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Direct measurements of particle flux along gap sides in castellated plasma facing component in COMPASS

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HIGHLIGHTS

- We designed a probe to measure plasma deposition into gaps during tokamak discharges.
- *Isat* profiles are measured on both side of the gap for different gap orientations.
- Ion current is measured at the bottom of the gap in the toroidal orientation.
- Kinetic simulations reproduce well experimental profiles qualitatively.

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ABSTRACT

In this paper, we report results of a dedicated experiment that gives the plasma penetration profiles inside a gap of a tokamak castellated plasma-facing component. A specially designed probe that recreates a gap between two tiles has been built for the purpose of this study. It allows to measure ion saturation profiles along the 2 sides and at the bottom of the gap for both poloidal and toroidal orientations. The novelty of such experiment is the real time measurement of the plasma flux inside the gap during a tokamak D-shaped discharge compared to previous experimental studies which were mainly post-mortem. This experiment was performed in the COMPASS tokamak and results are compared with particle-in-cell simulations. The plasma deposition is found to be asymmetric in both orientations with a stronger effect in poloidal gaps. The Larmor radius of the incoming ions plays a role in the plasma penetration only in poloidal gaps but seems to have little impact in toroidal gaps. Profiles are qualitatively well reproduced by simulations. Ion current is recorded at the bottom of a toroidal gap under certain conditions.

1. Introduction

In future fusion devices, as well as in present tokamaks, plasma-facing components (PFCs) of strong plasma–wall interaction regions are/will be castellated [1] in order to withstand strong thermo-mechanical stresses [2] due to intense, inhomogeneous particle and heat fluxes. The direct consequence of this castellation is an increase of the exposed surface of the PFCs due to the gaps between tiles or monoblocks. Plasma and charge exchanged neutrals will flow into the gaps where tritium can be trapped. Experimental studies in TEXTOR [3–5] have shown significant deposited layers in the gaps of an ITER-like castellated test-limiter and an enhanced deposition at the bottom of the gap. Enhanced re-deposition of eroded material is not a candidate to explain this last result [6]. Numerical studies using particle-in-cell (PIC) technique have also been performed in order to understand mechanism that govern particle flux deposition in castellated PFCs [6–9]. In order to assess experimentally the plasma deposition in such a complex geometry as gaps, we have developed a special gap probe, so-called *Sandwich Probe*, that recreates a part of a castellated limiter with 2 tiles separated by a small gap. A dedicated experiment was performed on the COMPASS tokamak [10] using the sandwich probe that can measure the ion saturation current profiles along the 2 gap sides during plasma discharges. The experimental set-up as well as

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the probe itself is detailed in Section 2. The results from the dedicated experiment on COMPASS are presented in Section 3 of this paper. Plasma deposition profiles are presented for the 2 possible orientations of the probe, parallel and perpendicular to the magnetic field lines. In Section 4, a comparison of these experimental profiles with results of 2D PIC simulations is presented, as well as a brief description of the kinetic model used to achieve those results. The main findings are summarized in Section 5 under the general conclusion.

2. Experimental set-up

2.1. Introducing the sandwich probe

The sandwich probe (SP) is a complex probe specially developed for this dedicated experimental study. Its head is made in a TZM (titanium, zirconium, molybdenum) alloy monoblock, with a 70 mm in diameter circular shape. The design of the sandwich probe was based on several complex techniques, which made its construction challenging. One of these was to cut a pocket in the molybdenum monoblock with a complex shape to make the body of the probe that face the plasma, using the electro-erosion technique. Another very challenging point was to realize a metallic coating of a thin molybdenum layer on boron nitride (BN). This has been possible thanks to the Combined Magnetron Sputtering and Ion Implantation technique [11] developed in Bucharest, Romania. This is the same technique that was used to make the W coating of JET CFC tiles for the ITER-like wall project [12] but for the first time applied to boron nitride. The final coating was not straightforward due to the porosity of the BN but the final result is a successfully solid Mo layer, which is less than 3 μm thick and with the hardness of the Mo coating being 800–900 HV 0.025. The layer can survive fluxes in the order of 10 MW/m^2. A coated sample was subjected to high heat flux test using the High Temperature Test Facility (HTTF) in Bucharest, Romania, where the heating occurs with an electron beam of 1.3 kW. The surface temperature was between 1200 and 1300 °C after a 5 s exposition. A cycle of one hundred pulses was applied with these parameters. No delamination of the coating was observed during this thermal fatigue test. This metallic layer is to create the base of the conducting segments that measure the ion saturation currents along the gap sides. For this purpose, we made some parallel cuts in the coating till reaching the insulator located below (i.e. the BN) in order to create measuring segments with an electric insulation between them. The spatial resolution is limited by the size of the cutting tool and we achieved the high spatial resolution of about 0.3 mm. There are 6 measuring segments on both sides of the gap, covering a depth of 4 mm. The SP is also equipped with a conductive segment at the bottom of the gap, −15 mm with respect to the entrance of the gap, in order to assess the deposition observed in [4] and not reproduced in [6]. Fig. 1 shows three photographs of the SP during its mounting. The SP is equipped with a Langmuir probe (LP), protruding outside the cap, to measure local plasma parameters such as density and temperature. Those values will be used as input for the PIC simulations. In order to monitor the surface temperature during experiments, a thermo-couple is also implemented in the body of the probe.

In Fig. 1(c), one can see the conductive segments that are biased with negative voltage in order to collect the ion saturation current (*Isat*) during the discharge. The probe head can rotate around its axis (vertical in Fig. 1) allowing to change the gap orientation to be either parallel or perpendicular to local magnetic field lines to investigate the plasma deposition in toroidal gaps (TG) or poloidal gaps (PG), respectively. In order to differentiate the 2 sides of the gap, we name side A, the side without the LP and side B, the other one. The gap is 1 mm wide.

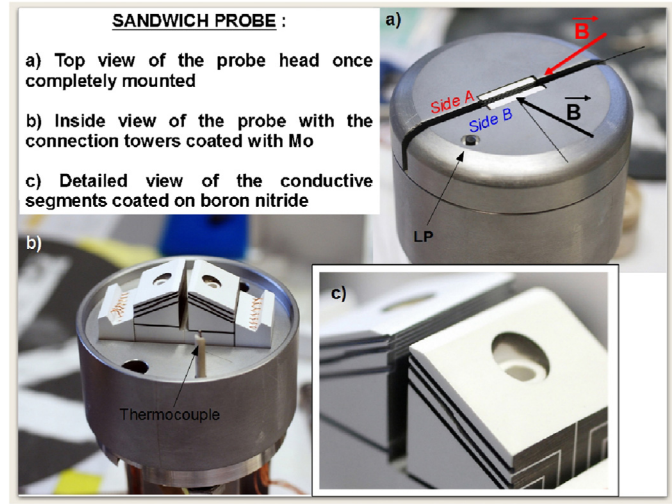

Fig. 1. Detailed photographs of the SP and its inner components.

2.2. Experimental set-up

Measurements were performed on COMPASS with the SP mounted on an horizontal manipulator at the outboard midplane (OMP) location. The probe position was fixed during the discharge and was 20 mm outside of the separatrix. The plasma configuration was the standard single-null high triangularity D-shape plasmas used on COMPASS. The experiment was made in ohmic mode with nominal values of Bt = 1.15 T, I_p = 180 kA and the line-averaged electron density varying in the range 2–6 × 10^{19} m^{-3} to study the effect of density on the plasma penetration. The segments were biased with a constant voltage V_{bias} = −100 V and the consequent ion saturation currents were measured as the drop voltage on independent resistors. The resistance value varies for each segment, increasing with the depth of each segments in order to compensate the low signal on the deepest segments due to the expected decreasing deposition. The values of each resistance were optimized for each segment with the expected currents estimated by PIC simulations and vary in the range 47.5–330 Ω. The experimental campaign was divided into 2 sessions. On the first one, the SP was in the TG configuration with the magnetic field lines parallel to the gap having ∼2° angle of incidence with respect to top surface of the probe head. 4 discharges were performed at nominal magnetic field as abovementioned and 2 additional discharges were performed at lower magnetic field (Bt = 0.92 T) in order to investigate the effect of the Larmor radius of incoming ions on the plasma penetration in the gap. Then the probe was turned by 90° to position it in the PG configuration for the second session. Similar series of discharges (4 + 2) were performed. The probe was monitored by the in situ thermocouple but during the 250 ms discharges on COMPASS operations were safe with a recorded temperature always $T^{thermocouple}$ < 80 °C. The *Isat* profiles were recorded on the 100 ms steady-state plateau of the discharges and averaged over 10 ms.

3. Experimental results

The first series of discharges deal with the TG orientation where the magnetic field lines are parallel to the gap. Fig. 2 shows the *Isat* spatial profiles along the side A (up) and side B (down) of the gap for the series of discharges with the higher toroidal magnetic field. Unfortunately, one can see that the two 1st segments are not working, as well as segment #4 of side B. A disruption which happened during the tuning of the plasma configuration destroyed them. The error bars on the curves are the standard deviation of recorded