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In search of an on-line backup density measurement for ITER

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For safe operation, ITER needs a reliable density measurement during all the plasma phases. This is the responsibility of the interferometer and polarimeter systems. Two systems on ITER will provide a line averaged density: the Toroidal Interferometer Polarimeter (TIP) is the main diagnostic while the Poloidal Polarimeter (PoPola) is the backup system. The TIP has been carefully designed to have intrinsic redundancies: multiple chords with independent optics and backends. Nevertheless, the risk exists that all chords might fail at the same time. To mitigate this risk an interferometer-polarimeter has been designed with 2 lines of sight in a different port. The availability analysis has shown that adding this two redundant chords would increase the availability of the measurement.

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1. Introduction

Tokamak operation requires a reliable density measurement. This is needed for safe operation in all plasma scenarios and during all the plasma phases (startup, ramp up & down, flattop, disruption mitigation). The measurement needs to be continuous and real-time with a 1 ms time resolution, fed to the central plasma control system. The parameter used for control is usually the line averaged density. To achieve the level of control required, different levels of accuracy are expected for the different phases as summarised in Table 1.

Phase	Measurement range (m^{-3})	Accuracy
Initiation	$< 1 \times 10^{19}$	100 %
Ramp-up & down	1×10^{19} to 3.5×10^{19}	10 %
Flattop	3.5×10^{19} to 4×10^{20}	2 %
Disruption mitigation	8×10^{20} to 2×10^{22}	100 %

Table 1: Line averaged density range and accuracy requirements for different scenario phases.

This paper describes the work carried out to ensure ITER has sufficient reliability in the density measurement for plasma control. First, the different diagnostics able to measure a line averaged density are presented in Section 2. The early conceptual design work for an online backup system is then described in Section 3. Finally, Section 4 reports on the reliability analysis for the ITER line averaged measurement.

2. Density diagnostics in ITER

Different diagnostics will be able to measured the electron density in ITER but a few will have a reliability and an accessibility able to fulfil the requirements for plasma control. Three main families of diagnostics are planned: interferometers and polarimeters, reflectometers and Thomson Scattering (TS) diagnostics.

Interferometers have a strong track record for delivering line averaged density measurements suitable for plasma control. Almost all operating tokamaks use an interferometer as the main density control diagnostic. Reflectometers and TS systems measure more detailed local density profiles but their operation might be limited in some scenarios. For instance hollow density profile measurement could be challenging for a reflectometer as well as high density or low magnetic field plasma due to the electron cyclotron resonance. Finally, it is difficult to use high power TS systems with the repetition rate (1 ms) required for ITER basic control and for startup densities.

ITER will use the Toroidal Interferometer Polarimeter (TIP) diagnostic as the main real time density control system. The backup function is assured by the Poloidal Polarimeter (PoPola) diagnostic. Their localisation and lines of sight in ITER vessel are shown on Figure 1.

2.1 Toroidal Interferometer Polarimeter

The TIP is a multi-chord 2-colours interferometer coupled with a polarimeter [1]. Each chord carries the beams of a CO_2 and a CO laser. The CO_2 laser, at 10.59 µm, is used as a traditional interferometer and also as a polarimeter to measure Faraday rotation. The CO laser, at 5.42 µm,

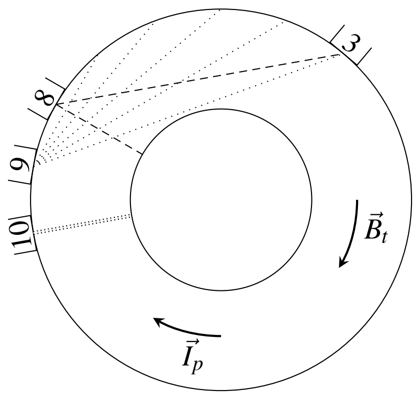

Figure 1: Localisation of the different laser-based density diagnostics in ITER equatorial ports. The different equatorial ports are numbered. TIP is emitting from port #9, PoPola from port #10 and the new online backup density diagnostic from port #8.

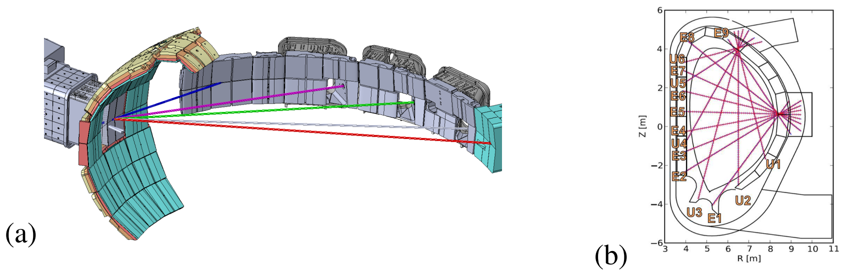

Figure 2: Lines of sights for (a) TIP and (b) PoPola systems.

is used to compensate for vibrations for the main interferometer. This combination is required because traditional interferometers in tokamaks suffer from fringe jump errors during fast transient events like ELMs or disruptions. The polarimeter has a lower sensitivity but, as its measurement angle is much lower than 2π, it will not be subject to fringe jumps. Polarimeter measurements also depend on a good knowledge of the total magnetic field map to be able to extract an absolute density measurement.

TIP system is divided into the back-end system in the diagnostic building with the laser sources, the beam optics, the detectors and the associated electronics; the transmission lines, from the diagnostic building to the port plug; the in-port mirrors and vacuum windows; the retro-reflectors, embedded into the blanket or diagnostic First-Wall (FW). As shown on Figure 1 and Figure 2a, there are 5 chords measuring a line-averaged density from equatorial port #9 but only the 4 chords probing the plasma centre are intended for plasma control. Each chord has independent back-ends, transmission lines, vacuum windows, mirrors and retro-reflectors. The only common items are the common FW aperture, port plug support and cooling for the TIP drawer and the fact that the systems are sharing the same room for the back-ends.

The TIP system will provide real-time line-averaged density measurement for plasma control during all the phases and within the requirements listed in Table 1. The system redundancy should provide very good availability for the measurement. Nevertheless, the common items listed above risk tripping up all chords simultaneously. The causes of failure of the entire TIP system could be a failure of the equatorial port #9, replaced by a dummy port. It could also originate from a design or assembly flaw not identified and common to all chords. Such flaw might be identified when the entire port is commissioned but could still result in a long wait for remedial action (redesign and manufacture of a drawer).

2.2 Poloidal Polarimeter

The PoPola is primarily designed to measure the plasma current profile but it has the capability to also measure the line averaged density. One CW CH_3OH laser at 118.8 µm is used to measure the polarisation rotation and ellipticity along 13 chords. The polarisation changes induced by Faraday rotation and Cotton-Mouton effects are used to infer the plasma current profile. In order to obtain the line averaged density, temperature profile and total magnetic field profiles are used.

While the PoPola system is able to measure line averaged density, its present backup status will only require it to be able to produce density measurements to allow graceful termination of the plasma discharge in the event of an online failure of the TIP system. A single laser is presently foreseen and therefore the availability of the PoPola is not sufficient for routine basic control.

3. Online backup density diagnostic

To mitigate the risk of failure of the TIP system, the design of an online backup density (OBD) diagnostic has been started.

3.1 System requirements

The main goal of this system is to provide a line averaged density measurement compatible with the requirements for plasma control. This system will be operating in all scenarios even when the TIP system is fully functional. In order to mitigate the equatorial port #9 risk of failure, this new system will be installed in a different port. These requirements will allow the OBD to take over responsibility of density measurement during a plasma experiment or even during a full experimental campaign in the event of TIP failure.

The evaluation of the different measurement techniques has shown that the only reliable choice for plasma control is a laser-based interferometer/polarimeter. As discussed in Section 2, microwave and TS systems are not mature enough to give the confidence they would operate reliably and within the control requirements during all scenarios.

Different wavelength ranges have been analysed: 1, 10 and 100 µm. While the 1 µm range would allow the use of optical fibres, the short wavelengths are more likely to be affected by mirror and retro-reflector degradation due to impurity deposition [2]. Fringe jump corrections using polarimetry at 1 µm would also be impossible. The 100 µm range has been discarded due to the challenges to find reliable high power CW lasers and concerns about refractive effects. Consequently, the 10 µm range has been selected.

3.2 Early conceptual design

The concept of an interferometer/polarimeter has been designed. It uses 2 lines of sight penetrating the vacuum vessel through equatorial port #8. One line has a tangential view, similar to the TIP chords, with a retro-reflector in the equatorial port #3. The other line is perpendicular with a retro-reflector implemented in the blanket FW. Both chords are shown on Figure 1.

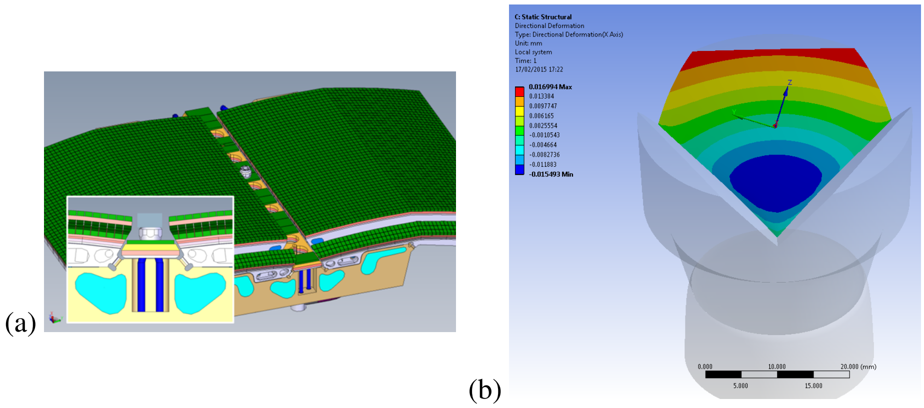

Figure 3: (a) Implementation of the First Wall retro-reflector in a blanket module. (b) FW retro-reflector deformation during operation due to plasma radiation. The deformation represented is the projection perpendicular to the retro-reflector surface ($\pm 17\,\mu$m).

The retro-reflector in the blanket module has been designed using the interface used by the FW samples diagnostic [3] as shown in Figure 3a. It is a corner-cube inserted in a cylindrical assembly. The space available being limited, it has 36 mm diameter and a 25 mm height. The diameter could be increased if the retro-reflector is not expected to be maintained using remote handling tools. The final height will be determined after analysis of the erosion/deposition ratio in this location. First thermal analysis have shown that under the expected radiation loads from the plasma (photons and neutrons), the normal deformation of its molybdenum reflective surface is about ± 17 mm as shown in Figure 3b. The assessment of the impact of such deformation on the system performance is being evaluated.

The system has 2 vacuum windows on the closure plate of the port plug. Mirrors are placed in the port plug to generate a labyrinth in order to avoid direct neutron streaming from the plasma to the port cell. Transmission lines are routing the laser beam from a dedicated room in the diagnostic building to the port cell.

The measurement methods is not decided yet but it is likely that both chords will either have a 2-colour[4] or a dispersion[5, 6] interferometer. The tangential chord will also rely on polarimetry to use the Faraday rotation for compensating the likely fringe jumps of the interferometer.

4. RAMI analysis

In order to quantify the improvement of adding an online backup diagnostic for the density measurement, a RAMI (Reliability, Availability, Maintainability and Inspectability) analysis has been carried out. All of the failure modes have been identified for the TIP and OBD system. The likelihood of occurrence and the severity (corresponding to any hours of tokamak operation downtime during recovery that are required) have been estimated. From this model, the criticality to tokamak operation of the different failure modes has been calculated to extract the ones which are most likely to cause significant downtime to ITER.

The main risks which are mitigated are those linked to the localisation of the diagnostics: port unavailability, incident in the diagnostic room, electromagnetic event for the port plug. On the

TIP		OBD		TIP + OBD
1 chord	4 chords	1 chord	2 chords	6 chords
77.37 %	**94.80 %**	77.59 %	84.88 %	**99.05 %**

Table 2: Density measurement availability. Availability evaluated over a 16 months operation period with 20 % duty cycle.

other hand, some risks cannot be mitigated by sole addition of a second similar diagnostic. These types of failures are mainly linked to the measurement principles: beam refraction, polarimetry distortion, first mirror and retro-reflector degradation. This analysis has also shown that it would be beneficial to split the TIP backend into two separate rooms to be able to maintain some chords safely without the risk of interfering with the operating ones.

Quantitatively, the availability is measured for the line averaged density measurement using the TIP, the OBD and both of them in parallel. The results are summarised in Table 2. Adding the OBD system improves the availability of the density measurement from 94.80 % to 99.05 %.

5. Conclusions

The development of an online backup density measurement has been started. Its integration into ITER equatorial port #8 has shown its feasibility. The RAMI analysis has demonstrated the improvement in availability this new diagnostic will bring. The design work will continue.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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