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Engineering Aspects of a Fully Mirrored Endoscope

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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT

The development of optical diagnostics, like endoscopes, compatible with the ITER environment (metallic plasma facing components, neutron proof optics,…) is a challenge, but current tokamaks such as JET provide opportunities to test fully working concepts. This paper describes the engineering aspects of a fully mirrored endoscope that has recently been designed, procured and installed on JET. The system must operate in a very strict environment with high temperature, high magnetic fields up to $B = 4T$ and rapid field variations ($\partial B/\partial t \sim 100$ T/s) that induce high stresses due to eddy currents in the front mirror assembly. It must be designed to withstand high mechanical loads especially during disruptions, which lead to acceleration of about 7g at 14Hz. For the JET endoscope, when the plasma thermal loading, direct and indirect, was added to the assumed disruption loads, the reserve factor, defined as a ratio of yield strength over summed up von Mises stresses, was close to 1 for the mirror components. To ensure reliable operation, several analyses were performed to evaluate the thermo-mechanical performance of the endoscope and a final validation was obtained from mechanical and thermal tests, before the system's final installation in May 2011. During the tests, stability of the field of view angle variation was kept below 1^o despite the high thermal gradient on endoscope head ($\partial T/\partial x \sim 500$K/m). In parallel, to ensure long time operation and to prevent undesirable performance degradation, a shutter system was also implemented in order to reduce impurity deposition on in-vessel mirrors but also to allow *in situ* transmission calibration. One of the main specifications of the shutter system was high reliability. This was considered as achieved when the prototype was successfully tested to 3000 cycles at a temperature of 300^oC.

1. INTRODUCTION

During the current ITER design phase, experimental tokamaks have to test and validate some of the future technological choices. This is one of the main ideas behind the ITER-like Wall upgrade that occurred in JET in late summer 2011 where the carbon based plasma facing components have been replaced with parts using the material mix mainly foreseen in ITER; tungsten and beryllium, more specifically divertor for the first one and the rest of the wall for the second.

However, some of the diagnostics had also to be updated to better monitor the new plasma-facing components and this is the reason of the development of KL11 endoscope.

2. SPECIFICATIONS AND REQUIREMENTS

2.1. SCIENTIFIC GOALS

The main aims of this endoscope were to measure the poloidal and toroidal distribution of the erosion of tungsten, the level of remaining carbon in the plasma, the re-erosion of beryllium in the new tungsten divertor and, more generally, impurities in the divertor plasma. For these purpose, it had to cover a wide spectral range from 350nm to 2500nm with optimised transmittance for observation in the near UV and in the blue spectral region to ensure the detection of the W I-emission line at 400.8nm, but also many other like Be II at 527nm, Balmer α at 656nm, or C I at 905nm. [1]

Another requirement was high flexibility combined with good space resolution. The spectroscopic system was thus based on cameras equipped with exchangeable interference filters. An added advantage is that this solution can be used for computer tomographic reconstruction, which is one of the final project goals [2].

2.2. TECHNICAL REQUIREMENTS

The endoscope had in addition some operational goals such as the survey of the integrity of the newly installed divertor, avoiding for example, too high temperatures operation or even melting of the tungsten.

On the optical side, the allocated port and the targeted components set the necessity to reach a resolution approaching the millimetre (divertor structure range) with a distance of about 8 meters between the flange and the components and a small entrance pupil (8mm, 4m away from object). Still on geometric specifications, the tilt angle of viewing direction was about 60^{o} with respect to port axis and a total depth of field of approximately 1400mm was requested.

The in-vessel part of the endoscope had to withstand high heat flux and neutron fluxes between 10^{13} and 10^{16} neutrons $m^{-2}s^{-1}$, and a protection system reducing deposition had to ensure a maximum lifetime of the optical components. The degradation of refractive material under neutron irradiation is one of the reasons for the adoption of the ITER like configuration with only reflecting optics in the vacuum. Figure 1 shows the simplified 3D model of the assembled endoscope at the JET torus to figure its environment.

The JET environment also imposed some high mechanical requirements such as operation in a toroidal field of 4.0 T and survival during plasma disruptions (up to $\partial B/\partial t \sim 100T/s$) that can induce high accelerations (7g) and oscillations at frequencies down to 14Hz limit; the latter implying restrictions on the resonance frequencies of the system.

3. CONCEPT AND DESIGN

3.1 GENERAL OVERVIEW

The endoscope is split in two majors parts, the in- and the ex-vessel sections. The vacuum tube, the shutter actuator, the optical head and its cover make up the in-vessel structure while the telescope, the cameras and the shutter outer reservoir are outside the vacuum boundary. They are separated one from the other by a double vacuum window and the port flange. The in-vessel components and the flanges are mainly made of stainless steel (304 and 316L) while the telescope (mirrors and structural parts) is entirely made of aluminium alloys. A general view of the JET Kl1 endoscope is given in figure 2.

3.2 ENDOSCOPE HEAD

The endoscope head presented in figure 3 mainly consists of two primary mirrors in a cylindrical chassis. The first mirror reflects the collected object plane light, 4 meters away, through the small optical aperture (Ø8mm). The second mirror is parabolic and images the object plane on the aperture of the head flange and the entrance pupil on the double vacuum window, all the way out through the baffles. The mirrors are made of a single hollowed and rigid piece of aluminium. Their holding system was challenging as it had to be rigid enough for operation, finely adjustable, partially electrically insulated (ceramic insulation on two of the three cylindrical attachments) in order to avoid eddy current loops and allow sufficient (mostly radiative) cooling. To fulfil all requirements several design and analysis iterations had to be made especially to accommodate disruptions occurring at high temperature [3].

3.3 TELESCOPE

The telescope was designed in order to distribute the light beam to the diagnostic and protection cameras. It contains four mirrors, which spread the light beam and focus it to an acceptable diameter for the cameras chips. A geometrical beam splitter positioned at an intermediate image plane, separates the beam in two branches. In each arm, a dichroic filter separates each half-beam into two channels, above and below 510nm (UV to blue and blue to IR). Two ports have also been foreseen to give the possibility to measure the endoscope global transmission in order to calibrate cameras measurements. The mirrors are fixed using a three point mounting system, usually applied by Kayser-Threde in space telescopes, made of hollowed pins, rigid enough to hold tightly the mirrors during vibration phases but flexible enough to ensure a fine adjustment during calibration. The large use of aluminium alloy was justified by the cantilever position of the telescope while stainless steel, even if more rigid, may have increased deformation due to higher inertia when vibrations occur. Even if it was not anodised, all structural parts were covered with black tissue to reduce specular reflection. The optical components outside the vacuum vessel are inserted in housing as presented in figure 4

3.4 THE SHUTTER

The pneumatic shutter is used to close the mechanical aperture in order to reduce the on-mirror particle deposition and associated induced reflectivity degradation or more generally to increase their lifespan. The shutter driver part is installed in the endoscope head and uses a pneumatic actuator (or piston) to move the shutter plate. It also includes a pull-back spring to ensure that, in case of failure, operation and measurement can be continued. The outer reservoir has been designed to ensure fine control of shutter plate position and adjustment of the gas pressure but above, to reduce plasma perturbation in case of a system leak into the vacuum vessel. The main criterion in its development has been reliability and failure scenario prevention which was achieved by a systematic study.

3.5 THE CAMERAS

CCD cameras have great advantages for spectroscopy as they allow real time measurements, give a global outlook with space resolution and also allow tomographic reconstruction. However, previous installed CCD cameras in JET suffered from short life span (several month of operation) until cooling of the CCD chips below 0°Cwas applied. This method allowed keeping the semiconductor properties of the photocells despite some damage through the neutron and gamma-ray fluxes. Bringing sub-zero cooling to the chip was achieved by mounting the sensor board directly on a Peltier cooler which on its hot side was fixed on a water cooled copper block.

On the structural side, the cameras had to be finely adjustable to accommodate small discrepancies of the light beam position.

Two types of cameras were installed; one with an image intensifier and the other without it. However, both of them were coupled to a taper to have the same image dimensions.

3.6 THERMO-MECHANICAL ANALYSIS

Given the very strict operating environment, some finite element method (FEM) analysis was required in order to verify design compatibility and forecast any possible future problems [3]. This led to iterations between design and FEM calculation as the endoscope had to be compatible with the most challenging scenarios of JET operation. It had for example to withstand disruption induced accelerations (7g @ 14Hz in vertical direction) while the front head cover received between 1,6 and 9,6 W/cm^2 handled through passive cooling. Most of the points and scenarios checked by FEM were also verified during validation tests. The temperature distribution of the ANSYS calculation for the highest temperature of 320°C is shown in false colours in fig. 5.

4. MANUFACTURING AND ASSEMBLY

The most critical components were the optical ones and more specifically, the mirrors. They had to fulfil high geometry tolerances accomplished by point-diamond manufacturing, in order to minimise image distortion and aberration and to ensure maximum reflectivity. These quality requirement were even more difficult to achieved as most of the optical surface were non planar. Only then the global endoscope transmittance satisfied the system specifications. This is the reason for a double quality control, performed by the manufacturer but also independently verified by the Kayser-Threde team (both with a Kugler Microtopography System).

All mirrors have been made of aluminium material (Al6061 as substrate), while the telescope mirrors outside the vacuum have been coated with silver to improve reflectivity in the targeted range. The surface form error and surface micro roughness for various mirrors are listed in table 1. The reflectivity was measured with an Ophir Laser Power meter (Model: Vega) and laser diodes of various wavelengths.

Different batches for Ag coating are the reason for the reflectivity deviation between mirrors as shown in figure 6.

5. TEST, INSTALLATION AND VALIDATION

Several tests have been run to check that the endoscope fulfilled its requirements. All were positive except transmission in the 400nm range, which was slightly lower than specified. However, replacing the telescope mirrors to address the issue was considered as too expensive relative to the expected gain.

5.1 VIBRATION TEST

Several vibration tests have been performed to verify the mechanical stability of endoscope and its line of sight, but also to determine the resonance frequencies of the assembly. A picture of the endoscope mounted on the vibration test stand is shown in figure 7. The results of the tests show resonance frequencies in all directions higher than 14Hz as was originally specified. This is the highest frequency of the torus during disruption phases.

5.2 THERMAL TEST

A thermal test was also performed in order to verify the performance and line of sight stability and the operational ability at high temperature. It was achieved by setting the endoscope in a vacuum test chamber with thermocouple and thermal element to heat and verify the achieved temperature. The vacuum was monitored to measure possible unexpected out-gassing of components.

In the investigated temperature range (Fig. 8) the results show a very low line of sight displacement (below 1°) which has been compensated.

CONCLUSION

The conception, design, manufacturing and installation of this endoscope required a wide range of competences from the definition of the scientific goals to the technical realisation. It could be achieved only by cooperation between institutes and companies and by merging their knowledge and knowhow. The endoscope was installed two months before the end of the ILW shutdown and since then it has served reliably as an important new diagnostic for JET experiments.

ACKNOWLEDGEMENTS

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Mirror	Surface Form Error (RMS)	Surface Micro Roughness (Rq)
M1	17 nm	1.7 nm
M2	31 nm	N/A
TM1	40 nm	3.1 nm
TM2	16 nm	4.3 nm

Table 1: Mirrors surface form error and micro roughness

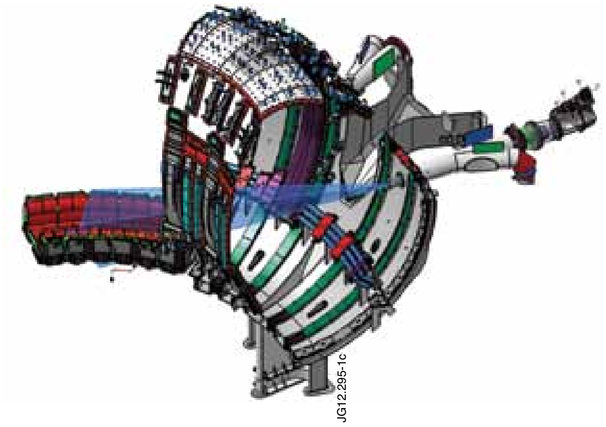

Figure 1: Endoscope in JET environment.

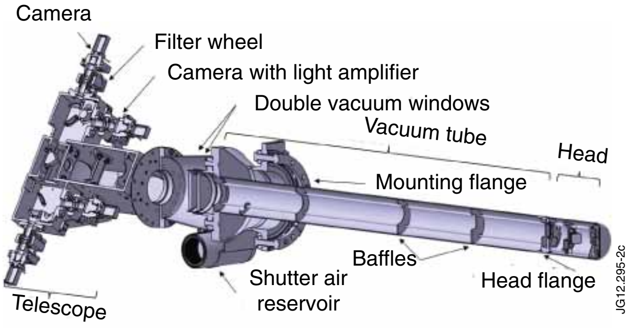

Figure 2: Endoscope general section views

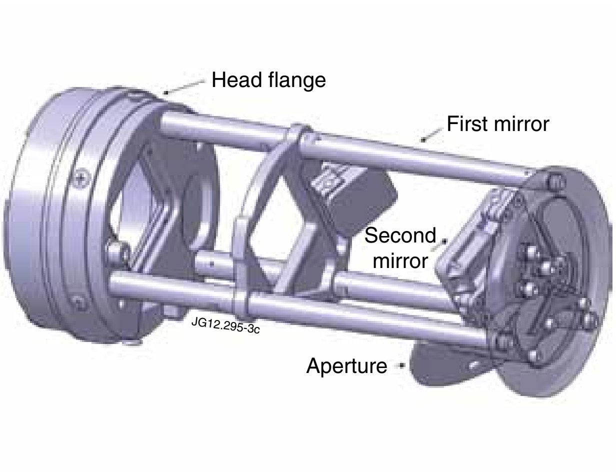

Figure 3: Endoscope head.

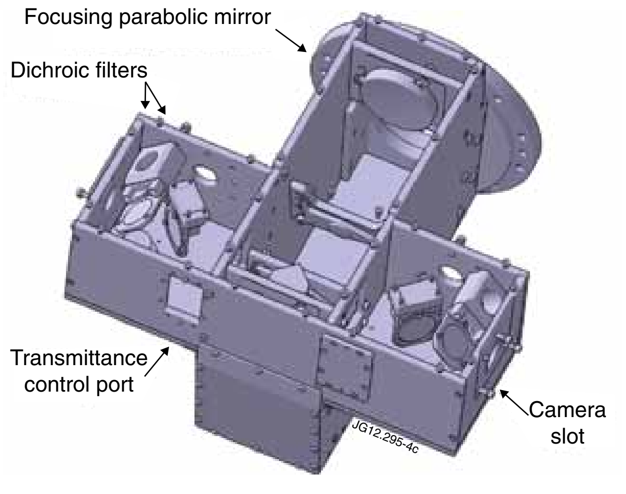

Figure 4: Ex-vessel endoscope housing with optical components.

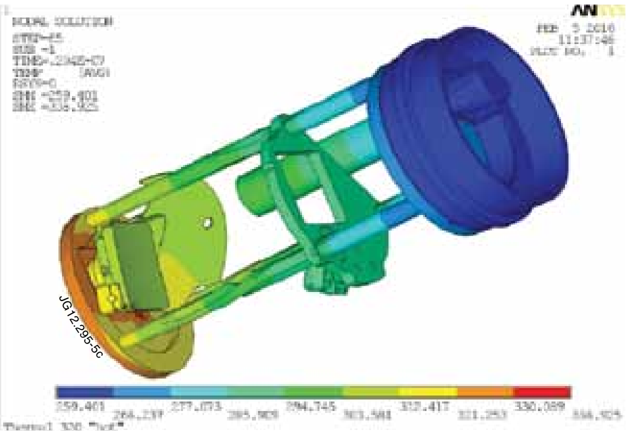

Figure 5: *Temperature distribution of endoscope head in load case* T_{max}*=320°C "hot" phase.*

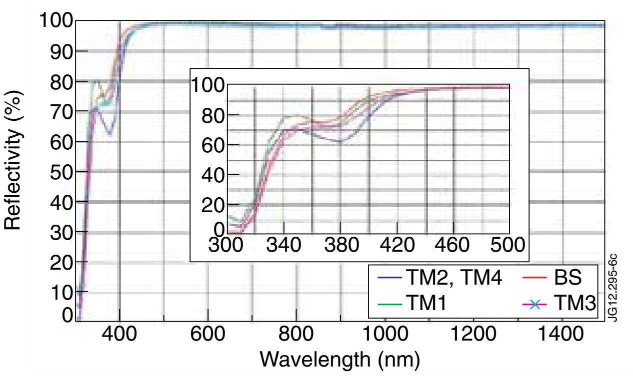

Figure 6: Reflectivity of the Ag prot. coating of the 5 external mirrors and geometrical beam splitter.

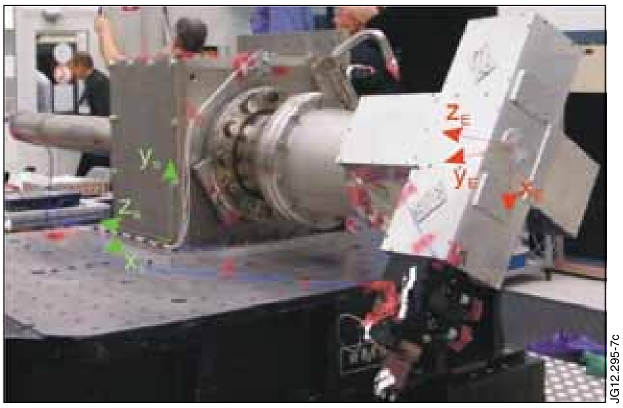

Figure 7: Vibration test setup.

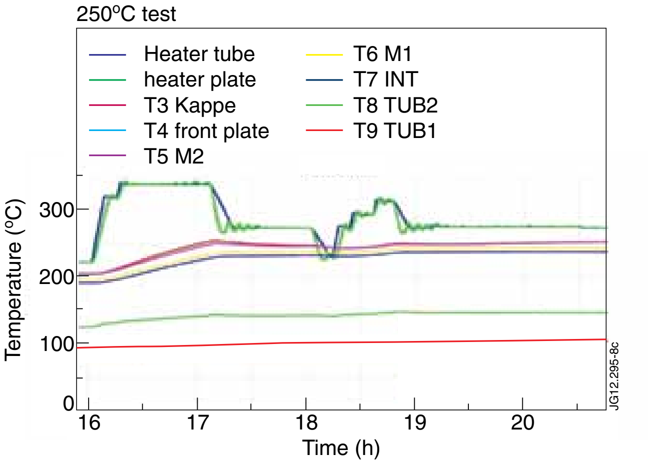

Figure 8: Endoscope thermal test response.