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Overview of optical designs of the port-plug components for the ITER Equatorial Wide Angle Viewing System (WAVS)

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ABSTRACT

The equatorial visible and infrared Wide Angle Viewing System (WAVS) for ITER is one of the key diagnostics for machine protection, plasma control and physics analysis. To achieve these objectives, the WAVS will monitor the surface temperature of the Plasma Facing Components (PFCs) by infrared (IR) thermography (3–5 μm range) and will image the edge plasma emission in the visible range. It will be composed of 15 lines of sight installed in four equatorial ports (no. 3, 9, 12 and 17) in order to survey at least 80% of the overall area of the vacuum vessel. This paper presents the optical design of port-plug which has to cope with both challenging performances (wide field of view, wide temperature range 200–2000 °C, high measurement accuracy required lower than 20%) and severe constraints such as harsh nuclear environment, complex interfaces. Indeed the optical components are embedded within the ITER Diagnostic Shielding Module, DSM, which is not usual for diffraction limited instruments. It is shown that nominal optical performance of the Port-Plug are limited by the diffraction only. In operation, this design has demonstrated its superiority on the former ones since it is much less sensitive to tolerance variations.

1. Introduction

The equatorial visible and infrared Wide Angle Viewing System (WAVS) for ITER is one of the key diagnostics for machine protection, plasma control and physics analysis [1]. These objectives will be achieved through infrared (IR) thermography (3–5 μm range) and visible observation (mainly in the H/Dα range @ 656 nm) of the main plasma facing components. It will be composed of 15 lines of sight installed in four equatorial ports in order to survey at least 80% of the overall inside area of the vacuum vessel.

On top of leading a European consortium including CIEMAT (in Spain) and Bertin Technologies (in France), CEA is developing the Port-Plug components of this diagnostic. The diagnostics Port 12 has to be available for the ITER first plasma (fall of 2025).

2. Design requirements

The coverage, the spatial resolution, the temperature range and the accuracy are the three main design drivers of the optical sub-system both in IR and visible wavebands.

The spatial coverage is a key parameter to ensure the monitoring of in-vessel components. For the 15 lines-of-sight of the equatorial WAVS, the objective is to survey 31% on outer divertor, 81% on inner divertor and 82% on main chamber. In order to meet the coverage requirements, three or four Lines-of-Sight (LoS) per Port will be implemented (three in the Port 12 and 4 in the other Ports): one LoS oriented towards the divertor inner target mainly (called “divertor view”), one LoS oriented to the left and one oriented to the right (called “tangential left and right views” respectively) looking at the first wall mainly, and another LoS oriented towards the upper divertor (called upper view). The two tangential views and the upper view have the same requirements, only the orientation differs.

The spatial resolution is also an important parameter which is a compromise between the large Field-of-View (FoV) required to meet the coverage, the optical quality of the system and the available detector formats. The detectors considered are those commercially available

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Table 1
Main optical design drivers.

FoV	Divertor: 45° x 36° Tangential: 54° x 43°
Wavelength range	IR: 4 µm ± 0.1 µm VIS: H/Dα (656 nm)
Focal length	Divertor: 25 mm Tangential: 10 mm
Pixel resolution	Divertor (IR): 3.5-20 mm/px Tang. (IR): 20-60 mm/px
EE	55% in 2 × 2 pixels
WFE overall	450 nm RMS (@4 µm)
WFE allocations	Port-Plug: 320 nm RMS Ex-Vessel: 280 nm RMS

today: 640 × 512 (1280 × 1024) of 15 µm pixels for low (high) resolution in IR; 1280 × 1024 (2336 × 1728) of 7 µm pixels for low (high) resolution in visible.

The wide temperature range [200–2000 °C] and the high accuracy required justify a fast optical system (around F/3) while preserving the image quality on the full FoV. The temperature accuracy is directly related to the fractional encircled energy (EE) which can be also translated into Wave Front Error (WFE). To reach temperature measurement accuracy better than 20% (with 10% goal) in the temperature range from 200 to 2000 °C, the fractional EE at 4 µm shall be higher than 55% which can be translated as 450 nm Root Mean Square (RMS) WFE for the entire optical train. This overall WFE budget has been allocated to Port-Plug and Ex-Vessel sub-systems as indicated in Table 1.

Due to the close vicinity of the plasma and the harsh environmental conditions, the number of optical components should be minimized in the Port-Plug and their design should be optimized to decrease the risks of failure while ensuring the required performance level.

3. Optical design description

In the Port-Plug, each LoS is sub-divided in three units: (Fig. 1)

- A first mirrors unit, with an off-axis ellipsoidal first mirror (M1) which forms an aberrated image close to a second folding mirror (M2);
- A Dog-Leg unit, with a pair of flat folding mirrors (M3 and M4), which is positioned to limit neutrons penetration;
- An optical relay unit based on two off-axis mirrors (M5 ellipsoidal and M6 hyperbolic). M5 creates an accessible intermediate image (which can be used as field stop if needed). Then M6 produces a collimated beam passing through the Window Assembly. The dimension of the beam is a compromise between the divergence of beam, its size, and the size of the Port-Plug optics in order to keep the size of the optics in the Ex-Vessel within a reasonable size.

As shown Fig. 2, this 3-mirror system (+ 3 flat folding mirrors) minimizes all major aberrations except for the field curvature and the distortion. The field curvature comes from the first mirror only. To correct for the field curvature in the Port-Plug, a combination of concave and convex mirrors should be used (instead of concave mirrors only), leading to much larger optical elements. However, the field curvature can be fully compensated by the Ex-Vessel optics without introducing complexity to the system. The distortion (about 12%) will be corrected by image processing.

It is worth noting that although a Dog-Leg (M3-M4) is not required for the optical aspects, it has been demonstrated that a 2-mirror labyrinth is mandatory for neutronic shielding protection [3].

4. Performances

The performances are assessed in terms of Wave Front Error (WFE) (Fig. 3) by using an ideal lens (paraxial) at the output of the Port-Plug to replace the entire Ex-Vessel optical train. The nominal design is perfectly corrected and limited by the diffraction. Indeed, the nominal WFE is about 70 nm RMS for the divertor view (40 nm RMS for the tangential views) which is a factor 4 (respectively 8) better than the diffraction limit.

However, the nominal performance of the Port-Plug design will be drastically affected by several factors described below.

4.1. Manufacturing and positioning errors

Manufacturing and positioning errors are intrinsic to the optical components themselves. Included in the positioning tolerances are the tilt and decentration of the optical elements, as well as distances between them. The manufacturing tolerances concern the radii of curvature (for the powered optics), or flatness (for the flat mirrors), and the surface shape (figure error).

The set of tolerances chosen for mirror manufacturing corresponds to the standards of the capabilities of the optical companies. The positioning of the optical relay (M5/M6) requires a specific attention since the tolerances are typically of the order of ± 20 µm. This is achievable with a dedicated mechanical structure and adjustments. The other tolerances can be managed with classical mechanical solutions.

The errors due to manufacturing, and positioning can be partially compensated prior the installation in the Port-Plug by using adjustment capabilities included in the opto-mechanical design. Because the aberrations are quite homogeneous in the FoV, the main compensation to be applied is refocus which can be done either in the Port-Plug directly or in the Port-Cell to take into account the entire optical chain. The Monte-Carlo analysis, including all the errors mentionned above, has shown that the refocusing compensation in the Port-Plug during alignment improved by a factor 3 the WFE in average.

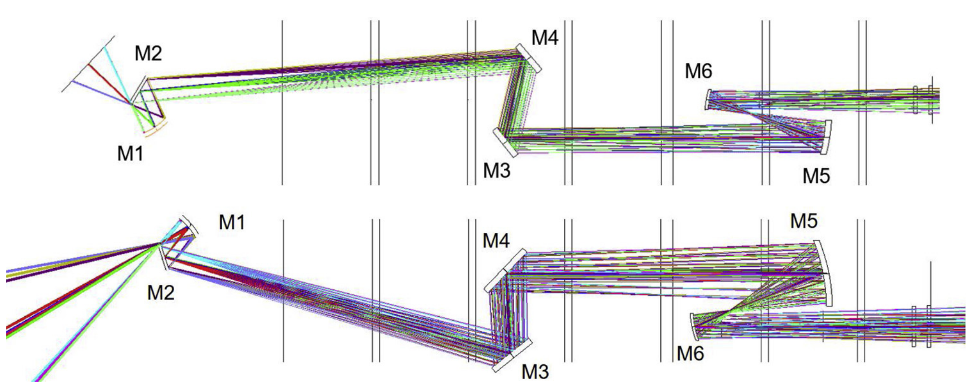

Fig. 1. WAVS Port-Plug Optical Layout (BOTTOM: divertor view seen from the side; TOP: right tangential view seen from the top). The vertical bars represent the vertical structures of the modular DSM.

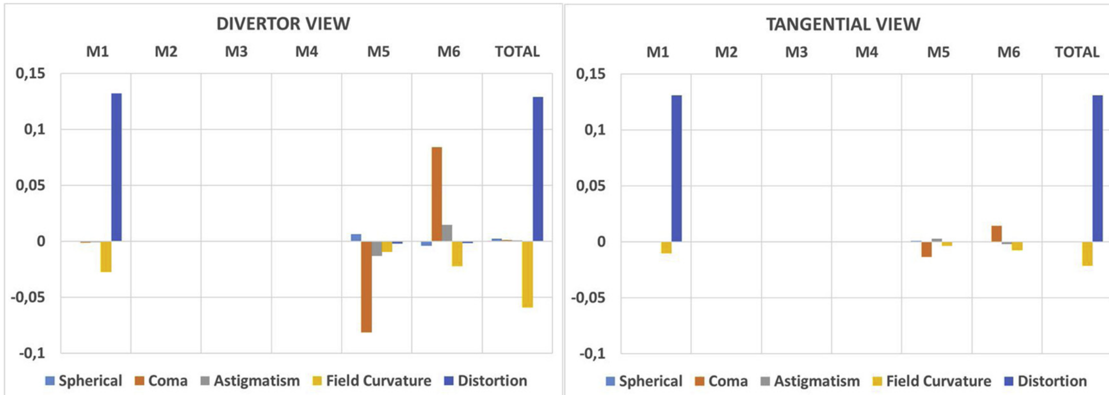

Fig. 2. Main optical aberrations of the Port-Plug optics (divertor and tangential views).

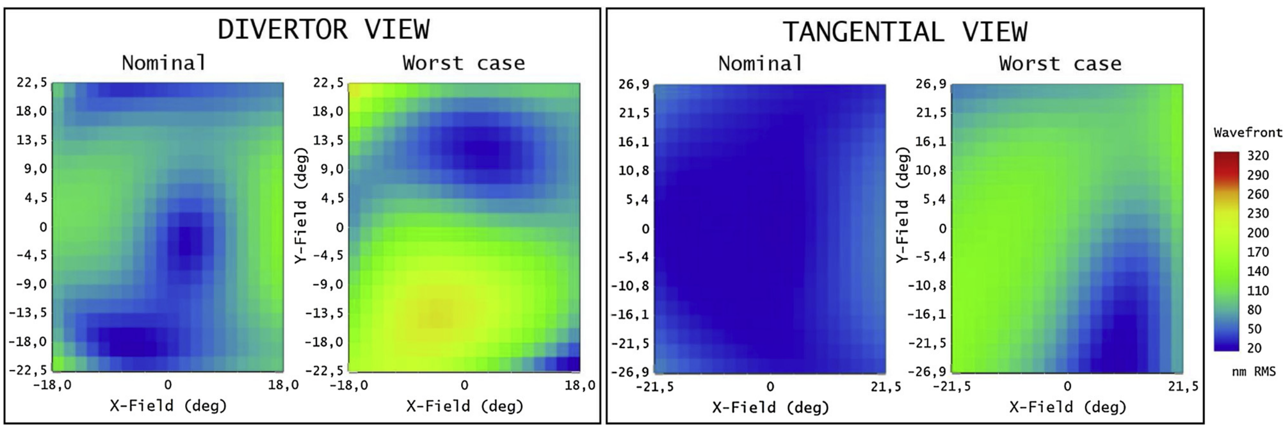

Fig. 3. Wavefront Error (WFE maps for the divertor view (left) and the tangential view (right). The nominal corresponds to the theoretical performance of the system (i.e. without errors). The worst case includes all manufacturing and mounting errors (described in Section 4.1). The upper limit of the scale corresponds to the WFE allocation for the Port-Plug in order to outline the remaining allocation for the thermo-elastic deformations due to operations and warm-up which are not considered here.

4.2. Thermo-mechanical deformations in operation

During operation, the WAVS Port-Plug will suffer from thermo-mechanical deformations due to thermal variations of the environment during plasma operations. Indeed as shown in Fig. 4 the optical components are embedded within the ITER Modular Diagnostic Shielding Module (M-DSM). Thermo-mechanical deformations concern the relative displacements of the optical elements (tilts and decenters), and their intrinsic deformation (radius of curvature and surface shape).

The main contributor is the radial elongation of the M-DSM which will change the separation between mirrors and produce defocus mainly. The first mirrors are actively cooled to limit deformations of their optical surface due to thermal loads which are critical. All these thermo-mechanical deformations will introduce errors that cannot be compensated.

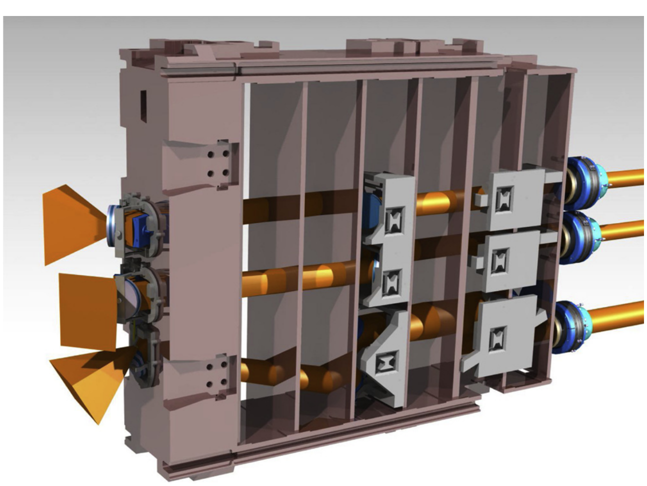

Fig. 4. In-vessel elements of the three Line-of-Sight for the equatorial Port 12. The DSM is shown in grey without shielding for clarity.

4.3. Warm-up residual errors

The warm-up residual errors correspond to the initial phase during which the Port-Plug is heated from ambient temperature (i.e. about 20 °C) up to operational temperature (i.e. about 70 °C). Indeed the system will be integrated and initially aligned at ambient temperature. The deformations from ambient to operational temperature will be assessed and anticipated from models. However, these models have intrinsic uncertainties (e.g. thermal expansion coefficients knowledge) and potential discrepancies with respect to the built which will lead to residual errors. These errors can be partially compensated if position corrections can be applied to the Port-Plug elements during the diagnostic commissioning.

5. Design selection rationale

The design presented at the CDR [1,2], and its evolutions [3], were based on a fully on-axis design with a Cassegrain telescope acting as relay optics. The proposed design differs from its predecessors by being

Table 2
Summary of the pro and cons of all possible configurations of the Port-Plug optical concept.

First Mirror	On-Axis		Off-Axis	
Optical Relay	On-Axis	Off-Axis	On-Axis	Off-Axis
Image quality	+ Good performance	- Poor image quality	+ Good performance	+ Good performance
Transmission	- Central obscuration	+ No obscuration	- Central obscuration	+ No obscuration
FoV	- Blind Spot	- Blind Spot	+ No blind spot	+ No blind spot
Interface In-Vessel/Ex-Vessel	- Additional lens needed	+ Afocal output	+ Afocal output	+ Afocal output

fully off-axis avoiding the limitations described below. The following sections compare these two configurations for the first mirrors and the optical relay. Table 2 summarizes qualitatively the main advantages and drawbacks for each possible configuration.

5.1. First mirror configuration

The use of an off-axis first mirror offers several advantages. In particular, it avoids drilling a hole in M2 making its manufacturing and cooling easier. The hole in M2 imposed to have M2 close to image plane to limit the portion of the FoV vignetted (blind spot). Without this limitation and by having the orientation of M2 not restricted by M1, the off-axis configuration offers more possibilities to accommodate all mirrors within the over-constrain environment of the M-DSM.

In the previous designs, the use of an off-axis first mirror was excluded because of the on-axis Cassegrain. Indeed the aberrations generated by the off-axis mirror cannot be compensated by a pure on-axis optical system. Then M1 had to remain on-axis leading to a hole in the secondary mirror of the Port-Plug and a blind spot in the FoV.

5.2. Optical relay concept

An on-axis Cassegrain introduces a central obscuration of about 15–25% (depending on the mechanical design). To limit this central obscuration, the size of the secondary mirror of the Cassegrain has been minimized, which in consequence increased the divergence of output beam (conservation of the *étendue*). Then to limit the beam divergence at the entrance of the Ex-Vessel, the use of an additional lens (acting as field lens) was mandatory.

To avoid central obscuration, the Cassegrain can be replaced by a group of two mirrors working off-axis. In the proposed design, these two mirrors share the same axis making their manufacturing and alignment easier. This configuration allows for increasing the size of the beam and for limiting its divergence. This kind of off-axis optical relay is compatible with both on-axis and off-axis first mirror solution. Indeed the relay optics can accommodate aberrations generated by the first mirror in both cases.

6. Conclusion

This paper provides a description of the WAVS optical design in the Port-Plug. The performances are described in terms of Wave Front Error. A description of the errors impacting the performance of the system is also given. The proposed design is within the allocated performance budget. In operation, this design has demonstrated its superiority on the former ones since it is much less sensitive to tolerance variations.

Acknowledgments

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