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Design and manufacturing progress of IRVIS endoscopes prototypes for W7-X divertor temperature monitoring

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The Wendelstein 7-X fusion experiment at Max-Planck-Institut für Plasma Physik (IPP) in Greifswald produced its first hydrogen plasma on 3rd February 2016. This marks the start of scientific operation. Wendelstein 7-X is to investigate this configuration's suitability for use in a power plant.

In order to allow for an early integral test of the main systems needed for plasma operation (magnet system, vacuum, plasma heating, control and data acquisition, etc), the divertor units and most of the carbon tiles covering the wall protection elements are being installed before the next experimental campaign (OP1.2). For the later operation phases, the heat fluxes coming from the plasma will be distributed over an area provided by the plasma facing components (i.e. divertor target plates, baffles). An important diagnostic for W7-X will be thermography systems monitoring the surface temperature of the divertor target plates by collecting and processing infrared (IR) and visible (VIS) light from the divertor region of the plasma. For this purpose the company Thales SESO has been assigned to design, build, test, deliver and install 2 first prototypes of IRVIS (InfraRed-VISible) endoscope systems for the divertor of the W7-X Stellarator. Thermography is part of the operational and protective divertor diagnostics and has to detect signals indicating anomalous operation scenarios. The design of the horizontal and vertical target plates and the baffles in the divertor should keep the local power load below 10 MW/m2. The IRVIS endoscope systems are designed to operate under heavy-duty conditions.

Keywords: W7-X, thermography, optical design, mechanical engineering, integrated design, manufacturing, tests.

1. Introduction

The Wendelstein 7-X stellarator will allow quasi-continuous operation 30 min with 10 MW of electron cyclotron radiation heating power. For that reason, an important diagnostic for W7-X will be thermography systems monitoring the surface temperature of the divertor target plates by collecting and processing infrared (IR) and visible (VIS) light from the divertor region of the plasma. 2 first prototypes have been designed for of the machine with optical system which combines infrared IR/visible endoscope which is presently being manufactured for the two divertor of module 5. For the future, ten such systems, as part of the machine protection system, will be required for real time monitoring of all ten discrete, water cooled divertor modules with high spatial 10 mm resolution, in order to prevent local overheating of the target tiles, which could easily lead to their destruction. On the physics side, the systems will be used for divertor symmetry investigations by studying the power load distribution on all targets modules. The horizontal and vertical target plates with the baffles in the divertor have been designed to keep the local power load below 10 MW/m^2. The plasma is viewed through a 10 mm diameter pinhole in a water cooled stainless steel plate. Fig. 1.

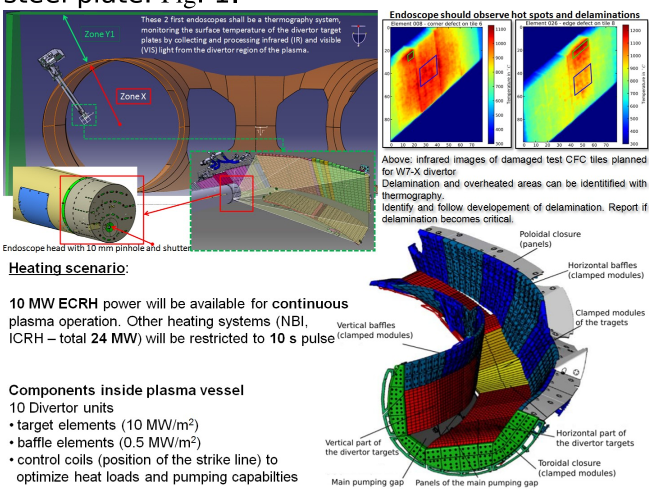

Fig. 1. Working environment of IRVIS endoscope

2. Supervision and protection of the divertor targets with IRVIS endoscope

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In order to be able to cope with the convectively lost power from the plasma, i.e., to maintain the integrity of the divertor, one needs to ensure that the power density distribution across all ten divertor modules is as equal as possible. A poor alignment of any of the divertor modules relative to the three dimensional magnetic field structure, as well as particle drift effects (e.g., E×B) drift or the localized losses of fast particles, can lead to destructive local overloading of the targets in one or several divertor modules. The divertor has to keep above the maximum tolerable power density of 10 MW/m^2. In particular at the beginning of the operation of W7-X, limitations in manufacturing accuracies, metrology, and knowledge about plasma vessel deformations after pump and cool down, as well as about magnetic field perturbations from small manufacturing inaccuracies of the overall magnet system, may lead to a misalignment of the divertor modules, largely based on the observed power load patterns, unavoidable. In particular the intrinsic island divertor magnetic field structure is extremely sensitive to very small local field perturbations larger than 10^{-4} $\Delta B_{radial}/B_{toroidal}$. For each ten divertor, the optical device is an endoscope of 2 m length with a Full Field of View (FFoV) of 115°×60° looking at the divertor. Fig. 2.

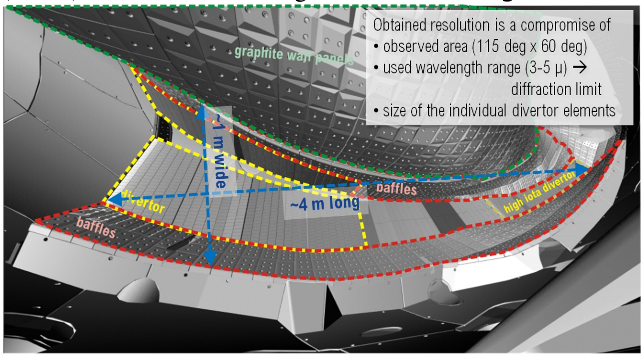

Fig. 2. View on the top W7-X divertor through an AEF port

The IRVIS endoscopes are part of the machine safety system since they need to ensure that no part of the divertor tiles ever exceeds 475 °C at the interlayer between the Carbon-Fiber reinforced Carbon (CFC) plasma facing material and the underlying water cooled CuCrZr block.

3. Optical design of infrared and visible optics

The current design of IRVIS endoscope is composed of four major elements: In-Vessel optical system (off-axis Cassegrain telescope system), ex-vessel optics (including dichroitic beam splitters, re-imaging optics and detectors), a cooled vacuum housing and an in-vessel shutter including drive and calibration equipment. The optics of the system can be divided into three parts: a mirror based optical head, creating an intermediate image, a Cassegrain telescope system, and individual lens based imaging optics adapted to the various detectors for IR (3–5 µm) and visible (0.35-0.8 µm) observations, with their optical light paths being separated by in-vacuum dichroic beam splitters. Each endoscope is equipped with a complex system of mirrors and lenses, allowing the observation of the divertor surface in infrared and visible light. Photons enter the endoscope through a pinhole and are directed via two mirrors (M1, M2 in Fig. 3) onto the off-axis Cassegrain optical system (M3, M4). From the M4 mirror, light passes through the window W2, where it is divided by the dichroic beam splitter (B1) into a visible and infrared beam and after passing through a set of correcting lenses it is detected by the sensors in cameras (C1 and C2). Mirror M5 and window W1 provides additional optical access to the entire divertor region.

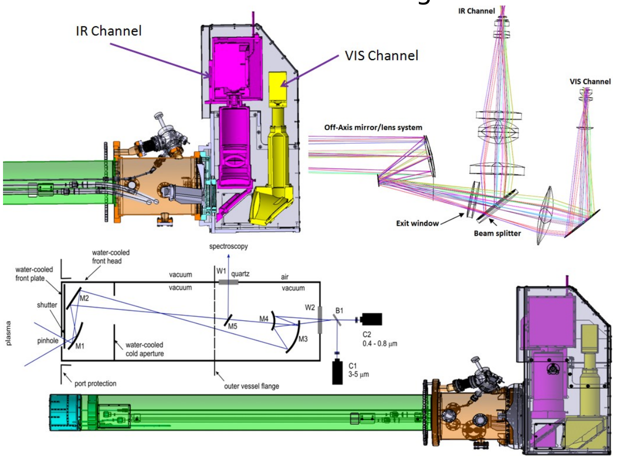

Fig. 3. Optical design of infrared and visible channels

When optimizing the system in Zemax the object points considered for the optimization has to be onto one surface. The design of the optical system is based on a plane object plan, centered on the mean FOV with the same total amplitudes. The resulting FOV is as follows:
-Vertical FOV: ± 30° - Horizontal FOV: ± 57.5°
-Tilt of object plan: Vertical: l0° Horizontal: 17.5°
An optimized lens system for the near UV and visible spectral range taking also the beam splitter into account has been designed. The UV/visible system uses the beam splitter in reflection and the IR system in transmission although using the IR light in reflection would enable to obtain a higher image quality. The following cameras have been chosen:
- Range 3 to 5 µm (IR): Infratec ImageIR 9300 camera, with Sensor InSb FPA 1280x1024 pixels, chip size 19,2x15,36mm, and pixel pitch 15 µm (C1).
- Range 350-800 nm (VIS): Zyla CMOS ANDOR camera with 2560x2160 pixels, chip size 16.6 x14 mm and pixel size 6,5 µm (C2).

4. Specification and theoretical endoscope performance

The objective of the IRVIS endoscope is to monitor the temperature of the divertor plates which is checked by

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calculating in 39 points and then perform optical tests at the coordinates given in Fig. 4.

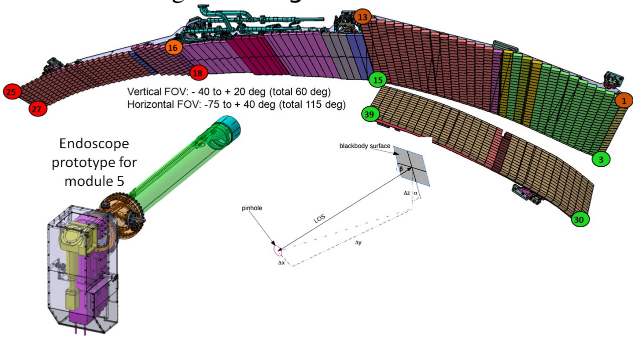

Fig. 4. 39 Reference points on the divertor surface

The system shall allow observation of the divertor surface at two different wave length ranges 3-5 µm and 0.35-0.8 µm. Therefore the common optical components must be compatible with both wavelength ranges (in particular mirrors). However, as the main aim of the endoscope is to monitor temperature of the divertor, optical properties

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must be optimized primarily for 3-5 µm observation of the divertor. The endoscope shall allow measurement of the temperature distribution on the divertor surface with a spatial resolution of 6 mm or better near the line of sight (divertor part marked in area I in Tab.1) and better than 10 mm away from line-of-sight at the wavelength of 3-5 µm (divertor parts marked II and III in Tab.1).

Area	Point	Specification			Theoritical endoscope performance		
		Object target (mm)	Image target (µm)	Image frequency (lp/mm)	MTF (%)	Nominal MTF (%)	Expected MTF (%) (Monte Carlo)
Area 1	1	6	56	18.4	40	75	57
	3		39	26.3		68	39
	13		86	11.6		80	74
	15		65	15.4		73	69
Area 2	16	10	62	16.2	30	77	61
	18		61	16.4		75	62
	25		30	33.1		54	30
	27		31	32.2		54	33
Area 3	30	10	59	17.2	40	80	52
	39		118	8.5		85	84

Tab.1. Specification and theoretical extrapolated performance

5. Mechanical design and manufacturing

The IRVIS endoscope is submitted to a lot of environmental constraints as high temperature, gravity, heat flux, ECRH stray radiation, limited space reservation, and assembly constraints which require technical measures to match the specifications.

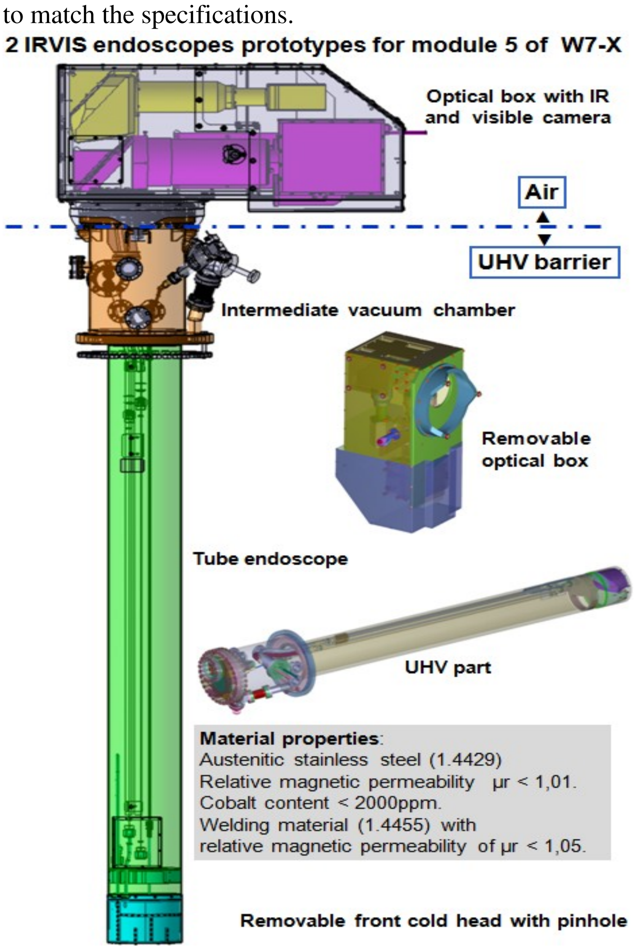

Fig. 6. Design and main components of IRVIS endoscope

For this purpose the company Thales SESO has been assigned to design, build, test, deliver and install 2 first prototypes of IRVIS endoscope systems for the divertor of the W7-X Stellarator. The prototype design of IRVIS endoscope is composed of four major elements: Intermediate vacuum chamber (with Cassegrain telescope system and interfaces), removable optical box (including dichroitic beam splitters, re-imaging optics and detectors), a vacuum tube endoscope and the in-vessel removable front cold head with pinhole (including shutter, drive and calibration equipment). Due to very narrow tolerances and high requirements on the assembly precision it was necessary that potential collisions of components had to be found out already before the design implementation and assembly. For that reason a strict space allocation has been determined by IPP for the mechanical design developed by Thales SESO. The global behavior of the endoscope has been analyzed under the gravity and under a gradient of temperature limited by the use of a cooling system. However some critical points have required thermal and mechanical analyses to choose the best material, design and technological solutions.

5.1 Intermediate vacuum chamber.

The intermediate vacuum chamber is made of austenitic stainless steel 1.4429 with 3.5mm thickness with a DN300CF flange to fix the endoscope to the AEF port. It contains the water pipes and power cables with feed through and interfaces, the M5 flat mirror for the spectroscopic channel, the spectroscopic window W1 and the M3 and M4 Cassegrain mirrors. The M3, M4 and M5 are mounted on a common mounting bracket and a sapphire window W2 for IR and VIS channels screwed on the DN250CF flange. A support with brackets was developed to maintain the optical box system. The actuator is a standard vacuum pneumatic rotary actuator with 24V DC solenoid and in UHV-compatible material. Its feedthrough is a DN16CF flange port mount. In the plasma vessel one of the requirements is the absolute tightness of medium feeding lines or components. Therefore all components are leak tested before their assembly. Connections made during assembly must be 100% leak tested and wherever it is possible, the tests are carried out under conditions, which are like those of later operation. Helium is used as standard tracer gas and the leak rate of the vacuum chamber at 1 bar Helium= 10^{-9} mbar·l/s.

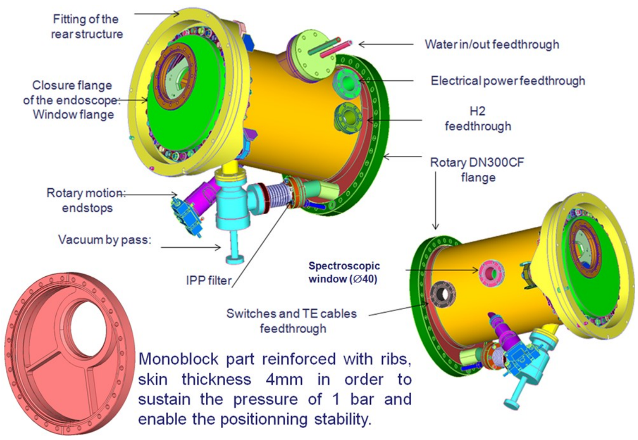

Fig. 7. Intermediate vacuum chamber with internal components

5.2 Optical box with IR and Visible camera

This part of the endoscope contains the IR and VIS optics and the associated cameras. The optics of each channel are inserted in 2 separated barrels (not represented for the protection of industrial right of ownership) which are supported by a common plate. Taking into account the tolerances, each channel is adjustable with respect to the optics before (Cassegrain and front optics: M1 to M4) but it is not necessary to adjust the optics inside a barrel. All optics are enclosed in a protection box in addition the infrared camera will be protected from ca. 100 mT magnetic field with soft-iron box and because of heat exchange it needs to be water cooled in order to keep the temperature below 70°C.

5.3 Tube endoscope with technical media

The tube is made from a folded 1.4429 stainless steel sheet thick 3mm of. All water pipes Ø10-12mm are connected on side to the cold aperture and up to the feed-through to flexible hoses Ø13.5-21mm. Shutter rod with connecting bellows to compensate shifts is maintain by fittings and bearings along the tube. The tube is welded to the DN300CF flange which is fixed to the port protection with 32 bolts. The tubes include a hatch to assemble and dismantle the head, cold aperture and the water cooling system (see details in Fig. 8).

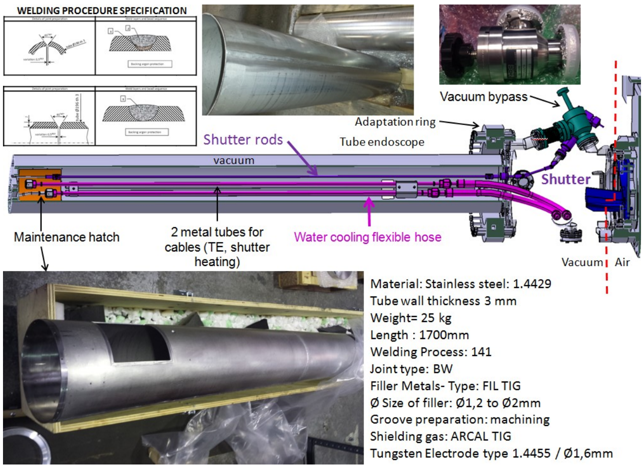

Fig. 8.Description of tube endoscope with technical media

5.4 Removable front cold head with pinhole

Choosing a pinhole instead of a window means that an influx of plasma impurities could enter inside the endoscope. It may result in a slow degradation of the optical system transmission, due to carbon deposition especially on the surface of the first mirror M1. For that reason M1 can be heated to a temperature of 350˚C to remove the impurities. High radiation coming from plasma (50 kW/m² at wavelength shorter than 6nm) would result in a high temperature of the front head, which would lead to thermal distortions and high background infrared radiation. Therefore, the head needs to be water-cooled. A water-cooling circuit with water at the pressure of 25 bar is required. Aim is to remove the thermal power from the endoscope front head and cold aperture in order to keep them below the temperature of 150°C. An important element is a shutter (Fig.9), which closes the pinhole directly after the discharges to reduce carbon deposition on the mirrors and is closed during plasma vessel conditioning, i.e. glow discharge cleaning. The shutter has two functions: i.) protects internal mirrors from impurities while not in operation and ii.) a build-in ceramic heater (up to 1000˚C) will be used for a calibration of the infrared and visible channel.

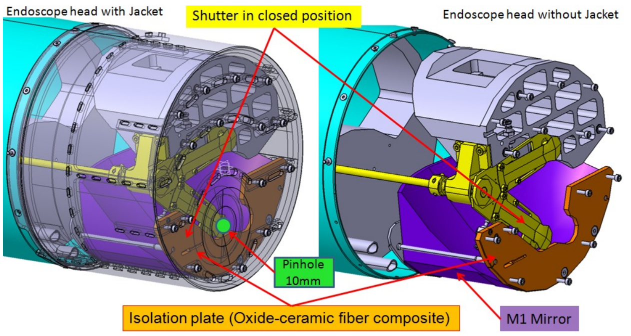

Fig. 9.Detailed design of cold head with pinhole and shutter

3. Test & assembly of IRVIS prototype on W7-X

The delivery of the first endoscope is planned for the middle of October 2016. Test and assembly are carefully planned and qualified. They contain all essential work and test steps with the necessary input documents to be used (working instructions, drawings, welding procedure specifications, change notes, technical guidelines, collision reports, test procedures, etc.). All this information will be helpful in the later commissioning and operation phase of the subsystems of the machine to minimize risks or to supervise them adequately. For assembly tests, IPP has developed a 3D mockup which is a working full scale model in a specific configuration of W7-X machine (Catia assembly). It roles is to give an overview to the designers, engineers or physicists working on components located in the Torus Hall. It allows also assembly teams to visualize the whole W7-X machine with all its peripheries at once.

Acknowledgments

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