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# Testing of tungsten coatings in JET for the ITER-like wall

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ABSTRACT

A CFC tile 5 from the JET outer divertor, and CFC tiles from neutral beam shine-through and re-ionisation regions were coated with tungsten and exposed during the 2005-7 JET campaigns in preparation for the ITER-like wall project. Approximately 1.6 microns of coating were eroded from the tile 5 during high-delta discharges when the outer strike-point is on the tile. The coatings on the other tiles were unaffected by NB-heating and divertor discharges, however a tile mounted near the centre of the Inner Wall Guard Limiter lost all its coating from the surface within 10 mm of the tile leading edge; this probably occurred during the ramp-up phase of JET discharges.



## 1. Introduction

JET is preparing to install an ITER-like wall (ILW) which will comprise solid beryllium (Be) tiles or Be-coated inconel tiles in the main chamber and tungsten (W) tiles or W-coated carbon-fibre composite (CFC) tiles in the divertor [1,2]. Experience has been gained in the use of W-coatings in previous JET campaigns, as marker layers to allow erosion/deposition to be assessed [3]. Data indicate that 3 μm W-coated films survive readily at the inner divertor of JET, since this is a net deposition zone, but at the outer divertor W-coatings installed for the 2001-4 campaign were eroded near the plasma strike-point by the plasma ions, with W re-deposited in areas shadowed from the ions such as valleys and pits in the rough CFC surface [4].

It is not known when during the 2001-4 campaign breakthrough of the CFC substrate first occurred, so it is not clear how much plasma flux was required to erode the W-coating up to that point. Furthermore, in 2004 the JET divertor cross-section was changed, with a new tile 5 added to allow high-delta (HD) plasma configurations closer to those proposed for ITER (see inset in Fig. 1). It was therefore decided to coat a tile 5 with W to gain further information on erosion rates, and for the new ITER-like HD discharges, during the 2005-7 JET campaigns.

Power load calculations indicate that under certain operating conditions the flux to some areas of the main chamber may be too large for Be tiles. These areas include the neutral beam (NB) shine-through regions and tiles installed near the beam ducts (in the ports through which the beams enter the torus) to protect from NB re-ionisation. Erosion has never been measured in these areas, so CFC tiles were W-coated and installed in each of these areas during the 2004/5 shutdown, and removed in 2007 for analysis.

## 2. Experimental

The tile 5 chosen already had a narrow stripe of marker coating along one edge (a W interlayer ∼0.1 μm thick covered with 10 μm carbon); to this two W-coated stripes ∼60 mm wide were added, one ∼0.7 μm and the other ∼1.6 μm thick. The shine-through areas in JET include some of the Inner Wall Guard Limiter (IWGL) tiles, and some of the recessed areas between limiters where there are Inner Wall Cladding tiles. Tiles on the JET IWGL limiters are mounted in pairs – left (L) and right (R) – there are 18 pairs per limiter numbered from top (1) to bottom (18). Two tiles were coated from the limiter in sector 7Z – one near the bottom (7Z17R), the other near the centre (7Z12L), though each should receive similar fluxes during NB-heating. Each tile had one-half (poloidally) coated with ∼3 μm W and the other half with ∼3 μm rhenium (Re). In the NB re-ionisation area Poloidal Limiter

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[1] See the appendix of M.L. Watkins et al., Fusion Energy, 2006; Proceedings of the 21st International Conference, Chengdu, IAEA, 2006.

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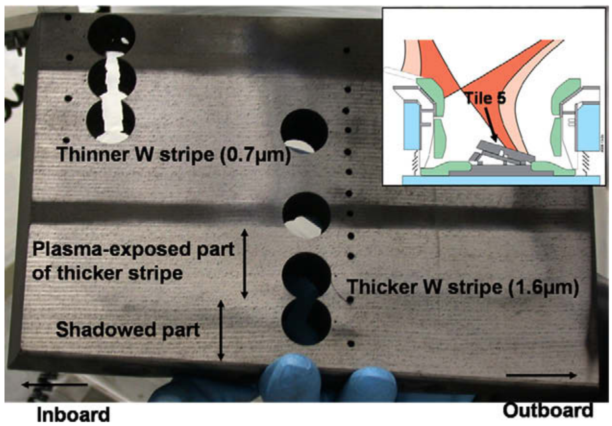


**Fig. 1.** Photograph of JET divertor tile 5, coated with two stripes of W, after exposure and removal of core samples for SEM analysis. Inset shows the divertor configuration.

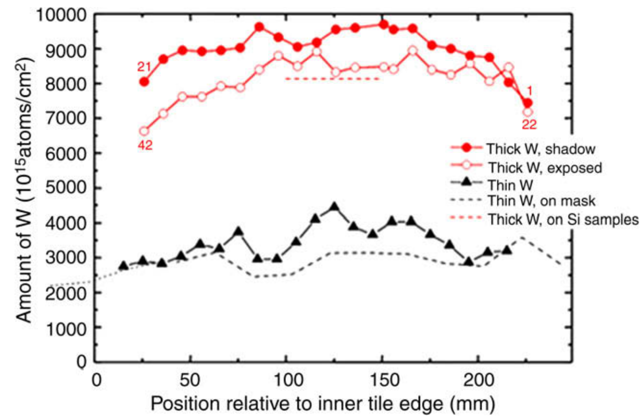


**Fig. 2.** RBS data showing the W levels on tile 5 stripes and masks.

Side Protection (PLSP) tiles 8B5 and 8B6 were coated over all the face closest to the NB ducts with ~3 μm W. The W and Re coatings were performed by DIARC© in Finland.

After removal from JET, the tiles were first analysed using the Ion Beam Analysis (IBA) technique Rutherford Backscattering (RBS); spectra were simulated to provide the thickness profile of the W layer on the carbon substrate as a mean over the 1 mm beam diameter, typically using a 3 MeV proton beam. A number of cores were then cut from the tiles so that Scanning Electron Microscopy (SEM) could be performed.

## 3. Results and discussion

There was insufficient time to check the coating thicknesses on the tile 5 prior to mounting, but masks used during the coating process to restrict the coatings to the appropriate stripe were retained for reference. It was also possible to determine the amount of erosion from the W-coated tile as part of the thicker coating was shadowed from the plasma by the adjacent load-bearing tile, and remained completely intact. Interestingly, RBS showed that the coating in the shadowed region was up to 15% thicker than on the relevant mask, suggesting that the amount of deposition onto different samples during a coating run may be influenced by the nature of the substrate being coated (e.g. surface roughness or composition may affect the efficiency of the deposition process). RBS analyses indicate that on average, about 10% less W remains in the region of the thicker stripe exposed to the plasma compared with the shadowed region, as shown in Fig. 2. The spectra from the exposed region show that almost all the surface is still W, but that the W concentration decreases away from the surface whilst the C concentration increases. RBS thus suggests that whilst the coating is being eroded and the covering of W has become very thin in places, W generally still covers the surface. This is consistent with the SEM back-scattered electron images in Fig. 3 in which high mass elements (e.g. W) show brightly, whilst low-Z materials (e.g. carbon) appear dark. All of Fig. 3(a) from the plasma-exposed region of the thicker coating appears bright suggesting that apart from one or two small spots (where asperities may have been rubbed off during handling), W still covers the surface. In contrast, for the thinner stripe, Fig. 3(b), it is clear that the W has been completely eroded from about one-half of the surface, whilst coating remains in dips and hollows in the CFC surface that provide some protection from the low angle ion flux (as was shown clearly in a previous experiment [4]). RBS shows that the surface is a mixture of W and C, but the integrated W signal from this stripe (i.e. averaged over 1 mm diameter) is still comparable with that from the mask. Assuming the original amount of W on the tile was ~15% greater than on the mask (as in the case of the thicker film), then it suggests only ~15% of W has actually been lost completely from the stripe. Since the SEM shows that roughly half the surface has no remaining W film, this further implies that the remaining coating is thicker, and most of the W eroded from exposed points is re-deposited in sheltered parts of the rough surface.

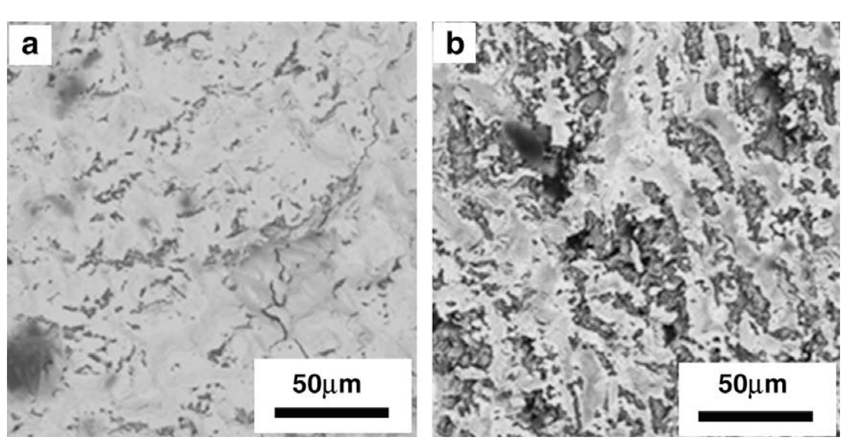


**Fig. 3.** SEM photographs from tile 5 (a) on the plasma-exposed part of the thicker W stripe and (b) on the thinner stripe.

The discussion above suggests that the erosion/re-deposition process occurs over a short distance, since most of the coating remains on the stripes. However, RBS does indicate that some W has been lost from the coatings, and W is found at the surface of the tile between the two stripes and between the thinner stripe and the edge of the tile. Between the two stripes there is a clear exponential decrease in amount of W on the surface going from the thicker stripe towards the thinner stripe, consistent with sputtered W from the thicker stripe being re-ionised and subsequently deposited along field-lines. The e-folding length for the fall-off is ~6.1 mm. Between the thinner stripe and the edge of the tile there is also a fall-off in W concentration; however, the exponent is complicated by a discontinuity at the edge of the 20 mm wide carbon/W marker stripe that was deposited along the edge of the tile. No evidence of the 10 μm carbon film remained, but some of the thin interlayer of W might be expected to remain (considering the behaviour of the other W stripes). The mean thickness of W in the 25 mm zone off the thinner strip is ~10% the amount in the thinner stripe, and some W is also found on the adjacent tile 5. The amount of W sputtered from the thinner stripe and re-deposited is thus within about a factor of two of the amount estimated to have been eroded totally from the stripe.

There was reasonable uniformity in the poloidal direction across the tile, except close to the outer edge of the tile – as shown for example in the difference between plasma-exposed and shadowed positions in Fig. 2. During the 2005-7 campaigns the outer strike-point was on tile 5 for less than half of the ~3500 pulses, but there was a spread of strike-point positions right across the tile, with the maximum number ~50 mm from the inner edge with an associated peak ion fluence (integrating toroidally) of $3 \times 10^{22}\ cm^{-2}$. The total energy to these tiles was approximately 29 GJ, assuming a mean ion energy of 30 eV. It must be noted that the flux is dominated by deuterium ions, however the W-erosion is almost exclusively by impurity ions (e.g. carbon), since only multiply-changed ions may have sufficient energy to exceed the threshold for W sputtering of ~200 eV. The fluxes of carbon ions at the divertor may have a different distribution, but cannot be measured in JET.

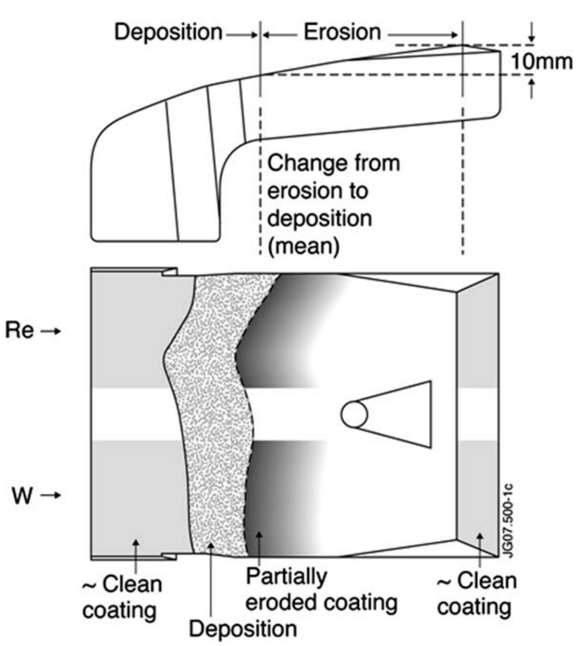


**Fig. 4.** Schematic of IWGL tile 7Z12L after exposure, with distances from the leading edge of the tile.

After exposure in JET, the coating on one of the two IWGL tiles from the beam shine-through region (7Z17R) was shown by IBA to be similar to the original 3 μm thickness. However, on the other tile the coating has been completely eroded over a toroidal width of ~70 mm where the tile is closest to the plasma boundary. As the tile curves further from the boundary into the scrape-off layer (SOL) some remaining coating is seen, and then this coating is covered with a layer of deposition, as shown schematically in Fig. 4. The integrated energy densities to tiles 7Z12L and 7Z17R during the divertor phases for the ~3500 discharges were similar at ~5300 and ~4700 $MJm^{-2}$, respectively, with peak power densities of 7.5 and 6.5 $MWm^{-2}$. Furthermore any shine-through effect would be uniform over each tile and not related to distance from the last closed flux surface (LCFS). Thus the differences between the two tiles cannot be attributed to shine-through or plasma loading during the divertor phase. However, this transition from a region of erosion to one of deposition is clearly characteristic of a plasma limiter. Plasma start-up is normally accomplished in JET at the outer limiter, but the plasma is then switched to the IWGL (when the plasma is reasonably circular) during a ramp-up period which varies in length from ~1 to 10 s, depending on the breakdown scenario. In this period the LCFS will be at the IWGL surface, with ion temperatures typically 50–200 eV and incident ion energies three times that for D, together with a significant impurity (carbon) concentration giving potentially several times increased energy. Thus erosion on tile 7Z12L is far more dramatic than at any point in the divertor – the W (and Re) coatings are completely stripped from the plasma-exposed surface for a distance of ~10 mm into the SOL from the leading edge of the tile (Fig. 4). As the plasma is typically centred above tile 12, one might expect that at least as much erosion will occur on tiles 8–11, especially as a marker stripe on a tile 11 was similarly stripped during the 2001-4 JET campaign. By comparison, the leading edge of tile 17 is already >>10 mm from the LCFS during this phase so the coatings are not eroded.

The coatings on the tiles installed to protect from NB re-ionisation were also intact, and in places were covered with a deposited film, so no re-ionisation effects could be seen.

## 4. Conclusions

A tile 5 was coated in one region with ~1.6 μm W and another region with ~0.7 μm. Part of the former region was shadowed from the plasma by the adjacent tile 5, and here the coating is completely intact. In the plasma-exposed part SEM images show the coating is thinning, and CFC is exposed at a few places such as at asperities and ridges on the rough CFC surface. The thinner coating has been completely eroded from about one-half of the surface, and the remaining coating is clearly thicker in dips and hollows in the CFC surface that provide some protection from the low angle ion flux. Thus the 1.6 μm coating was eroded by fluences of up to $3 \times 10^{22}\ cm^{-2}$ when the outer strike-point was on tile 5 (a minority of the 2005-7 pulses). The integrated power flux over the entire ILW campaign is expected to be much greater, and a margin must be left to allow for surface roughness effects, so a minimum of 20 μm W-coating thickness is planned, as is discussed further in Ref. [2].

There are no indications of neutral beam shine-through or re-ionisation effects on tiles exposed during the JET 2005-7 campaigns. The ITER-like wall project will use W-coated CFC in these areas, and the affected IWGL tiles will be retracted 15 mm behind the other (beryllium) limiters; these experiments show that this is essential near the mid-plane, but to prevent erosion of the W-coating and exposure of carbon during the ramp-up phase while the IWGL is used as a limiter, irrespective of possible shine-through effects.

## Acknowledgements

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