3D PIC simulations of gap crossings in castellated plasma-facing components

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Abstract

This paper presents particle-in-cell simulations of castellated plasma-facing components (PFCs). The subject of the study is an investigation of elevated heat loads received by the PFCs and plasma penetration into gaps between tiles. Both of these problems are of high importance for ITER when estimating the life time of its PFCs. Localized heat loads can potentialy lead to a damage of the tiles, while the plasma penetration is related to fuel rentention in the gaps due to formation of hydrocarbon layers.

This problematics has previously been targeted by 2D PIC simulations using our in-house code SPICE2, where toroidal and poloidal gaps had to be simulated separately. This paper presents result of a full 3D3V code SPICE3, which allows to simulate a more realistic geometry of the tiles including the gap crossings.

The results of simulations show that the crossing acts as a transport channel for electrons, allowing them to enter the plasma shadow in poloidal gaps. The combination of the plasma flow and ExB drift in the crossing directs ions onto a hotspot, which is receiving high heat load.

Introduction

The gap simulations are interesting because of the implications for ITER and other next step devices. The gaps set operational limits to the machine because of fuel retention [1] and because of elevated heat fluxes, which occur on gap edges. The simulations of heat fluxes for ITER tiles have already been performed using the 2D code SPICE2 [2], however such simulations assume infinite length of the gaps. Real PFCs have finite dimensions and their gaps intersect in crossings. The crossings are expected to influence the plasma behaviour because of a combination of plasma flows. This interplay may result in a formation of a hotspot with elevated heat flux. In order to investigate such problem, a full 3D simulation is needed. The results will be compared to previous 2D simulations to validate the infinite gap assumption.

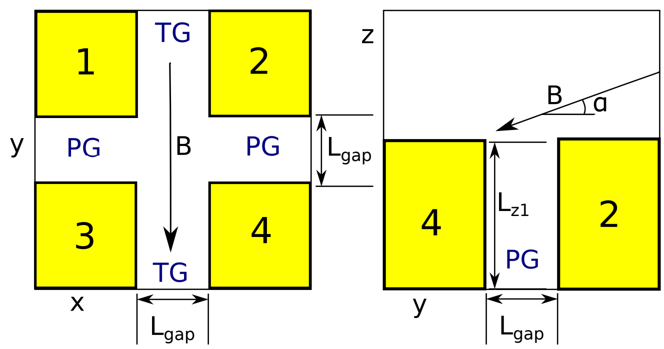

Figure 1: Schematic view of the gap crossing, top view (left) and side view (right).

SPICE3 code

SPICE3 [3] is a full 3D3V cartesian PIC code, an extension of the existing SPICE2 code [4] [5]. The simulation region contains 4 blocks, which represent 4 corners of tiles and form a crossing of a poloidal gap (PG) and toroidal gap (TG) as shown in Fig. 1. Due to computational constraints on the size of the region, only a part of a tile is simulated in the vicinity of the crossing. All blocks are kept at floating potential. The magnetic field is parallel to the toroidal gap and has a given inclination α with respect to the tile top surface.

In order to investigate physical processes related to plasma interaction with the crossing, an example simulation with parameters relevant to SOL plasma conditions was performed. The plasma conditions were as follows: plasma density $n = 2 \times 10^{18}$ m^{-3}, ion temperature $T_i = 50$ eV, electron temperature $T_e = 25$ eV, magnetic field magnitude $B = 2.0$ T and the magnetic field inclination $\alpha = 10°$. The gaps were 0.5 mm wide and 1.0 mm deep.

Note that these parameters are realistic for contemporary tokamak SOL, however far from expected ITER conditions, where the plasma density and magnetic field strength will be much higher. The available space of plasma parameters is severely restricted by computational demands. However, the key parameter, the ratio of ion Larmor radius to gap width, is kept the same as expected in ITER - of the order of unity. The aim of this simulation is to demonstrate transport mechanism related to the presence of gap crossing, not to predict exact values of heat fluxes on ITER divertor tiles.

Results of simulations

Simulations show that the electrons can leak into the poloidal gap via the crossing. A fraction of electrons which enter a toroidal gap interact with the potential structure formed in the crossing and are pushed by an $\mathbf{E} \times \mathbf{B}$ drift inside the poloidal gap. Such electrons exhibit a complex set of motions. To illustrate the problem, we have represented one schematic trajectory in Fig.

2. The fastest motion is the Larmor gyro rotation (not shown in Fig. 2 due to the scale of the figure). Since the tiles are at floating potential, the electrons don't have enough energy to hit the tiles and recombine but they bounce between gap sides. The slowest motion is due to the $\mathbf{E} \times \mathbf{B}$ drift, which pushes them through the poloidal gap (to the left in Fig. 2). This way they can leak through the entire gap independently from its length and escape at the next crossing back into the toroidal gap. This mechanism modifies the space charge distribution inside PG, which in turn changes the potential structure and affects the ion penetration inside the gap It is a novelty, which can be only observed in a full 3D simulation.

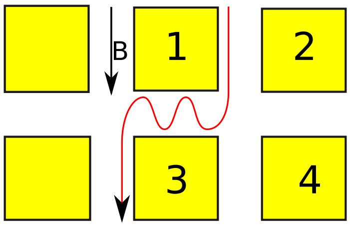

Figure 2: Trajectory of an electron coming from the TG and leaking into the PG.

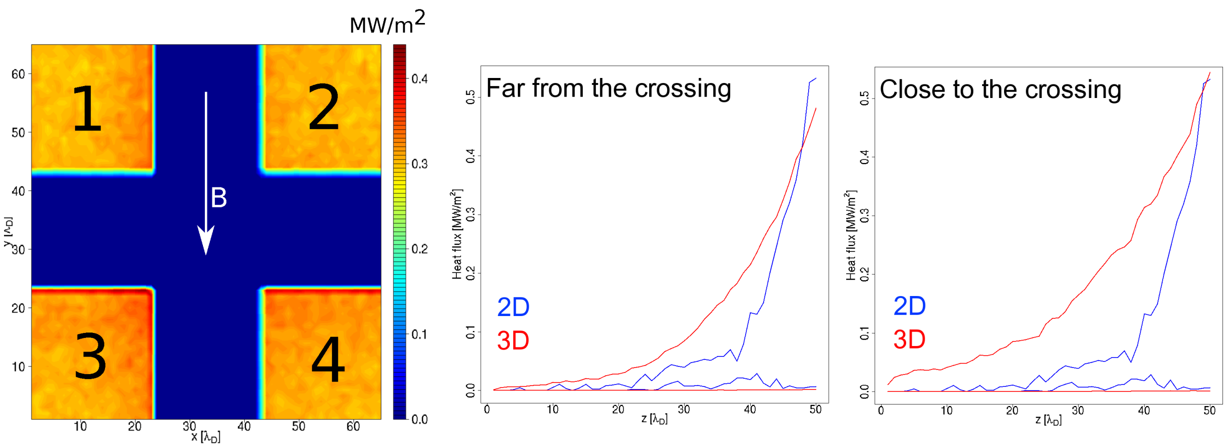

Figure 3: Power flux falling onto the top surface of the tile (left), power flux profiles inside the poloidal gap (right). The red curve shows 3D simulation, blue curve 2D simulation.

Maximum of the power flux

One of the applications of the PIC simulations of divertor tiles is to predict heat fluxes falling onto the tile surfaces. Fig. 3 (left) shows the power flux hitting the top tile surface. The variation of the flux across the surface is not very pronounced, however the bottom left corner of the crossing receives a flux increased by 20% comparing to the rest of the surface. The place with the largest power flux (0.55 MW/m^2) is located on the plasma wetted side of PG close to the gap crossing. This maximum is the same as observed in the 2D simulations. This does not mean that the heat flux distribution remains unchanged irrespective of the presence of the gap crossing. Rather than the peak value of the heat flux, we can calculate the heat flux Q_z integrated along the gap (z direction) for a given location in the gap. The 2D simulation yields $Q_z = 4.68$ MW/m, while the 3D simulation shows variation on the plasma-wetted side of PL between 6.3 (far away from the crossing) and 8.3 MW/m (close to the crossing), which is increase by 35% and 77% respectively. The comparison of the fluxes with the 2D results is shown in Fig. 3 (right). This is an important difference, as the integrated power flux will have an effect on the tile temperature.

Summary and outlook

The new 3D3V simulations revealed new phenomena in the plasma interaction with the divertor tiles, which could not be modeled by a 2D code. The new mechanism observed is the electron leakage inside the poloidal gaps. The electrons coming from a TG are driven inside the PG by an $\mathbf{E} \times \mathbf{B}$ drift, which enables them to travel through the entire gap. As a result, the integrated power flux inside the poloidal gap is higher than predicted by a 2D simulation. The maximum increase of power flux is located on the plasma-wetted side of a poloidal gap close to the gap crossing, approximately twice the value obtained by a 2D simulation. All these results are only valid for a case where the toroidal gaps are perfectly aligned to the magnetic field and so the electrons can freely enter the toroidal gaps.

Future studies will further develop problematics presented in this paper, trying to perform simulations for ITER realistic conditions. There will be also studies of scenarios, where the toroidal gaps are not perfectly aligned with the magnetic field and so the electrons have limited access inside them. The resulting modification of the heat deposition patterns could be useful for the design of ITER divertor, enhancing the life time of the tiles.

References

[1] T. Loarer, J. of Nucl. Mat. **390-391**, (2009)

[2] R. Dejarnac, M. Komm, J.P. Gunn and R. Panek, J. of Nucl. Mat. **390-391**, (2009)

[3] M. Komm, J. Adamek, R. Dejarnac, J. P. Gunn and Z. Pekarek, Plasma Phys. Control. Fus. **53**, (2011)

[4] R. Dejarnac, M. Komm, J. Stockel and R. Panek, J. of Nucl. Mat. **382**, (2008)

[5] R. Dejarnac, M. Komm, J.P. Gunn and R. Panek **818-821**, (2009)