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FAST ION EFFECTS DURING TEST BLANKET MODULE SIMULATION EXPERIMENTS IN DIII-D

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[1]Plasma Physics Laboratory, Princeton, New Jersey
[2]University of California-Irvine, Irvine, California
[3]Helsinki University of Technology, Helsinki, Finland
[4]Japan Atomic Energy Agency, Naka-gun, Ibaraki Japan
[5]ITER Organization, Cadarache, France
[6]Oak Ridge National Laboratory, Oak Ridge, Tennessee

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A major goal on ITER is to study tritium breeding in 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. These distortions can reduce the confinement of fast ions, especially the fusion-born alpha particles. The confinement of fast beam-ions was studied in DIII-D in the presence of a scaled mock-up of two TBMs for ITER. The TBM on DIII-D has four protective carbon tiles arranged vertically (Fig. 1) with a thermocouple placed in the center of the back of each tile. Heat loads on the four plasma facing carbon tiles were measured and temperature increases of up to 200°C were found for the two central tiles closest to the mid-plane when the TBM fields were activated. These measurements agree qualitatively with results from the full orbit-following beam-ion code, SPIRAL, that predict beam-ion losses localized to the central two carbon tiles near the plasma midplane when the TBM fields are energized.

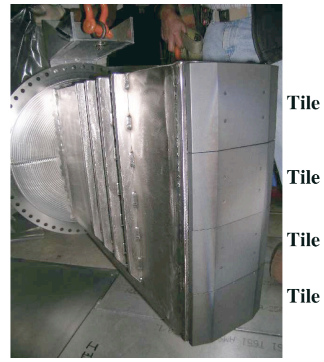

Fig. 1. A picture of the DIII-D TBM mock-up assembly with the four protective carbon tiles visible at the right.

The SPIRAL code is a full orbit following Lorentz solver with slowing down and collisions included. The code takes EFIT axisymmetric equilibria and superimposes the full 3-D ripple field induced by the TBM. The code solves for the trajectory of birth energy beam ions using the actual toroidally asymmetric beam deposition profile calculated using TRANSP. The particles are followed beyond the separatrix to a cylindrical surface at the radius of the TBM. A distribution of 105 D_2 ions per beam source with 60 to 80 kV birth energy are followed for 40 ms. Analysis is performed on a discharge with 5 beam sources for a total of 5.5 MW beam power in DIII-D. Figure 2(a) shows the calculated beam ion heat deposition on the TBM tiles, indicating the heating is localized to the two central tiles closest to the midplane. Figure 2(b) shows the integrated power on each tile vs the separation between the TBM front surface and the plasma separatrix. The SPIRAL analysis shows the rapid increase in the beam losses to the central two TBM tiles with decreasing separation. The simulations indicate that the fast-ion losses due to the TBM fields are from ions born near the plasma edge on co-going orbits. The additional losses due to the TBM fields are of the order of 1% to 5% depending on the beam geometry (co vs counter, tangential vs perpendicular). The losses are maximized for tangential co-beam injection as these particles have the largest drift orbit shift to the low field side of the torus where the TBM field is localized. The losses are smallest for counter tangential injection as these drift orbits shift inward, away from the TBM field.

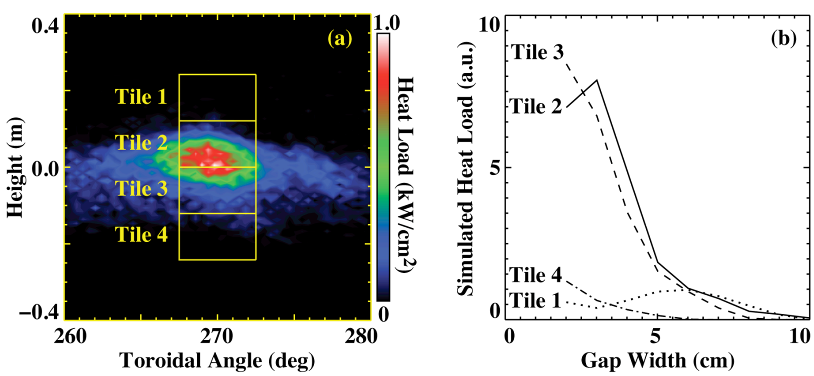

Fig. 2. (a) The calculated spatial distribution of the heat load on the four TBM tiles indicated with the yellow boxes. (b) The calculated heat load for the 4 TBM tiles as function of the gap between the last closed flux surface and the TBM surface for a 1 MW tangential beam.

Figure 3(a) shows the time evolution of the thermocouple measurement on the backside of the four tiles, indicating strong localization of heating to the two central tiles nearest the midplane. Figure 3(b) shows the measured peak tile temperature vs separation of the TBM to the separatrix for nominally identical plasmas indicating sensitivity of the temperature on the central two tiles to the plasma separation. This is qualitatively consistent with calculated losses based on the SPIRAL analysis in Fig. 2(b). Peak temperature rises of up to 200°C were observed at the smallest displacement to the separatrix for fully energized TBM coils.

The thermocouple response was modeled with the ANSYS code in which the power deposition profile from SPIRAL was used. Figure 4(a) shows the Finite Element Model of the ATJ carbon tile with the heat distribution superimposed on the front surface based on the SPIRAL analysis. Figure 4(b) shows the temperature evolution of the tile taking into account radiation losses and conduction to the TBM steel port structure. The analysis shows that a peak temperature of 200°C can be obtained on the thermocouple for an incident heat load of 2% of the total beam power. This is in the range of the losses calculated using SPIRAL. The time to peak and the rate of decay of the thermocouple temperature reading is qualitatively consistent with the data on DIII-D. Interestingly, the peak front surface tile temperature reaches 1400°C according to the ANSYS analysis. At this temperature the tile would have been incandescent, however, no cameras were oriented to observe the tile front surface.

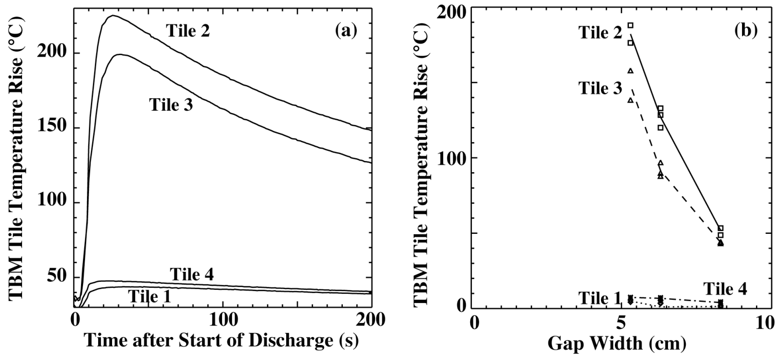

Fig. 3. (a) Tile temperatures during and after a DIII-D discharge measured with the thermocouple at the back of the protective carbon tiles. (b) The measured temperature rise of the four tiles for a 1 s long TBM pulse as a function of the outer gap.

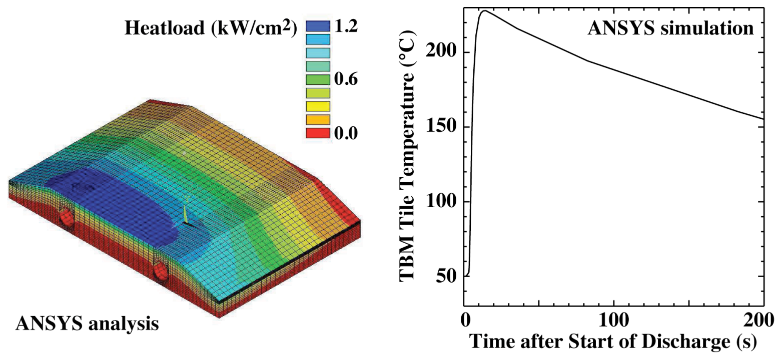

Fig. 4. Calculated thermocouple response for tile 2 as function of time.

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 SPIRAL analysis that indicates only edge deposited beam ions are lost to the TBM. These results suggest that fast ion confinement will not be significantly degraded by the TBM fields in ITER, however more quantitative analysis is required to validate SPIRAL calculations on DIII-D for predicting front surface heating of the ITER TBM modules due to fast ions.

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