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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

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ABSTRACT

Considering multi-physics requirements and loads in the early design phase as well as during the later experimental verification is especially important for the design of fusion devices due to the extreme environmental conditions and loads. Typical disciplines in design of fusion devices are thermodynamics, structural-mechanics, electro-magnetics, and optics. The interaction of these disciplines as well as an efficient approach to implement this interaction in numerical and experimental simulations is presented as applied at the new JET KL11 divertor endoscope design and verification process. The endoscope´s first pictures already showed the very good performance of the instrument.

1. INTRODUCTION

The new JET KL11 endoscope´s aim is to monitor the emission of impurities of the ITER-Like Wall installed at JET in 2010. The major design goals of the reflective opto-mechanical design are the spatial resolution (2mm), the optical transmittance (>30%) and the survival of VDE accelerations and electromagnetic loads. The design of the endoscope opto-mechanical system has been optimised to fulfil these requirements under the plasma induced elevated temperature (up to 300°C) and vacuum. How these multi-physic requirements have been covered by FEM-analysis and experimental testing is presented within the next sections. This has been the KRP-Mechatec´s work package of the presented project. Further information on the KL11 design can be found in [1]; its performance is presented in [2] and [3].

2. DESIGN AND VERIFICATION PROCESS

The design and verification process of the KL11 endoscope includes various fields of physics which have been simulated and experimentally verified as shown in Fig.1.

3. DESIGN AND FE MODEL DESCRIPTION

The final design of the KL11 endoscope is described briefly by means of the resulting Finite Element (FE) model (see Fig.2). Here only the components subjected to high thermo-mechanical loads are presented, a more detailed design description is given in [1-3].

4. OPTO-THERMO-MECHANICAL BEHAVIOUR

The opto-thermo-mechanical behaviour describes the optical performance due to mechanical deformations under thermal load. It is the major design criteria to fulfil the endoscopes requirements also during JET operation.

4.1 ANALYSIS

The goal of the opto-thermo-mechanical analysis is to verify that the optical design fulfils the given optical requirements under the specified thermal loads.

In a first step the transient thermal boundary conditions have been derived and a thermal FE-model has been set up as follows:

- The in-vessel tube and the endoscope have been modelled with a coarse mesh of 3D-thermal solid elements SOLID70 as shown in Fig.3
- The connection between different parts have been modelled with constraint equations (CEINTF).
- Radiation: The radiosity method has been used inside the in-vessel tube. The emissivity of all surfaces is set to $\varepsilon = 0.4$ (used, contaminated materials). The emissivity of the mirror surfaces has been set to $\varepsilon = 0.07$.
- The heat flux at the endoscope head is taken from [4]
- The endoscope to vacuum vessel flange temperature is set to 50°
- For the surrounding port of the endoscope tube the following maxima temperatures have been assumed: 200°C, 250°C and 320°C

A transient thermal analysis has been performed with the following load phases:

In Fig. 4 the various heat fluxes and environmental temperature gradients applicable for the JET installation are shown.

The outcome of the thermal analysis is the transient temperature distribution of the optical head as shown in Fig.5.

The worst case temperature distributions have been mapped to the fine structural model also including the material nonlinearities. The main result of this static mechanical analysis are the deformation of the optical components as can be seen in Fig.6.

Finally the calculated mirror deformations, translation and rotation have been introduced to the optical analysis (ZEMAX) and a LOS and MTF analysis has been performed (work package of Kayser-Threde).

4.2 EXPERIMENT

The goal of the opto-thermo-mechanical experiment was to prove the as-built endoscope´s performance under the JET thermal environment. To achieve this the worst case temperature distribution forecast as derived from the analysis (sec. 4.1) should be applied. For this test a dedicated thermal vacuum chamber was built having the following major components:

- an optical feed-through at the entrance pupil
- a thermal actuator around the endoscope head with a maximum temperature of >600°C
- a movable, thermally controlled shroud to adjust the temperature gradient
- a vacuum chamber that housed the whole endoscope with p<1e-6mbar
- 9 thermocouples to measure the applied temperature

The CAD design (size and temperature of actuator and shrouds) of the TV-chamber is supported by FE thermal analysis of the test setup. The thermal actuator for the endoscope optical head is shown in Fig.7 (the actuators stainless steel body is not shown, heating wires are red, cooling pipes are blue). For the verification of the optical performance the endoscope was equipped with its camera system and a optical target was placed in the field of view as shown in Fig.8.

The temperature as presented in Fig. 9 was applied at the endoscope head. After a settling cycle an optical measurement (LOS and MTF) has been performed at the several temperature levels. It can be stated that the opto-thermo-mechanical design fulfils the requirements with respect to image quality and thermal stability (for details see [2,3]).

5. DYNAMIC BEHAVIOUR

The dynamic behaviour of the endoscope is investigated and designed such:
not to have modal coupling of the endoscope and the vacuum vessel (endoscope frequency > 20Hz)
not to have plastic deformation of the mirror mounts under VDE accelerations (7g in each axis)

5.1 ANALYSIS

The aim of the modal analysis is to identify the eigenfrequencies and mode shapes of the endoscope assembly. The aim of the quasi-static analysis (7g in each direction) is to identify the local stresses which shall be quite below the temperature dependent yield strength of the respective material and to proof the screwed connections. The first eigenfrequency is a beam 1st bending mode at 24 Hz as can be seen in Fig.10.

The 7g quasi-static analysis showed a minimum factor of safety of 5 proving the robustness of the system.

5.2 EXPERIMENT

The aim of the dynamic experiment is to verify the modal analysis results and to show that the as-built endoscope can sustain a vibration load of 7g in the frequency range from 10Hz to 16Hz without loss of alignment. The test setup is shown in Fig.11 and Fig.12. Optical tests (MTF and LOS) have been performed before and after the loading test.

6. ELECTROMAGNETIC BEHAVIOUR

The aim of the identification of the electromechanical behaviour is to prove the robustness of the opto-mechanical system to withstand VDEs without loss of alignment.

6.1 ANALYSIS

An electromagnetic analysis was performed to simulate endoscope loads during JET VDEs. A multi-step approach was developed as follows:

- transient analysis with the vertical and radial magnetic flux to get derive the eddy-currents
- the eddy currents (J) have been overlaid with the static magnetic field (B) to derive the magnetic forces according to $F_{mag} = J \times B$
- calculation of stresses and screw load and margin of safety (MoS) w.r.t. plastication (see Fig.13)

SUMMARY

In May 2011, the KL11 endoscope was successfully installed on the torus and delivered, from the very first JET pulse, images of the emission of the selected transition lines. The high optical quality was achieved by including multi-physic simulations and tests in the development program. The interaction of simulation, design and test is of great importance at such multi-physic loading scenarios.

ACKNOWLEDGMENTS

We would like to say “thank you” to our project partners being: JET, Forschungszentrum Jülich (FZJ), Kayser-Threde GmbH (KT) for the very good team work. Special thanks attribute to

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[4]. “DES-Project – Radiation Load Calculation“ 20/09/2009, A. Huber

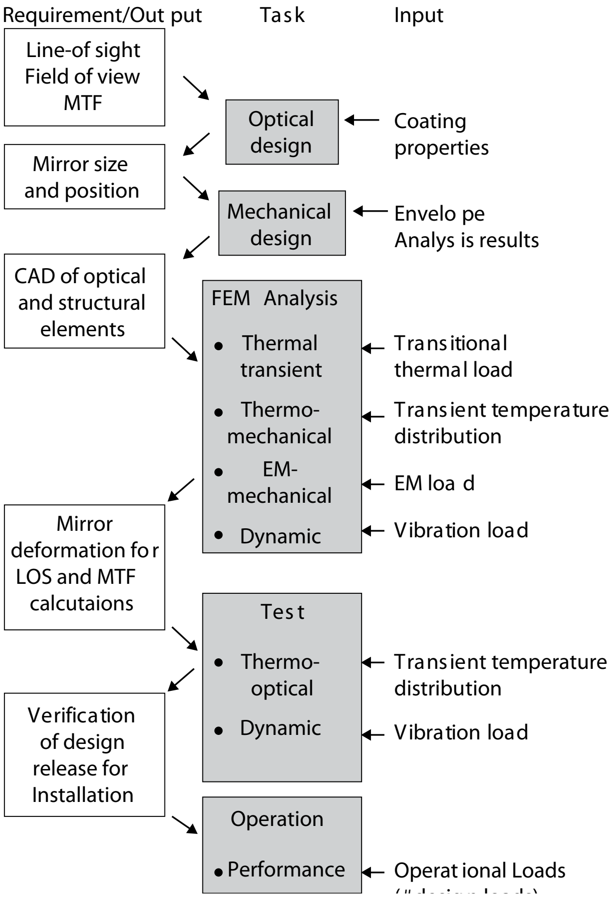

Figure 1: KL11 design and verification process

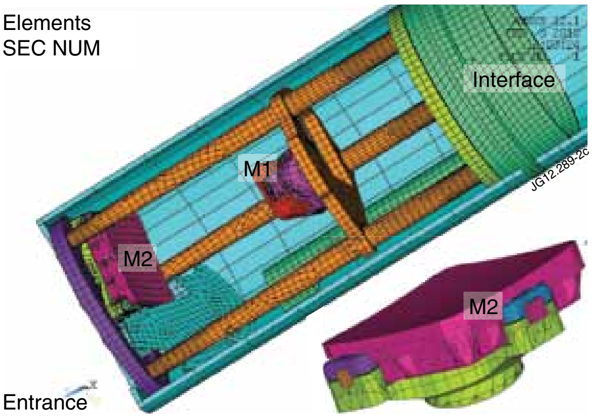

Figure 2: Optical head final design (M2 separated).

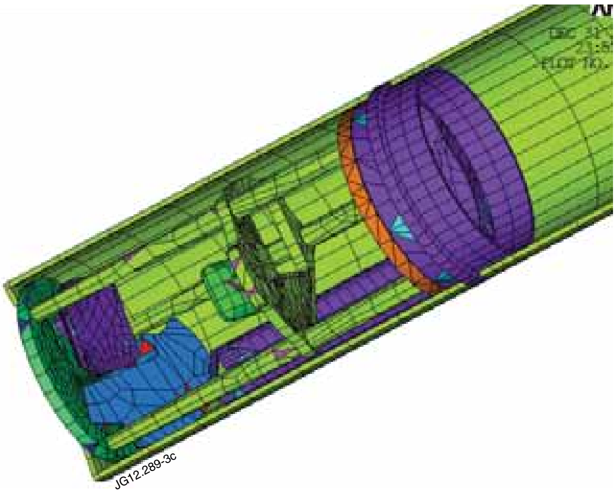

Figure 3: Mesh of endoscope head used for thermal analysis.

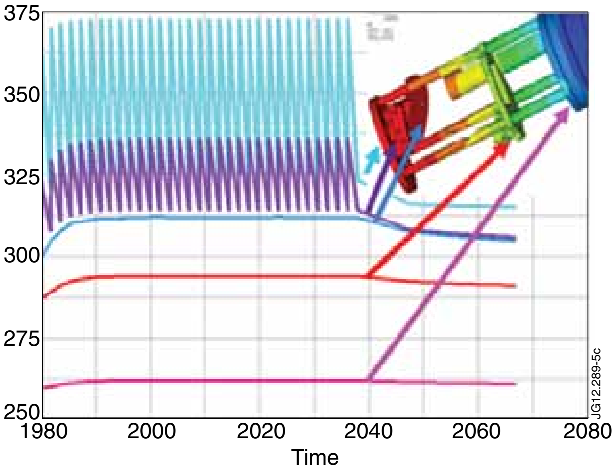

Figure 4: JET thermal environment.

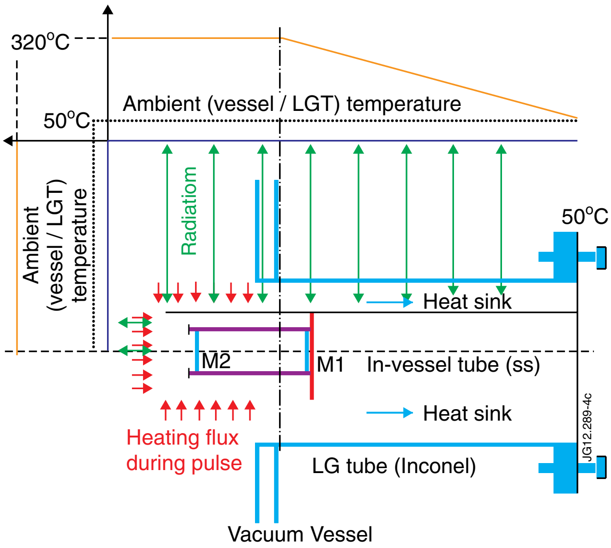

Figure 5: Transient temperature development during load phases.

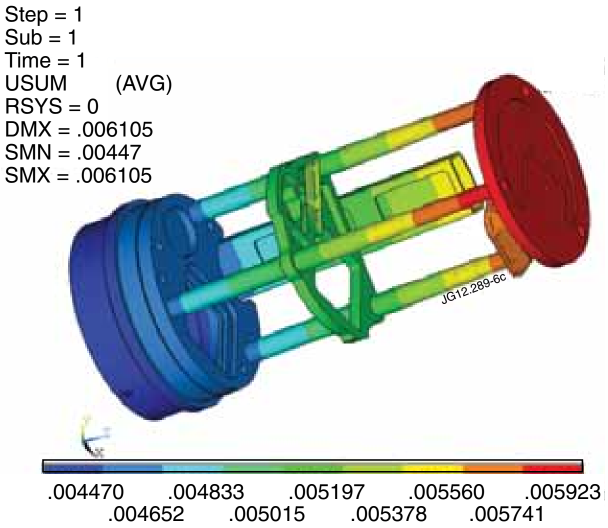

Figure 6: Thermal deformation of the optical components.

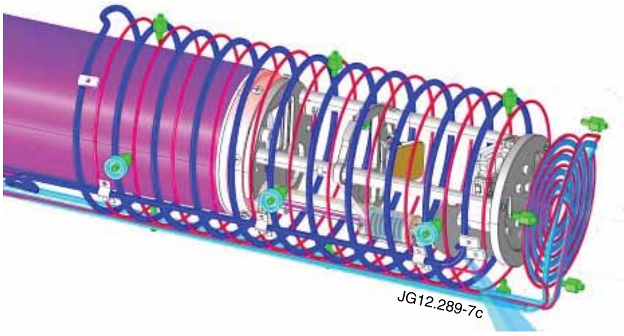

Figure 7: CAD the optical heat actuator for the TV test.

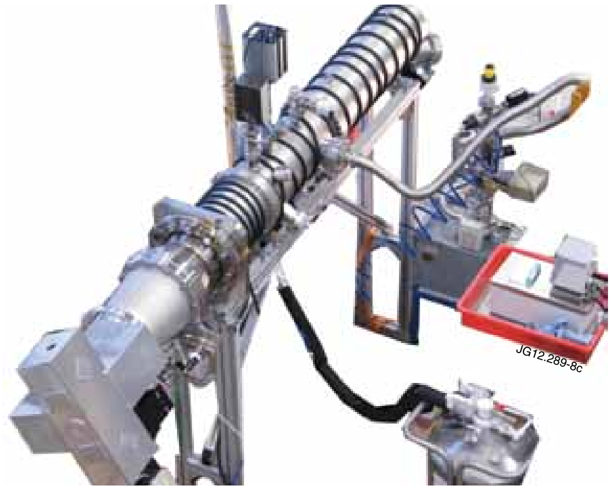

Figure 8: Test setup for thermo-optical test.

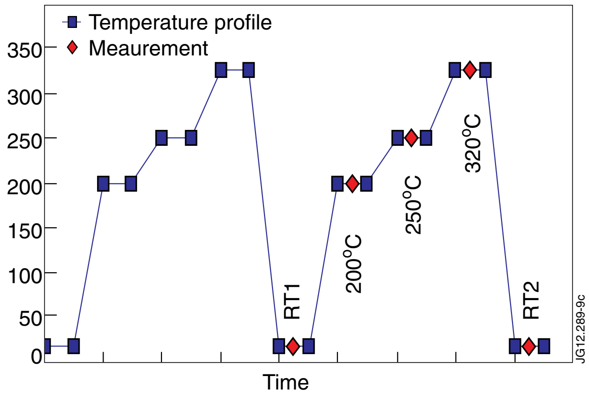

Figure 9: Temperature profile for opto-thermo-mechanical test.

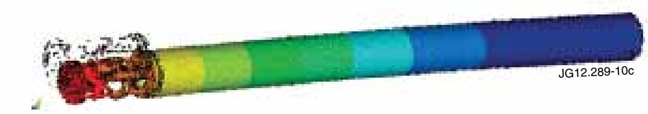

Figure 10: First mode shape of the endoscope at 24Hz.

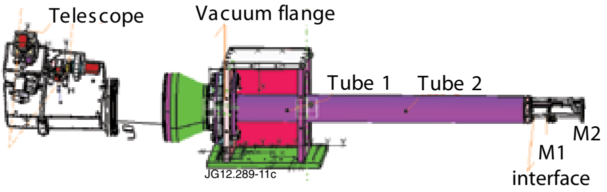

Figure 11: Designed Test setup for dynamic testing (optical target not show)

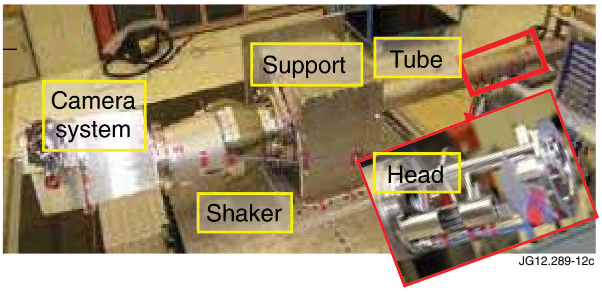

Figure 12: Installed test setup for dynamic testing (optical target not show, optical head separated).

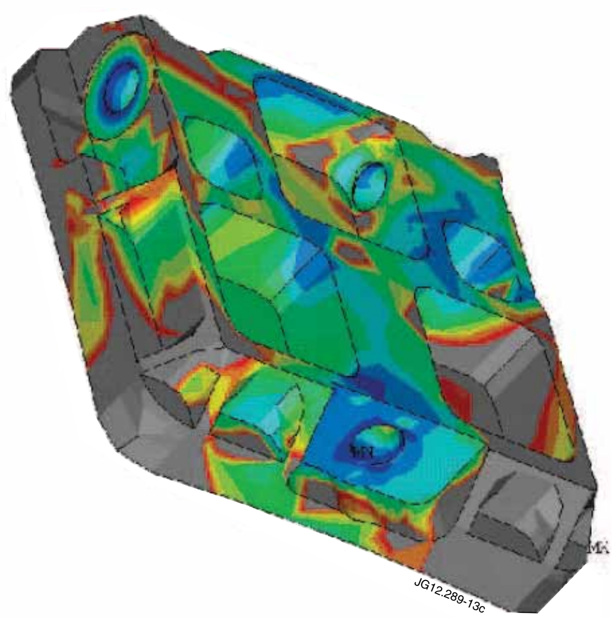

Figure 13: Margin of safety (MoS) of M2 due to EM-load (blue: low MoS, red/grey: high MoS).