Overview of high priority ITER Diagnostic systems status

M. Walsh, P. Andrew, R. Barnsley, L. Bertalot, R. Boivin[a], D. Bora, R. Bouhamou, S. Ciattaglia, A. E. Costley, G. Counsell[b], M. F. Direz, J. M. Drevon, A. Encheva, T. Fang[c], G. Janeschitz, D. Johnson[d], J. Kim, Y. Kusama[e], H. G. Lee[f], F. Le Guern[b], B. Levesy, A. Martin, P. Maquet, K. Okayama, R. Reichle, K. Patel, C. S. Pitcher, A. Prakash, S. Simrock, N. Taylor, D. Thomas, V. S. Udintsev, Y. Utin, P. Vasu[g], G. Vayakis, E. Veshchev, C. Walker, A. Zvonkov[h]

ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France (michael.walsh@iter.org)
[a]ITPA Diagnostics Chair, DIII-D National Fusion Facility, General Atomics, CA
[b]Fusion for Energy, 08019 Barcelona, Spain
[c]ITER China office, Beijing, P.R. China
[d]US ITER Project Office, Oak Ridge, TN 37830, USA
[e]Japan Atomic Energy Agency (JAEA) 801-1 Mukoyama, Naka-shi, Ibaraki 311-0193 Japan
[f]National Fusion Research Institute, Daejeon, Republic of Korea
[g]Institute for Plasma Research, Bhat, Ganghinagar 382428 India
[h]Russian Research Center "Kurchatov Institute", Moscow, Russian Federation

Abstract The ITER device is currently under construction. To fulfil its mission, it will need a set of measurement systems. These systems will have to be robust and satisfy many requirements hitherto unexplored in Tokamaks. Typically, diagnostics either occupy a removable item called a port plug, or are installed inside the machine as an intricate part of the overall construction. Limited space availability has meant that many systems have to be grouped together. Installation of the diagnostic systems has to be closely planned with the overall schedule. This paper describes some of the challenges and systems that are currently being progressed.

1. Introduction

Diagnostics are a critical part of an operational ITER. They will provide all the information on the performance and performance optimisation [1]. At this stage of the tokamak device development, it is imperative that access, boundaries and requirements are well established. This will allow a smooth path towards implementation of the measurement systems as well as minimising effort and ultimately cost. The ITER device will distinguish itself by being the biggest magnetic fusion device ever built and the first to be licensed as a nuclear facility. It will have operating conditions that have not previously been explored. These include a combination of fusion power and long pulse operation. The combination of the above creates a set of conditions that place many diagnostics in a completely new regime. While optical systems have to access the plasma, they have to also be shielded to avoid direct particulate contamination as well as neutron and mechanical stresses. As well as this, minimisation of activation is required outside the vacuum boundary. These requirements combine to provide a challenging base from which to design the systems. Much R&D is ongoing to provide a sound basis for many of the designs [2,3].

2. Overview

The ITER plasma has a very ambitious objective with baseline scenarios [4] such as ELMy H-mode aiming at Q=10 for >300s and Hybrid aiming at Q=5 for up to 2000s and advanced scenarios aimed at demonstrating DEMO conditions. The device will run at typically 15MA of plasma current and disruptions will have to be minimised. A key ingredient in helping to achieve these objectives is the diagnostics. An appropriate set of these will allow the required observations of the various parameters and hence a reliable and effective way to progress the development of the various operating scenarios. To aid this objective, a set of diagnostic systems have been proposed for this machine. A key set of these systems have been retained in the baseline. Currently, approximately 45, different diagnostic systems are planned to be installed around the ITER tokamak. Amongst others [5], they cover the following areas, neutrons, magnetics, passive spectroscopy, active spectroscopy, infrared thermography, particle monitoring and tritium & dust. The required measurements are broadly divided in to 3 categories, i) for machine protection or basic control, ii) advanced performance control, and iii) evaluating the plasma performance and understanding important physical phenomena. The process to implement these systems on ITER is based on a sharing agreement across the member Parties. In order to be realised, systems have to typically go through phases of design review from concept through preliminary to detailed design. For most diagnostics, a concept design review is mandatory to allow the specific project to be formally launched. A few systems such as the port plugs (see *FIG 1*) have to go to preliminary design review before they can be formally launched. The project has identified a number of systems as urgent in order to be able to achieve the more immediate integrated project deadlines scheduled. These systems are composed of parts of the magnetics, port plugs and various individual diagnostics that reside in the vacuum vessel, first wall or inside the cryostat. As a result of this, these systems are receiving urgent attention. Several diagnostics have already successfully passed the design review stage. These are discussed later.

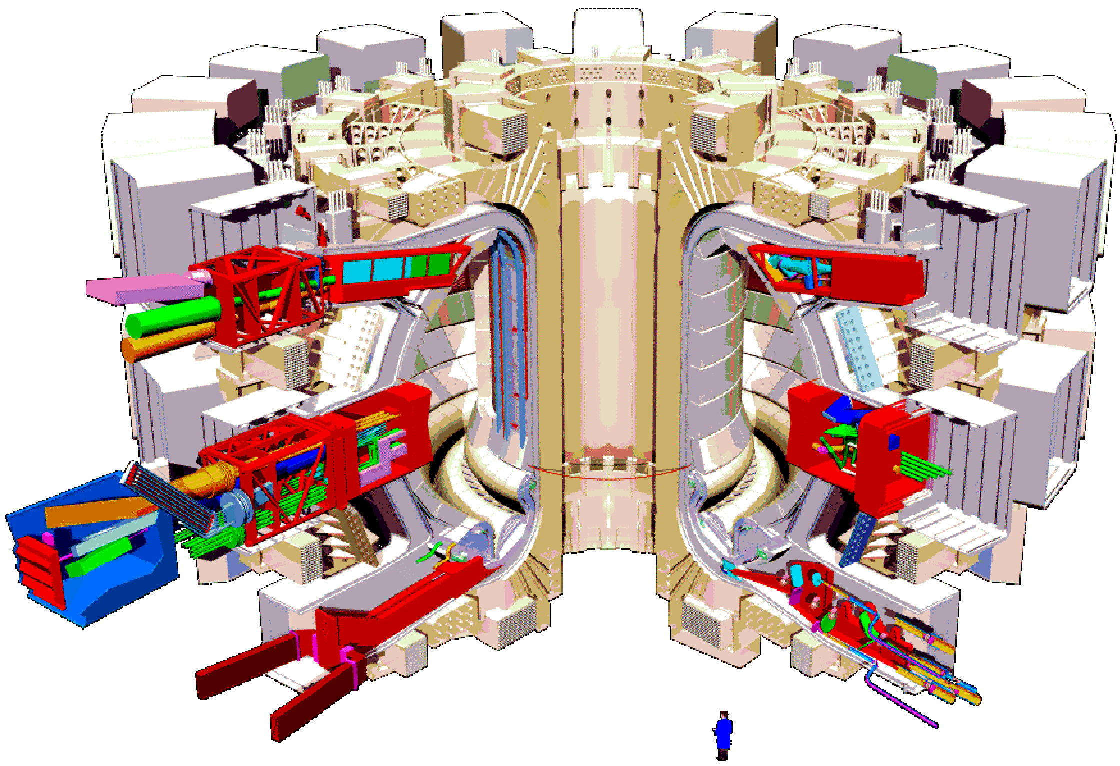

FIG 1: Cutaway illustration of the ITER device showing the port access at the upper, equatorial and lower areas.

Satisfying the Reliability, Accessibility, Maintainability and Inspectability (RAMI) requirements for the systems is of paramount importance for the reliable operation of a complex plant system such as ITER. Since the diagnostics system contributes to diverse functionalities such as (i) to ensure safety of the system (ii) to ensure investment protection and basic machine control (iii) to ensure advanced machine control, and (iv) to provide physics research parameters, required inherent availability and reliability for each function will be different. The ITER Project Requirement Document provides currently a challenging target for availability and reliability close to 98% as a whole diagnostics system while waiting the flow down of this to the individual diagnostics which is underway [6]. As this is a shared requirement, redundancy in systems and across systems is essential to achieve these values. In addition, identifying critical spares and defining maintenance and operation procedures for each diagnostics will add significant value to achieve ITER's ambitious global inherent availability target of 60%.

The final test of the systems will take place once they are installed and operated in the real device. In many cases, simulation and test will provide a very good basis for simulation of the real environment. There are however, some issues that will not be fully resolved until the machine is in operation. One of these will be the impact of the plasma on the first mirrors. As a result of this, it is imperative that these systems are tested on the machine and well in advance of the 'hot' phases of the machine. Other issues such as the impact of neutrons on the final magnetics design will have to wait for the DT phase to be fully tested. As a result of this, special precautions are being taken to ensure that such critical systems will operate reliably.

A special set of diagnostics related to Tritium, dust and erosion are being developed for ITER. These are discussed in paper [7] at this conference.

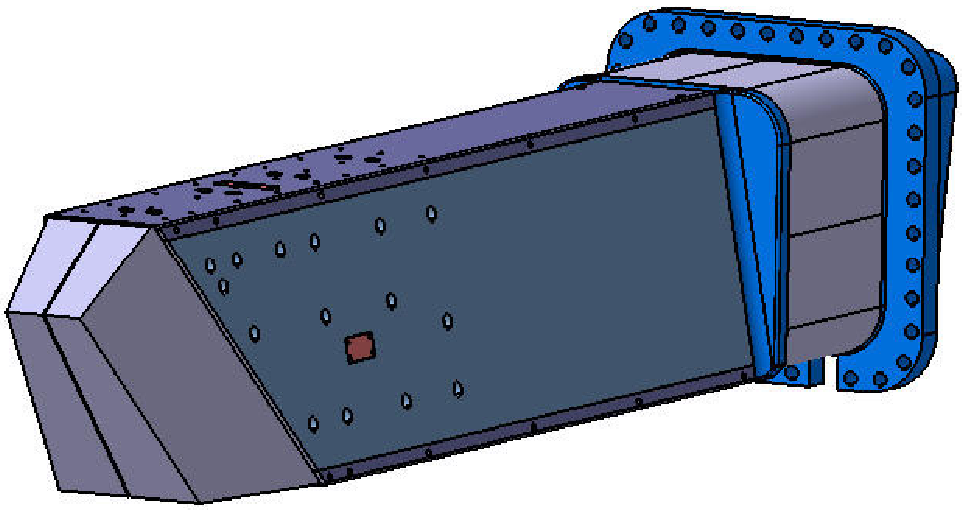

FIG 2: Structure of upper port plug. The port plug itself is mainly a shell. The inside is taken up by diagnostic systems integrated in robust extractable structures.

3. Upper port plug design requirements and status

Diagnostic access to the plasma in the upper part of the ITER vacuum vessel is mainly through what are called upper port plugs. These are managed and removable access points to the vessel. Diagnostics can be assembled in these port plugs ex-machine and brought together for installation at the appropriate time during the tokamak assembly. The opportunity to maintain these in the hot cell facility is a very important requirement as it allows for recovery from any system issues that may arise during the lifetime of the machine. The diagnostic Generic Upper Port Plug (GUPP) design (see *FIG 2*) is meant to be common to all (or most) upper port-based diagnostic systems. It provides a common platform, or support/container for a variety of diagnostics. In addition, the port plug

structure must contribute to the nuclear shielding, or plugging, of the port and further contain circulated water to allow cooling during operation and heating during bake-out.
The upper port plugs have five main requirements; they have to interface to the vacuum vessel, they have to withstand the large electromagnetic and thermal forces, they have to support the diagnostics that are within, they have to be maintainable and they need to provide the same functions as the blanket (i.e. plasma heat flux and radiation shielding). The current design of this system is now at an advanced stage. In the area of the neutral beam, the upper ports access to the machine is very restricted due to building changes to accommodate the large beam components. As a result of this, a special arrangement is being developed where a smaller structure is planned to form the main diagnostic access mechanism.

4. Magnetic measurements

ITER is currently planned to have an extensive set of magnetic measurements as is common on all the current large tokamaks. Combined these are used to protect the machine and control and study the plasma. In the pre-tritium phases, the current technologies used for making the measurements are adequate; this is not true afterwards where issues such as radiation-induced EMF can reduce the sensor accuracy and lead to reduced machine performance. Several approaches are being studied to solve this problem. One of the solutions is to correct the in-vessel signals using sensors sandwiched between the vessel and the thermal shield, where the radiation levels are ~1000 times lower. This minimises related effects, but the vessel EM shielding filters the measurements with a time-constant ~0.1 - 0.6 s. The net effect is that these measurements allow long-pulse operation but cannot be used in isolation for real time applications needed for protection and plasma control. Because of their location, these sensors will be inaccessible early in the tokamak assembly and must be manufactured correspondingly earlier. This is readily achievable for pickup coils. Steady state methods such as Hall probes or MEMS are also under consideration. These can provide additional information as well as drift-free operation, but require more R&D and are therefore more challenging. Other solutions involve the development of radiation-hard in-vessel pickup coils that aim at reducing parasitic voltages during full power operation to the level of tens of nanovolts, thus allowing unhindered full performance operation for 3600s. These sensors should be ready for first plasma by the end of 2019, but upgrades are possible up to blanket installation if ongoing R&D delivers significant improvements in reliability. In order to minimise risk, some of these approaches are being pursued in parallel.

5. Infrared Systems

The infrared systems in the ITER [8] device will be to study the device boundary during operation. This will be able to show if any hot areas are developing and guide the tokamak operator in the operation of the device. This system will also be the subject of first mirror issues. While the observational wavelength is longer than in the visible and hence one expects the effect of particulate matter to be somewhat less, integrated operation time will come in to play. In the IR system, it is important to ensure that an appropriate calibration mechanism is included. Another problem that needs to be tackled here is the issue of wall reflections. In ITER, the wall will be very reflective and this will lead to data interpretation issues either due to increased noise in the system or reflections presenting themselves as hotspots. In addition to this, deposits and dust on hot surfaces will show up brightly in the IR images. In situ measurements of thermal properties are needed to determine power fluxes on such surfaces.

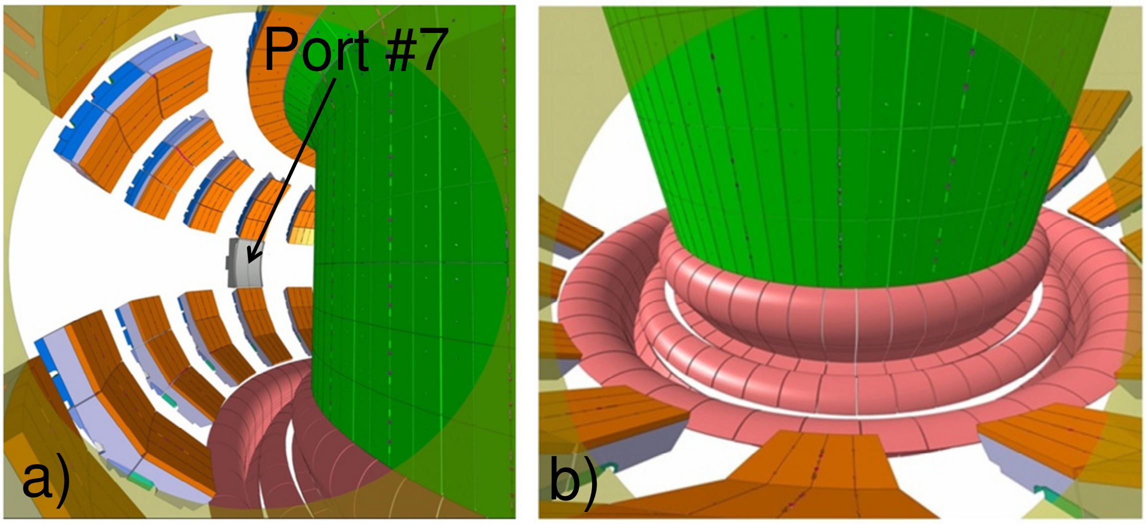

FIG. 3: Views from equ. port # 12: a) left tangential view: equ. port #7 contains a port-plug blanket; b) divertor view.

In ITER, a number of systems are planned (see *FIG 3*) to cover key areas. Six systems with one view per system are planned in the upper ports. They cover the largest part of the surface of the outer divertor target and a large fraction of the baffle and dome area in the spectral ranges 3-5 microns for the IR and additionally 400-700 nm for the visible, the former allowing spectrally resolved observations (at least 2 colors). Four systems with 3 views each (a left and a right tangential view and a divertor view) are situated in the equatorial ports. They cover the heating ports, the beam shine-through areas, most of the inner upper divertor target and most of the blanket, being spectrally resolved like the upper port system. The divertor view is specifically aimed at high spatial resolution and spectrally resolved measurements in the divertor region with resolutions of down to 3mm required.

6. Data Acquisition

The integration of the diagnostics plant systems with CODAC [9] will be an important step to ensure that ITER can be operated as a fully integrated and automated facility for controlled fusion experiments.

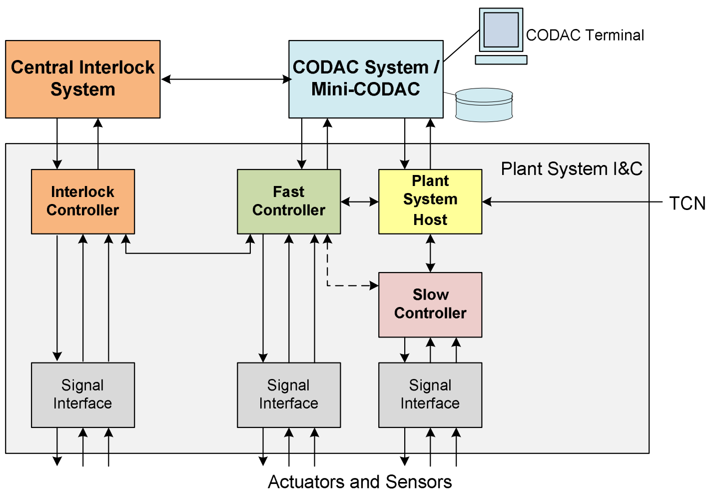

FIG 4: Architecture of central and plant system instrumentation and control including network interfaces.

The diagnostics systems instrumentation and control (I&C) consists of signal conditioning electronics, data acquisition, signal processing resources and communication links demanding state-of-the-art commercial technology to provide the required resources for data acquisition and signal processing. The block diagram in *FIG 4* shows the plant system I&C architecture with the main components including the plant systems host (PSH), slow and fast controllers, signal interface and the network connections to the central systems. The functional specifications of the diagnostics systems follow the signal chain with the elements: signal capture, signal transmission, signal conditioning, signal detection, data acquisition, signal processing, signal communication link and include additional functionality required for operation such as auxiliary system and engineering system functions. The amount and complexity of instrumentation increases from sensor to signal processing significantly and the highest level of standardization can be achieved for data acquisition and signal processing. Sensor and signal transmission systems usually require slow controls (shutter controls, gate valves, temperature sensors, power supplies etc.) which can be implemented with PLC based slow controllers. Data acquisition systems for fast controllers include fast analog to digital converters and the signal processing for camera images. The signal processors such as FPGAs, DSPs, CPUs and GPUs are usually equipped with high speed serial communication links such as GbE and PCI express.

7. Integration

Diagnostics systems cover many areas of the tokamak (see *FIG 5*), both inside and outside the vacuum vessel. While much work has been carried out to integrate these in to the ITER device, the issue of bringing these systems to reality is now beginning. The challenges here are numerous with interfaces to almost all areas of the plant. Multiple diagnostics sharing port plugs provide significant challenges. Areas such as I&C will have to be fully integrated from the beginning.

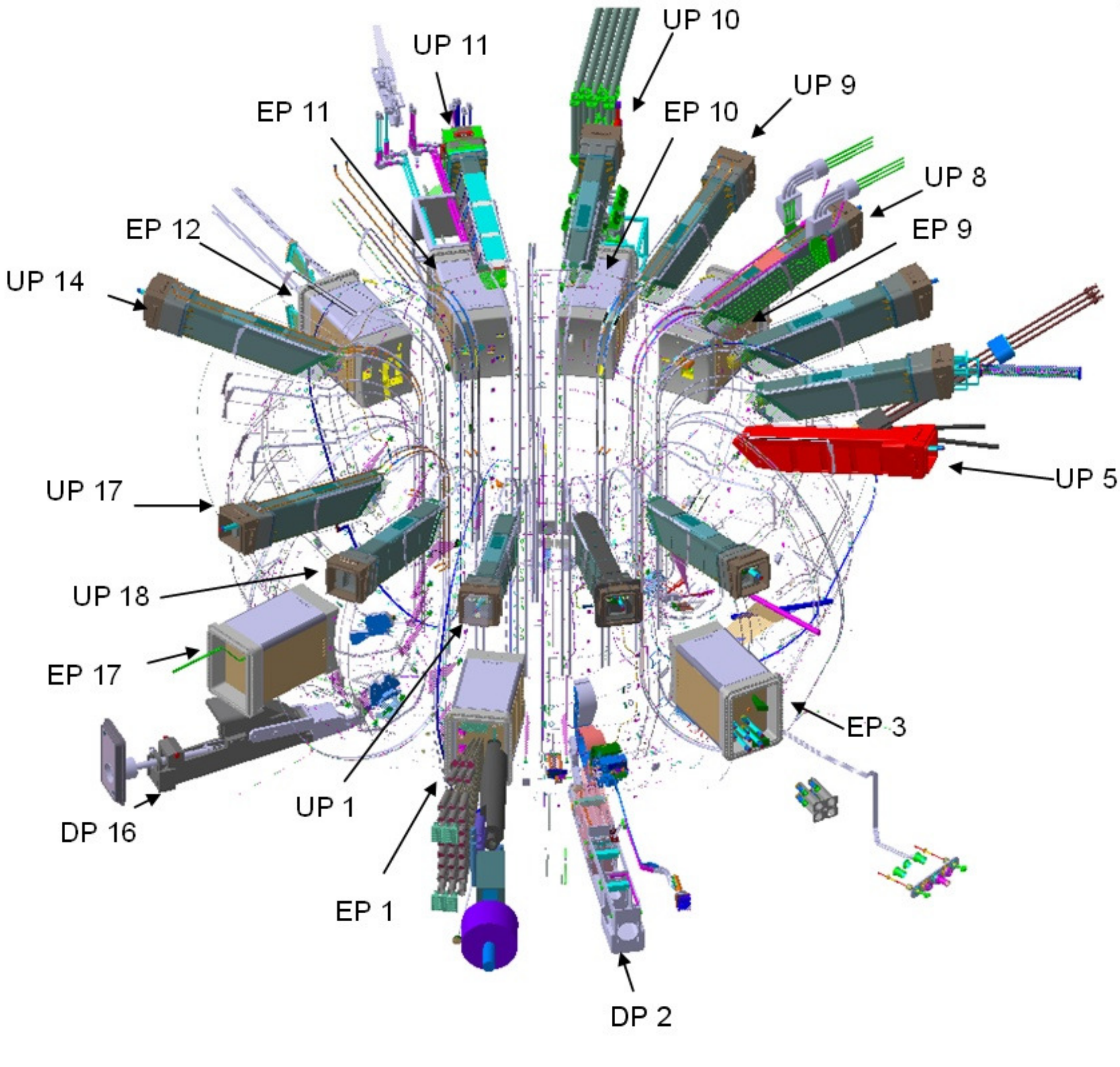

FIG 5: Global view of diagnostic systems on ITER

In-vessel systems have to match with the demands of the first wall, the vacuum vessel and the limited access from in to ex vessel. The completion of the vacuum vessel design is now providing a strong reference for the completion of the design of many systems. These include diagnostics such as the in-vessel neutron monitors, microwave systems (mainly reflectometers) and magnetics. Finalisation of the cryostat and ancillary items will also provide further stability to making the link from the in-vessel all the way to the data acquisition systems.
The in-vessel systems in ITER are currently well advanced, with main vacuum vessel, ports and in-vessel coils interfaces fixed [10]. Interfaces to the other major components in-vessel are also being progressed. This includes the blanket modules and the feed-out for connectors and wiring. A significant amount of wiring has to pass from the vessel. Currently, routing paths for all these are defined. The forces and conditions in vessel are such that the wires and their connections need very special attention to maintain reliability. Various loom concepts are currently under study.
The microwave diagnostics have special requirements as they have to have conductive waveguides to efficiently carry the microwave signals. To minimise the forces on these, a waveguide is planned which is made up of a lower conductivity support structure with an internal thin coating of a suitable conducting material such as copper. Analysis of these hybrid-structures shows that they are capable of surviving the forces inside the device.

The integration of the port structures and their corresponding diagnostic equipment provides many challenges. Firstly, these systems have interfaces to many plant areas. These include the first wall, the vacuum vessel, cryostat, the diagnostics within and many interaction points all the way from the tokamak through the port cell and diagnostic hall. The upper port, lower port and equatorial ports all have different challenges but amongst them is the incorporation of the various systems in a coherent and reliable way. Currently, some diagnostic systems have undergone design reviews. For the upper ports, these include the vacuum ultravoilet spectroscopic system [11] and the infrared viewing system. For the equatorial area, these include the neutral particle analyser, residual gas analyser (RGA), equatorial 7 neutron flux monitor and for the lower ports, another RGA. Some areas of these systems where interfaces are not yet well defined have been highlighted for immediate action. A special plasma current measuring system is placed in the Toroidal Field coil structure has also been reviewed as this is amongst the first required deliveries. This is designed to provide a method of measuring current that has minimum neutron effects.

Other interfaces such as windows have to have special consideration in the ITER device as they provide part of the confinement barrier for in-vessel radioactive material and will need special safety approval. The current strategy for dealing with this is to have a double window arrangement with interspace monitoring. In special cases where high power is being transmitted through the window, these windows will also have a shutoff valve. An example of a welded and a bolted option is shown in *FIG 6*. Presently, there are more than 130 window assemblies predicted. These are planned to be fitted on the port plug flanges where environmental conditions are more favourable and accessibility and inspection is possible. A number of standard sizes are being proposed to minimise cost and allow a sensible number of spares to be required during operation.

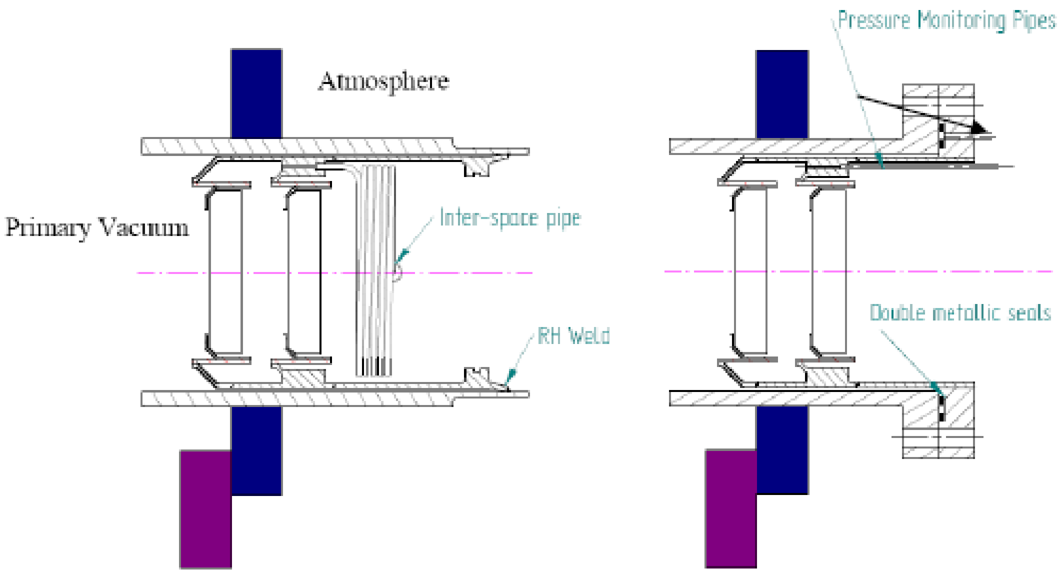

FIG6: Options being considered for the window arrangements. This includes a bolted and welded flange.

8. Summary

The diagnostic system in ITER is now entering a new phase where a focus is on detailed design and construction. Many systems have undergone conceptual design reviews and the designs will subsequently be completed by the respective domestic agency. The first systems are due for arrival in early 2014 in order to match the construction phases of the machine.

9. Acknowledgement

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