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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. A hot spot on the TBM surface was found when neutral beams were injected and the TBM fields were engaged while the fast-ion core confinement was not affected. Different orbit-following codes predict the formation of a hot spot on the TBM surface in good agreement with the experiments. The hot spot is formed by beam-ion losses from the edge of the plasma. The codes agreed amongst each other on the power deposited at the hot spot. The simulated power deposition profiles were used to calculate the measured temperature response of the tile. A good qualitative agreement was found for the time history of the tile temperature but the peak temperatures were not well reproduced. This is probably caused by the beam-ion distribution that was used in the simulations. From these experiments it can be concluded that effective mitigation techniques exist if hot spots from fast-ion losses form due to TBM fields which is good news for ITER.

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 substantial fraction of the lost alpha particles 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 were 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 midplane when the TBM fields were activated. The clearest sign of beam-ion losses in the TBM experiments was the temperature increase of the protective carbon tiles of the TBM (Sec. 2).

The beam-ion confinement was studied with the ASCOT code [4] and the DELTA5D Monte Carlo code [5], 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 TRANSP analysis [6] of the studied discharges. All three codes indicate that an area with 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 present no significant heat loads were found. In order to compare the calculated heat loads with the measured tile temperatures heat transport calculations through the tiles were done because of the localized heat load and the thickness (2.5 cm) of the tiles (Sec. 3). The consequences for the ITER TBM experiments are discussed in Sec. 4. with a summary and outlook given in Sec. 5.

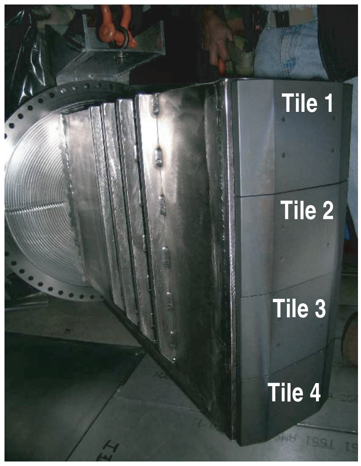

FIG. 1. The four protective carbon tiles on the DIII D TBM mock-up assembly.

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 toroidal magnetic field was 1.7 T, the plasma was current was 1.4 MA, and 5.8 MW of neutral beam heating was applied resulting in an ELMing H-mode with some tearing mode activity while no Alfvén eigenmode activity was observed during the phase that TBM 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.

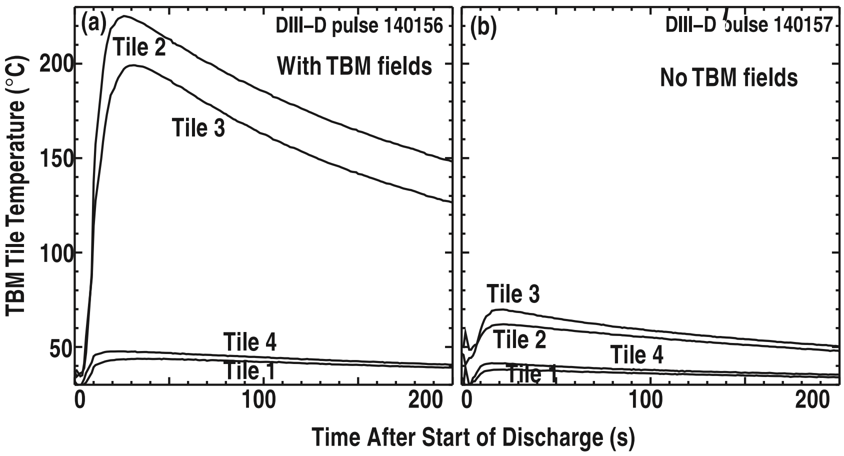

FIG. 2. Tile temperatures measured with the thermocouple at the back of the carbon tiles during and after two similar DIII-D discharges. In (a) the TBM fields were present while in (b) they were not present.

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 [8] it was found that the maximum plasma displacement towards the first wall was less than 1 cm [9], so the observed TBM tile heating is not caused by thermal plasma touching the tiles because the minimum gap width was 5 cm in the experiments. In discharges where the heating power was changed from neutral beam to electron cyclotron heating, only small increases in the tile temperature (< 5°C) were observed for all four tiles when the TBM fields were switched on indicating that beam-ions have to be present to create the hot spot on the TBM tiles.

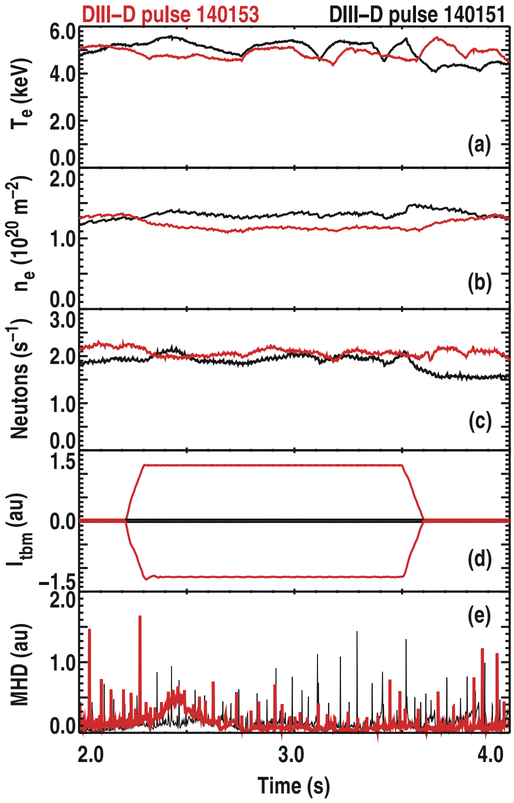

FIG. 3. The central electron temperature (a), density (b), neutron rate (c), TBM coil currents (d), and MHD activity (e) for a discharge without TBM fields in black (pulse 140151) and one with the TBM fields engaged in red (pulse 140153).

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 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.

In the following we will show that the observed TBM tile heating can be attributed to a hot spot due to fast-ion losses caused by the TBM fields and that the delay between the end of the discharge and the maximum temperature is caused by thermal transport through the 2.5 cm thick carbon tiles.

3. Particle-loss and Heat-load Simulations

Beam-ion transport was calculated with three different codes: the ASCOT and DELTA5D codes which are guiding-center following codes and the SPIRAL code which is a full-orbit following code. The ASCOT 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 three codes solve for the trajectory of birth energy beam ions using the actual toroidally asymmetric beam deposition profile calculated by TRANSP. 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 $\chi = v_{\parallel}/v = 0.5$ and with a width of 0.4 at half of its maximum. The particles were followed beyond the separatrix to a cylindrical surface at the radius of the TBM. Slowing down and collisions [10] 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 three 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 and SPIRAL code. The calculated total power deposited in the hot spot (integrated toroidally over ϕ=[80,90] deg and vertically over $Z = [-0.4, 0.4]$ m) is in very good agreement between the SPIRAL and ASCOT codes as can be seen in Table I.

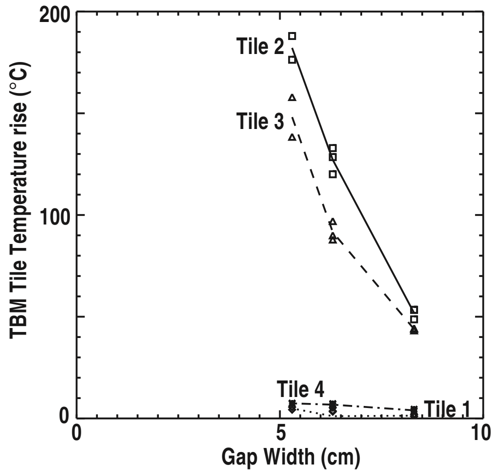

FIG. 4. The measured temperature rise of the four tiles for a 1 s long TBM pulse as a function of the outer gap. Each symbol is a separate discharge.

The footprint of the hot spot is somewhat larger in the ASCOT results compared to the SPIRAL results leading to lower peak heat fluxes in the ASCOT case. Both SPIRAL and ASCOT find that the hot spot is centered vertically on the middle two tiles (Fig. 5) which is in good agreement with the tile-temperature observations. 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 might be due to fact that ASCOT is following the guiding center of the particles while SPIRAL is following the full particle orbit. A more detailed comparison between the two methods is currently being pursued.

Table 1. The power deposited in the hot spot created by the TBM fields as calculated by the ASCOT and SPIRAL code for the three gap width settings. The power in columns three and four was integrated over an area given by ϕ=[80,90] deg and Z=[-0.4,0.4] m. The power deposited onto the TBM tiles was calculated with the SPIRAL code.

DIII-D	Gap	Hot Spot Power (kW)		Power (kW) Deposited At			
Pulse	(cm)	ASCOT	SPIRAL	Tile 1	Tile 2	Tile 3	Tile 4
140156	5.2	179.8	196.7	0.1	88.1	41.3	1.7
140153	6.5	186.8	189.6	1.0	107.1	30.6	0.6
140144	8.1	155.3	155.2	0.8	81.8	27.3	0.0

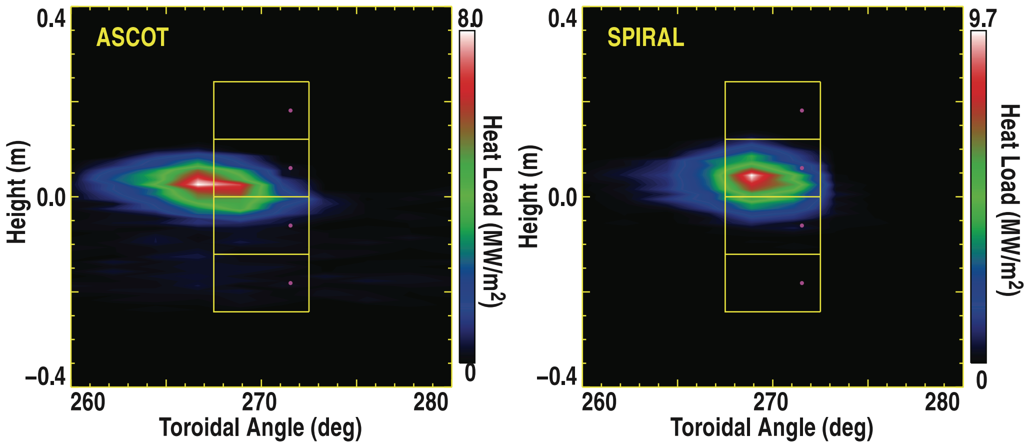

FIG. 5. Heat loads on the first wall near the TBM tiles, indicated in yellow, as calculated with the ASCOT code and the SPIRAL code for a gap width of 5.2 cm (DIII-D discharge 140156). Note the difference in the color scale. The purple dots indicate the location of the thermocouples at the back of the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

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 vertical limiters present, sticking 2.9 cm out from the outer cylinder, around 90, 225, and 315 deg. When those limiters are included in the simulations the power deposited in the hot spot at the TBM is reduced by about a factor of five, indicating that the limiters can remove a significant amount of power that would otherwise have gone to the surface of the TBM.

This reduction can be understood from the fact that passing particles that are born at the high-field side around $r/a = 0.85$ (Fig. 6) have orbits that are shifted outward compared to the flux surfaces. Therefore, those particles will pass outside the plasma at the low-field side into the region where the magnetic field disturbance due to the TBM is the strongest. Because of the high toroidal localization of the TBM fields it can take a few toroidal passes before those particles cross through the strong TBM fields. With the limiters included, those particles can be removed before they reach the TBM location.

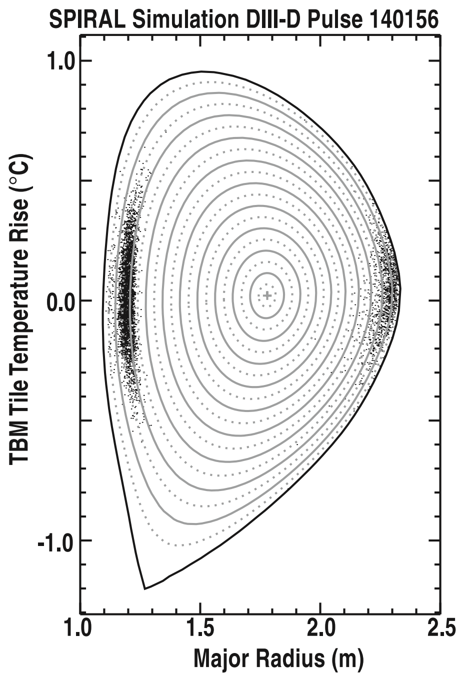

FIG. 6. Initial location of the beam-ions that are lost to the hot-spot at the TBM tiles in the SPIRAL simulations.

Although limiter temperature excursions are not a good measure for fast-ion losses because both fast ions and thermal ions are lost on the limiters, it was found experimentally that the temperature increase of the limiters in similar discharges with and without TBM fields present was the same. In the SPIRAL simulations it was found that the fast-ion heat deposition on the limiters was very similar for cases with or without TBM fields (less than 10% difference) which does not contradict the observations.

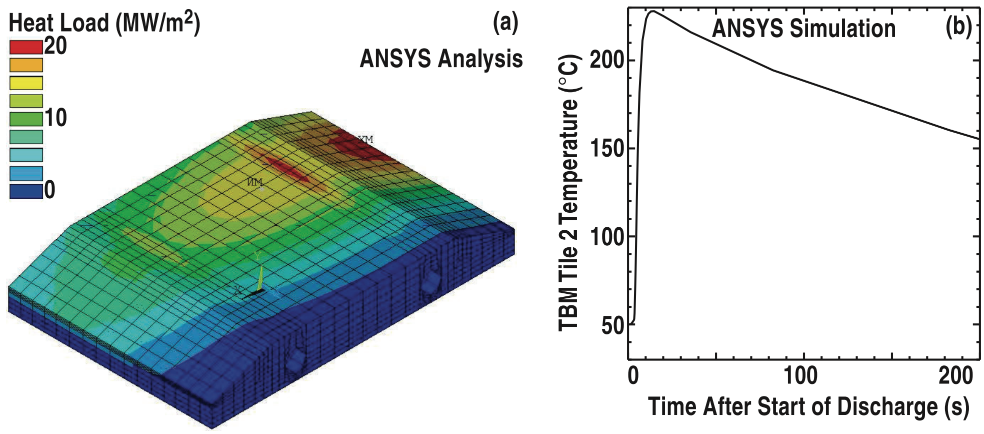

FIG. 7. (a) Initial heat load on the tile and (b) calculated thermocouple response as calculated with the ANSYS code.

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 response of the tiles to the heat load has to be modelled. We have calculated the dynamic temperature response with the 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. The time to peak and the rate of decay of the thermocouple temperature are qualitatively consistent with the DIII-D data. Interestingly, the front surface reached temperatures of well above 1500°C according to the ANSYS analysis. At these temperatures the tile would have been incandescent. Unfortunately, no cameras were oriented to observe the tile front surface.

Experimentally, a large variation in the tile temperature was found as function of the gap width (Fig. 4). When the heat loads as obtained from the fast-ion loss simulations are used [about 10 MW/m^2 for all three gaps width settings which is consistent with the finding that the calculated power deposited in the hot spot does not vary significantly for the three gap widths (Table 1)], we find a tile-temperature rise of 80°C to 90°C for all three gaps widths.

In order to investigate this discrepancy, we have to remark that the power which is deposited onto the TBM tiles depends on the footprint of the hot spot and on the peak heat load. The footprint is determined by the magnetic field topology in front of the TBM and is not expected to vary significantly for the three gap width settings, although there are some differences in the footprint as calculated by the SPIRAL, ASCOT, and DELTA5D code. The peak heat load is determined by the beam-ion deposition profile which was taken to be the same for the loss calculations. In order to investigate which heat loads are needed to get the observed tile temperatures, we have used the hot spot footprint as found with SPIRAL and varied the peak heat load in the ANSYS simulation as shown in Fig. 8. From this figure we can see that we have to lower the peak heat load to 5 MW/m^2 for a gap width of 8.1 cm while for a gap width of 6.5 cm 16 MW/m^2 and a peak heat load of 25 MW/m^2 for the smallest gap width of 5.2 cm.

One explanation for the discrepancy between the peak head load calculated with particle-orbit following codes and the ones deduced from the heat transport calculations is that the beam deposition used in the orbit-following codes is incorrect. This is currently under investigation.

4. ITER

Fast ions in ITER are created in fusion reactions in the plasma core and to a lesser extent from neutral beam injection (NBI). In the DIII-D experiments it was found that the core confinement was not affected by the TBM fields, a fact that is also supported by fast-ion loss calculations for ITER [1, 2]. Some caution, however, has to be taken in extrapolating the loss results from the current DIII-D experiments to ITER. The TBM fields in DIII-D were chosen in such a way that DIII-D represented a scaled-down version of ITER. Fast-ion parameters such as the slowing-down time and critical energy were not in the scaled range of the ITER parameters. The fast ions in the DIII-D experiments were close to the critical energy while in ITER the alpha particles are born well above the critical energy while the slowing-down time for fusion-born alpha particles in ITER is on the order of one second compared to the fast-ion slowing down ten times lower in the DIII-D experiments. Moreover, in the DIII-D experiments the beam-ion distribution was highly anisotropic and the trapped-particle loss cone was hardly covered by this distribution. The fusion-born alpha distribution in ITER is isotropic and a fraction of the alpha particles is born inside the loss cone and may contribute significantly to the heat load on the TBM tiles.

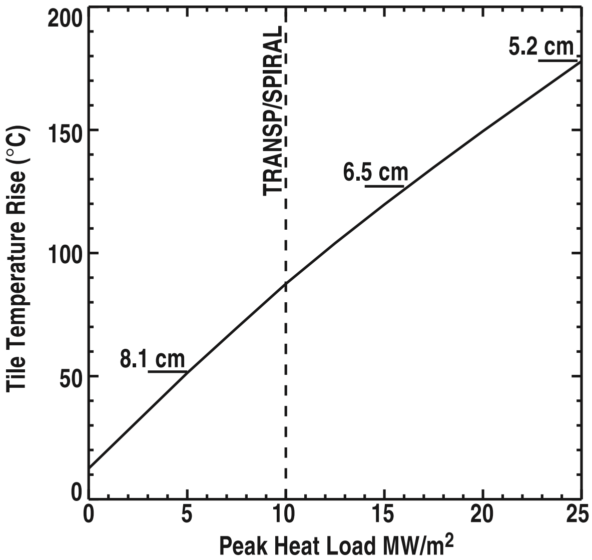

FIG. 8. Tile temperature rise as function of the peak head load as calculated with the ANSYS code for a hot spot footprint calculated with SPIRAL. The experimentally found tile temperature increases are indicated with their respective gap widths and the calculated heat load as found from using the TRANSP fast-ion distribution in SPIRAL is shown as a vertical dashed line.

Therefore, in ITER one still has to be concerned about the creation of hot spots on the TBM surfaces. However, the DIII-D experiments have shown a viable way to reduce the heat loads by increasing the gap between the separatrix and the plasma-facing surface of the TBM. In those experiments the maximum tile temperature dropped by more than 120°C when the gap was increased from 5 to 8 cm. In the particle-loss simulations it was also found that vertical limiters can also help to reduce the heat loads on the TBMs whereby the toroidal location of those limiters is not too critical.

5. 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 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.

Beam-ion loss calculations with different fast-particle orbit-following codes confirmed that the observed heating of the two central tiles is caused by beam-ion losses. Those lost beam-ions were found to come from ions that were deposited near the plasma edge. The fast-ion confinement in the plasma core was not affected by the TBM fields.

The peak tile-temperature measured at the back of the tile was reached after the pulse is over which is in accordance with heat-transfer calculations in which the heat load profile was used from the beam-ion loss simulations. The peak tile temperatures were not well reproduced in those calculations which is probably caused by the beam-ion distribution used in the simulations. More work is underway to understand and resolve this difference and validate the code predictions with experiments.

Although there are some significant differences between the fast-ion population in the current experiments and in ITER, it can be concluded that the fast ion confinement will not be significantly degraded by the TBM fields in ITER. Even if fast ion losses are a substantial threat to the TBM experiments, effective mitigation techniques exist to reduce the the formation of hot spots on the TBM surfaces in ITER. The current experiments have shown that the heat load can be reduced strongly by increasing the gap between the separatrix and the plasma facing front of the TBMs while the simulations have indicated that vertical limiters on the low-field side vessel wall can also be beneficial to reduce the heat loads on the TBMs further.

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