Princeton Plasma Physics Laboratory

PPPL- 4630

PPPL- 4630

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

G. Kramer, R.V. Budny, R. Ellis, M. Gorelenkova, W.W. Heidbrink, T. Kurki-Suonio, R. Nazikian, A. Salmi, M.J. Schaffer, K. Shinohara, J.A. Snipes, D.A. Spong, T. Koskela, and M.A. Van Zeeland

May, 2011

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

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

G.J. Kramer[1], R.V. Budny[1], R. Ellis[1], M. Gorelenkova[1], W.W. Heidbrink[2], T. Kurki-Suonio[3], R. Nazikian[1], A. Salmi[3], M.J. Schaffer[4], K. Shinohara[5], J.A. Snipes[6], D.A. Spong[7], T. Koskela[3], and M.A. Van Zeeland[4]

[1] *Princeton Plasma Physics Laboratory,*

PO Box 451, Princeton, NJ 08543-0451, USA

[2] *University of California-Irvine, Irvine, CA 92697, USA*

[3] *Aalto University, 00076 Espoo, Finland*

[4] *General Atomics, P.O. Box 85608, San Diego, CA 92186-5608*

[5] *JAEA, 80101 Mukouyama, Naka City, Ibaraki, 311-0193, Japan*

[6] *ITER Organization, Route de Vinon sur Verdon,*

13115 St. Paul-lez-Durance, France and

[7] *Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831,USA*

(Dated: May 31, 2011)

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 of the protective tiles on the front of 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 are in good agreement with each other on the total power deposited at the hot spot predicting an increase in power with decreasing separation between the plasma edge and the TBM surface. A thermal analysis of the heat flow through the tiles shows that the simulated power can account for the measured tile temperature rise. The thermal analysis, however, is very sensitive to the details of the localization of the hot spot which is predicted to be different among the various codes.

I. 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 increase the fast ions losses from neutral beam injection and fusion-born alpha particles [1]. 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] a scaled mock-up of two TBMs for ITER was placed in the machine to study the plasma response to the error fields induced by the TBM as shown in Fig. 1. In this paper the effects of the TBM fields on the confinement of fast beam-ions is reported. 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. 2). Temperature increases of up to 230°C were measured (Fig. 3) at the back of the two central tiles closest to the mid plane when the TBM fields were activated (Sec. II). Beam-ion loss simulations were performed with a number of codes and they indicate that this temperature rise is an indication of beam-ion losses caused by the TBM fields. The beam-ion confinement was studied with the ASCOT code [4] the OFMC code [5, 6] and the DELTA5D Monte Carlo code [7], which are guiding center following codes and the SPIRAL code [2] which is a full gyro-orbit following code. A number of TBM discharges were analyzed to perform a benchmark between the codes and to validate the results with the observations. The codes indicate that a localized area of high heat loads is formed on or near the middle of 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 (Sec. III).

A finite element method was used to simulate the thermocouple response for the calculated heat loads from the different codes which is then compared directly with the measured tile temperature excursions during the experiments (sec. IV). Although the simulations are in fair agreement with the experiments, some caution has to be taken in the extrapolation of these results to ITER as discussed in sec. V while the conclusions are summarized in sec. VI.

II. 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. 3 the time history of the TBM tile temperatures is compared, while in Fig. 4 a comparison of the time-history of the plasma parameters is made between a discharge with the TBM coils engaged and the corresponding discharge without TBM fields. In all the discharges the toroidal magnetic field was 1.7 T, the plasma 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 eigenmodes were observed during the phase that the 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.

In the discharges where the TBM coils were not energized the tile temperature rose less than 20°C after the discharge was completed [Fig. 3(b)] while in discharges with the TBM fields present the temperature of the middle two tiles (tile 2 and 3 in Fig. 3) 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. 5.

When the TBM fields are present, the thermal plasma is locally pulled outward in the direction of the wall. From two independent 3D equilibrium calculations performed with the VMEC and IPEC codes [11] respectively, it was found that the maximum plasma displacement towards the first wall was less than 1 cm. Therefore, the observed TBM tile heating is not caused by thermal plasma touching the tiles 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. The ELM behavior did not change between the shots in which the TBM fields were engaged and the reference shots without TBM fields as can be seen in Fig. 4e and therefore, the measured tile temperature increase in the TBM shots is not caused by a change in ELM behavior.

Additional fast-ion diagnostics, such as fast-ion D_α (FIDA) [12] and neutron scintillators [13], were used to detect possible signs of central fast-ion loss or redistribution. Within the 5% experimental uncertainties no significant change in the fast-ion population was found in the core of these plasmas as can be seen in Fig. 4c for the neutron signals. This is consistent with the beam-ion loss simulations that indicate only edge deposited beam ions are lost to the TBM as can be seen from Fig. 6.

III. PARTICLE-LOSS AND HEAT-LOAD SIMULATIONS

Beam-ion transport was calculated with four different particle-orbit following codes: the OFMC, and DELTA5D codes which are guiding-center following codes the SPIRAL code which is a full-orbit following code and the ASCOT code which has both guiding-ceter following and full orbit capabilities [9]. The ASCOT, OFMC, and SPIRAL codes use EFIT axisymmetric equilibria with the vacuum 3-D ripple field induced by the TBM superimposed on it as a perturbation 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 [10]. 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, χ, distribution that was centered at $\chi = v_\parallel/v = 0.5$ 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 [14] 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.

No hot spot was found at the location of the TBM in simulations without the TBM fields included while a distinct hot spot appears when the TBM fields are present as can be seen in Fig. 7. The ASCOT, OFMC, and SPIRAL codes show the formation of a hot spot on the central two TBM tiles as is shown in Fig. 8 whereby losses from all the injected beams contribute to the hot spot. The DELTA5D code finds a hot spot that is toroidally and vertically displaced from the TBM tiles. The DELTA5D model model differs from the other three through its direct coupling to a 3D equilibrium. It is at an earlier stage of development and further convergence studies and benchmarking will be required to understand and verify the different structure of fast ion loss patterns that it predicts. The calculated total power deposited (integrated toroidally over ϕ=[260,280] deg and vertically over $Z = [-0.4, 0.4]\,\mathrm{m}$) is in good agreement between the ASCOT, OFMC, and SPIRAL codes as can be seen in table I. The DELTA5D code gives a similar value for the total deposited power when the power is integrated over a larger area (integrated toroidally over ϕ=[230,330] deg and vertically over $Z = [-0.4, 0.4]\,\mathrm{m}$) as can be seen in table I.

In the above results an axisymmetric wall was used as shown in Fig. 6 with a maximum radius of 2.38 m from 0.4 m below to 0.4 m above the mid plane. 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 simulations, the power deposited in the hot spot at the TBM is reduced as can be seen in table I, indicating that the limiters can remove some of the power that would otherwise have gone to the surface of the TBM.

Experimentally, a large increase in the tile temperature was found when the gap between the separatrix and the TBM surface was decreased as was shown in Fig. 5. The ASCOT, OFMC, and SPIRAL codes were able to reproduce this result. All three codes agree well on the total power deposited in the hot spot and they were able to reproduce a decrease in power with a widening gap between the plasma and TBM surface as can be seen in Fig. 9 for cases without limiters and with limiters included. This is in line with the experimental observations. In the experiments, however, the temperature at the back of the tiles is measured while in the simulation the heat loads on the front of the tiles are calculated. In order to make a more accurate comparison between simulations and experiment heat flow calculations through the 2.5 cm thick tiles have to be performed.

IV. HEAT TRANSFER CALCULATIONS

In order to compare the plasma-facing surface heat loads calculated by the ASCOT, OFMC and SPIRAL codes against the measured tile backside temperatures, dynamic spatial-temporal temperature distributions in a tile model were computed using the finite element ANSYS code. An example of the simulated temperature response at the thermocouple location in which radiation losses and conduction to the TBM steel port structure were included, is shown in Fig. 10(a) where the power deposition profile from the SPIRAL code was used [Fig. 10(b)]. The calculated tile temperature is a more sensitive test for the different simulation codes than the total power deposited in the hot spot because the different codes predict small differences in heat load footprints while the temperature rise on the back of the tile is very sensitive to the details of the heat load profile on the front.

A comparison between the measured and simulated tile temperature rise for tile 2, the tile with the highest heat load, is shown in Fig. 11. From this figure it can be seen that although the codes agree well on the total lost power, they agree less well on the temperature rise as measured with a thermocouple on the back of the tile. In the heat transfer calculations we have used the heat loads and foot prints that were found by the different codes. The location of the foot prints as predicted by the codes varies between the different codes as well as the size of the foot prints as can be seen in Fig. 8. While the ASCOT and OFMC codes show little variation in the calculated tile temperature rise as a function of the gap width, the SPIRAL code is able to reproduce the trend in peak temperature as function of the gap width as seen in the experiments.

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 and 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. Therefore, more accurate measurements of the thermal deposition footprint on the tiles are needed. An improved placement of the thermocouples recessed into the tiles closer to the front surface can yield a more accurate estimate of the front surface heat load.

V. ITER

Fast ions in ITER are created in fusion reactions in the plasma core and closer to the edge from NBI injection. In the DIII-D experiments it was found that the core confinement was not affected by the TBM fields, a fact that is supported by fast-ion loss calculations for ITER [1, 2, 15]. 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 ten times lower fast-ion slowing down time 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 beam-ion 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 to the heat load on the TBM tiles. Furthermore, Alfénic activity can be excited by the alpha particles which can induce fast-ion losses from the core that can contribute to increased heat loads to the TBM surfaces.

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 the DIII-D experiments the maximum tile temperature dropped by more than 120°C when the gap was increased from 5 to 8 cm. In the DIII-D particle-loss simulations it was also found that vertical limiters can help to reduce the heat loads on the TBMs whereby the toroidal location of those limiters is not too critical. A similar conclusion was drawn in [15] where it was shown from ITER fast-particle loss simulations that limiters can reduce the the TBM head loads to harmless levels when vertical limiters are included.

VI. SUMMARY AND OUTLOOK

Experiments in DIII-D have shown that the 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 fast-particle orbit following codes ASCOT, DELTA5D, OFMC, and SPIRAL. 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 the two central TBM tiles which is in agreement with the experiments. The hot spot calculated with the DELTA5D code, however, misses the protective TBM tiles and is displaced toroidally and poloidally reflecting the 3-D VMEC equilibrium which was used in the DELTA5D code.

When the simulated heat loads from ASCOT, OFMC, and SPIRAL are used to calculate the response of the thermocouple on the back of the TBM tile, temperatures are found that are well within a factor of two of the observed temperatures. The difference in simulated temperatures from the various codes can be attributed to differences in the calculated hot-spot foot prints. In order to distinguish experimentally between the different simulated footprints, multiple temperature measurements are needed for the middle two tiles where the hot spot is located.

Notice: This manuscript has been authored by Princeton University under Contract Number DE-AC02-09CH11466, C-G903402, DE-FC02-04ER54698 and DE-AC05-00OR22725 with the U.S. Department of Energy. The publisher, by accepting the article for publication acknowledges, that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The supercomputing resources of CSC-IT center for science were utilized in the studies. This work was partially funded by the Academy of Finland projects 121371 and 134924. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

---

[1] SHINOHARA K., et. al., Fus. Enginering Des. **84** (2009) 24

[2] KRAMER, G.J., et al., Fusion Energy Conference 2008 (Proc. 22nd Int. Conf., Geneva, 2008) CD-ROM file IT/P6-3, http://www-pub.iaea.org/MTCD/Meetings/FEC2008/it_p6-3.pdf

[3] Schaffer, M.J., et al., ITER Test Blanket Module Error Field Simulation Experiments at DIII-D, submitted to Nuclear Fusion (February 2011)

[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] SHINOHARA K., et. al., Nucl. Fusion **43** (2003) 586

[7] SPONG, D.A., et al., Plasma Phys. Report **23** (1997) 483

[8] LAO, L.L., et al., Nucl. Fusion **30** (1990) 1035

[9] SNICKER, A., et al., IEEE transactions on Plasma Phys. **38** (2010) 2177

[10] BUDNY, R.V., et al., Nucl. Fusion **35** (1995) 1497

[11] PARK, J.K., et al., Phys. Plasmas **14** (2007) 052110

[12] LUO, Y., et al., Rev. Sci. Instr. **78** (2007) 033505

[13] HEIDBRINK, W.W., et al., Rev. Sci. Instr. **68** (1997) 536

[14] BOOZER, A.H. and KUO-PETRAVIC, G., Phys. Fluids **24** (1981) 851

[15] KURKI-SUONIO, T., et al., Nucl. Fusion **49** (2009) 095001

	Hot Spot Power (kW)		Power on tile 2 (kW)	
Simulation Code	No limiters	Limiters	No limiters	Limiters
ASCOT	130	107	35	32
DELTA5D	118	—	—	—
OFMC	143	123	70	66
SPIRAL	146	114	76	66

TABLE I: The power deposited in the hot spot created by the TBM fields as calculated by the ASCOT, DELTA5D, OFMC, and SPIRAL codes for DIII-D pulse 140156 with a gap of five cm. The power was integrated over an area given by ϕ=[260,280] deg and Z=[-0.4,0.4] m for ASCOT, OFMC, and SPIRAL while for DELTA5D the integration was performed over the same Z-range and ϕ=[230,330] deg.

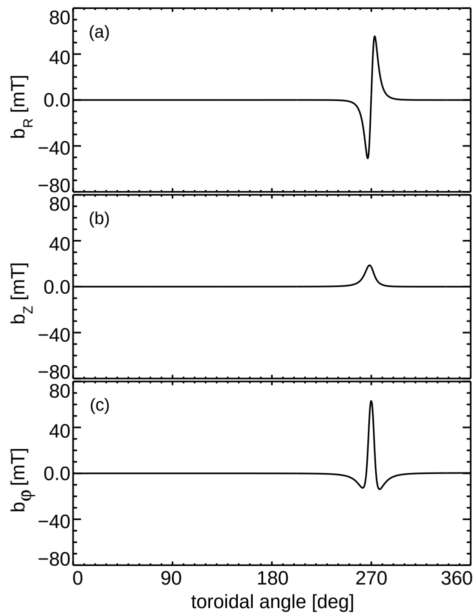

FIG. 1: The (a) radial, (b) vertical, and (c) toroidal magnetic field components generated by the TBM mock-up in DIII-D on the mid-plane at the low-field side plasma edge.

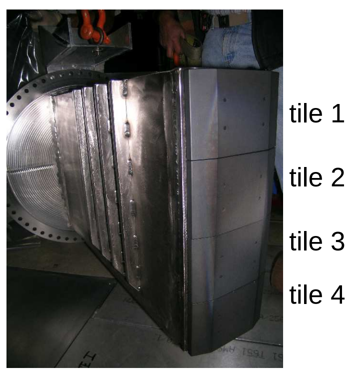

FIG. 2: The four protective carbon tiles on the DIII D TBM mock-up assembly.

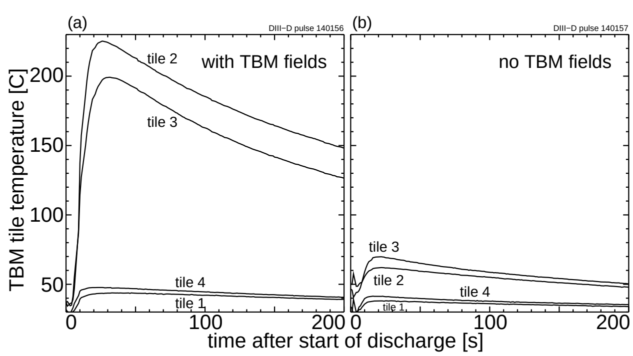

FIG. 3: Tile temperatures measured with the thermocouple at the back of the carbon tiles during and after two similar DIII-D discharges. In (a) the TBM fields were present while in (b) they were not present.

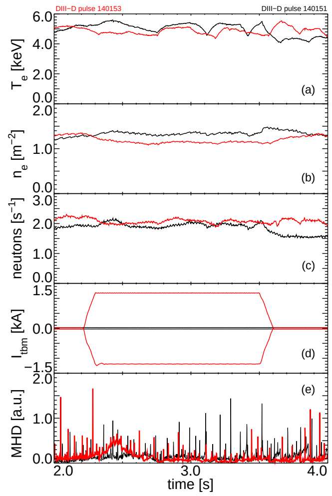

FIG. 4: The central electron temperature (a), density (b), neutron signal (c), TBM coil currents (d), and MHD activity (e) for a discharge without TBM fields in black (pulse 140151) and one with the TBM fields engaged in red (pulse 140153).

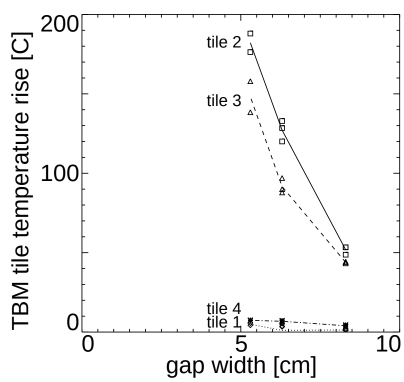

FIG. 5: The measured temperature rise of the four tiles for a 1 s long TBM pulse as a function of the outer gap. Each symbol is a separate discharge.

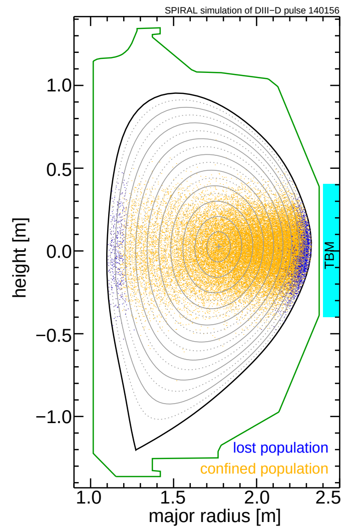

FIG. 6: Initial location of the confined (yellow) and lost (blue) beam-ions from a SPIRAL simulation that included the TBM fields.

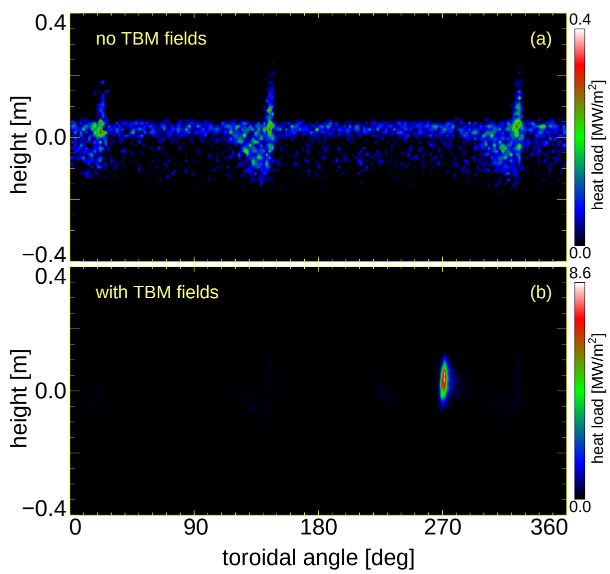

FIG. 7: Heat loads on the first wall as calculated with the SPIRAL code (a) without the inclusion of the TBM fields (DIII-D discharge 140157) and (b) with the TBM fields (DIII-D discharge 140156). Note the large change in color scale between the two graphs.

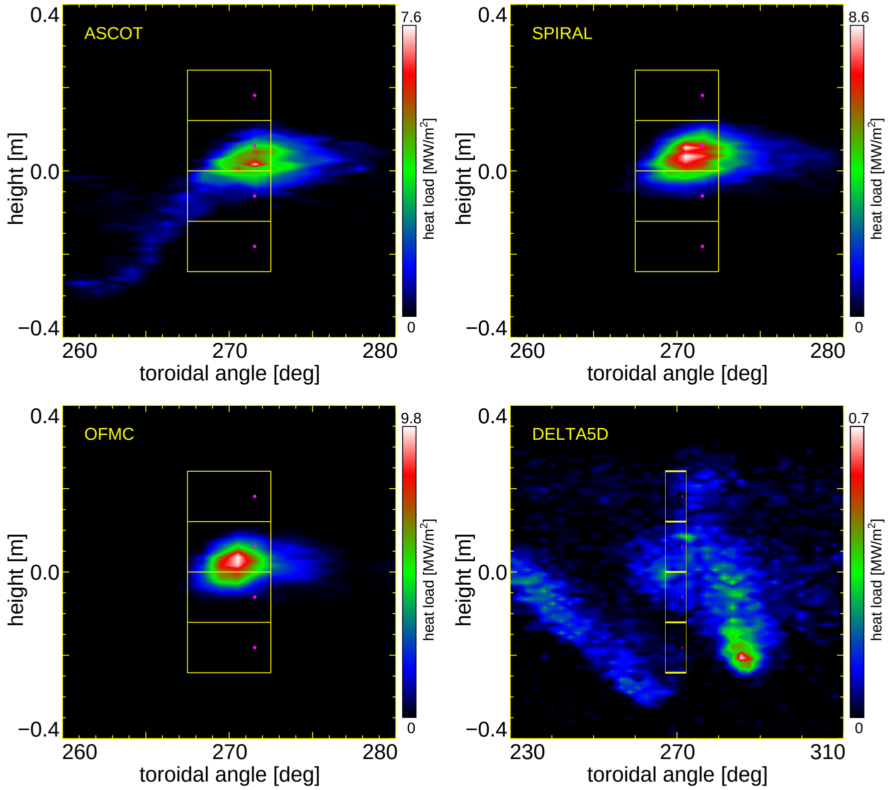

FIG. 8: Heat loads on the first wall near the TBM tiles, indicated in yellow, as calculated with the ASCOT, SPIRAL, OFMC, and DELTA5D codes for DIII-D discharge 140156. Note the difference in the color scale. The purple dots indicate the location of the thermocouples at the back of the tiles.

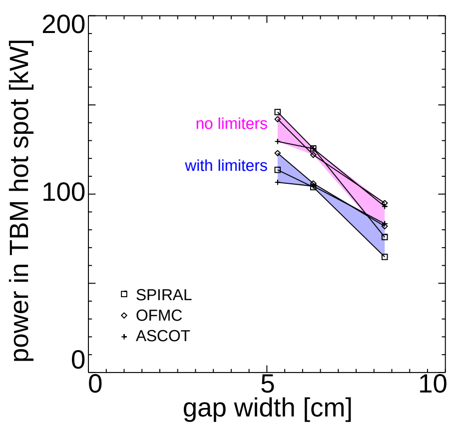

FIG. 9: Power in the hot spot created by the TBM fields as calculated by the ASCOT, OFMC, and SPIRAL code as function of the gap between the separatrix and the TBM surface.

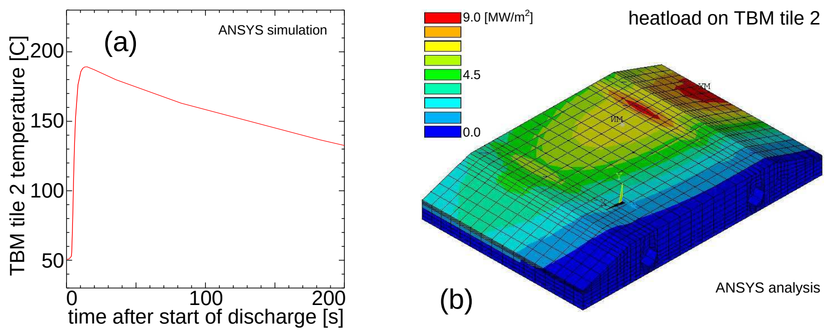

FIG. 10: (a) Thermocouple response as calculated with the ANSYS code and (b) the initial heat load on the tile.

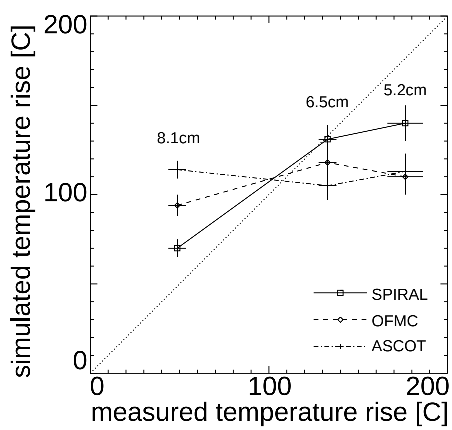

FIG. 11: A comparison between the measured and simulated temperature rise for tile 2 at the location of the thermocouple as calculated with the ASCOT, OFMC, and SPIRAL codes. The gap width is indicated for the three experimental temperatures.

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov