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Design overview of ex-vessel components for the Wide Angle Viewing System diagnostic for ITER Equatorial Port 12

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ABSTRACT

The ITER equatorial visible and infrared Wide Angle Viewing System (WAVS) provides surface temperature measurements of plasma facing components by infrared (IR) thermography being one of its main roles to protect them from damage. It also images the plasma emission in the visible range. The diagnostic, which comprises 15 lines of sight distributed in four equatorial ports (3, 9, 12 and 17), will contribute to Machine protection, Basic control and Physics analysis in ITER. The design of the diagnostic in the equatorial port 12 (EP12) - comprising three lines of sight - is currently being developed within a Framework Partnership Agreement through a Specific Grant granted by F4E to the Consortium formed by CEA, Ciemat and Bertin Technologies. EP12 has to be operative for the ITER first plasma. The overview of the WAVS opto-mechanical design for the ex-vessel components in EP12 will be presented in the paper. The ex-vessel optics are composed of mirrors and refractive elements which relay the exit image of the port plug at the vacuum window up to the cameras placed inside a shielded cabinet in the Port Cell. The image relay through the Interspace, Bioshield and Port Cell has to cover a length of almost 10 m in order to reach the detectors. The refractive elements are arranged in sub-assemblies (optical modules) mechanically mounted in barrels and next assembled on a support structure. The assembly of these modules on site will be also presented in the paper. Furthermore, the Optical Hinge which is the first component of the ex-vessel optical chain (formed by two folding mirrors) aims to compensate the differential motion between the vacuum vessel and the building, in normal operation and baking. The mechanical assembly and the operation of this component will be also described in the paper.

1. Introduction

The ITER equatorial visible and infrared Wide Angle Viewing System (WAVS) will measure the surface temperature of plasma facing components by infrared (IR) thermography (3–5 μm, optimized in the spectral band 4 ± 0.1 μm) being one of its main roles to protect them from damage. It will also image the plasma emission in the visible (VIS) range (400–700 nm, optimized in the spectral band for the Hidrogen/Deuterium-alpha (H/Dα) 656 ± 1 nm). The main design drivers of the WAVS system are the coverage inside the vacuum vessel (VV), the spatial resolution, the temperature range and the accuracy, both in IR and VIS wavebands.

The main measurement requirements for the WAVS system [1,2] are listed in Table 1. The diagnostic comprises 15 Line of Sight (LoS)

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distributed in four equatorial ports (3, 9, 12 and 17) aimed at surveying at least 80% of the overall area inside the vessel. In this way, three LoS have been implemented in the Equatorial Port 12 (EP12) and four in the other ports. The diagnostic will contribute to Machine protection, Basic control and Physics analyses in ITER operation.

The WAVS system in the EP12, consists of two views oriented to opposite toroidal directions in the VV (tangential right and left views) and the third one oriented to the divertor inner vertical target and a fraction of the inner First Wall (FW) optimized for the coverage of the Collective Thomson Scattering (CTS) shinethrough area [1,2]. The divertor view has higher spatial resolution than the others. The Field of View (FoV) inside the VV encompassed by the three LoS in EP12 is shown in Fig. 1.

The design of the diagnostic in this port is well advanced since it has to be operative for the ITER first plasma (scheduled for the end of 2025). In this sense, the development of the diagnostic in EP12 represents a first of a kind that will provide the technical basis for the subsequent development of the system for the other ports. This article presents the mechanical design of the ex-vessel components in EP12 at their preliminary phase, such that the Preliminary Design Review (PDR) was passed in the last quarter of 2020. PDR of the ex-vessel part was decoupled from in-vessel PDR that was also successfully passed in December 2019. The bases for the development of the current design related to R&D activities and design at system level can be found in [3,4] respectively.

2. Diagnostic design overview

The optical design of the WAVS system in the different ports is composed of mirrors and refractive elements located across the Port Plug (PP), Interspace (IS), Bioshield (BS) and Port Cell (PC). The optics relay the VV image up to the cameras placed inside a Shielded Cabinet (SC) in the PC covering a length of almost 13 m from the first optical surface in the PP until the detectors. The SC will provide local neutron, gamma and magnetic shielding for the electronics in the PC (in particular for the cameras) to meet the availability and system performance requirements [1,2]. Signal transmission will be done to the diagnostic building where the hardware for the data acquisition and processing is placed.

Most of the optics constitutes a common path to both spectral bands (VIS and IR) and at the end of the system a dichroic beam splitter inside the cabinet, divides the VIS and IR beams redirecting them to their corresponding sensors. In each dedicated channel, two cameras have been implemented with a total of 4 cameras per LoS. The EP12 optical path is represented in Fig. 2 showing the different parts: 1-The *in-vessel optics* [5], is based on reflective components and formed by the following units: a) the First Mirror Unit (FMU) with an off-axis ellipsoidal first mirror (M1) which forms an aberrated image close to a second folding mirror (M2); b) the Hot Dog-Leg mirrors Unit (HDL) constituted by a pair of folding mirrors (M3, M4) which send the light through the vacuum window and constitute the neutron shielding inside the PP; 2-The *ex-vessel optics,* laid through the IS, BS and PC, is based on independent optical modules along the path that can be assembled, integrated and verified as independent subsystems; this modularity implies an important advantage in terms of the assembly and tests on site as well as on the maintenance activities. The ex-vessel optical chain is composed of the following subsystems: a) in the Interspace: the Optical Hinge (OH), the Optical Relay Unit (ORU) and the Interspace Afocal Module (IAM); b) in the Bioshield: the Cold Dog Leg (CDL) - Objective Unit (OU) and the Collimator Unit (CU); c) in the PC: the Port Cell Afocal Module (PCAM) and Shielded Cabinet Components (SCC). In Fig. 3 it is represented the opto-mechanical layout of the ex-vessel subsystems in the EP12. A more detailed explanation of the different subsystems is included in section 3.

Table 1
Main measurement requirements for the WAVS system.

PARAMETER	SPECTRAL RANGE	RANGE TO COVER	TIME RESOLUTION	SPATIAL RESOLUTION	ACCURACY
Surface Temperature, Divertor	IR	200°- 3600 °C	10 ms, full frame 2 ms, sub-frame (1/5 of full frame)	—	20% for 200°- 400 °C 10% for 400°-3600 °C
Surface Temperature, First Wall (FW)	IR	200°– 2000 °C	10 ms	12 mm for views with reduced FoV - 24 mm for the rest	20% for 200°- 400 °C 10% for 400°- 3600 °C
Surface Luminance, First Wall (FW)	VIS	$40 – 10^5$ cd.m^2	10 ms	6 mm for views with reduced FoV 12 mm for the rest	30% abs, 1% rel
D_2,T_2 influx in Divertor	VIS	$10^{19} – 10^{25}$ atoms. s^{-1}	1 ms	50 mm	30%

3. Ex-vessel components mechanical design

Attending to their location in EP12 the ex-vessel subsystems of the WAVS are presented next.

3.1. Ex-vessel sub-systems in the interspace (Fig. 4, Table 2)

The first subsystem of the ex-vessel optical chain is the OH, constituted by a pair of flat (folding) mirrors per LoS. It aims to compensate the differential motion between the vacuum vessel and the building in plasma operation and baking, in order to ensure the alignment of the PP exit optical beam (at the vacuum window) with the optics in the IS. This subsystem has been identified as a critical item of the ex-vessel chain and a prototype will be developed in order to validate the final design. The OH consists of two folding mirrors, the upper one movable (OH1) and the lower one fixed (OH2). Both are assembled on their respective mounts and mechanically connected to a structure which provides support for the OH and the ORU. The mount supports include regulation mechanisms in the vertical and the horizontal planes while the opto-mechanical dressing of the two OH mirrors provides tilt/tip alignment capabilities. To provide the function assigned to the OH (the compensation of the thermal displacement of the vacuum vessel) the upper mirror is driven vertically to the operation position through an accurate guiding system by means of a piezo actuator and a set of electrical reference switches. This guiding mechanism is integrated in the opto-mechanical mount of the upper mirror (see Section 4).

The common structure formed by two vertical plates internally armed by transversal beams, provide support to the OH and ORU transferring the loads to the Interspace Support Structure (ISS). Some openings have been done in the lateral plates to relieve some weight as well as to facilitate the adjustment tasks on the mirrors. Next to the OH, the ORU completes the optical train of the PP. It is formed by two off-axis ellipsoidal mirrors (per LoS) - M5 (fixed) and M6 (manually adjustable) - which produce an aberration-free collimated beam for the next subsystem (the IAM) and keep the beam size as small as possible. The ORU subassembly presents alignment capabilities in tip/tilt and in height.

Fig. 4 shows the disposition of the ex-vessel subsystems in the IS whilst their main parameters are listed in Table 2. In the figure on the left, the front lateral plate of the OH—ORU structure has been removed to show the internal set up of the different components.

The next subsystem in the optical train is the IAM which constitutes the first refractive module of the optical system. It consists of two identical doublets (per LoS), the first one produces a real image at half way of the optical system whilst the second acts as a collimator producing a collimated beam that enters the optics in the BS. The mount of the doublets is made in barrels, which are inserted at both ends of a support tube. The latter is designed to account for the straylight rejection, vibration and operational temperature that guaranty the optimum performance of the system. This modular assembly aims to get the required tolerances between doublets to be assembled, aligned and focused at the factory. The installation of these modules already optically corrected at the factory is an important advantage from the point of view of the verification activities on site, as they save time and reduce cost. To facilitate the assembly and disassembly operations, the support tubes will be manufactured splitted into two halves, assuring that the accurate position of the optics inside is maintained after reassembly of

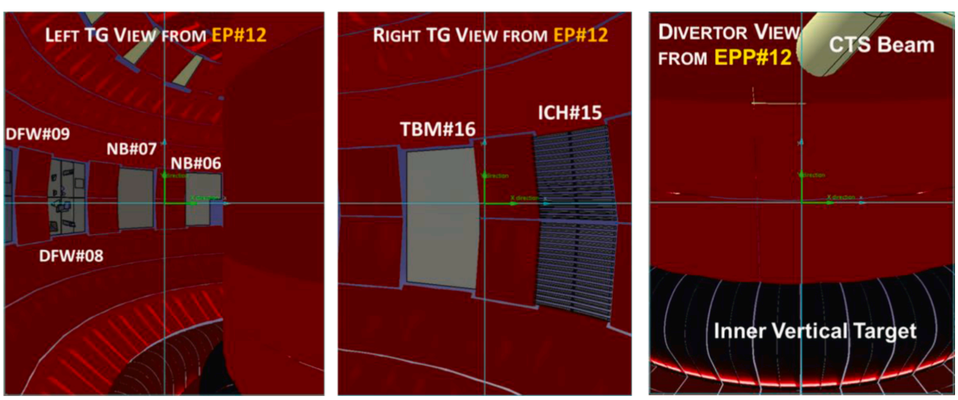

Fig. 1. Field of view from the three Line of Sight in EP12.

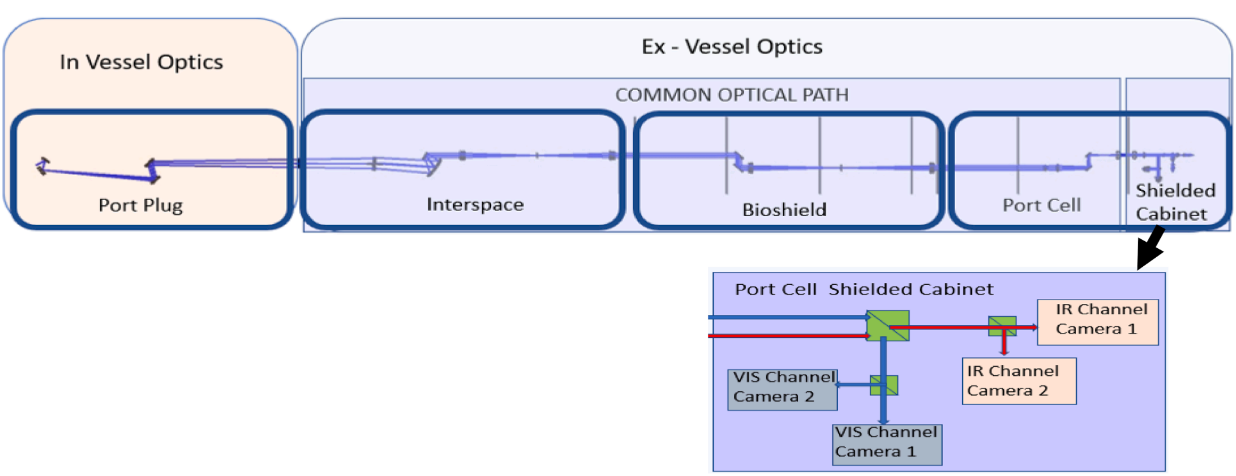

Fig. 2. WAVS optical layout for one LoS in EP12 (top view).

the two halves. The three support tubes are assembled on a common structure formed by two parallel plates connected by a crossing H beam on the top. This structure accommodates a total of 9 rods and 6 flanges for the three LoS's providing at the same time mechanical support and alignment capabilities for the optics. Each tube is mechanically connected to the structure by L-beams through a rotational mechanism that allows the fully alignment of the tube in the space. Centering and tilt adjustment are performed by means of 3 screws located at 120° at both ends of the tube. The details of the support tubes for the IAM optics can be seen in Fig. 5.

The structural integrity of each IS subsystems has been demonstrated through the Finite Element Analysis (FEA) performed in the frame of the PDR [6,7], withstanding the different load conditions described in the corresponding System Load Specifications, according to the applicable Codes & Standards and design rules. Likewise, the results of the analyses show that the thermomechanical deformations in plasma operation meet the optical criteria established for the system performance.

As a general basis, the design of the IS components is based on bolting connections to be compliant with the requirement of avoiding as much as possible welding connections in order to facilitate the dismounting of the components (activated) at the end of the ITER operation.

3.2. *Ex-vessel opto-mechanical components in the Bioshield (Fig. 6 and Table 2)*

The first component located in the BS is a CDL to be compliant with the requirement of minimizing the radiation exposure to workers in the PC. It is formed by a set of two folding mirrors tilted at 45° that in addition to provide a radiation shielding, it also allocates alignment capability for the LoS. Next to the CDL, it is placed the second refractive module of the optical system (Afocal Module 2) constituted by two units, the OU and CU: this optical module is physically splitted in two parts to accommodate the optics between the shielding modules of the BS and PC as it can be seen in Fig. 3. The OU and the CU are both constituted by doublets, possessing mechanisms for the axial regulation and the adjustment in the plane normal to the optical beam.

The CDL and the OU are supported on the same optical breadboard

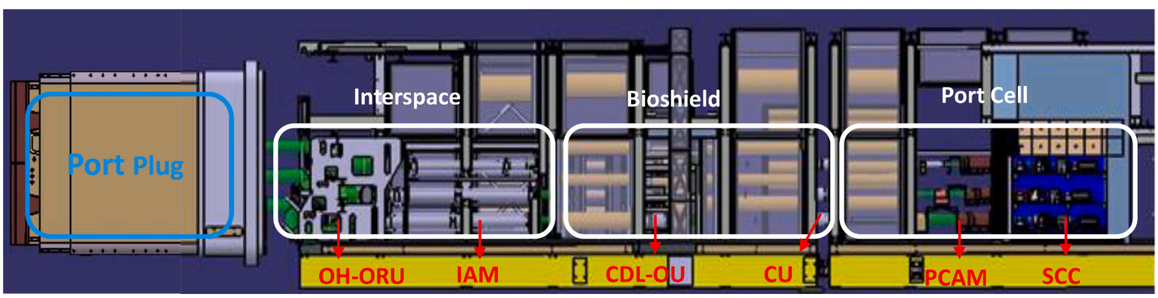

Fig. 3. Opto-mechanical layout of the ex-vessel subsystems in EP12 (side view).

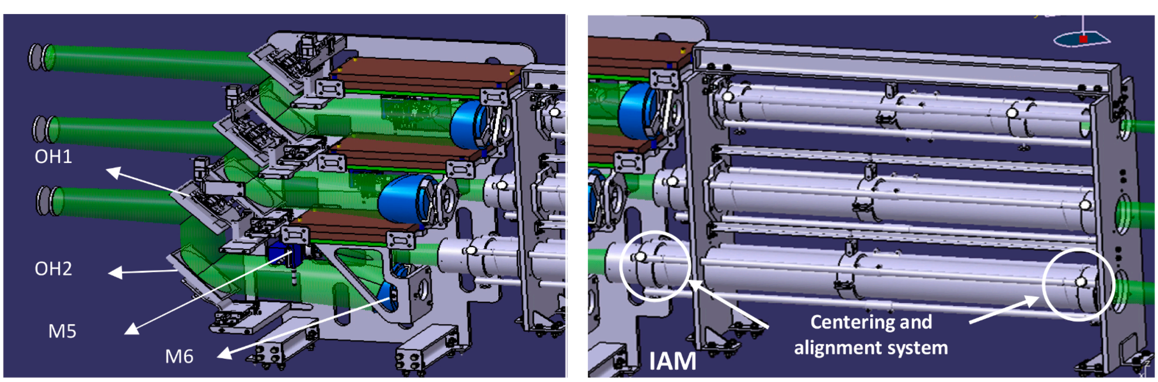

Fig. 4. Ex-vessel subsystems in the Interspace in EP12: OH—ORU (left) and IAM (right).

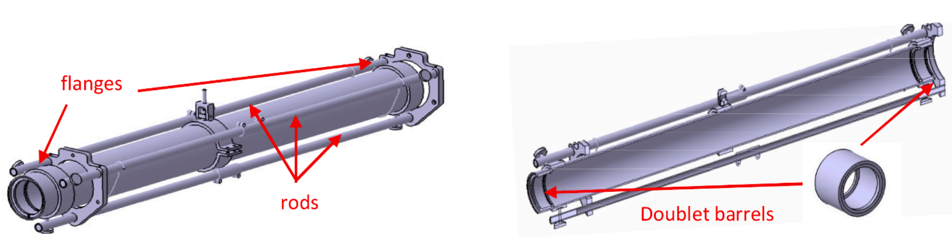

Fig. 5. Details of the support tube for the IAM optics.

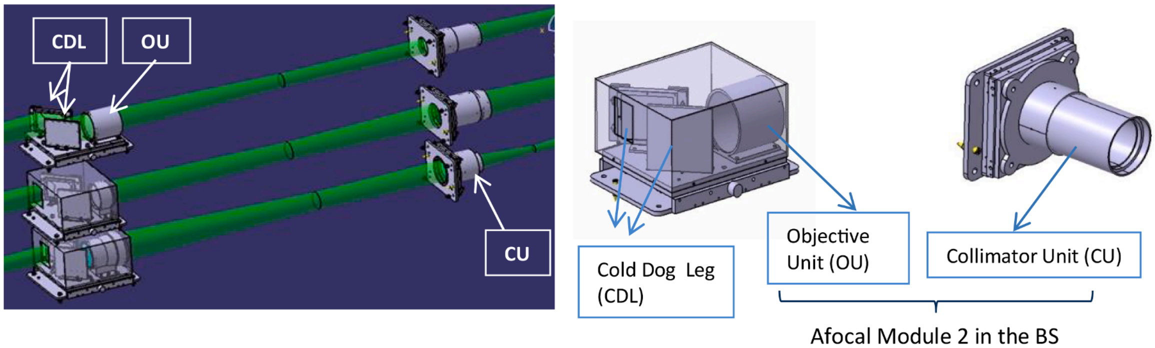

Fig. 6. Cold Dog Leg (CDL) and Afocal Module 2 (OU and CU) placed in the BS in EP12.

while the CU is supported on the rear side of the BS shielding module (facing the PC) through an embedded plate and fastened by bolts.

The subsystems placed in the BS are shown in Fig. 6 whilst their main parameters are listed in Table 2.

3.3. Ex-vessel opto-mechanical components in the Port cell (Fig. 7 and Table 2)

The optics in the PC is also refractive except for the beam splitters and folding mirrors. It is constituted by the third afocal module (PCAM) and all the optical components inside the cabinet (SCC). The former is aimed at keeping the collimated beam at the entrance of the SC, while the division of the VIS and IR optical path takes place inside the cabinet, directing the beams to their corresponding sensors. The following components are placed inside the SC: beam splitters, IR Objective with mounts (formed by 5 lenses), VIS objective with mounts (formed by 4 lenses), 4 cameras, 2 filter wheels, 4 focusing motors. All these components (per LoS) are supported on the same optical breadboard.

The first optical element inside the cabinet, is a dichroic beamsplitter at 45° that separates the radiation between the IR and the VIS spectral range by transmitting in the IR and reflecting in the VIS. The dichroic beamsplitter is mounted on a commercial kinematic support that allows tip/tilt adjustments for alignment purposes. In the IR channel a second beam splitter (dichroic) is implemented aimed at having two identical IR cameras to provide redundancy for temperature measurements concerning the assigned function of Machine Protection. For both cameras, the IR objective, consists of 5 lenses mounted on the motion platform of a motorized linear stage that shall be actuated remotely for the image focusing. In the same way, the VIS band is splitted in two paths (50:50 ratio) by a beam splitter aimed at the implementation of a second camera devoted to physics impurity studies. For both cameras, the VIS objective consists of 4 lenses provided with motorized linear stages for refocusing as done for the IR channels. Moreover, the diagnostic is equipped with a filter wheel on each visible LoS, allowing images to be

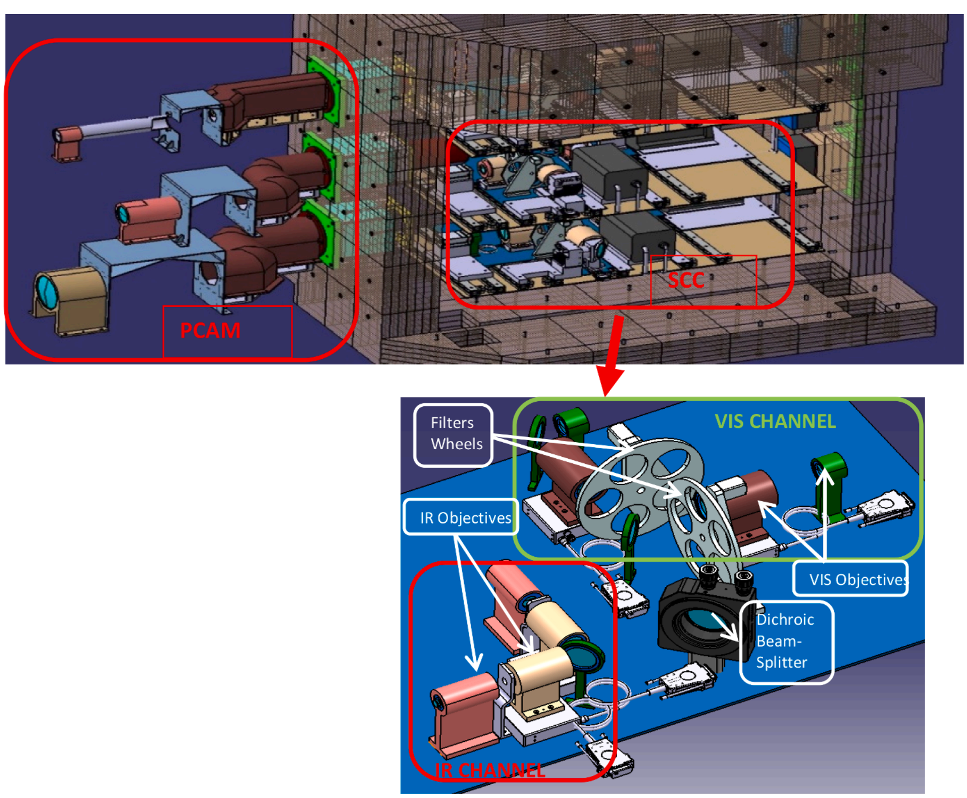

Fig. 7. Ex-vessel subsystems located in the PC EP12: PCAM and SCC (detailed on the right).

Table 2
Main characteristics of the WAVS ex-vessel subsystems/components.

SUBSYSTEMS/ COMPONENTS		WEIGHT (kg)	MATERIAL	MAXIMUM VOLUME (mm^3)
OH—ORU support structure		450	Stainless steel 316L	0.7×10^9 (OH-ORU includ.)
OH mirrors / mounts		77	Zerodur Ag coated/ stainless steel 316L	———
ORU mirrors / mounts		372	Zerodur Ag coated / stainless steel 316L	———
IAM lenses / mounts	Tube TAN RIGHT	50	Sapphire and CaF_2 / Stainless steel 316L	$\Phi_{ext} = 118$ $L = 1400$
	Tube TAN LEFT	67	Sapphire and CaF_2 / Stainless steel 316L	$\Phi_{ext} = 150$ $L = 1690$
	Tube DIVERTOR	77	Sapphire and CaF_2 / Stainless steel 316L	$\Phi_{ext} = 160$ $L = 1880$
IAM support structure		177	Stainless steel 316L	0.8×10^8 (tubes includ.)
CDL-OU lenses / mounts	TAN RIGHT	57	Fused silica / Sapphire - CaF_2/ Stainless steel 316L	$449 \times 295 \times 220$
	TAN LEFT	58	Fused silica / Sapphire - CaF_2 /Stainless steel 316L	$369 \times 355 \times 238$
	DIVERTOR	63	Fused silica / Sapphire - CaF_2/ Stainless steel 316L	$424 \times 335 \times 255$
CU lenses / mounts, structures	TAN RIGHT	20	Sapphire - CaF_2 / Stainless steel 316L	$290 \times 230 \times 240$
	TAN LEFT	20	Sapphire - CaF_2 /Stainless steel 316L	$290 \times 230 \times 254$
	DIVERTOR	25	Sapphire - CaF_2 / Stainless steel 316L	$290 \times 230 \times 269$
PCAM lenses/ mirrors/ mounts, structures	TAN RIGHT	20.5	Fused silica /Sapphire – BaF_2/ Stainless steel 316L	$1069 \times 222 \times 1069$
	TAN LEFT	40	Fused silica /Sapphire – BaF_2 - ZnS/Stainless steel 316L	$1090 \times 353 \times 1090$
	DIVERTOR	43	Fused silica /Sapphire – BaF_2 - ZnS/Stainless steel 316L	$1061 \times 385 \times 1061$
SCC mirrors/BS/lenses/ mounts (all LoS)		43	Fused silica/Si, Fused silica, Ge/ Ge, ZnS, Si, SF6, BK7/stainless steel 316L	1077×532 (mm^2)

captured at different wavelengths by rotation of the wheel. A general view of the PC optic-mechanical design can be seen in Fig. 7 where the PCAM and SCC are represented. The main parameters of these subsystems are listed in Table 2.

4. The optical hinge mechanical assembly

The motion of the vacuum vessel due to thermal expansion in plasma operation (100 °C) and baking (200 °C) produces relative displacements

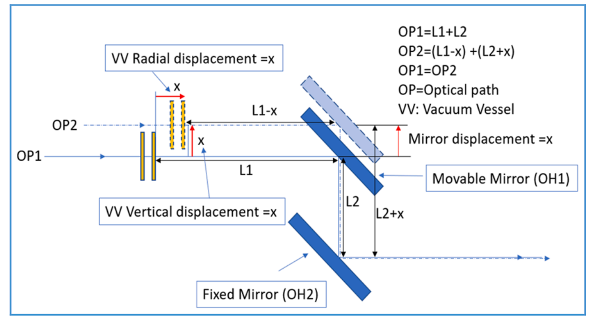

Fig. 8. Compensation of the VV displacements with respect to the building made by the upper mirror OH1.

between the optical components inside the PP and the ones located in the IS (tokamak building). These displacements have an impact on the optical performance degrading the image quality and moving the image out of the center of the sensor. The optical correction will be done by means of the Optical Hinge, in particular by the proper displacement of the upper mirror OH1. Due to the fact that the motion of the VV in the radial and the vertical directions are very similar (around 16 mm in plasma operation and around 37 mm in baking) the correction can be done by a single linear vertical movement of the upper mirror OH1 (e.g. with a single degree of freedom) as shown schematically in Fig. 8.

The vertical displacement of the OH1 mirror will be driven by a piezo-electric actuator mechanically coupled to the mirror up to the correct position determined by electrical switches which will be calibrated during the commissioning of the diagnostic. The mechanical setup of the upper and lower mirrors, piezo actuator and electrical switches can be seen in Fig. 9.

Three different scenarios have been considered for the motion compensation of the VV according to its temperature state: a) VV temperature at 20 °C, as it corresponds to the commissioning phase at ambient as well as the maintenance periods; b) VV temperature at 100 °C, that corresponds to the plasma operation state and, c) VV temperature at 200 °C which corresponds to the baking state. According to each scenario, the OH1 mirror will be moved to one of the three pre-fixed positions (previously calibrated during the commissioning phase) by means of the piezo actuator and the set of reference switches.

The pre-selection of the actuator has been done based on the piezo-electric technology which has shown a good behavior under high magnetic fields and radiation environment. Likewise, the electrical switches have been selected based on radiation-resistant materials, compliant to ITER specifications.

The Optical Hinge has been identified as a critical subsystem of the ex-vessel part, thus a prototype has been planned in order to validate its performance. A mock-up 1:1 of the mirrors (mechanical mounts and the structure) will be manufactured to test the actuator and the switches under the different operation scenarios. Moreover, gamma and neutron radiation tests will be done on the piezo-actuator to check its compatibility with the ITER environment in the IS.

5. Conclusions

This article provides an overview of the ex-vessel opto-mechanical subsystems which form the WAVS diagnostic in EP12. They are arranged through the IS, BS and PC according to the end to end optical design of the WAVS diagnostic in EP12 reached at the preliminary design phase. The main characteristic of the design carried out is the modularity of the system based on modules optically corrected that can be assembled, integrated and verified on site independently. The structural integrity of the mechanical subsystems and components as well as the optical performance in the operational conditions have been checked with the

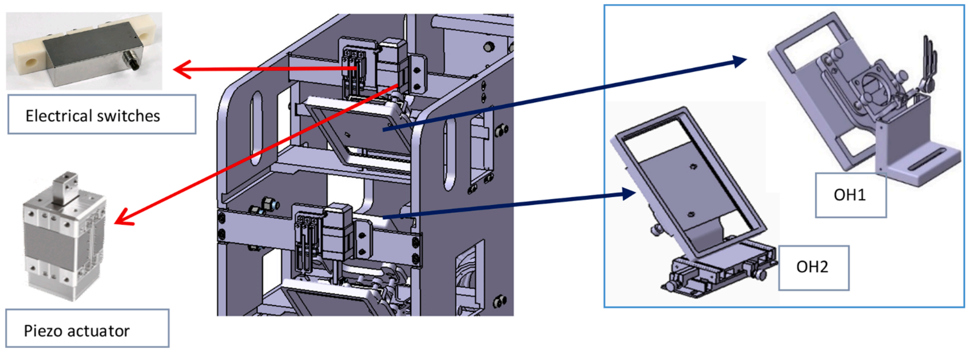

Fig. 9. Mechanical setup of the OH mirrors, piezo actuator and electrical switches.

correspondent structural analyses made in the frame of the PDR [6,7]. Moreover, a brief description of the mechanical assembly and operation of the OH has been presented.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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