

For optical systems in the divertor, the problem of re-deposited material could be severe. The use of baffles is a possible solution. Studies of the mechanisms of material erosion and re-deposition are underway on existing tokamaks (mainly for studying the associated problem of tritium retention) but will also be useful in this context.

Some systems require corner cube reflectors to be mounted on the backplate which supports the blanket modules. This is a difficult interface and it is not clear whether the present design concepts meet the requirements. The principal systems involved are the Interferometer/Polarimeter for measuring the plasma density and the Multichannel Polarimeter for measuring the internal (plasma generated) magnetic field.

Microwave systems have relatively few issues. The most significant difficulty is the installation of antennas and waveguides at various locations in the poloidal cross-section, particularly on the high field side. These are required for the Plasma Position Reflectometer and for some measurements with the Main Plasma Reflectometer.

For most systems, alignment, calibration, and compensation for relative movement of different system components are key issues but are not thought to present insurmountable problems.

6 Summary

The combination of the harsh environment, stringent general design requirements, and the need for high performance, poses a substantial challenge to designers of diagnostic systems for ITER. A combined effort of diagnostic specialists and engineers in the ITER parties, with a small team in the JCT, has developed the designs of representative systems which, it is believed, meet this challenge. There are unresolved design issues for some systems and these will naturally form the focus of future work. The success of the endeavor to date owes much to the fruitful pooling of resources and expertise of the four ITER partners, and bodes well for the future construction of the systems.

Acknowledgement

This report is an account of work undertaken within the framework of the ITER EDA Agreement. The views and opinions expressed herein do not necessarily reflect those of the Parties to the ITER EDA Agreement, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER EDA Agreement.

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