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The ITER Equatorial Visible/Infra-Red Wide Angle Viewing System: Status of design and R&D

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HIGHLIGHTS

- The status of Equatorial Visible/Infra-Red Wide Angle Viewing System is presented.
- An assessment of measurement parameters relevant for machine protection has been done.
- Remaining uncertainties will be clarified during the System Level Design (SLD).
- WAVS design is not considered mature enough to launch prototypes of subcomponents.
- Mandatory prototypes and qualification tests are already identified.
- Next stage (SLD) will enable to do trade-offs and address pending design issues.

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ABSTRACT

The Equatorial Visible/Infra-Red Wide Angle Viewing System (WAVS) is one of the ITER key diagnostics owing to its role in machine investment protection through the monitoring of Plasma Facing Components (PFCs) by Infra-Red thermography and visible imaging. Foreseen to be installed in 4 equatorial port plugs to maximize the coverage of divertor, first wall, heating antennas and upper strike zone, the WAVS will likely be composed of 15 lines of sight and 15 optical systems transferring the light along several meters from the PFCs through the port plug and interspace up to detectors located in the port cell. After a conceptual design phase led by ITER Organization, the design is being further developed through a Framework Partnership Agreement signed between the European Domestic Agency, Fusion for Energy, and a consortium gathering CEA, CIEMAT (with INTA as third party) and Bertin Technologies company. The next design step is the System Level Design (SLD) which will enable to consolidate the WAVS specifications as well as the performance realistically achievable (taking into account ITER and project constraints). The SLD has been preceded by a preparatory phase aiming at clarifying the WAVS functions and identifying critical prototyping.

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The outcomes of this preparatory phase are reported in this paper. First a review by the consortium of the WAVS measurement specifications is presented, for the purpose of a clearer separation of measurement parameters mandatory for machine protection (with stringent requirements) from those relevant for machine control and physics studies. Secondly the main features of the diagnostic are summarized, including a description of its current design, a preliminary analysis of its interfaces and a high level functional analysis. Finally the status of the R&D which may be necessary to validate the diagnostic design is presented. On the one hand, this R&D could consist in testing materials and coatings of optical components to characterize their behavior under the harsh environment of ITER. On the other hand R&D activities could concern prototyping and testing of subsystems of the diagnostic which have been identified as critical, such as the first mirrors and their associated devices (shutter and cleaning system) and the differential movement compensation system.

1. Introduction

The Equatorial Visible/Infra-Red Wide Angle Viewing System (WAVS) is one of the key diagnostics of ITER owing to, in particular, its role in machine investment protection, through the monitoring of surface temperature of Plasma Facing Components (PFCs) by Infra-Red (IR) thermography and visible imaging. Under the responsibility of the European Domestic Agency (DA), it is installed in four Equatorial Port Plugs (EPPs) belonging to non-EU ITER partners: EPPs #3 and #9 (US DA), EPP #12 (CN DA) and EPP #17 (ITER Organization (IO)). Initially composed of three lines of sight (LOS) per port plug [1] (two horizontal tangential LOS for the view of the first wall and heating antennas, one vertical LOS looking at the divertor), EU DA and IO have recently agreed on developing the design with a fourth view for the monitoring of the upper strike zone (Fig. 1) [2,3]. In total the WAVS will be composed of 15 LOS and 15 optical systems transferring the light along several meters from the PFCs through the Diagnostic Shielding Modules (DSM) in the port plug up to detectors located in the port cell.

Several studies related to this diagnostic have been performed in Europe over the last decade [1,4–6] before a conceptual design phase led by IO. Since then, the WAVS design is being further developed through a Framework Partnership Agreement (FPA) concluded between the European DA and a consortium gathering CEA, CIEMAT (with INTA as third party) and Bertin Technologies company. The outcomes of the first study conducted in the frame of this FPA, aiming at clarifying the WAVS specifications and identifying critical prototypes, are reported in this paper.

In Section 2, a clear separation between measurement parameters relevant for Machine Protection (MP) from those appropriate for machine control and physics studies is proposed. Section 3 summarizes the main features of the WAVS, including a description of its current design, a preliminary analysis of its interfaces and a high level functional analysis. Section 4 presents the status of the R&D that may be necessary to validate the diagnostic design. This R&D could consist in testing materials and coatings of optical components to characterize, in particular, their behavior under the harsh environment of ITER (in terms of radiation and temperature). R&D activities could also concern prototyping and testing of subsystems which have been identified as critical, such as the first mirrors and their associated devices (shutter and cleaning system), as well as

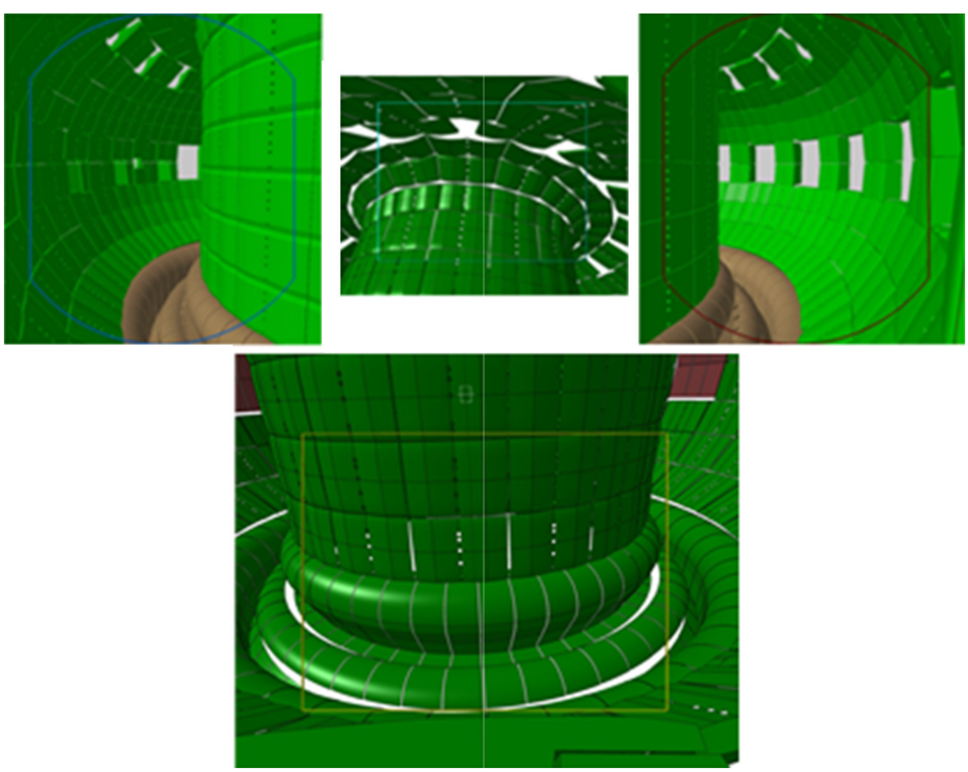

Fig. 1. Different views of the WAVS diagnostic (top: tangential left, upper, tangential right; bottom: divertor).

the differential movement compensation system at the junction between in-vessel and ex-vessel components.

2. Measurement specifications

2.1. Introduction

Fig. 2 provides the list of primary parameters to be measured by the WAVS [3]. Two of these parameters have a MP role: the maximum surface temperature on the divertor tiles and the visible luminance of the first wall. The other parameters are used for the basic control of the machine (first wall surface temperature), for its advanced control (surface temperature and power load on the divertor) and finally for physics studies (first wall surface temperature during Edge Localized Modes (ELMs), Runaway Electron energy and current).

Following the panel report of the WAVS Conceptual Design Review [7] which has recommended to consider MP parameters as design drivers, an analysis of the latter and their specifications (in terms of range, spatial and temporal resolutions, accuracy) has been done to find the most relevant parameter ranges with respect to the WAVS investment protection function.

2.2. Assessment of most relevant ranges for MP parameters

A first clarification concerns the optimal spectral range of measurement. Due to the temperature range to be measured for MP (600–2400 °C for the divertor in tungsten, 600–1000 °C for the first wall in beryllium in normal plasma operations), the most adequate range of wavelength for MP appears to be the Mid Wavelength Infra-Red (MWIR) (3–5 μm). At this stage, measurement in the visible range (0.4–0.8 μm) is not considered as a priority for surface temperature related MP purposes, even if complementary measurement in the visible (as well as in the Near Infra-Red range (NIR)) could be useful for cross correlation in the case of high temperatures stemming from transient thermal events (e.g. loss of detachment, unmitigated ELMs, disruptions). Nevertheless, from an operational point of view, qualitative analysis through visible measurements is judged compulsory for the routine operation of a tokamak, making also the visible branch an MP measurement. In particular measurement of H_α (656 nm) appears to be of interest for the plasma discharge analysis. In these conditions it could be acceptable, if MP parameters are considered as main design drivers, that performance of the diagnostic for wavelengths lower than H_α is not fully optimized, or is not maintained during the whole diagnostic life.

Regarding resolutions, the spatial one must be optimized for the monitoring of the inner divertor and will result from constraints of integration and needed coverage (12 cassettes). Moreover, only the peak temperature measurement on the divertor (and not the temperature profile) is considered for MP, with a maximum error of 10%. The spatial (angular) resolution is supposed to be identical for the tangential and upper views, and will be constrained by the limited allowable room in the DSM (in the current design it is two times lower than that for the divertor view). In case of conflict between coverage and resolution, coverage is assumed to have priority. If one focuses on temporal resolution and latency, a time resolution of 10 ms for a full frame is considered acceptable for MP measurement, and is achievable by cameras commercially available off-the-shelf. Such performance leads to a latency of 30 ms (based on the hypothesis of an image processing using 3 frames), which is also assumed sufficient for MP.

It is to be underlined that the WAVS performance described previously is only indicative. Measurement realistically achievable by the diagnostic (under project constraints) will be assessed through upcoming design phases (especially in the System Level Design or SLD).

3. Main features of the diagnostic

3.1. Summary of the current IO design

Each LOS collects the light from the PFCs through first mirrors located in the Diagnostic First Wall (DFW) and transfers it to the detectors installed in the port cell over a distance of around 15 meters. In the design presently proposed by IO, each LOS is composed of the following successive subsystems (Figs. 3 and 4, [3]):

- in the port plug: a set of 3 first mirrors, 2–4 dog leg mirrors and a finite conjugate imaging relay made of 2 on-axis confocal mirrors;
- in the interspace: a differential movement compensation system under the form of an optical hinge (preceded by a field lens), a Cassegrain telescope, a dichroic beam splitter separating visible and IR spectral bands and a first relay of lenses (1 relay per spectral band);
- in the bioshield: 2 dog leg mirrors (1 periscope per spectral band);

Measurement Role	Measurement	Parameter Name	Other primary diagnostic for these measurements
1a.1 Machine Protection	16. Divertor operational parameters	Max. surface temperature	GA UP VIS/IR
	17. First wall (FW) visible image & wall temperature	FW Surface luminance	GA UP VIS/IR
1a.2 Basic Control	17. First wall (FW) visible image & wall temperature	FW Surface temperature	GA UP VIS/IR
1b Advanced Control	38. Heat loading profile in divertor	Surface temperature	G6 Div Therm, GA UP VIS/IR
		Power load	G6 Div Therm, GA UP VIS/IR
2 Physics	17. First wall (FW) visible image & wall temperature	FW surface temperature during ELMs	GA UP VIS/IR
	15. Runaway electrons	Emax	EE Hard x-ray, E7 radial x-ray, BD vertical gamma ray, B7 radial gamma ray
		I runaway	

Fig. 2. Primary parameters to be measured by the WAVS.

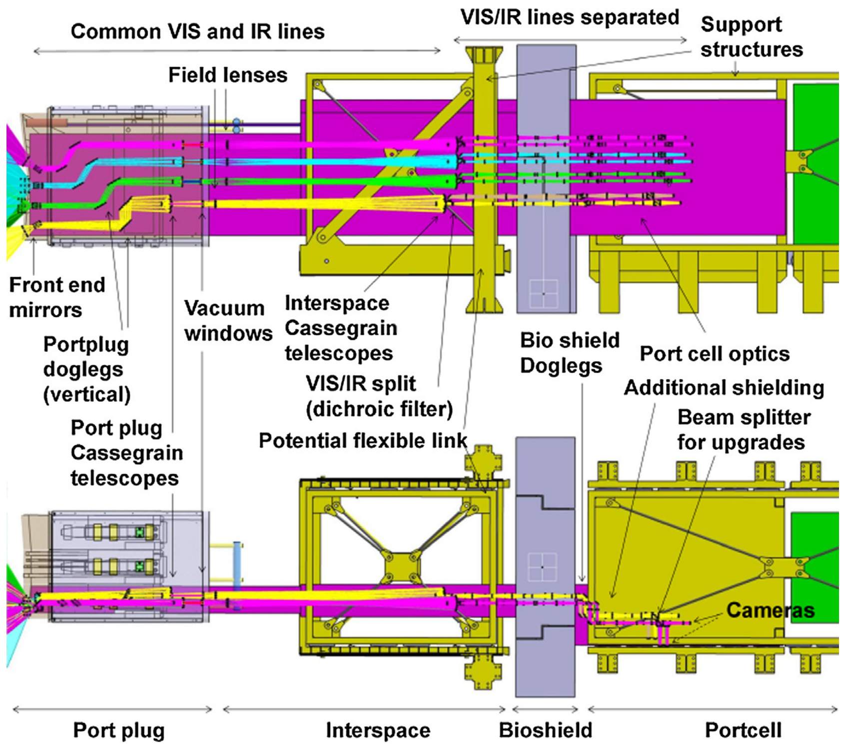

Fig. 3. WAVS side view (top) and top view (bottom).

- in the port cell: for both spectral bands 6 relays of lenses leading to a detector.

With 170 components per LOS and 15 LOS, the total number of items reaches around 2600 for the whole diagnostic. One objective of the next design phase (SLD) will be to optimize it by trying to decrease the number of components. This would be particularly relevant within the port interspace and port cell where the current design foresees around 70 lenses for each spectral band. This great amount of optical components, in addition to high cost and predictable alignment issues, induces a drastic reduction of diagnostic performance (e.g. transmission of respectively 0.2% and 1.5% in the visible and IR ranges in the current design).

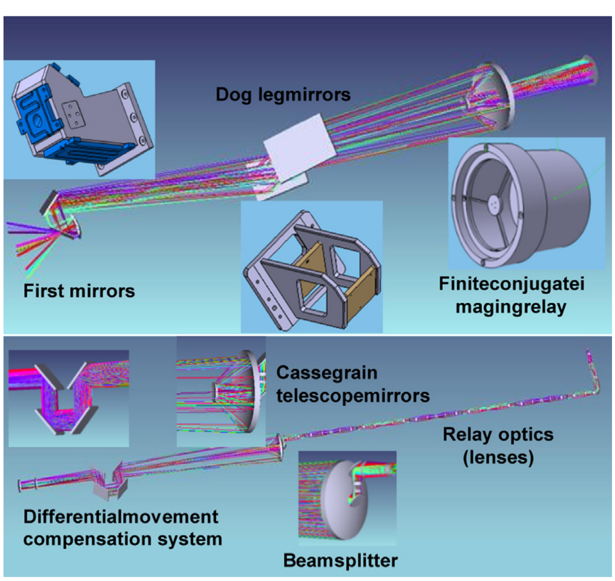

Fig. 4. WAVS in-vessel (top) & ex-vessel components (bottom).

3.2. Interfaces

The status of interfaces involving the WAVS has been updated, through the analysis of existing interface documents produced by IO.

Among the interfaces which have not yet been defined, those between the diagnostic and the 4 equatorial port plugs in which it is installed seem particularly tricky, and will need to be agreed and frozen as early as possible with the port integrators of EPP#3, #9, #12 and #17. Fig. 5 represents a schematic view of the interfaces between the WAVS and EPP#3.

Furthermore critical interfaces have been identified. Internal critical interfaces are related to the cleaning system, the shutter and the additional cooling loop for the first mirrors (if deemed appropriate). External critical interfaces are those with the DSM, the port plug closure plate, the DFW, the feedthroughs, the vacuum windows, the bioshield and the remote handling tools.

3.3. Functional analysis and RAMI

The functional and RAMI analyses (Reliability, Availability, Maintainability, Inspectability) performed in the frame of CDR [3] have been updated in order to clarify the diagnostic functionalities needed for measuring MP parameters. The preliminary state of the functional analysis is that five main functions have been determined: three are operational functions enabling to measure the main primary parameters, one is a support function and the last one regards calibration and maintenance. These main functions have been broken down into basic functions. After the review of these functions by F4E and IO, the following step will be to associate to basic functions the components necessary to fulfill them. Based on values of MTTF (Mean Time To Failure), MTTR (Mean Time To Repair) and duty cycle of these components, it will be then possible to build Reliability Block Diagrams and perform Failure Mode Effects & Criticality Analyses.

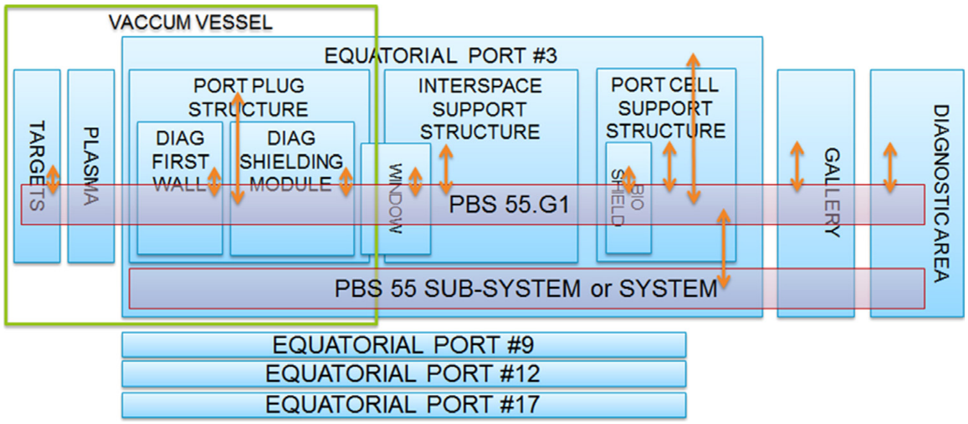

Fig. 5. Interfaces of WAVS (PBS 55.G1) with EPP#3 – arrows stand for interfaces between WAVS and EPP#3 elements.

4. Status of R&D

4.1. First mirrors and protection devices

First mirrors are key components of optical systems while exposed to particularly hostile environmental conditions (erosion and deposition, neutron and gamma fluxes). They have been extensively studied since several years by the Specialists Working Group on First Mirrors from the Topical Group on Diagnostics of the International Tokamak Physics Activity (ITPA) [8]. Regarding the WAVS, full scale circular actively cooled mirrors (109 mm in diameter) with flat shape have already been successfully designed, manufactured and polished with blanks of stainless steel and TZM (molybdenum alloy) with nickel interlayer, and reflective thick coatings (3–5 μm) of rhodium and molybdenum [9]. Nevertheless, additional investigations are needed to check the feasibility of an active cooling on non-flat and non-circular mirrors, to determine the manufacturing limitations of such complex pieces and the achievable image quality, which can be jeopardized by the mirror heating and resulting optical surface deformation during plasma discharges.

Apart from their machinability and structural behavior, the choice of material and coating for the first mirrors is also driven by their ability to withstand possible cleaning operations as well as plasma erosion, whose intensity remains still unknown, depending on the position and exposition of first mirrors and on their protection by the DFW. Therefore, if it were confirmed (as mentioned in Section 2.2) that full performance of the diagnostic is not demanded for wavelengths lower than H_α the constraint on the choice of material and coating would be relaxed. Indeed, this is mainly in this range of wavelength (lower part of the visible range) that the degradation of performance of first mirrors has been observed in existing tokamaks, due to erosion and/or deposition phenomena leading to a loss of reflectivity.

The last required property for potential materials and coatings is their neutron and gamma radiation hardness. Based on a thorough justification, the latter will be evaluated through irradiation testing campaigns.

Besides, future design steps should confirm whether first mirrors will need to be protected by shutters during conditioning phases, which is the present baseline assumption. Only simple conceptual designs of shutters have been proposed so far for the WAVS [3,6]. If such component was proved to be useful, it will need to be implemented in the tight environment of first mirrors. Since it is in the close vicinity of plasma, its design will certainly need to be qualified through prototyping and testing in ITER-like environmental conditions.

Finally, if an in situ cleaning system was also deemed necessary, it will be first qualified in a dedicated R&D program before envisaging a real prototype.

4.2. Ex-vessel optical components

The selection of materials and coatings for the optical components located outside the vessel is less constrained since the environment is less severe in this region. Nevertheless neutron and gamma radiation remains non-negligible for optical elements and must not induce a too prejudicial loss of optical properties and diagnostic performance. Therefore irradiation testing could help identifying suitable materials among the envisaged candidates for refractive elements (lenses, dichroic beam-splitters) and anti-reflection coatings (for lenses, filters and beam-splitters).

4.3. Differential movement compensation system

A differential movement compensation system must be integrated between the port plug and interspace to cope with differential movements between in-vessel components attached to the vacuum vessel and ex-vessel ones, linked to the tokamak building, to avoid image and photometric signal degradation. A system based on an optical hinge is currently foreseen in the IO design (Fig. 4). When a more detailed design of this device is available (in SLD or further design phases), a prototype may be needed to validate the efficiency of this crucial component to maintain the alignment of optical elements throughout the LOS.

5. Conclusion

This paper provides, before launching the SLD phase, the status of the WAVS design as well as ideas on the planned R&D. Progress has been made in the form of an initial assessment of measurement parameter ranges relevant for the machine investment protection. Remaining uncertainties (such as the relevancy of measurement in the short wavelength of the spectrum) will need to be clarified during the SLD. Concerning prototyping, the WAVS design is not considered mature enough to launch prototypes of subcomponents in a near future, but mandatory prototypes and qualification tests are already identified. Next stage (the SLD) will enable to do the necessary trade-offs and address the pending design issues, while considering the time constraints imposed by the ITER overall schedule.

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