Fast Ion Effects during Test Blanket Module Simulation Experiments in DIII-D

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Abstract. Fast beam-ion losses were studied in DIII-D in the presence of a scaled mock-up of two Test Blanket Modules (TBM) for ITER. Heating on the TBM surface was found when neutral beams were injected and the TBM fields were engaged. The fast-ion core confinement was not significantly affected. Different orbit-following codes predict the formation of a hot spot on the TBM surface arising from beam-ions deposited near the edge of the plasma. The codes were in general agreement with each other on the localization of the hot spot and the total power deposited. The power was calculated to increase with decreasing separation between the plasma edge and the TBM surface. While this trend is in qualitative agreement with the measurements, thermal tile analysis suggests that more power is deposited than is calculated by the codes, particularly at the smallest separation. Uncertainties in the tile analysis are discussed and suggestions for future experiments are proposed.

1. Introduction

ITER plans to study tritium breeding using test blanket modules. Six Test Blanket Modules (TBMs), two in each of three equatorial ports, are being envisioned for ITER. These TBMs contain a significant amount of ferritic steel, and therefore, the TBMs will create three highly localized distortions of the magnetic field which can reduce the confinement of fast ions, especially the fusion-born alpha particles. In alpha-particle confinement simulations for ITER it was shown that a fraction of the lost alphas is deposited on the surface of the TBMs thereby creating hot spots [1, 2].

During TBM experiments in DIII-D [3] in which a scaled mock-up of two TBMs for ITER was placed in the machine, one of the topics that was studied was the confinement of fast beam-ions. The mock-up TBM on DIII-D has four protective carbon tiles arranged vertically with a thermocouple placed on the back of each tile (Fig. 1). Temperature increases of up to 230°C were measured (Fig. 2) for the two central tiles closest to the mid plane when the TBM fields were activated. A possible indication of beam-ion losses in the TBM experiments was the temperature increase measured at the back of the protective carbon tiles of the TBM (Sec. 2).

The beam-ion confinement was studied with the ASCOT code [4] the OFMC code [5] and the DELTA5D Monte Carlo code [6], which are guiding center following codes and the SPIRAL code [1] which is a full gyro-orbit following code. In all the simulations the same beam deposition profiles were used that were obtained from a post-processor of a TRANSP analysis [7] of the studied discharges. All four codes indicate that a localized area of high heat loads is formed on or near the middle two protective TBM tiles due to beam-ion losses in the presence of the TBM fields, while without the TBM fields no significant beam-induced heat loads were found. In order to compare the calculated heat loads with the measured tile temperatures, heat transport calculations were performed. Thermocouples are on the back of the 2.5 cm thick tiles close to the right-hand edge looking outward in major radius. Thermal analysis was required to infer the surface heat load from the back of the tile. While the trend of the thermocouple data is consistent with the calculated loss, thermal analysis indicate higher heat loads than calculated. The thermal calculations are very sensitive to the thermal deposition profile, which is not measured directly in these experiments. Proposals for improved diagnostics are made to resolve this uncertainty. A summary and outlook given in Sec. 4.

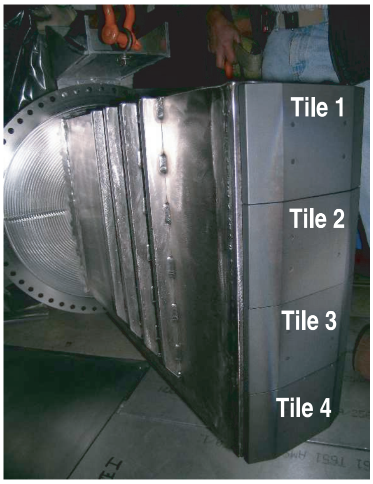

FIG. 1. The four protective carbon tiles on the DIII D TBM mock-up assembly.

2. Experiment

A number of similar discharges were made in DIII-D in which the distance between the separatrix and the plasma-facing surface of the TBM was varied between five and eight cm. For each separation a number of discharges were made with the TBM coils energized for up to 1.5 s, together with a reference discharge without the TBM fields for comparison. In Fig. 2 the time history of the TBM tiles is compared, while in Fig. 3 a comparison of the time-history of the plasma parameters is made between a discharge with the TBM coils engaged and the corresponding one without TBM fields. In all the discharges the

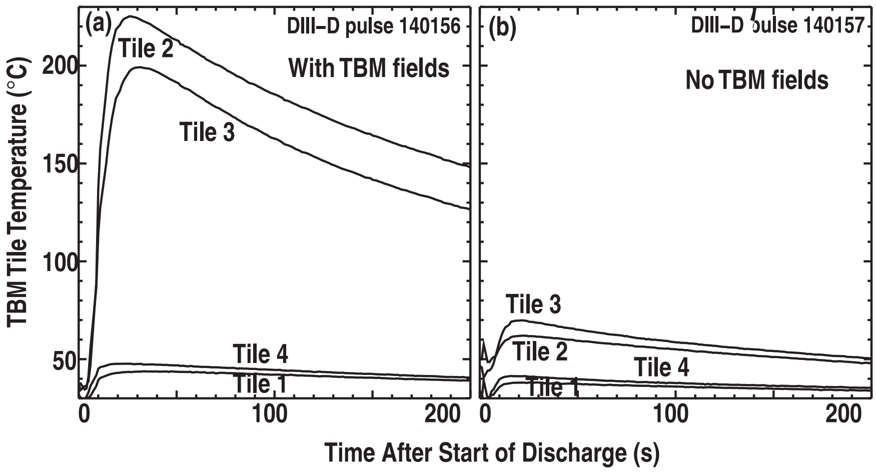

FIG. 2. Tile temperatures measured with the thermocouple at the back of the carbon tiles for two similar DIII-D discharges. In (a) the TBM fields were present while in (b) they were not present.

toroidal magnetic field was 1.7 T, the plasma current was 1.4 MA, and 5.8 MWs of neutral beam heating was applied resulting in an ELMing H-mode with some tearing mode activity while no Alfvén eigenmodes were observed during the phase thatTBM fields were present. TBM tile temperatures were measured with a thermocouple mounted on the back of the 2.5 cm thick carbon tiles. The tile temperatures were recorded continuously during the TBM experiments.

In the discharges where the TBM coils were not energized the tile temperature rose less than 15°C after the discharge was completed [Fig. 2(b)] while in discharges with the TBM fields present the temperature of the middle two tiles (tile 2 and 3 in Fig. 2) increased up to 230°C. The maximum temperature was reached around 15 s after the discharge was finished. The change in tile temperature is well reproducible on a shot to shot basis and it is a strong function of the outer gap as can be seen from Fig. 4.

When the TBM fields are present the thermal plasma is pulled outward in the direction of the wall. From 3D equilibrium calculations performed with the IPEC code [9] it was found that the maximum plasma displacement towards the first wall was less than 1 cm [10], so the observed TBM tile heating is not caused by thermal plasma touching the tiles. This is because the minimum gap between the separatrix at the outer mid-plane and the TBM tile surface was 5 cm which was much larger than the temperature scale length in the scape-off layer.

Additional fast-ion diagnostics, such as fast-ion D_α (FIDA) and neutron scintillators, were used to detect possible signs of central fast-ion loss or redistribution. Within the experimental uncertainties no significant change in the fast-ion population was found

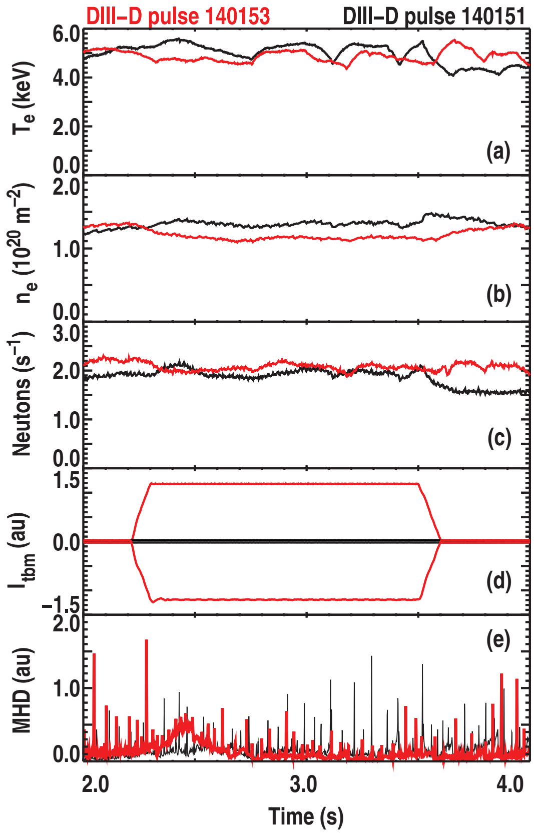

FIG. 3. The central electron temperature (a), density (b), neutron rate (c), TBM coil currents (d), and MHD activity (e) for a discharge without TBM fields in black (pulse 140151) and one with the TBM fields engaged in red (pulse 140153).

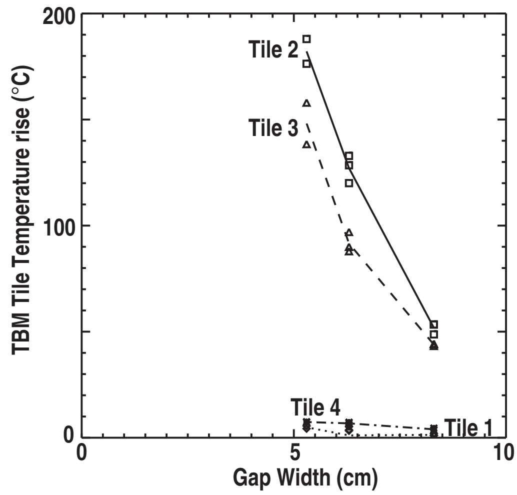

FIG. 4. The measured thermocouple temperature rise at the back of of the four tiles for a 1 s long TBM pulse versus the outer gap width. Each symbol is a separate discharge.

in the core of these plasmas, consistent with the beam-ion loss simulations that indicate only edge deposited beam ions are lost to the TBM.

3. Particle-loss & Heat-load Simulations

Beam-ion transport was calculated with four different codes: the ASCOT, OFMC, and DELTA5D codes which are guiding-center following codes and the SPIRAL code which is a full-orbit following code. The ASCOT, OFMC, and SPIRAL codes use EFIT axisymmetric equilibria with the full 3-D ripple field induced by the TBM superimposed on it while the DELTA5D code uses VMEC 3D equilibria with the TBM fields included in a self-consistent way. All four codes solve for the trajectory of birth energy beam ions using a toroidally asymmetric beam deposition profile calculated by a post-processor running on TRANSP output. This removes the uncertainty on the birth profiles when the results from the different codes are compared. Up to five beams were used with acceleration voltages of 59, 75, and 80 kV in accordance with the experiments. The beams were all injected in the co-current direction thereby creating an anisotropic pitch-angle, χ, distribution that was centered at $\chi = v_{\|}/v = 0.5$ and with a width of 0.4. The particles were followed beyond the separatrix to a cylindrical surface at the radius of the TBM. Slowing down and collisions [11] were included in all the codes and particles were typically followed for 40 to 60 ms. The energy slowing-down time for 80 keV deuterium ions in the plasmas under study was about 60 ms at the plasma center.

All four codes show the formation of a hot spot on or near the central two TBM tiles as is shown in Fig. 5 for the ASCOT, SPIRAL and DELTA5D codes. The DELTA5D code finds a a more extended hot spot which is due to the 3-D equilibrium that was used in that calculation. The calculated total power deposited (integrated toroidally over ϕ=[80,90] deg and vertically over $Z = [-0.4, 0.4]$ m) is in good agreement between the four codes as can be seen in Table I.

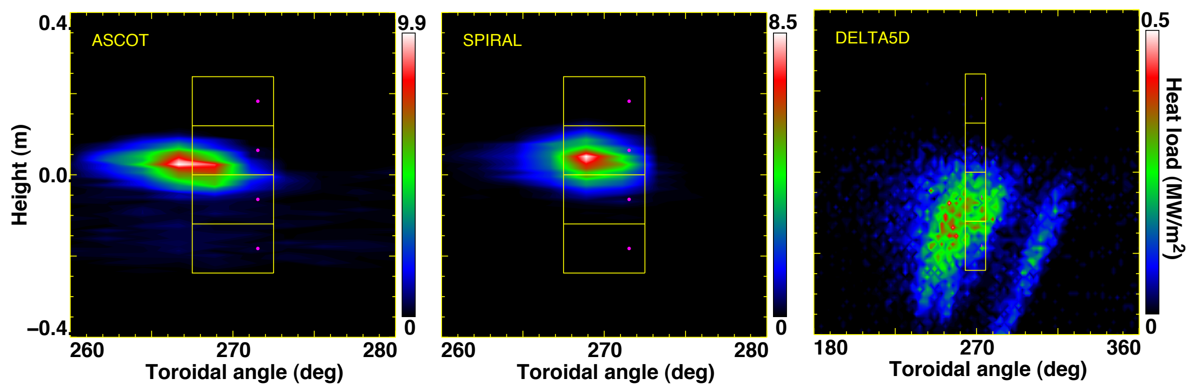

FIG. 5. Heat loads on the first wall near the TBM tiles (yellow outlines) as calculated with the ASCOT, DELTA5D and SPIRAL code for a gap width of 5.2 cm (DIII-D discharge 140156). Note the difference in the color scale. The purple dots indicate the location of the thermocouples at the back of the tiles.

However, the footprint of the hot spot is somewhat larger and shifted toroidally by about three degrees in the ASCOT results compared to the SPIRAL results while the foot print of the DELTA5D code is significantly larger and shifted downward. Both SPIRAL and ASCOT find that the hot spot is centered vertically on the middle two tiles (Fig. 5), consistent with the experimental observations. However, the DELTA5D hot spot is shifted below the mid plane which is inconsistent with the thermocouple data. In the toroidal direction the ASCOT hot spot footprint is larger than the SPIRAL one. Moreover, when the gap between the separatrix and the TBM tiles is decreased from 8 to 5 cm the footprint in the ASCOT simulations moves away from the tiles toroidally by 3 deg. in the plasma current direction. Such a movement is also visible in the SPIRAL simulations but it is less than 0.3 deg. As the input (magnetic fields, density and temperature profiles, and fast-ion distributions) of the ASCOT and SPIRAL codes is the same, the difference in the footprints between the two codes may be due to guidecenter (ASCOT) and full orbit (SPIRAL) differences. A detailed investigation is under way to understand the difference.

Table 1. The power deposited in the hot spot created by the TBM fields as calculated by the ASCOT, DELTA5D, OFMC, and SPIRAL codes for the pulse with the smallest gap. The power was integrated over an area given by ϕ=[80,90] deg and Z=[-0.4,0.4] m for ASCOT, OFMC, and SPRIRAL while for DELTA5D integration was performed over the same Z-range and ϕ=[50,150] deg.

	HotSpotPower(kW)	
Simulation Code	No limiters	Limiters
ASCOT	190	tbd
DELTA5D	185	tbd
OFMC	tbd	123
SPIRAL	139	117

In the above results the outer wall was taken as a cylinder with a major radius of 2.38 m. However, In DIII-D, there are three poloidal limiters projecting 1.0 cm inward, around 95, 230, and 310 deg. When those limiters are included in the SPIRAL simulations the power deposited in the hot spot at the TBM is reduced by 15%, indicating that the limiters can remove some of power that would otherwise have gone to the surface of the TBM.

Experimentally, a large variation in the tile temperature was found as function of the gap width (Fig. 4). A similar trend was found in the hot-spot power calculated with the ASCOT and SPIRAL codes as can be seen in Fig. 6. The inclusion of limiters reduces the hot spot power as calculated with the SPIRAL code by 15% while the total power on tile 2 is reduced by less than 5% and on tile 3 by about 30%.

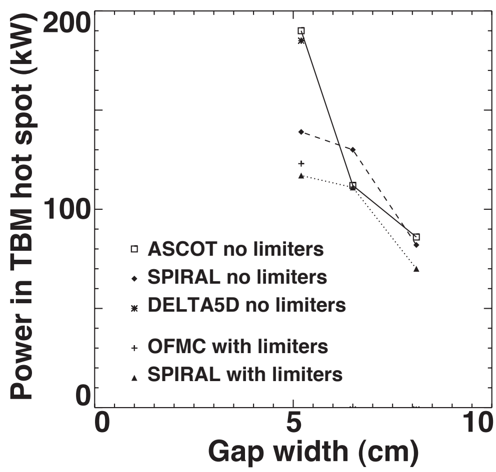

FIG. 6. Hot spot power induced by the TBM fields versus the gap width calculated with various codes.

In the particle loss simulations, heat-loads on the wall and the TBM tiles are calculated. In order to compare those heat loads with the measured tile temperatures, the temperature

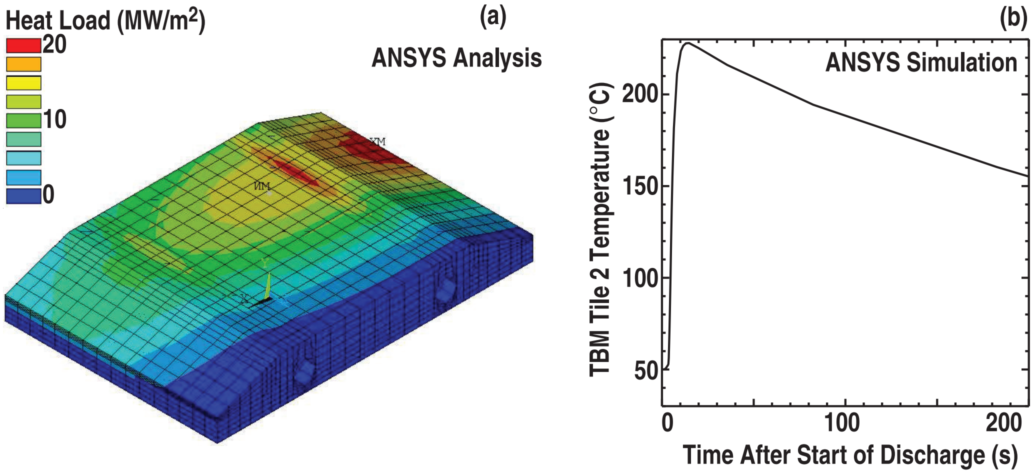

FIG. 7. (a) Initial heat load on the tile using the SPIRAL hot spot and (b) the ANSYS calculated thermocouple response.

response on the back of the tiles has to be modeled with the calculated heat load on the tile surface. We have calculated the dynamic temperature response with the finite element ANSYS code in which the power deposition profile from the SPIRAL code was used [Fig. 7(a)]. The calculated temperature evolution at the location of the thermocouple in which radiation losses and conduction to the TBM steel port structure were included, is shown in Fig. 7(b). A peak temperature of 230°C can be obtained at the thermocouple location when the footprint of the hot spot from SPIRAL is used with a peak heat load of 25 MW/m^2 [Fig. 8], and a total heat load of 412 kW of which 206 kW is deposited on tile number two. This should be compared to the SPIRAL calculated peak heat load of 8.5 MW/m^2 and a total heat load of 139 kW and 69 kW deposited on tile two. Therefore, there is a large discrepancy, roughly a factor of three, between the calculated losses and expected heat load from the thermal analysis.

In the ANSYS modeling the highly localized hot spot as found from the loss simulations was used and this hot spot was shifted away from the tile center and the thermocouple location. In order to match the measured thermocouple temperatures, very high peak head loads are needed. If we arbitrarily increase the size of the hot spot then thermal analysis indicate that less power is needed to reach the same temperature on the thermocouple. In the limiting case of a uniform heat load on the tile, high temperatures at the thermocouple location are found at much lower heat loads as can he seen from the dashed curve in Fig. 8. In order to help resolve the discrepancy between the simulated heat loads and the thermal tile analysis, thermal imaging measurements of the power-loss foot print on the

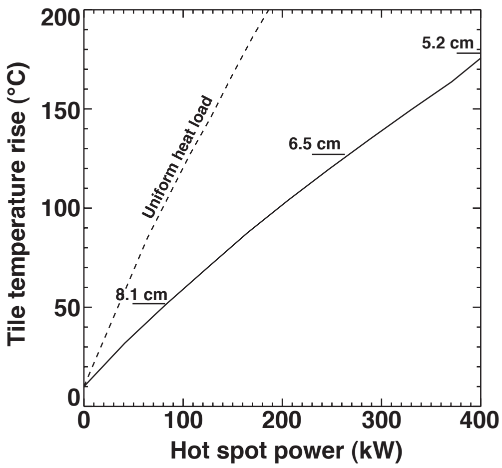

FIG. 8. The ANSYS calculated temperature rise versus the hot spot power with the hot spot foot print taken from SPIRAL (solid line). The dashed line indicates the tile temperature when a uniform heating was assumed.

front surface of the tile is needed. This will help to further constrain the thermal analysis and to validate the loss foot print using orbit loss codes. Interestingly, the present thermal analysis indicates that the front surface of the tiles should reach temperatures up to 1500°C, which make them incandescent. Unfortunately, no cameras were oriented to observe the tile front surface.

It should be noted that several assumptions are made in order to model the thermocouple reading from the incident thermal radiation. A major source of uncertainty is the conduction between the carbon tile and the stainless steel port. A further source of uncertainty is the thermal impedance between the thermocouple an the carbon tile. And finally, a surface emissivity has to be assumed in order to model the radiative power. Each of these assumptions introduce uncertainties that can effect the interpretation of the thermocouple reading and therefore the inference of the front heat load. This underscores again the need for accurate measurements of the thermal deposition footperint on the tiles. In addition, improved placement of the thermocouples and recessing the thermocouples closer to the front surface of the tiles can yield a more accurate estimate of the front surface heat load.

4. Summary and Outlook

Experiments in DIII-D have shown that magnetic fields generated by a scaled mock-up of two TBMs for ITER create a hot spot on the two central carbon tiles that protect the TBM surface when NBI was injected. It was found that the maximum tile temperature decreased rapidly when the gap between the separatrix and the TBM tile surface was increased.

A benchmark study was performed between the ASCOT, DELTA5D, OFMC, and SPIRAL codes. The codes agree well on the total power that is lost due to the TBM fields. the ASCOT, OFMC, and SPIRAL codes find a highly localized hot spot on or very close to the two central TBM tiles. The hot spot calculated with the DELTA5D code, however, is spread toroidally and poloidally much more then the three other codes, and is deposited below the mid plane.

Using the calculated highly localized power deposition profiles from SPIRAL as input to the thermal analysis for the tile yields much higher expected head load than found from the orbit simulations. However, various sources of uncertainty exist in the thermal analysis and in addition, the results are very sensitive to the size of the hot spot.

In order to resolve the discrepancy between the simulated heat loads and the ones that are needed to explain the measured thermocouple readings, thermal imaging measurements are needed of the hot spot on the TBM tiles. In addition, thermocouples should be added elsewhere on the tile mounted closer to the surface in order to detect inhomogeneities in the thermal deposition profile.

In order to model the heat loads on the TBM surfaces of ITER with confidence, the discrepancy between the thermal calculations and the fast ion loss simulations has to be resolved.

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References

[1] KRAMER, G.J., et al., Fusion Energy Conference 2008 (Proc. 22nd Int. Conf., Geneva, 2008) CD-ROM file IT/P6-3
[2] KURKI-SUONIO, T., et al., Nucl. Fusion **49** (2009) 095001
[3] SCHAFFER, M.J., et al., this conference, Paper ITR/1-3
[4] HEIKKINEN, J.A. and SIPILÄ, S.K., Phys. Plasmas **2** (1995) 3724
[5] TANI, K., et al., Journal of Phys. Soc. Jpn. **50** (1981) 1726
[6] SPONG, D.A., et al., Plasma Phys. Report **23** (1997) 483
[7] BUDNY, R.V., et al., Nucl. Fusion **35** (1995) 1497
[8] LAO, L.L., et al., Nucl. Fusion **30** (1990) 1035
[9] PARK, J.K., et al., Phys. Plasmas. **14** (2007) 052110

[10] PARK, J.K., private communication (2010)
[11] BOOZER, A.H. and KUO-PETRAVIC, G., Phys. Fluids **24** (1981) 851