EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(05)47

M.J. Rubel, G. De Temmerman, J.P. Coad, J. Vince, F. Le Guern, A. Murari,
R.A. Pitts, C. Walker and JET EFDA contributors

Mirror Test for ITER at the JET Tokamak: An Overview of the Programme

Mirror Test for ITER at the JET Tokamak: An Overview of the Programme

M.J. Rubel[1], G. De Temmerman[2], J.P. Coad[3], J. Vince[3], F. Le Guern[4], A. Murari[5],
R.A. Pitts[6], C. Walker[7] and JET EFDA contributors*

[1]*Alfvén Laboratory, Royal Institute of Technology (KTH), Association EURATOM-VR, 100 44 Stockholm, Sweden*
[2]*Institute of Physics, University of Basel, CH-4056 Basel, Association EURATOM, Confédération Suisse, Switzerland*
[3]*EURATOM-UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom*
[4]*EFDA-JET, Close Support Unit, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom*
[5]*Consorzio RFX, Association EURATOM-ENEA, I-35127 Padua, Italy*
[6]*Centre de Recherches en Physique des Plasmas, Association EURATOM, Conférédation Suisse,*
EPFL, 1015 Lausanne, Switzerland
[7]*ITER International Team, Garching Joint Work Site, 85748 Garching, Germany*
** See annex of J. Pamela et al, “Overview of JET Results ”,*
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004)).

Preprint of Paper to be submitted for publication in
Review of Scientific Instruments

ABSTRACT

Metallic mirrors will be essential components of all optical spectroscopy and imaging systems for plasma diagnosis that will be used at the next-step magnetic fusion experiment, ITER. Any change of the mirror performance, in particular reflectivity, will influence the quality and reliability of detected signals. At the instigation of the ITER Design Team, a dedicated technical and experimental activity aiming at the assessment of mirror surface degradation as a result of exposure to the plasma, has been initiated on the JET tokamak. This paper provides a comprehensive overview of the mirror test programme, including design details of the mirror samples and their supports, their locations within JET and the issue of optical characterisation of the mirrors both before and after exposure. The post exposure characterisation is particularly challenging in JET as a consequence of an environment in which both tritium and beryllium are present.

1. INTRODUCTION

Mirrors and windows are essential components of optical spectroscopy and imaging systems for plasma diagnosis, both in industrial apparatus for plasma processing and in devices used for the study of controlled thermonuclear fusion (e.g. tokamaks). In tokamak experiments, for example, “first mirrors” are often placed inside the confinement chamber and used to relay optical signals to spectroscopic equipment located remotely from the tokamak itself. In today’s experiments, discharge durations and duty factors are usually too small to be of significance for first mirrors, but in the next step device, ITER (International Thermonuclear Experimental Reactor), there will be a radical upscale in material erosion and migration from the first wall and in the fluence of (mostly charge-exchange) neutral particles escaping the plasma [1,2]. Moreover, all optical diagnostic systems in ITER will employ metallic first mirrors - Figure 1 illustrates the approximate locations and sizes of these mirrors as they are currently foreseen in the ITER poloidal cross-section.

Erosion of mirrors by particle impact changes surface roughness and modifies the surface chemical composition. Eroded impurities, released elsewhere by plasma-surface interaction, will also re-deposit on mirror surfaces, leading to the formation of surface coatings with high potential to degrade the mirror reflectivity [3,4]. The issue of surface coating is particularly worrying given that in JET, the areas of thickest deposited layers found on surfaces by post-mortem analysis following experimental campaigns have been formed in remote areas of the inner divertor region [5-7] - precisely one of the locations in which first mirror installation is planned in ITER (see Figure 1).

The limited access to in-vessel components in ITER calls first mirror test to be performed in present-day devices. Even if the fluences and duty cycle of ITER cannot be matched, important information can be gathered now in smaller devices regarding the long term probability that material damage and mirror reflectivity are likely to be seriously affected. Dedicated experiments have been performed in several limiter tokamaks, where mirrors were exposed for short [8] or long term [9] periods of plasma operation. The issue is also being addressed in the programmes of the NSTX tokamak at PPPL [10] and other machines (e.g. DIII-D at General Atomics) but the results have not been published yet. A comprehensive First Mirror Test (FMT), requested by the ITER Design Team, has been initiated at the JET tokamak.

This contribution outlines some of the technical elements of this programme and describes how the mirror surface properties are characterised. On JET, in which both tritium and beryllium are present, special precautions are required to ensure that mirror samples, once retrieved after exposure, can be properly analysed under the restrictions imposed for safe handling of materials contaminated after exposure in the environment containing beryllium and tritium.

2. EXPERIMENTAL PROGRAMME AT JET

A number of features make JET the ideal facility on which to perform an FMT: (a) a divertor tokamak with an ITER relevant configuration, (b) long plasma pulses of 20 s or longer, (c) beryllium environment (d) a comprehensive overview programme of erosion and re-deposition in concurrent deposition monitoring activities which can be performed in parallel with mirror exposures. The FMT programme itself is included within the framework of a wider “Tritium Retention Study” (TRS) and aims at the study of morphology changes occurring on surfaces of selected mirror materials. Within the TRS programme, erosion and re-deposition processes are monitored using a set of dedicated tools which include quartz microbalances (QMB) [11,12] and additional deposition monitors. The mirror samples have been installed in the vicinity of these monitoring devices [13].

2.1. MIRRORS AND MIRROR CARRIERS

Since the erosion-deposition patterns vary strongly with poloidal location it is important for meaningful comparison between samples that they are placed in equivalent poloidal positions [6,14]. The restriction on the number of available locations mean that only a certain number of mirror samples could be mounted in JET. As a consequence, tests of only two different materials are possible in each location. On the advice of the ITER Design Team, polycrystalline molybdenum and stainless steel have been chosen as mirror materials. These materials are on the list of candidates for the ITER mirrors. Though the final decision regarding the choice has not been taken yet, the tests performed with steel and Mo have been considered to be important.

Figure 2 illustrates the two types of mirror design being used - flat front and chamfered at 45 degrees. They are first polished using an abrasive paper followed by a polishing cloth with fine-grain diamond paste. Thirty-two samples have been produced (16 made of stainless steel 316L and 16 from polycrystalline molybdenum delivered by Plansee AG) and mounted into specifically designed carrier units and installed in JET. Each mirror sample has a “feet” for unambiguous positioning within the carrier. The technical drawing in Fig.3(a) provides an example of one of the stainless steel cassettes with several channels to house the mirrors. The number of channels in a cassette, three or five, is dependent on the available space in the various locations in JET were the carriers are installed. Each cassette is of a “pan-pipe” shape and is composed of two detachable plates. The photograph in Fig.3(b)shows how slots are arranged in the cassette base to accept the "feet" machined into each mirror sample block. This construction allows both deposition inside the pan-pipes channels and on the mirror surfaces to be assessed. The exposure of mirror surfaces at various inclination angles and with different distances with respect to plasma is also possible with this FMT design. As Section 3 will describe, optical properties of all mirrors were characterised with spectrophotometry and ellipsometry prior to the installation in the torus.

2.2. LOCATIONS IN THE TORUS

The photograph in Fig.4(a) shows a wide-angle view of the interior of the JET vacuum vessel as it was at the beginning of experimental campaigns in late 2005 when the first mirrors described here were installed. This marks the beginning of experiments with the new MarkII-HD divertor configuration, seen in the lower part of the vessel and shown in a schematic cross-section in Figures 4b and 4c. The divertor is designed such that plasma shapes can be used with high triangularity and at high power - the low field side divertor strike points, where the exhausted power is highest will be located on the large, load bearing plate in the centre of the divertor (known as the LBSRP). The cassettes with mirrors are placed in five locations: three sets positioned in the divertor (inner, outer, base) and two at the midplane on the low magnetic field side of the main chamber wall. The temperature of mirrors during the long term exposure is expected to be 200-220^{o}C on the main chamber wall and around 100^{o}C in the divertor.

Figure 5 illustrates in a 3D CAD representation the disposition in the divertor of the cassettes and other TRS deposition monitors. Figure 6 shows photographically how the cassettes under the LBSRP are located. The arrangement of devices in the outer divertor is similar to that in the inner leg (see Fig.5(c)). The other monitors of erosion and deposition are: indexable (rotating) collectors for time-resolved studies of deposition and QMB devices which may be heated (to 350^{o}C, the heater is below the quartz crystal) or cooled (to 50^{o}C, QMB is attached to the water-cooled support structure of the divertor). Figure 5 also illustrates how QMB and rotatable deposition monitors are located in close proximity to the mirror samples [13], allowing the results obtained from the mirror analysis to be compared with time-resolved studies of deposition rates and the way in which they are affected by temperature (by comparison with the QMB data). The cassettes placed on the main chamber wall are protected by magnetic shutters which open only when the tokamak toroidal magnetic field is present. The shutters protect the samples from deposition of beryllium during the regular evaporations of Be onto the JET wall. The complete main chamber cassette assembly, including one of the TRS indexable deposition monitors is shown in Figure 7.

Installation of all deposition monitoring devices in the JET vacuum vessel is compatible with remote handling [16]. Moreover, their production using certified materials and manufacturing in certified mechanical workshops is in full conformance with the Quality Assurance procedure at JET: the use of certified materials, manufacturing in certified workshops and monitoring of all steps in production and assembly.

The construction phase, commissioning and installation of the diagnostic tools for FMT have been completed. The experiment itself will be carried out for several months during machine commissioning and experimental campaigns in 2005 and 2006. Following the exposure, the units will be retrieved from the torus and replaced with a new set for the next campaigns. The retrieved mirrors will be studied with a number of optical and surface analysis methods. The exposure at JET will result in the contamination of mirrors by beryllium and tritium. Therefore, a special spectrophotometric equipment has been assembled to enable optical studies of contaminated materials.

3. OPTICAL CHARACTERISATION OF MIRRORS

3.1 PRE-CHARACTERISATION OF MIRRORS

Prior to their installation in JET, detailed optical characterization of the mirrors has been performed at the University of Basel, Switzerland. Total, diffuse and specular reflectivity was measured by means of a UV-VIS-NIR spectrophotometer (Varian Cary 5) equipped with a 110 mm diameter integrating sphere under normal incidence in the spectral range 250-2500nm. Figure 8 shows an example of the total, diffuse and specular reflectivity measured before the experiment both for a stainless steel and a molybdenum mirror. In addition, the optical constants of the mirrors (n, k) were determined using a MAI (Multiple Angle of Incidence) spectroscopic ellipsometer (Sentech SE850) in the wavelength range 350-800nm for the incident angles 45, 55 and 65^{o}**.** The principle of ellipsometry [17] is based on the determination of the complex reflectance ratio, $\rho = r_p / r_s$ of the amplitude reflection coefficients r_p and r_s of light polarized parallel (p) and perpendicular (s) to the plane of incidence as a function of the angle of incidence and of the wavelength. The ρ value is complex and is usually represented as $\rho = \tan\Psi e^{i\Delta}$ with $\tan\Psi = \frac{|r_p|}{|r_s|}$ and $\Delta = \Delta_p - \Delta_s$, and where the argument Δ_x (x=p, s) represents the phase shift of the electromagnetic wave reflected from the sample. Calculation of refractive (n) and absorption (k) indices is made using the following equations assuming a semi-infinite substrate:

$$n = \sin\Phi_0 \tan\Phi_0 \cos 2\Psi \tag{1}$$

$$k = \sin\Phi_0 \tan\Phi_0 \sin 2\Psi \tag{2}$$

where Φ_0 is the incident angle.

From these measurements and using Bennett's formula [18], it is possible to make an estimation of the surface RMS (root-mean-square) roughness. Mean values of 3 and 4 nm have been obtained for stainless steel and molybdenum respectively.

As a consequence of the requirement for a large number of samples at small physical dimension, it has proven difficult to obtain a set of mirrors with identical reflectivity. Nevertheless, as shown in Figure 9, there is relatively little scatter in R from sample to sample –the maximum deviation of any given from the average reflectivity is < 5%.

3.2 EQUIPMENT FOR STUDIES OF CONTAMINATED MATERIALS

The mirrors will be contaminated by beryllium and tritium during their exposure in the JET vacuum vessel. Post exposure reflectivity measurements thus require spectrophotometer equipment compatible with highly contaminated material. To overcome the non-negligible complications introduced by such requirement, special spectrometric equipment has been constructed at JET. Such equipment must satisfy the following requirements: (i) the use of an integrating sphere which allows the measurement of both total and diffuse reflectivity (the specular reflectivity being calculated as the difference between these two values); (ii) wavelength range 350-1700nm to cover the visible and near-infrared; (iii) physical separation of the integrating sphere and spectrometer to minimize the size of the glove box which must be constructed to enclose the contaminated mirrors. A schematic drawing of the system is shown in figure 11a. The following items have been chosen as the best compromise between safety and budgetary restrictions and the requirements for measurement range and accuracy:

- optical spectrometer with a 2048 pixel CCD (charge coupled device) detector and a 200μm entrance slit (350-1100nm) ;
- optical spectrometer with a peltier cooled 256-element InGaAs diode array detector (900-1700nm);
- 50mm diameter integrating sphere coated with PTFE (*PolyTetra*-Fluoro Ethylene, i.e. Teflon®). A gloss trap coated with a black absorbing material is used to exclude specular reflection and measure only the diffuse reflectivity;
- 400μm core diameter optical fibres.

The equipment has been calibrated using samples whose reflectivity was measured both by the spectrophotometer and by ellipsometry in Basel. Results, presented, in Fig.10 are found to be in good agreement over the whole wavelength range. Some of the optical windows presently used on JET for spectroscopic diagnostics are actually located at position relevant for future first mirrors in ITER. It is therefore expected that useful information might be gathered by measuring the transmission of such windows, which have been exposed to plasma for very long periods. A sample holder for transmission measurements has also therefore been included inside the glove box. A picture of the final setup is shown in Fig.11. Only the measurement units (i.e. the integrating sphere and transmission sample holder) are installed in the glove box. The connection to the spectrometers and the light source is made by means of optical fibres.

CONCLUSION

An important contribution of this work to the field of plasma diagnostics is in the development of a comprehensive experimental approach that enables testing of first mirrors for spectroscopy systems in next-step tokamaks. The experiment at JET has been optimised to produce a maximum outcome by selecting representative mirror locations, providing a careful and compact design of carriers and embedding the FMT in the broad programme of erosion and deposition studies. This experiment will provide a large number of samples exposed under fusion relevant conditions at various strategic locations (main chamber wall and divertor) of direct relevance to ITER first mirror emplacement. A cost effective and compact solution has also been found for the post-exposure, optical characterisation of tritium and beryllium contaminated first mirror samples and vacuum windows. The results of these long-term experiments should enable improved planning of the next steps to be taken in the test programme of optical components for tokamak plasma diagnosis.

REFERENCES

[1]. G. Federici et al., Nucl. Fusion **41** (2001) 1967.
[2]. R. Pitts et al., Plasma Phys. Control. Fusion, **47** (2005) B303.
[3]. V. Voitsenya et al., Rev. Sci. Instr. **70** (1999) 790.
[4]. A. Berdamid et al., Phys. Scr. T103 (2003) **109**.
[5]. J.P. Coad et al., J. Nucl. Mater. **290-293** (2001) 224.
[6]. M. Rubel et al., J. Nucl. Mater. **313-316** (2003) 323.
[7]. J.P. Coad et al., J. Nucl. Mater. **313-316** (2003) 419.
[8]. P. Wienhold et al., J. Nucl. Mater. **337-339** (2005) 1116.
[9]. M. Lipa et al., Fusion Eng. Des. in press.
[10]. C. Skinner et al., J. Nucl. Mater. **337-339** (2005) 129.
[11]. H.G. Esser et al., Fusion Eng. Des. **66-68** (2003) 855.
[12]. H.G. Esser et al., Phys. Scr. T111 (2004) 129.
[13]. P. Coad et al., *"Diagnostics for Studying Erosion and Deposition Processes in JET",* Fusion Eng. Des., in press.
[14]. P. Coad, M. Rubel and C.H. Wu, J. Nucl. Mater. **241-243** (1997) 408.
[15]. J. Ongena, *"JET's contribution to fusion science and ITER"*, Phys. Scr., in press.
[16]. A. Rolfe, Fusion Eng. Des. **36** (1997) 91.
[17]. Handbook of optical constants of solids, E.D. Palik, Acad. Press, 1985.
[18]. H.E. Bennett. J. Opt. Soc. America **53** (1963) 1389.

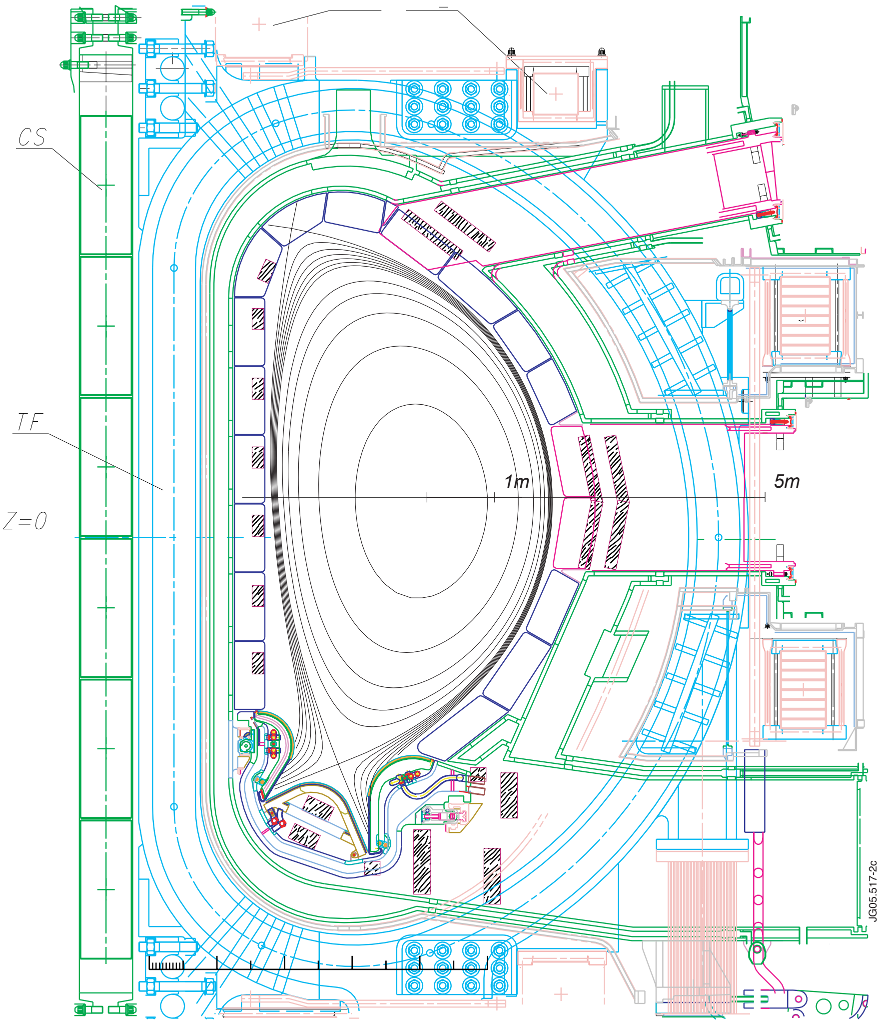

Figure 1: Cross section of ITER with marked locations of first mirrors. Mirrors appear in the drawing as textured rectangles.

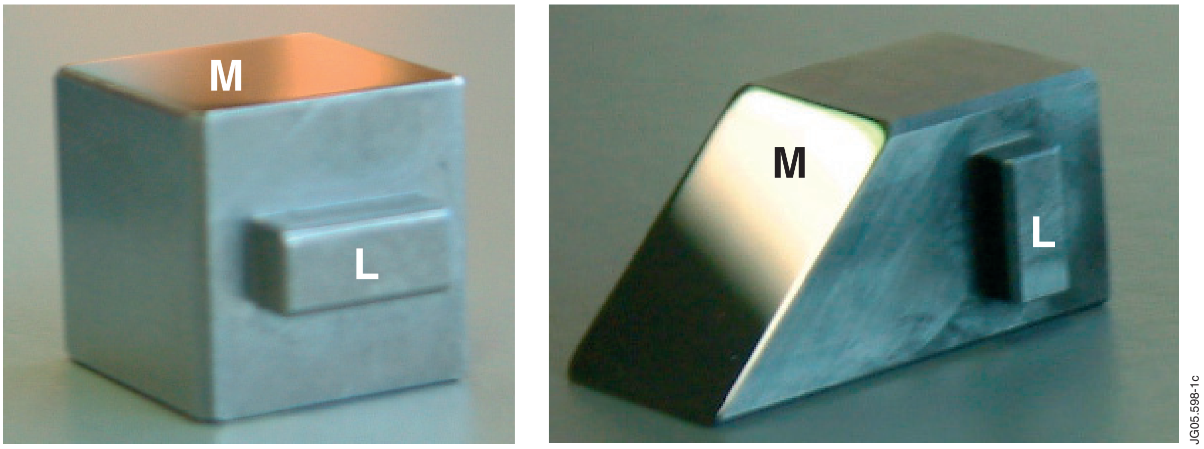

Figure 2: Flat-front and angled mirrors for FMT. The mirror surface is marked with (M) and the leg for mounting the samples in the cassette is marked with (L).

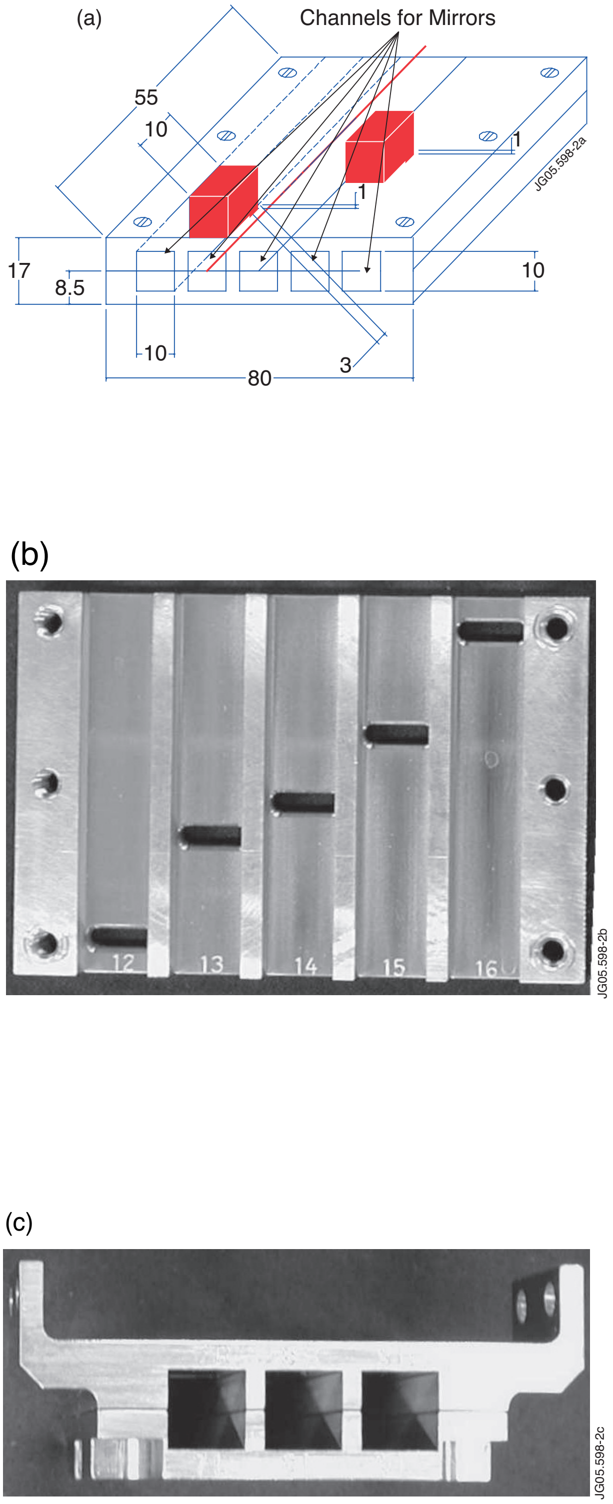

Figure 3: A schematic view of a cassette for the mirrors tested in JET (a), a base of a five-channel cassette with slots for mirror blocks (b), a three-channel cassette for the inner divertor (c).

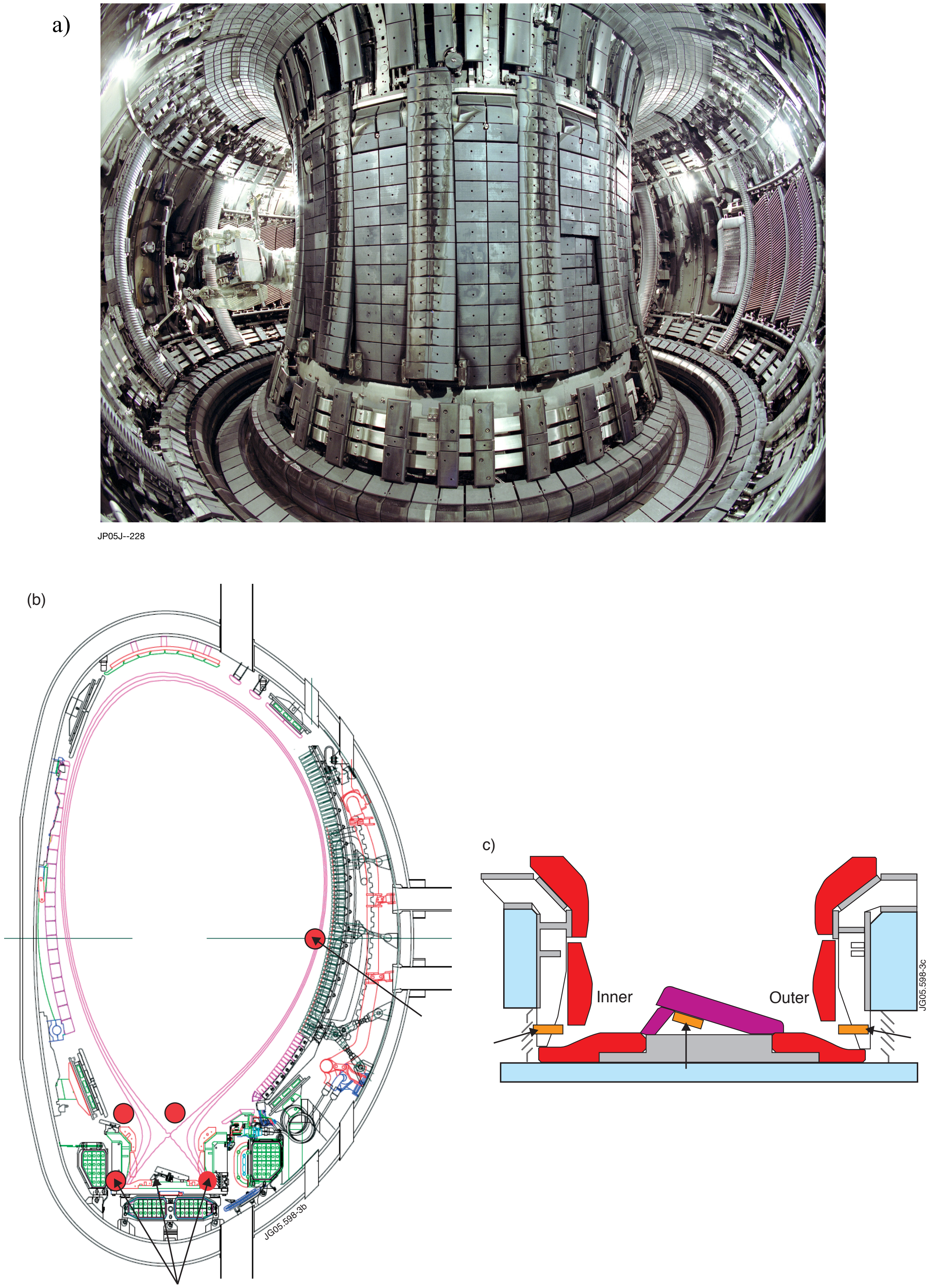

Figure 4: Toroidal view into the JET vacuum vessel with the MarkII-HD divertor (a); poloidal cross section of the torus (b); poloidal cross-section of the divertor (c). The location of cassettes with mirrors are marked with arrows in figures (b) and (c).

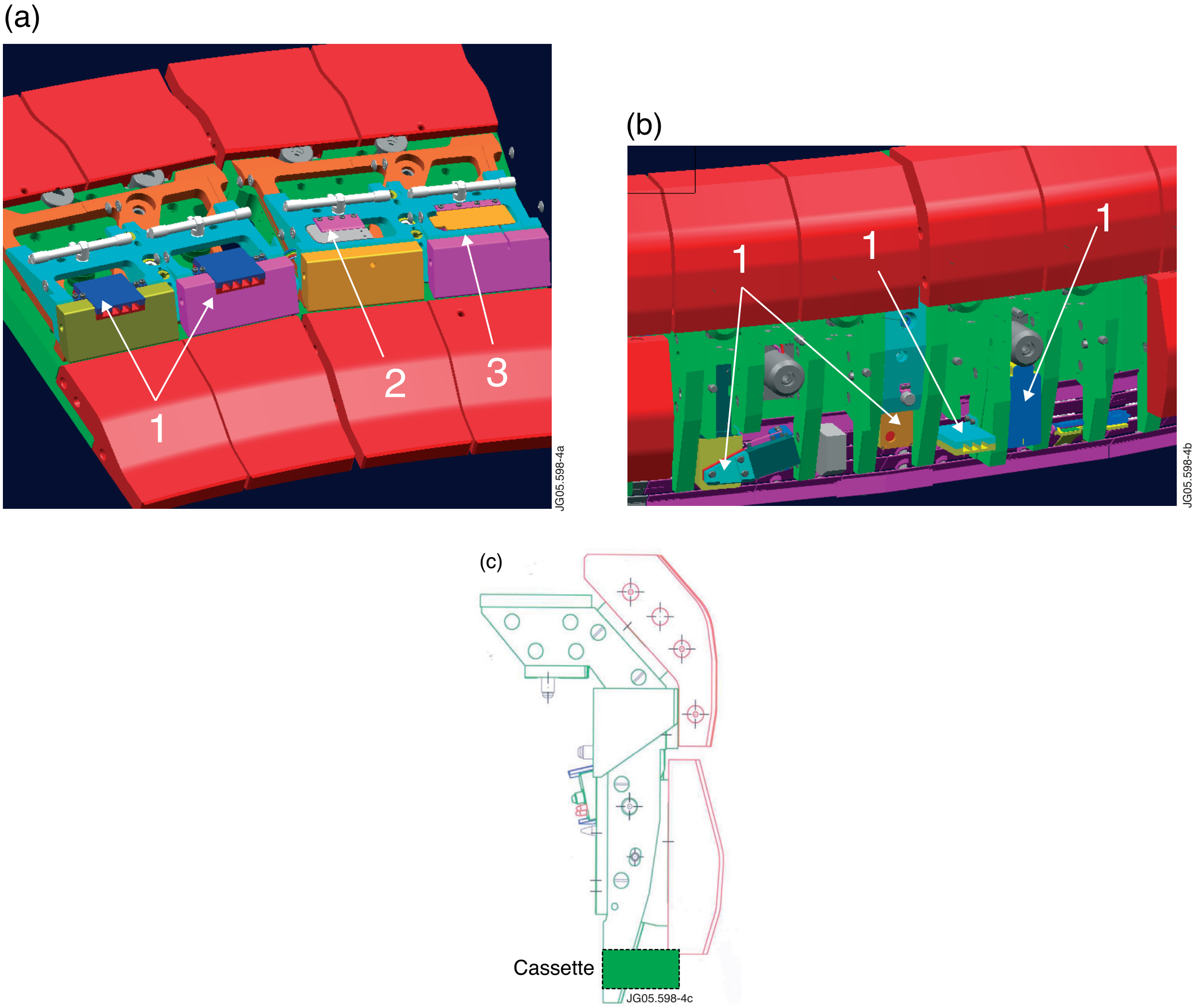

Figure 5: Location of cassettes with mirrors (1), quartz microbalance devices (2) and rotable deposition monitors (3) in the base divertor module (a) and in the inner divertor (b) and (c). For clarity of presentation the Load Bearing Plate was removed from the pictures.

Figure 6: Cassettes with mirrors in the divertor base modules.

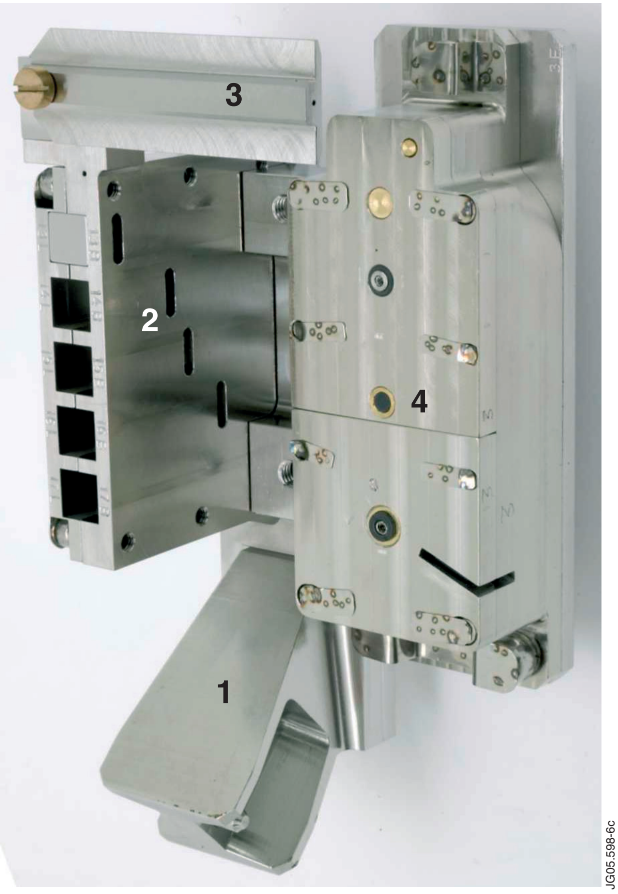

Figure 7: Bracket assembly for installation on the main chamber wall: holder (1); cassette with mirrors (2); magnetic shutter (3); rotatable deposition monitor (4).

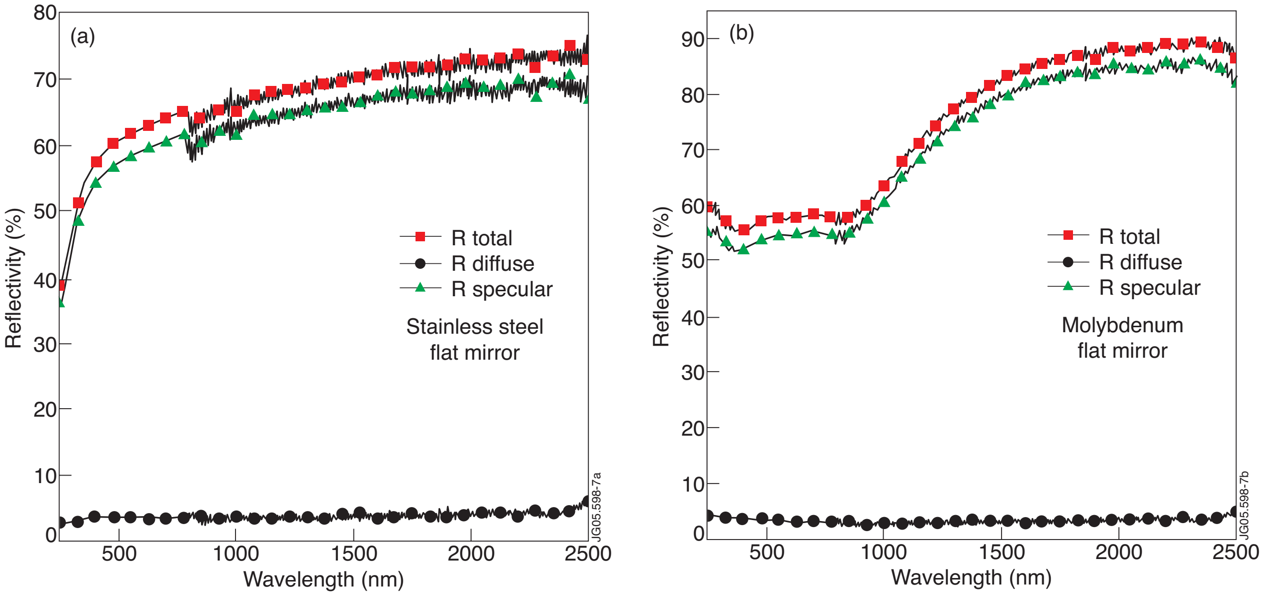

Figure 8: Total, diffuse and specular reflectivity of (a) a stainless steel and (b) a molybdenum mirror measured before exposure with a spectrophotometer.

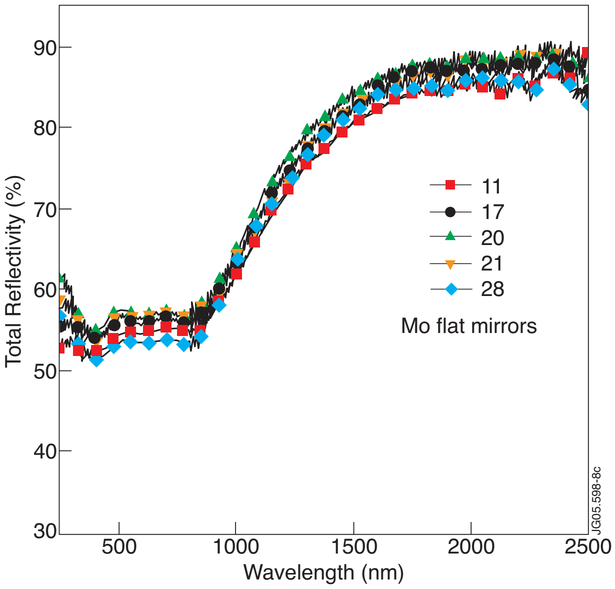

Figure 9: Total reflectivity of various molybdenum mirrors before their installation in JET.

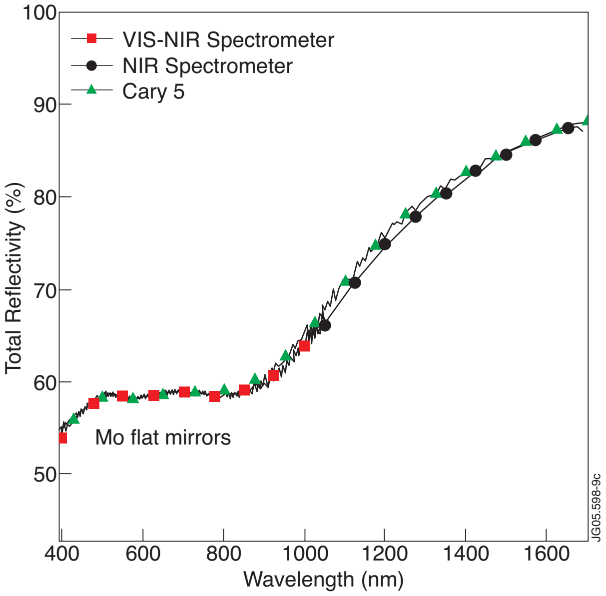

Figure 10: Comparison between a total reflectivity measurement made with the setup installed at JET and with the spectrophotometer used for mirror pre-characterisation.

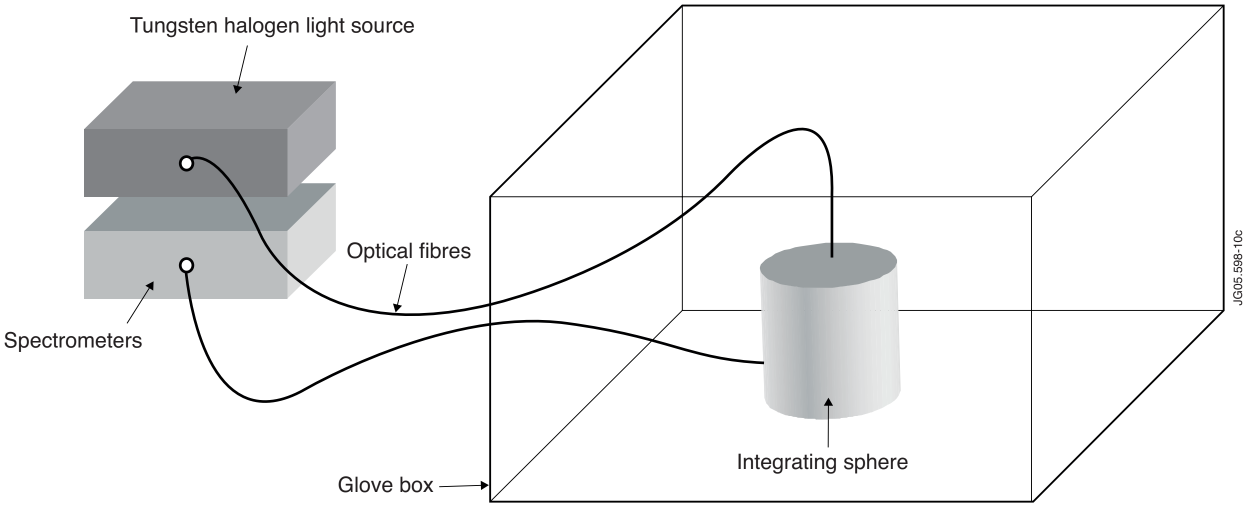

Figure 11: A scheme of the experimental set-up.