

## Operational impact on the JET ITER-like wall in-vessel components



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### HIGHLIGHTS

- Power handling of beryllium plasma facing components exceeded expectations.
- Local beryllium melting from power handling experiments to test the design limits.
- Local beryllium melting from disruptions.
- No change observed for most of the tungsten and tungsten-coated components.

### ARTICLE INFO

#### Article history:

Received 13 September 2013

Received in revised form

31 December 2013

Accepted 8 January 2014

Available online 11 March 2014

#### Keywords:

Beryllium

Tungsten

Plasma facing components

JET

### ABSTRACT

The JET ITER-like Wall (ILW) provides the same plasma facing component configuration as ITER during its active phase: beryllium in the main chamber and tungsten in the divertor. Moving from a carbon-based wall to an all metals wall requires some operational adjustment. The reduction in radiation at the plasma edge and in the divertor can lead to high power loads on the plasma facing components both in steady state and in transients and requires the development of radiative scenarios and the use of massive gas injection to mitigate disruptions. These tools are even more important now because an all metal wall is much less forgiving to thermal overloading the carbon based wall used to be. Here the impact of the first 11 months of operation on the ILW plasma facing components is discussed.

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### 1. Introduction

In preparation for ITER, JET has changed its plasma facing components to reproduce the same material combination ITER is planned to have in the active phase: beryllium in the main chamber and tungsten in the divertor [1]. The new components were installed in 2010–2011 shutdown and have experienced 11 months operation (August 2011–July 2012) before a further intervention (July 2012–May 2013) when a number of tile assemblies have been replaced.

During the operational period, in-vessel inspections using cameras which can be inserted vertically in fixed location were able to follow the development of the condition of the plasma

facing components. In the intervention, an in situ photographic survey and ex-vessel inspection of a sample of tile assemblies revealed further details on the effect plasma operation had on the plasma facing components of the ITER-like wall (ILW). This paper will focus on the discussion of changes to the condition of the ILW components and the aspects of plasma operations driving them.

Beryllium in the main chamber resulted in increased ease to achieve plasma breakdown and reduced need for conditioning. However, it also exposed weaknesses in the plant protection systems. Section 2 discusses the effect of the wall material on the plasma initiation and its operational impact.

Differently from the disruptions with the carbon wall where most of the available energy was radiated, only a small fraction of the plasma energy is radiated during disruptions with the ILW [2]. Consequently, the plasma remains hot during the current decay, which is slower and delivers more energy to the wall. This resulted in beryllium melting at the top of the machine and higher electro-mechanical impulses, making the use of disruption management strategies including massive gas injection a requirement. Disruptions on the ILW are discussed in Section 3.

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<sup>1</sup> See the Appendix of F. Romanelli et al., Proc. 24th IAEA FEC, San Diego, 2012.

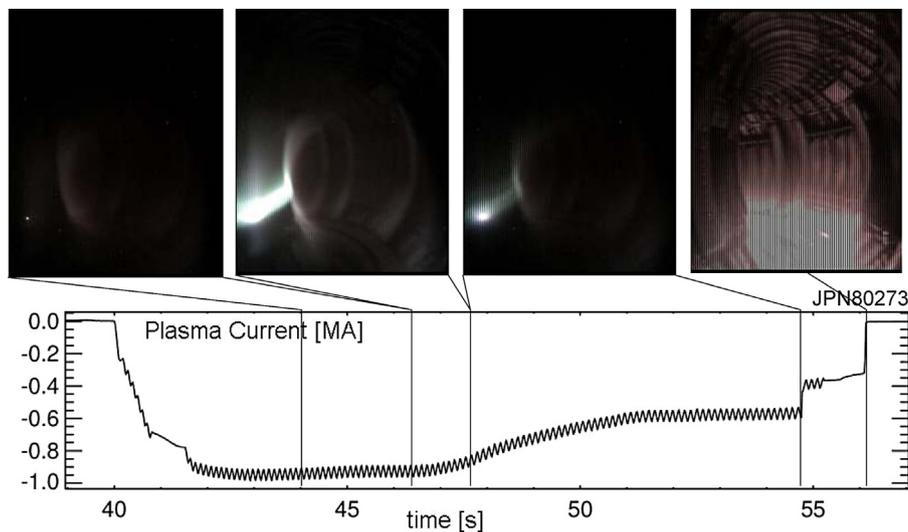


Fig. 1. Slide-away event in pulse 80273 which caused minor damage to one inner wall tile assembly.

Maximization of the main chamber power handling capability was a key driver of the ILW design [3,4] and it is discussed in Section 4. The main chamber power handling has achieved and possibly exceeded the design targets with effective shadowing of all edges over a range of magnetic configurations. Experiments designed to approach the design limits unintentionally caused toroidally non-uniform melting of the upper portion of some of the inner wall guard limiters and the outer wall poloidal limiters. The bulk tungsten divertor tile has been tested close to its energy and surface temperature limits without problems. There is no evidence of delamination due to thermal fatigue or significant erosion of W-coated divertor tiles in either the inner or outer divertor.

## 2. Robust plasma initiation

After installation of the ITER-like Wall in JET, a plasma ( $\geq 1$  MA and  $\geq 5$  s) was achieved at the first attempt, following a conditioning cycle including baking at  $320^\circ\text{C}$  and about 100 hours of glow discharge. Since the first plasma breakdown, no overnight glow discharges and no beryllium evaporation were necessary throughout the whole campaign, while they were routine (weekly) for operation with carbon walls. Differently from operation with the carbon wall, no non-sustained breakdown was recorded, even following substantial disruptions. This less demanding conditioning is due to the beneficial effect of beryllium as a first wall material [5]. The avalanche phase continues to be dominated by the pre-fill pressure and its composition, but the burn-through phase strongly depends on the plasma facing material: the levels of the main impurities such as carbon changed significantly, affecting the density and radiation in the burn-through phase. At a given density the radiation with the carbon wall is significantly higher than with the ILW, sometimes causing a non-sustained breakdown. The lower radiation efficiency of beryllium in comparison to carbon, allows for a faster burn-through.

Emergency shutdown of a JET pulse with the carbon wall involved switching off the gas injection. With the ITER-like wall the low outgassing plus dynamic pumping meant that this same procedure can produce extremely low plasma densities leading to slide-away electron beams. This indeed happened within  $<150$  pulses from the first plasma with the ILW. Pulse 80263 was a commissioning plasma run in limiter configuration letting the central solenoid free-fall after inversion, when the plasma is created. A spurious plant alarm stopped the pulse; the gas injection was

stopped and the small amount of gas in the torus was ionized and accelerated to relativistic speeds. The chain of events was unraveled and a solution devised, but not implemented in the pulse schedule handling software before the same spurious plant alarm reoccurred. The second event, pulse 80273 shown in Fig. 1, consisted of  $>900$  kA for 5 s and followed by  $>600$  kA for a further 9 s. The beam came into contact with the inner wall occasionally as well as in its last instability. This resulted in some very localized damage to beryllium limiters (the size of two half castellations,  $12\text{ mm} \times 12\text{ mm}$  in one toroidal position) and to several of the tungsten coated CFC tiles protecting the bottom of the inner wall guard limiters. Once the revised requirement for gas injection was implemented in the pulse schedule handling software, no event like that happened in the rest of the 11 months of operation. Fortunately, the location of contact between the slide-away beam and the inner wall guard limiter was sufficiently remote from the plasma separatrix not to affect the subsequent plasma operation.

## 3. Disruptions

In the first 11 months of operation with the ILW, no disruption produced significant beams of runaway electrons. While massive gas injection using high fraction of argon in deuterium was avoided to prevent deliberate runaway generation, controlled radiative collapse of high toroidal field intermediate plasma current limiter plasmas using argon [6] did not produce measurable runaway electrons despite being a reliable method to generate runaway electron beams with the carbon wall.

Disruptions with the ILW are different from those with the carbon wall where most of the available energy was radiated. With the ILW low radiation from beryllium impurities and reduced wall inventory to be liberated after the thermal quench means high plasma temperature during the current decay and higher convective heat loads.

The slow current quench makes the effective electromechanical loads of the disruptions larger on the vessel supports. The resonant mode of the vessel excited by the axi-symmetric disruption loads has a frequency of  $\sim 14$  Hz, which is longer than the typical current quench. Consequently the vessel displacement depends more strongly on the impulse than the magnitude of the disruption loads. This resulted in larger reaction forces and displacements of the vessel ports following disruptions of comparable plasma current and shape. As the strain at the base of the vessel ports depends on its

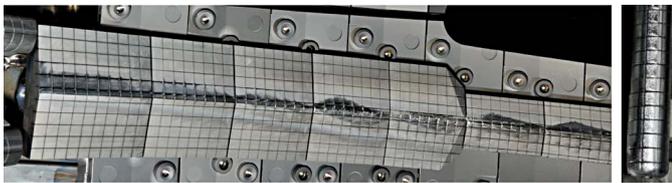


Fig. 2. Examples of superficial melt damage to the upper dump plate and inner protection.

displacement and is critical to the vessel life consumption, limiting the duration of the current quench is attractive.

The higher convective heat loads caused by the reduction of radiated power during the current quench have caused superficial damage on the upper dump plates and the upper inner protection plates, as shown in Fig. 2, because disruptions in the ILW tend to go more often upwards, even at relatively low plasma current (for example, a 2.5 MA event took the span of several castellations to melting temperature). Although this damage is inconsequential to plasma operation, it could become more substantial at higher plasma currents and cause problems elsewhere in the main chamber; small drops on the divertor were often observed and burnt off in a few pulses without affecting performance, larger ones could become noticeable.

To reduce heat loads and to manage electro-mechanical loads massive gas injection has become mandatory for plasma currents above 2.5 MA and has so far been seen to successfully mitigate disruptions [2].

4. Power handling

The most demanding operational condition for the main chamber power handling components of the ILW is limiter configuration [3,7]. The tile assemblies have been designed for a set of reference limiter configurations and operation in X-point configuration with sufficient clearance between the wall and the separatrix has not challenged the design so far, even in pulses with very high levels of additional heating.

To experimentally confirm the designed power handling capabilities, a series of neutral beam heated limiter plasmas has been run. Based on the near infrared and infrared camera measurements, with the calibrations available at the time, and under the assumption of toroidal symmetry, while these pulses were run, it was estimated that they resulted in temperatures below the beryllium melting temperature. However, in-vessel inspection revealed melt damage to some of the inner and outer limiter which could only be traced back to the last series of pulses run to test the ILW main chamber power handling (83610-83620). Closer inspection of the near infrared camera data showed that one of the inner wall guard limiters not selected as part of the protection regions of interest reached much higher temperature than the one monitored and

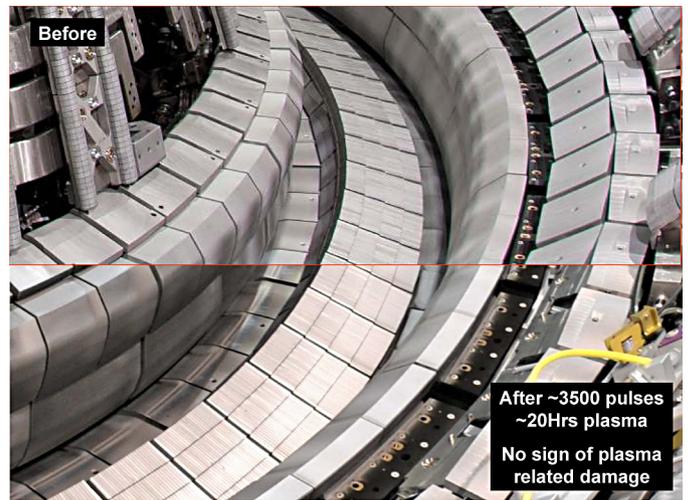


Fig. 4. Split view of the divertor (before at the top and at the bottom after 11 months of operation) showing bulk tungsten and tungsten coated CFC tiles, both exhibiting little sign of wear and tear.

plumes left the tiles at times consistent with spikes in beryllium radiation. Following the in situ high resolution photographic survey more melted locations were found. The pattern of melting on the inner wall is shown in Fig. 3. This pattern seems to support other observations [8] that the scrape off layer is very thin, and the slight relative misalignment of the limiter beams (also reported in Fig. 3) could be sufficient to explain the toroidal asymmetry of the heat load.

Although it was undesirable to melt the inner and outer limiter tiles, this has provided an experimental confirmation of the power handling capabilities of the tiles, which can be used to tune the administrative operational limits: starting at 400 °C, 4.4 MW for 10 s in limiter configuration are sufficient to reach beryllium melting temperature. Having decided to replace the damaged beryllium slices only on the outer wall, the inner wall tiles can be used to monitor the progress of the damage and its effect on plasma operation. In addition, having reached melting with a single configuration and only 2 or 3 pulses in each location offered the opportunity to study beryllium melt layer physics [9]. The liquid beryllium is moved against the gravity force. This required a current density higher than 6 kA/m<sup>2</sup>, much more than can be sustained by thermo-emission at the melting temperature, only possible accounting for secondary electron emission and plasma pressure force.

Fig. 4 shows a split view of the divertor before and after 11 months of plasma operation. Apart from some discoloration due to erosion and deposition, there is no evidence of delamination due to thermal fatigue or de-bonding in the tungsten-coated tiles in either the inner or outer divertor. The bulk tungsten divertor tile has been tested close to its energy and surface temperature limits

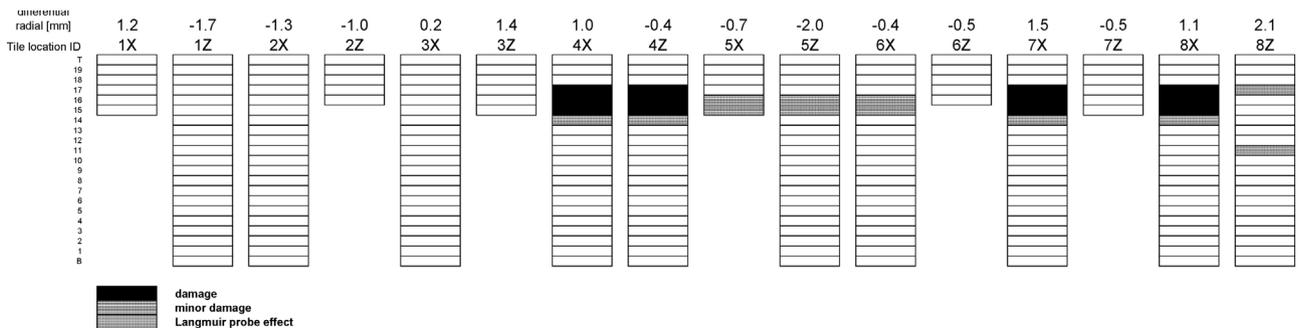


Fig. 3. Schematic map of the inner wall plasma limiting tiles showing the locations where melt occurred.



**Fig. 5.** Collection of tungsten melts: (top) inboard edge of one lamella on the outermost stack; (middle) Langmuir probe tips melted and cracked; filtered visible camera view showing one set of Langmuir probes (top chain of dots) and the lamella melt of the top picture (large isolated hot spot).

without problems. During operation several drops of beryllium landed on both the bulk tungsten and the tungsten-coated divertor tiles. These were seen as hot spots appearing and then rapidly (in a few pulses) vanishing; some recent ones left discolored patches of some  $\text{mm}^2$ ; even more recent ones were still present and some have been collected.

As far as we know only one location had melted tungsten, rather than beryllium. This was in the same module as one set of Langmuir probes and in view of one of the near infrared cameras, as shown in Fig. 5. This camera recorded the presence of the hot spot due to the melted globule of tungsten generated since a filter was added till the end of plasma operation, that is  $>1000$  pulses, including those with the strike point in the vicinity of the globule and the highest neutral beam power achieved in this operational period. This observation shows that operation with a limited amount of misshaped tungsten is compatible with operation, as it went unnoticed until it was found during ex-vessel inspection of the tile. The location of the lamella chip is rather fortunate, as the outboard edge of the lamella adjacent on the inner side (top in Fig. 5) shadows it for most plasma configurations.

Fig. 5 also shows the damage accumulated by the divertor Langmuir probes. There are signs of melting on some of the Langmuir probe tips in all poloidal positions and in all three toroidal sets. However, those located where the strike-point used to reside



**Fig. 6.** Langmuir probe on the inner wall guard limiter and damage on the neighboring beryllium tile.

the most during high power operation are the most damaged, as are those in the toroidal position where electron collection was performed. Here two effects combine: the probe surface angle is steeper than that of the lamella and the power is enhanced by drawing electron current. Both these drivers for damage can be addressed, respectively by redesigning the probes and by limiting the voltage bias in operation.

Also some of the main chamber Langmuir probes had power handling issues. Fig. 6 shows the top probe on the inner wall. Here, while the probe seems to have survived, the neighboring tile has been damaged. Like in the melting caused by the power handling experiments, the molten material has moved against gravity, indicating that some charge collection must have been preset. However, the cause of the melting is unclear. Even if the probes came into contact with the beryllium, heat transfer is very poor. As the Langmuir probe is very thin, it should have the same temperature both sides excluding radiation as cause of damage.

## 5. Summary

Key features different in the operations with the ILW with respect to the carbon wall at JET are:

- Slide-away electron beams are possible after premature plant stops if the plasma is not fuelled because of the ILW low out-gassing.
- Because of the reduction in intrinsic radiation during ILW disruptions, convective heat loads are larger and current quench durations are longer (resulting in larger electro-mechanical impulse on the vacuum vessel and therefore larger reaction forces and stresses) than they were with the carbon wall. Consequently massive gas injection is routinely used when the plasma current is larger than 2.5 MA to regain a substantial fraction of radiated power and shorten the current quench duration.
- Power handling performance was consistent with design expectations. However, in the main chamber the axi-symmetry assumption has been challenged by relatively small absolute

installation tolerances hinting to the scrape of layer being very thin.

- The Langmuir probes in both the divertor and the main chamber had power handling issues: in the divertor causing damage to the probes only and in the main chamber causing damage to the neighboring beryllium tiles.

### Acknowledgments

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was also part-funded by the RCUK Energy Program under Grant EP/I501045.

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