Physics of toroidal gap heat loading on castellated plasma-facing components

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For power handling reasons, the water cooled, plasma-facing components in the ITER tungsten divertor will be castellated, comprising tens of thousands of individual monoblocks (MB). Gaps in both the toroidal (TG) and poloidal (PG) directions introduce leading edges onto which plasma heat flux can be focused, even if misalignments between neighbouring MBs are eliminated. Depending on the magnetic configuration, regions which would be shadowed in a purely optical picture can be accessed by ions with finite Larmor radius, a problem which can be particularly acute during Edge Localized Modes (ELM) when energetic ions from the pedestal region impact the target during the transient heat pulse. Heat loads on the ITER MBs are being assessed using 3D ion orbit calculations [1], guiding efforts to find a shaping solution which avoids gap edge over-heating. Toroidal bevelling will hide leading edges on each side of PGs from inter-ELM heat loads (at the expense of higher perpendicular loads on the top surface), but a solution for hiding all the long TG edges on both inner and outer targets has not yet been found. The ion orbit simulations predict that even mitigated ELMs can melt TG edges in the strike point regions, posing a potential MB lifetime risk.

Although the consequences of TG loading may be significant for ITER, the phenomenon had never actually been seen in a tokamak until a series of dedicated experiments, reported here, was performed on the COMPASS tokamak. The low magnetic field in COMPASS makes the ratio of the ion Larmor radius to the gap width relevant to ITER ELMing conditions. Using special instrumented central column graphite tiles bearing poloidal and toroidal gaps, viewed with a high spatial resolution (0.5 mm/pixel) infra-red camera diagnostic, clear evidence for TG heating has been obtained for the first time. By changing the direction of the poloidal and toroidal magnetic fields, the four possible configurations of field line interactions with TGs have been examined. The resulting heat load distributions have been compared with heat flux profiles derived from both the optical approximation and simulations using the 2D particle-in-cell code SPICE, including self-consistent electric fields.

In two of the field configurations, plasma flux is observed to impinge on the unshadowed TG side, as expected optically, but in the other two, heat is deposited on both gap sides, and therefore in the magnetically shadowed regions, in excellent agreement with SPICE code results. This same code has been used to benchmark the 3D ion orbit calculations for ITER [2], providing confidence both in the existence of the TG loading phenomenon and in the validity of the simpler ion orbit approach. The experiment-code comparison has also emphasized the role played by local non-ambipolarity in determining the distribution of heat loading. In a separate experiment, time-varying bias voltage waveforms have been applied to a specially designed electrically insulated TG to select between electron-dominated and ion-dominated regimes. In the case of two-sided deposition and depending on bias voltage, the heat load is observed to switch sides, following theoretical expectations. These unique experiments demonstrate not only that TG loading does occur, but that the physics of this phenomenon is understood and must be accounted for in the ITER divertor shaping design.

[1] J.P. Gunn et al., *Nucl. Fus.* **57** (2017) 046025
[2] M. Komm et al., *Nucl. Fus.* **57** (2017) 126047