NJOC-CP(16) 15442

Z Vizvary et al.

Engineering design and analysis of an ITER-like first mirror test assembly on JET

Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Unions Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Engineering design and analysis of an ITER-like first mirror test assembly on JET

Z. Vizvary[1*], B. Bourdel[2], A. G. Carrasco[5], N. Lam[1], F. Leipold[3], R. A, Pitts[4], R. Reichle[4], V. Riccardo[1], M. Rubel[5], G. De Temmerman[4], V. Thompson[1], A. Widdowson[1]

1 CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

2 Ecole Polytechnique, Route de Saclay, 91120, Palaiseau, France

3 Technical University of Denmark, Department of Physics, DK-2800 Kgs. Lyngby

4 ITER Organization, Route de Vinon-sur-Verdon - CS 90 046 - 13067 St Paul Lez Durance Cedex, France

5 Fusion Plasma Physics, Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden

The ITER first mirrors are the components of optical diagnostic systems closest to the plasma. Deposition may build up on the surfaces of the mirror affecting their ability to fulfil their function. However, physics modelling of this layer growth is fraught with uncertainty. A new experiment is underway on JET, under contract to ITER, with primary objective to test if, under realistic plasma and wall material conditions and with ITER-like first mirror aperture geometry, deposits do grow on first mirrors. This paper describes the engineering design and analysis of this mirror test assembly.

The assembly was installed in the 2014-15 shutdown and will be removed in the 2016-17 shutdown.

Keywords: ITER-like first mirror, JET, additive manufacturing, remote handling, disruption loads

---

author's email: zsolt.vizvary@ukaea.uk

1. Introduction

Optical diagnostic systems rely on first mirrors which are the components that guide/direct light to the detector of the diagnostic system. As such they are plasma-facing components (PFCs) and are subject to deposition and/or erosion. The resulting modifications to the mirror front surfaces can have a profound impact on the performance of the associated diagnostic. In a device like ITER, where maintenance and cleaning of these elements is extremely difficult, it is crucial to try and predict the level of erosion/deposition expected in advance of operation. Unfortunately, physics simulations of these processes are fraught with uncertainties and small adjustments in input parameters can lead to predictions ranging over orders of magnitude. In this case, the only option is "design by experiment".

First Mirror Testing (FMT) has been performed at JET for many years (see e.g. [1-3]), both with carbon walls (2004-2009) and in the ITER-Like Wall (ILW) beryllium-tungsten environment (2011 – present). In the latter case, mirrors mounted on the outboard main chamber wall were observed, encouragingly, to be very clean after exposure to a full ILW plasma campaign [3]. However, these mirror samples where not exposed under ITER relevant geometrical conditions in the sense that ITER mirrors will sit behind apertures engineered into the neutron shielding blocks of the diagnostic first wall. A new experiment was thus proposed in 2014 by the ITER Organization (IO) to expose an ITER-like mirror assembly in JET to study whether under exposure to relevant plasma fluxes (either ion fluxes during glow discharge cleaning or charge-exchange neutral fluxes during plasma operation) would lead to enhanced deposition as a result of erosion of material from the apertures. This work was subsequently performed under IO Contract and this paper describes the engineering design of this new, ITER-like FMT.

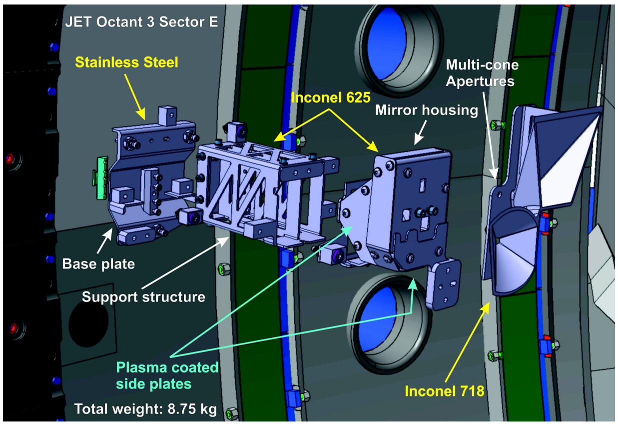

Fig.1. Exploded view of ITER first mirror design

The only available in-vessel support for this assembly is a welded mounting bracket no longer used by other deposition/erosion diagnostics. Tests on mock-ups and calculations define the maximum load for this bracket. The mirrors are very close to the plasma, resulting in conflicting electromagnetic and thermal requirements. The components need to be sufficiently massive to cope with the thermal loads (setting a minimum wall thickness), but at the same time resistive enough to keep the disruption loads within those allowed by the mounting bracket. In addition, installation must be performed fully by Remote Handling only. As a consequence, the design evolved into a four part structure: interface — support — housing — aperture cones (Fig. 1). Wall thicknesses were minimized, the housing surfaces are plasma sprayed with alumina to insulate them and the support shape was also designed minimizing the formation of current loops. The most challenging components to manufacture were the multi-cone apertures. This was not suitable for conventional machining, hence additive manufacturing was used.

2. Analysis

The analysis effort was focused on the structural integrity of the component and especially its fixation to the existing unused bracket in the JET vacuum vessel. It is driven by the mass of the whole structure and more importantly by the electromagnetic loads which peak during disruptions.

The eddy current loads on the initially proposed design created moments on the rail which were well over the allowable limits for the support bracket. Several design changes have been made to reduce these loads. Two ideas drove these changes:

- Break up current loops: the resulting torques depend on the area enclosed by the currents.
- Reduce wall thickness as much as possible thus increasing the resistivity of the material.

The latter is mainly limited by the temperature in the structure during plasma operation. The structure must have sufficient thermal capacity to ensure that the peak temperature stays below 1200°C (the lower end of the melting temperature range of Inconel 718), or even lower if the component has a structural importance.

Electromagnetic and thermal analyses have been carried out using ANSYS to check the mechanical loads and the peak temperatures. The weld and bolt strength were then checked by analytical calculations.

2.1 Transient thermal analysis

Transient thermal analysis has been performed in order to check the maximum temperature in the structure. The assumed heat load was 300 kW/m^2, according to JET design criteria for main chamber components. The boundary conditions are 200°C at the bolt locations at the support bracket on the vacuum vessel wall; radiation to the 200°C vacuum vessel with 0.5 emissivity is also applied. The heat load is applied for 20s. Although this setup is quite simple the temperature results should be a good indication of whether they are acceptable.

It was found that walls of the cones cannot be reduced to less than 3 mm, as the peak temperature with this wall thickness is already close to 1000°C. The melting temperature of Inconel 718 is in the range of 1260-1336°C, however mechanical properties already begin dropping over the range 650-700 °C. Since the aperture cones have no other structural role than to support their own weight, the peak computed temperature of ~1000 °C is deemed acceptable.

2.2 Electromagnetic analysis

The structure is affected by both the poloidal (θ) and normal (n) magnetic field change during disruptions, the toroidal (Φ) field variation is assumed to be zero. The assumed duration of disruption is 10ms. The magnetic field and field variation values at the mirror location are:

$$B_\phi = -3T \quad , \quad B_\theta = 1.2T \quad , \quad B_n = 0.4T \quad .$$

$$\dot{B}_\theta = \pm 120 T/s \quad , \quad \dot{B}_n = \pm 80 T/s \quad .$$

The eddy current analysis has been carried out using ANSYS [4]. To be able to obtain a reasonable mesh the cad model of the mirror assembly had to be simplified. Since preliminary analyses showed that there is a substantial contribution due to the current loops from both the poloidal and the normal field variation, it was decided that the side plates of the mirror box will be plasma sprayed and bolts will have top hats to cut eddy current loops and reduce the torques acting on the mirror box. The absence of toroidal field variation means that the FE model does not even contain these plates. A separate analysis on the omitted plates showed that the electromagnetic torques are indeed negligible ($M_\phi = 2.3 \cdot 10^{-3} Nm$, $M_\theta = 7.8 \cdot 10^{-3} Nm$, $M_n = 3.01 \cdot 10^{-2} Nm$). Although the FE model is a much simplified version of the real structure, it is still representative from the electromagnetic point of view. Even with the simplifications the geometry is complicated; it is therefore assumed that the structure is fully penetrated by the magnetic field. This will result in an overestimation and hence conservative estimate of the loads (Table 1).

During the FE analysis the aperture cones and the base plate were assumed to be stainless steel, following the original material choice at the beginning of the project. Subsequently, the decision was taken to manufacture them in Inconel 718 which has slightly higher resistivity. As a result, the induced eddy currents induced will be slightly lower than estimated here.

Table 1. Mechanical Loads in toroidal, poloidal and normal directions.

Moments	$\dot{B}_\theta$	$\dot{B}_n$	Gravity	Sum
M_ϕ [Nm]	2.4	22.8	12	37.2
M_θ [Nm]	6.6	57.9	0	64.5
M_n [Nm]	39.5	2.8	0	42.3

The support bracket has been welded along two edges to the vessel wall. The welds have been tested by an eccentric force, which is used as a reference in our analytical calculations. The reserve factor for the weld was 1.4 due to electromagnetic load for the final design. The calculated stress from the test was also higher than that of the combined gravity and electromagnetic load. This gives additional confidence that the strength of the bracket welds is sufficient.

The support bracket has 4 bolt holes for M6 bolts. It was decided that all 4 will be used to withstand the electromagnetic loads.

3. Material qualification

The aperture cones are made from Inconel 718 using additive manufacturing technology: selective layer melting (SLM). SLM offers significant advantages for JET in-vessel components over conventional machining including (a) more complex geometry options, (b) rapid production of small batches and (c) little or no wastage of parent material.

Although Inconel 718 is a well known material in JET, due to the new manufacturing technology a qualification program was put in place.

The qualification process has included:

- Mechanical tests:
    - Static tensile at RT (Room Temperature) and at 450 °C
    - Fatigue tests at RT
- RGA (Residual Gas Analysis)
- Porosity and chemical analysis
- Microstructure using SEM (Scanning Electron Microscope)
- Mechanical proof test on a prototype of a different component (a limiter assembly)
- Creep testing (still in progress, the aperture cones will not operate in the creep regime)

Table 2. SLM Tensile Test Results (Batch no. C1653D).

Testlog	Sample ID	E [GPa]	0.2% PS [MPa]	UTS [MPa]	Elon. [%]	R/A [%]
113858	45° Part A	215	729	1052	34.6	29.2
113859	45° Part B	214	731	1054	35.4	32.9
113860	45° Part C	214	735	1055	34.6	39.0
113861	Vertical Part D	178	713	1006	35.7*	48.2
113862	Vertical Part E	176	715	1006	36.2	48.0
11386	Vertical	177	718	1009	36.0	49.2

3	Part F					
11386 4	Horizontal Part P	185	776	1096	32.6	46.7
11386 5	Horizontal Part Q	185	772	1093	33.2	48.5
11386 6	Horizontal Part R	185	763	1087	33.2	50.2
11386 7	Vertical Part G @450 °C	163	619	858	34.4[*]	42.8
Wrought Inconel 718		*200*	*1124*	*1365*	*21*	*30*

[*] Indicates if the specimen broke outside the middle 1/3 of the gauge length.

SLM parts are produced by laser melting a pattern into a fine layer of metal powder which is laid onto a table-mounted base-plate in very thin layers (about 30 µm thick) which are gradually built up into the finished component. An M270 SLM machine table (270 mm X 270 mm) was used to produce testing samples and all the parts for this work.

The first batch required more builds in order to develop the best method for reducing distortion on the finished parts, in particular for the main body. Each build included four 10mm cubes for chemical, porosity and microstructure tests, but the mechanical test pieces were generated in separate builds as shown (Figure 2) where the powder had been removed, prior to separating the parts from the base-plate.

The tensile test results for the samples are in Table 2. The table includes wrought Inconel 718 properties for comparison [5].

Whilst not strictly necessary in order to qualify the SLM process for JET, it was decided to perform some additional metallurgical examinations in support of the adoption of SLM as a suitable manufacturing process for JET in-vessel components.

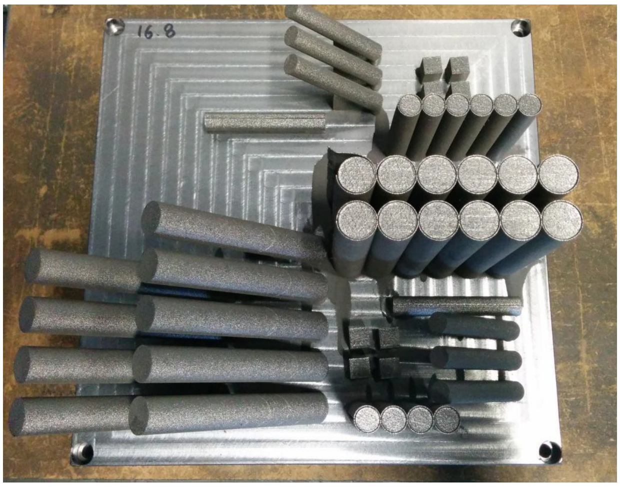

Figure 2. SLM Build C1653B

The results of these tests allow the following conclusions to be drawn:

- An early batch of SLM material produced poor ductility but the reasons for the problem were understood by the supplier and a second batch was successfully produced with good ductility.
- The use of SA (Solution Annealed) rather than PH (Precipitation Hardened) material is recommended as it offers mechanical properties (sufficient strength and ductility) that are suitable for this application. This does not, however, rule out the use of PH material in SLM for other applications.
- Tests have been successfully completed to show that the SLM material has low porosity and a sound micro-structure. Outgassing tests have also been successfully completed.
- A prototype (for a different, structurally loaded, component) has successfully passed mechanical tests that exceed the expected maximum operational loads by a factor of 1.25: this prototype was manufactured using SLM in the SA condition.
- A cost comparison has shown that SLM is competitive compared with conventional machining.
- This work has confirmed that SLM offers key advantages for JET in-vessel components:
    - Flexibility to make parts with complex geometry.
    - Rapid production of small batches.

4. Mirror sample pre-characterization

All mirrors were pre-characterized before installation in the ITER-like holder. The mirrors were made of polycrystalline molybdenum. Total and diffuse reflectivities were measured in the visible and near infrared range (400 - 1600 nm). The measurements were performed using a tungsten halogen lamp, a CCD spectrometer for the visible range, an InGaAs photodiode spectrometer for the near infrared range and an integrating sphere of 80 mm of diameter. Figure 3 shows the reflectivity traces for one of the mirrors. Total reflectivity is about 55 % in the visible range and it increases over 80 % in the near infrared range, whereas diffuse reflectivity is maintained below 4 % across the studied spectral range. The other mirrors presented very similar results, with a difference of less than 2 % between traces.

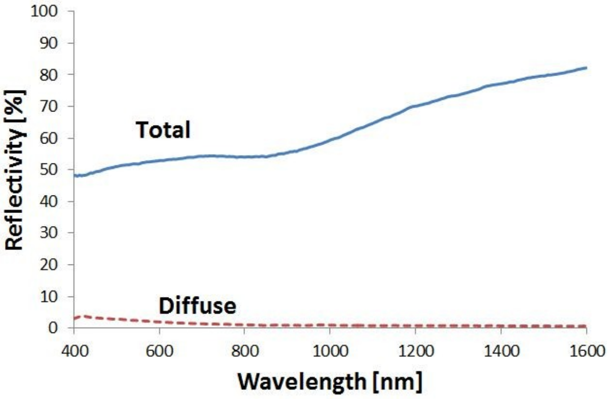

Figure 3. Reflectivity of one of the mirror samples.

5. Summary

A new ITER First Mirror test assembly has been designed, analysed and installed into the JET vacuum vessel. The structure was installed remotely on an existing unused bracket near the outboard midplane, which imposed strong limitations on the combined weight and electromagnetic loads induced during disruptions. The mirrors are very close to the plasma resulting in conflicting electromagnetic and thermal requirements. The components needed to be sufficiently massive to cope with the thermal loads (setting a minimum wall thickness), but at the same time resistive enough to keep the disruption loads within those allowed by the mounting brackets.

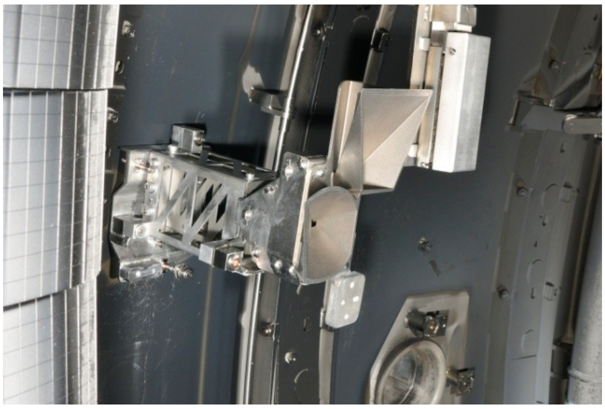

Figure 4. ITER First Mirror installed in JET

The final design included components that have been produced by additive manufacturing, whose material qualification program is also presented. This showed that the chosen manufacturing process (selective layer melting) can be adopted as a suitable candidate for manufacture of components for use in the JET vacuum vessel.

The assembly was installed in the 2014-15 shutdown (Fig. 4) and will be removed in the 2016-17 shutdown.

Acknowledgments

The design and manufacture of the mirror assembly was funded by the ITER Organisation and the installation was carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission or of the ITER Organisation. To obtain further information on the data and models underlying this paper please contact publicationsmanager@ccfe.ac.uk.

The authors also would like to acknowledge that the successful completion of this work relied on the dedicated input from many people including, in particular, Dan Kirk from CRDM (High Wycombe) and from CCFE: Rob Lobel, John Williams, Nick Pace, Kevin Cull and Paddy Doyle.

References

[1] M. Rubel, G. De Temmerman, P. Sundelin J.P. Coad, A. Widdowson, D. Hole, F. Le Guern, M. Stamp, J. Vince, JET-EFDA Contributors: An overview of a comprehensive First Mirror Test for ITER at JET, Journal of Nuclear Materials, Volumes 390–391, 15 June 2009, Pages 1066–1069

[2] M. J. Rubel, G. De Temmerman, J. P. Coad, J. Vince, J. R. Drake, F. Le Guern, A. Murari, R. A. Pitts, C. Walker and JET-EFDA Contributors: Mirror test for International Thermonuclear Experimental Reactor at the JET tokamak: An overview of the program, Rev. Sci. Instrum. 77, 063501 (2006)

[3] D Ivanova, M Rubel, A Widdowson, P Petersson, J Likonen, L Marot, E Alves, A Garcia-Carrasco, G Pintsuk and JET-EFDA Contributors: An overview of the comprehensive First Mirror Test in JET with ITER-like wall, 2014 Phys. Scr. 2014 014011

[4] V. Thompson, Y. Krivchenkov, V. Riccardo, Z. Vizvary: Analysis and design of the beryllium tiles for the JET ITER-like wall project, Fusion Engineering and Design, Volume 82, Issues 15–24, October 2007, Pages 1706–1712

[5] Special Metals Inconel 718 datasheet (Publication Number SMC-045) Table 19, http://www.specialmetals.com/documents/Inconel alloy 718.pdf