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Thermal management of tungsten leading edges in DIII-D

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HIGHLIGHTS

- Experience with tile alignment, documentation and thermal modeling are important aspects of thermal management in DIII-D.
- Various approaches to leading edges and thermal management were investigated for tungsten coated TZM inserts installed for the DIII-D Metal Tile Experiment.
- The DIII-D team completed a second W leading edge experiment using the DiMES materials probe on support of ITER.

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ABSTRACT

The DiMES materials probe exposed tungsten blocks with 0.3 and 1 mm high leading edges to DIII-D He plasmas in 2015 and 2016 viewed with high resolution IRTV. The 1-mm edge may have reached >3000 °C in a 3-s shot with a (parallel) heat load of ~80 MW/m^2 and ~8.6 MW/m^2 on the surface based on modeling. The experiments support ITER. Leading edges were also a concern in the DIII-D Metal Tile Experiment in 2016. Two toroidal arrays of divertor tiles had W-coated molybdenum inserts 50 mm wide radially. This paper presents data and thermal analyses.

1. Introduction

Power exhaust is perhaps foremost among the issues for ITER and post-ITER devices, and for existing confinement devices as they increase power. A concern in all high power devices is alignment of plasma facing components (PFCs) to avoid protruding (leading) edges that intercept field lines and incur very high loads. A desire to validate the impact of leading edges on requirements for aligning ITER's divertor prompted the tungsten transient melt experiment in JET's ITER-like divertor [1–4]. Alignment was also a concern in the Metal Tile Experiment (MTX) in the 2016 DIII-D campaign.

MTX focused on high-Z impurity sources and transport in the plasma edge [5]. Spectroscopy and post-test examinations of tiles from several locations were part of the experimental plan. MTX is part of a broader long range goal to develop and test advanced divertor configurations and to validate reactor-relevant materials [6].

Thermal management is the theme of this paper. It describes thermal modeling of a tungsten (W) leading edge experiment in 2016 and concerns and related thermal modeling for the MTX. DiMES is the Divertor Materials Evaluation System. Another paper in this conference, an overview paper by Rudakov et al. on DiMES support for ITER [7], includes photos of DiMES with the W blocks and describes other DiMES experiments performed in support of ITER. The W leading edge experiment in 2015 was reported at APS [8].

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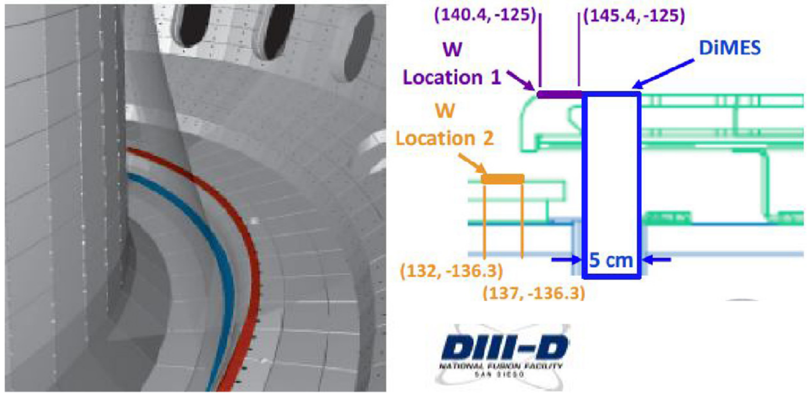

Fig. 1. Location of rows of tiles with TZM inserts and position of DiMES on divertor shelf.

2. Power handling for the MTX

The 2016 DIII-D campaign included the 2nd leading edge experiment and a major vent for the installation of two toroidal arrays of divertor tiles for the MTX. The strategy for thermal management in DIII-D includes specifications, experience with installation and provisions to mitigate hot spots. Among the latter are filleted edges and thermal modeling that confirms acceptable temperatures and stresses. Exceptions are where sharp edges are specified as for the DiMES W block leading edge experiment.

2.1. MTX thermal management

Each array in the MTX (Fig. 1), one on the divertor shelf (red) and the other on the floor (blue), had W-coated TZM (molybdenum alloy) inserts. These were 50 mm wide radially, 9.5 mm thick, and bolted from the back. The shelf tile inserts had a 1–2 μm thick ^{182}W coating done at ORNL. The floor tile inserts had ~12 μm thick natural W coating.

The inserts fit into slots in newly made Sigrafine R6710 tiles. This fine grained graphite has been successfully used in the ASDEX Upgrade tokamak [9] and is stronger than the ATJ, previously used in DIII-D but no longer available. Each insert spanned the toroidal width of a tile. The inserts comprised two segmented and nearly complete toroidal rings of W surfaces facing the plasma.

The conditions for the MTX included L and H mode plasmas and with ELMs. The design specified a maximum misalignment of adjacent tiles of 0.3 mm based upon the previously noted experience with tile installation.

A bolted bar holds down the feet of adjacent tiles. This mounting scheme minimizes edge to edge misalignments while allowing some rocking of the tiles. The bullnose tiles, with their central hole for the hold down bar, are an exception.

The DIII-D team has collaborators at many institutions, e.g., the co-authors. This group considered several approaches for the leading edges, including "roof top" (chevron shape) or "fish scale" tiles as well as bevels, chamfers and fillets. The latter are edge modifications. With roof top and fish scale treatments, both the inserts and tops of the tiles are tilted.

The approach for thermal management in the MTX had to support the primary goal for the interpretation of the spectroscopy. In the end, the specified edge treatment was a 2-mm fillet which is standard for DIII-D tiles.

2.2. MTX thermal analysis

The thermal analyses in Fig. 2, for MTX's Preliminary Design Review, used the skewed triangular strike point (SP) profile (inset in Fig. 2). The model by GA engineer Murphy (top, ANSYS) shows the result for of a flat insert/tile with a 2-mm fillet. T-max on the insert surface is 1118 °C at the end of a 3.5 s shot for an insert 0.3 mm above its neighbor. The conditions were: 150 MW/m^2 along the field line ($q_{||}$), 6.5 MW/m^2 peak (SP) toward the inside of the insert and a 2.5° angle of incidence. Nygren's model (bottom, ABAQUS[1]) had a similar heat load. In a case with 3 sets of 2-ms ELMs (10X heat) plus 48 ms at 6.5 MW/m^2 after a 3-s shot, T-max cycled from 1151 to 1826, then 1188–1863, and 1214–1889 °C.

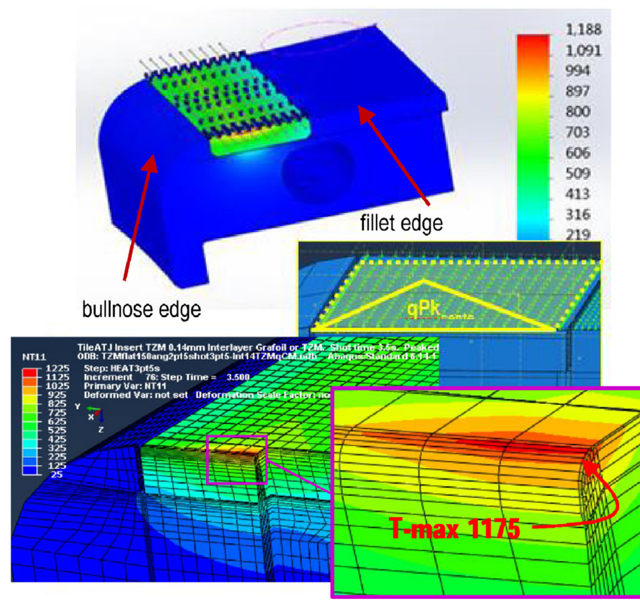

Fig. 2. Thermal models of bullnose tile with TZM insert. Temperature ranges (color) differ in the figures.

Fig. 3 shows an early thermal analysis of a fish scale configuration. Roof top (chevron) and beveled tiles received similar analysis, again with 150 MW/m^2 $q_{||}$ as the steady state heat load. The basic feature is shadowing of the leading edge by the adjacent tile. The plasma footprint begins away from the leading edge as evident from the hotter (red) region of the insert. The exposed leading edges in these early cases were much larger (~1 mm) than the 0.3-mm requirement later adopted as a design specification for installation of the tiles.

The fish scale and roof top configurations can completely hide insert edges that would become exposed due to misalignment in a configuration with flat inserts. However, a fish scale configuration requires that the campaign be run with one toroidal field direction, whereas the experimental plan called for both directions.

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