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Measurement of plasma flows into tile gaps

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ABSTRACT

Particle fluxes falling into narrow gaps are of high interest since international thermonuclear experimental reactor plasma facing components will be castellated. In order to investigate the plasma deposition in gaps between tiles, we have developed a special probe that recreates a gap and that can measure the ion saturation current profiles along its both sides. Measurements were performed in the tokamak Czech Academy of Sciences TORus and are compared with a self-consistent kinetic model. The simulations reproduce well the observed asymmetry of the plasma deposition in both poloidal and toroidal gaps and the intensity of the collected currents is well-estimated. However, the agreement is less perfect for poloidal gaps due to the presence of a positive peak on the negative potential inside the gap. Therefore, the plasma deposition does not decay exponentially like in toroidal gaps. Nevertheless, this unique set of experiments confirms globally the results of our model.

1. Introduction

Particle fluxes in tile gaps are of high interest since we know that international thermonuclear experimental reactor (ITER) plasma facing components will be castellated [1]. The ITER divertor will be split into tiles for thermo-mechanical purpose. A recent hot topic that worries the community is the tritium accumulation in the gaps. The question is to know whether a significant amount of tritium will be trapped in between the tiles or not. This is an issue for ITER as we know that the vessel inventory is limited from safety considerations to 700 g. Recent experimental studies [2–4] demonstrated that the fuel (D + T) and some impurities do accumulate in the gaps. However, all those previous experimental studies are shot- or campaign-averaged and do not give information on how the plasma flows between the tiles. First self-consistent, kinetic simulations [5] started to explain the physical process of plasma flows into gaps between tiles for different orientations with respect to the magnetic field lines. In order to investigate more deeply the related physics of the plasma deposition inside those narrow structures, we have developed a special probe to measure the penetration of the plasma into the gaps.

2. Experimental setup

The probe head is schematically depicted in Fig. 1. The probe consists of two blocks, which are spaced by 1.1 mm to simulate a gap. A fraction of each block is composed of stainless steel segments, which are electrically insulated from each other and from the body of the block. The actual construction of the two blocks is presented in Fig. 2. As we can see on that picture, each component of the dismantled probe, A and B, consists of a set of 11 conductive segments insulated to each other by a 0.1 mm teflon foil. Each segment has a surface of 10 × 0.3 mm and therefore the probe can cover a range of about 4.5 mm along the gap, i.e., in the radial direction. This coordinate is denoted z in the future figures, with $z = 0$ corresponding to the plasma edge at the entrance of the gap. The segments are biased with a negative voltage ($V_{bias} = -100$ V) in order to collect the ion saturation current (I_{sat}). The two components A and B are mounted face-to-face in order to create a gap of 1.1 mm width and the probe is inserted in the tokamak Czech Academy of Sciences TORus (CASTOR) scrape-off layer (SOL) from the top. Two configurations are investigated experimentally as shown in Fig. 3. The first one corresponds to the gap parallel to the magnetic field lines (noted as 'toroidal gap') and the second one when the gap is perpendicular to the magnetic field lines (noted as 'poloidal gap'). In the latter case, we studied the plasma collection as a function of the incident angle, α_{PG} in the figure, by changing the probe inclination with respect to the magnetic field lines. In toroidal gaps, the probe was not movable and the angle remained fixed at $\alpha_{TG} = 0°$ with an accuracy of ±2°. The experimental data are compared with the results of self-consistent, kinetic simulations performed by a 2D particle-in-cell code (SPICE) which is described in [5] and which was used for a numerical study of plasma deposition in castellated tile gaps. The code simulates the plasma flow inside the gap without taking into account physical processes which are a direct consequence of the plasma–wall interactions since the surfaces are absorbing. Recycling, secondary electron emission, erosion and ionization are not taken into account. Typical CASTOR hydrogen plasma parameters in the edge region are simulated ($n_e = 10^{18}$ m^{-3}, $T_e = T_i = 20$ eV) giving a ratio of gap width to Larmor radius equal to two, identical to the one in the previous study [5].

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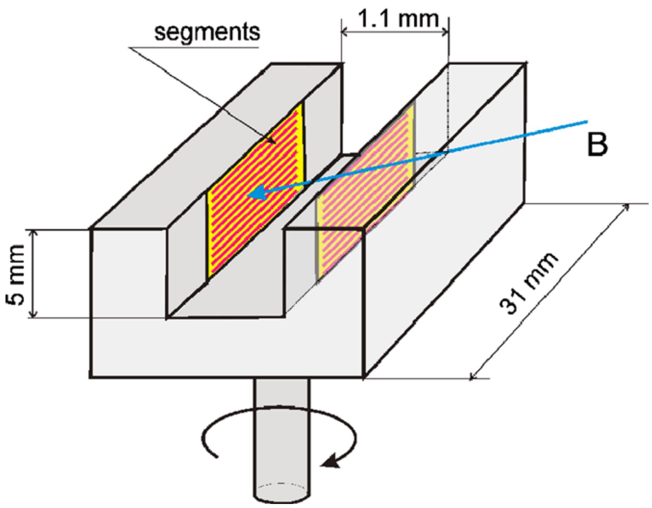

Fig. 1. Schematic view of the 'sandwich' probe.

Fig. 2. Photo of the two sides components of the dismantled 'sandwich probe' for measuring the plasma deposition into a gap between tiles. The gap between opposite sides was adjusted to 1.1 mm.

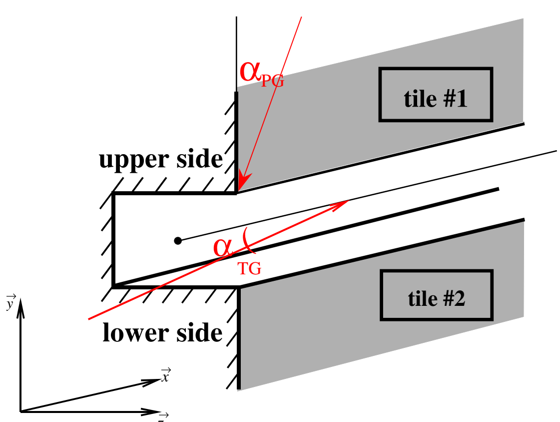

Fig. 3. Schematic view of both toroidal (α_{TG}) and poloidal (α_{PG}) orientations of the gap with respect to the magnetic field lines.

The parameters of the reproducible discharges are presented in Fig. 4. The averaged values are taken on the steady state phase between 15 and 20 ms. The results are presented in the two following sections corresponding to the two gap orientations. We have to note that we do not expect any currents flowing between the segments, especially from one side to another, perturbing the measurements because they are biased at the same potential. Moreover, the resistivity of two consecutive segments is infinite, the insulation foils were thick enough. The resistivity of two consecutive segments has also been measured after the campaign and remains unchanged. Therefore, the electrical properties of the segments were not modified by coating due to long exposure in the plasma. The duration of the pulses (20 ms in average) and the dedicated experimental campaign were short.

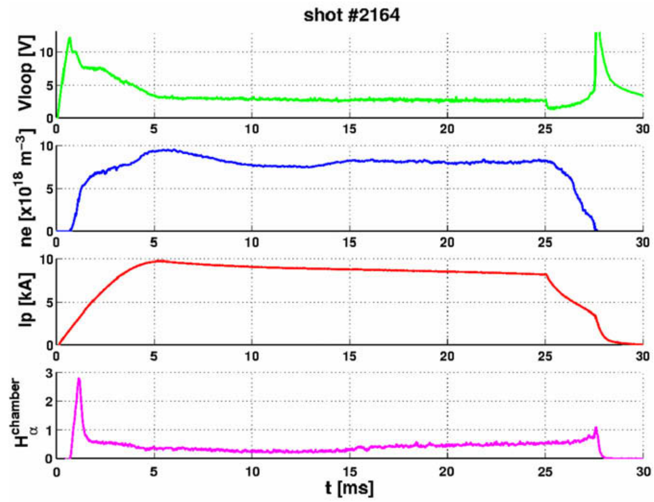

Fig. 4. Plasma parameters of the reproducible discharges with from top to bottom: loop voltage, line averaged density, plasma current and H_α signal at the chamber.

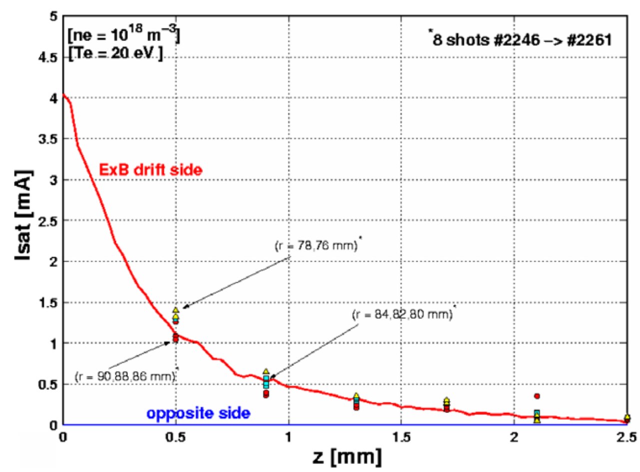

Fig. 5. Ion saturation profile along a toroidal gap measured by the probe for eight reproducible shots at different radii (points) and calculated by the 2D self-consistent PIC code (red/blue full-line curves). It has to be noted that only one side of the probe shows signal.

3. Toroidal gaps

Fig. 5 shows the ion saturation current distribution along a toroidal gap measured by the probe for a set of eight reproducible shots at different radii as mentioned in the figure, the six first segments being represented. The red circles[1] correspond to three shots in the limiter shadow at $r = 90$, 88 and 86 mm. The blue squares correspond to three shots at $r = 84$, 82 and 80 mm. The yellow triangles are the deepest in the plasma with radii $r = 78$ and 76 mm. These points are compared with the result of the kinetic calculations (the red/blue full-line curves). We observe here two important features that characterize the plasma deposition in

[1] For interpretation of color in Figs. 1–8, the reader is referred to the web version of this article.

toroidal gaps. The first significant result is that the plasma is deposited only on one side of the probe. Indeed, the probe measures a signal only on the side favored by the $\mathbf{E} \times \mathbf{B}$ drift and almost nothing on the other side (noise). This physical phenomenon is due to strong gradients of the electric field inside the gap as explained in [5] and experimental data are in good agreement with the numerical predictions. The probe was designed according to SPICE modeling and we can see that the absolute values match well the theoretical curve.

Second of all, we observe that the plasma deposition decreases exponentially along the gap with an e-folding length of 0.5 mm, which is also well-reproduced by the PIC simulations. We observe that the deposition is done on a distance roughly two times the gap width. It has to be noted that the reproducibility of the I_{sat} values for the eight shots is good even though they correspond to different radii as mentioned previously. The radial profile of the ion saturation current is generally flat in the CASTOR SOL as we can see in Fig. 6 of [6].

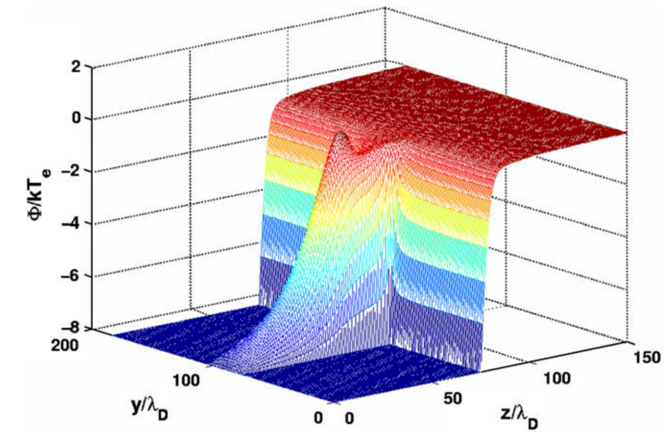

Fig. 7. Computed electric potential normalized to kT_e in a poloidal gap between two tiles for $\alpha_{PG} = 45°$.

4. Poloidal gaps

Fig. 6(a) shows the ion saturation current distribution along a poloidal gap measured for different inclinations of the probe with respect to the magnetic field lines. The deposition shown here corresponds to the plasma facing side of the probe. We observe exponential decays with an e-folding length varying between 0.35 and 0.55 mm only for low angles ($\alpha_{PG} \leqslant 32.8°$) whereas the plasma seems to penetrate deeper and linearly for angles greater than 32.8°. The profiles calculated by SPICE are shown in Fig. 6(b) with the same scaling and we can observe that a similar behavior is reproduced, with a non-exponential decay for high inclinations. For the low angles, we observe exponential decays with an e-folding length of 0.25 mm for $z \geqslant 0.5$ mm (corresponding to the second segment and more). The predicted I_{sat} absolute values are in the same range as in the experiment, however we notice that the measured deposition is deeper (with higher absolute values inside the gap), especially for larger angles. We have to note that the current measured by the segments is overestimated by the presence of secondary electron emission (SEE). What we measure is not the real I_{sat} and a correction due to the SEE should be taken into account to reduce the absolute values. Moreover, the ionization of the neutral cloud coming from recycling in front of the gap might increase the net I_{sat} calculated by the code. However, the fraction of neutrals estimated in front of the probe as the same fraction of neutrals at the chamber by the H_α signal (see Fig. 4) does not seem to play a fundamental role.

Concerning the electric potential inside the gap calculated by SPICE, we notice a positive 'bump' on the negative potential (see Fig. 7). This 'bump' is explained by charge separation; the electrons are strongly magnetized and follow the magnetic field lines whereas the ions with larger Larmor radii are demagnetized and thus a positive charge density forms [5]. Depending on its value, this positive 'bump' can prevent a more or less significant part of the incoming ions to enter the gap. For example, if we decrease the density by a factor of four, for the same α_{PG} and T_e, we observe a reduction of this 'bump' with as a consequence a decrease of the fraction of plasma entering the gap from 85% to 78%. The size of the 'bump' increases with the angle, i.e., when the geometrical projection is larger and for the larger angles here, the fraction of plasma entering the gap varies between 15% and 20% of the unperturbed, incoming flux taken far from the gap. We explain the difference in the experimental/numerical profiles by an overestimation of the size of this 'bump' feature by our code. It has been observed experimentally in a ball-pen probe (Katsumata type probe oriented perpendicularly to the magnetic field lines) that an electronic current is measured inside the tube far from the entrance of the probe [7]. This means that some electrons enter the tube where no electronic current is expected. This physical process is still under investigation and SPICE simulations do not show any electronic current inside a ball-pen probe. By not taking into account some electrons inside the gap, we overestimate the size of the positive bump. A smaller 'bump' on the potential would allow more ions to enter the gap and therefore to go deeper as it is observed exper-

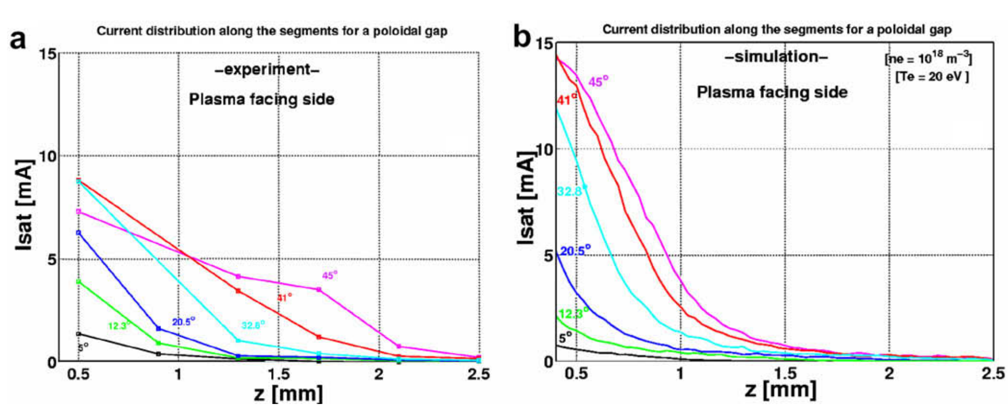

Fig. 6. Ion saturation profile along a poloidal gap measured by the probe (a) and calculated by the 2D self-consistent PIC code (b) for different inclinations with respect to the magnetic field lines (from 5° to 45°) and for the plasma facing side.

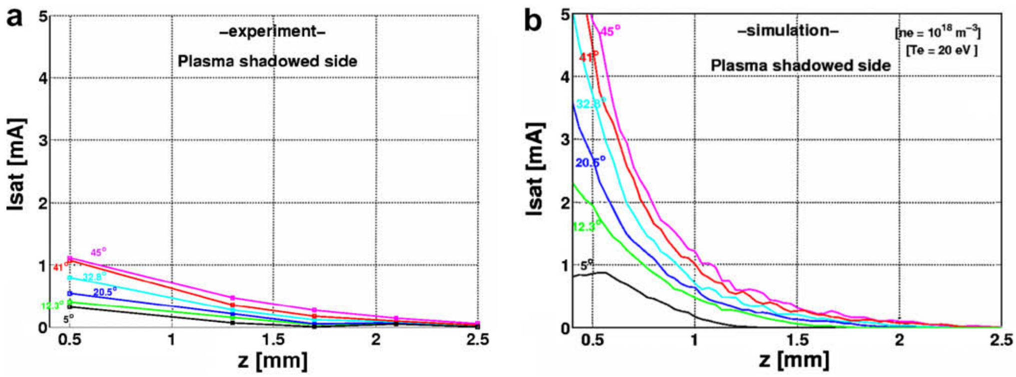

Fig. 8. Ion saturation profile along a poloidal gap measured by the probe (a) and calculated by the 2D self-consistent PIC code (b) for different inclinations with respect to the magnetic field lines (from 5° to 45°) and for the plasma shadowed side.

imentally. Moreover, the code does not take re-ionization and the SEE.

On the other side of the probe (plasma shadowed side), we do observe a small signal with a 10 times lower intensity (see Fig. 8(a)). The simulations reproduce the plasma facing/shadowed side asymmetry as we can see in Fig. 8(b) with the presence of a signal on this side in the contrary of the toroidal case where the deposition is done only on side. The presence of an I_{sat} signal on the shadowed side is also consistent with the positive 'bump' on the potential inside the gap, which is strong enough to repel the incoming ions [5] towards the surface that is not directly wetted by the plasma. However, as we can see in Fig. 8(b), SPICE overestimates the absolute values of I_{sat} at the entrance of the probe. Although the radial decrease in the gap is in a rather good agreement for all the angles from the second segment, I_{sat} experimental data are lower than the predicted ones by a factor of five on the first segment. This local feature is also in agreement with the fact that we overestimate the size of the 'bump' on the potential in the simulations, which is mainly located at the entrance of the gap. A smaller positive 'bump' in the gap due to the presence of electrons will repel less ions and therefore I_{sat} on the shadowed side would be decreased. Inside the gap, where the effect of the 'bump' is none, we have an agreement like in the case of a toroidal gap, where no 'bump' is observed on the potential.

5. Conclusion

We have developed a unique probe to measure the plasma deposition into gaps between tiles. The experimental data from probe exposures in the CASTOR boundary plasma qualitatively match with the 2D self-consistent kinetic calculations and confirm the recent numerical study of plasma deposition in castellated gaps [5]. In the case of toroidal gaps, we have a quantitative and qualitative agreement. Significant ion saturation currents are detected on only one side of the gap (the side favored by $\mathbf{E} \times \mathbf{B}$ drift) due to strong gradients of the electric field like the model predicts for these plasma conditions. In the case of poloidal gaps, one observes qualitative agreement between simulations and experimental results. Simulations qualitatively confirm the asymmetric ion flux present on the both sides of the gap. The simulations fail, however, to predict the measured extend of plasma penetration deep into the gap volume. Indeed, a positive 'bump' forms on the electric potential inside the poloidal gap and can repel a fraction of the incoming ions. An overestimation of this 'bump' in the simulations can explain the deeper experimental ion gap penetration on the plasma facing side compared to the code predictions. Moreover, the secondary electron emission also plays a role in the difference between the predicted and experimental signals and should be included in the code. This set of experiments confirms nevertheless the understanding of the physical processes that govern the plasma deposition inside gaps thanks to our model.

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