

Simultaneous poloidal measurements using new magnetically driven reciprocating probes in COMPASS

R Dejarnac^{1,4}, J P Gunn², M Dimitrova¹, M Hron¹, R Panek¹, J-Y Pascal²,
C Saragosti-Chausy³, P Tamain² and the COMPASS team

¹Institute of Plasma Physics, Czech Academy of Sciences,
182 00 Prague, Czech Republic

²CEA, IRFM, F-13108 Saint Paul-Lez-Durance, France

³Ecole Nationale Supérieure des Arts et Métiers ParisTech, F-75013 Paris, France

E-mail: dejarnac@ipp.cas.cz

Abstract. Particles and heat transport in the scrape-off layer (SOL) of tokamaks is not yet fully understood. COMPASS is a small-size tokamak where the edge plasma is well diagnosed in view of studying the competition between the parallel and the cross-field transport in the SOL. In order to better characterize SOL dynamics, in particular the poloidal asymmetry of the main parameters' radial profiles, two new in-situ magnetically driven reciprocating manipulators have been recently installed in COMPASS. These manipulators, the so-called pecker probes, are two additional poloidal measurement points to the existing two (vertical and horizontal) reciprocating manipulators. The pecker probes are located at the low field side of COMPASS at $\pm 47.5^\circ$ with respect to the outer mid-plane and are equipped with identical tunnel probe heads, providing simultaneous measurements of the ion saturation current density J_{sat} , the electron temperature T_e and the parallel Mach number $M_{||}$ with high temporal resolution. In this paper, a detailed description of the pecker probe system in COMPASS is described and first measurements are presented.

1. Introduction

The COMPASS tokamak is well suited [1] for studying the particle and heat transport in the scrape-off layer (SOL). It is a small and flexible machine where it is easy to use several types of probes to characterize the SOL physics [2-7]. An advantage of COMPASS is its being equipped with two reciprocating manipulators, one vertical from the top of the machine and one horizontal at the outer mid-plane, allowing two independent and simultaneous measurement points in the poloidal plane. In order to increase this spatial resolution from two to four measurement points, two new in-situ linear, magnetically driven reciprocating manipulators, based on the novel technique developed in [8], have been recently installed and commissioned in COMPASS ports in the same poloidal plane at $\pm 47.5^\circ$ with respect to the outer mid-plane. These manipulators, the so-called pecker probes (PPs) because of the resemblance with a woodpecker, are based on the rotation of an energized coil in the tokamak total magnetic field. The coil is fixed on a rotating axis and provides a leverage which is converted to linear

⁴ To whom any correspondence should be addressed.



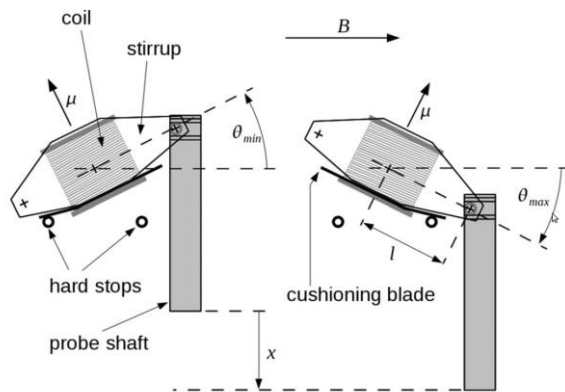


Figure 1. Schematic of PP geometry. The vertical direction corresponds to the tokamak minor radius, along which the probe moves at a distance x . On the left, the probe is drawn fully retracted (coil angle $\theta = \theta_{\min}$, probe position $x = 0$ mm). On the right, it is fully inserted (coil angle $\theta = \theta_{\max}$, probe position $x = x_{\max}$). The magnetic moment μ produced by the coil current and the lever arm l are indicated. $\theta = 0$ corresponds to the coil axis being perpendicular to the magnetic field B , when the probe is half way between its minimum and maximum positions [8].

described as a synergetic numerical-experimental approach to fundamental aspects of turbulent transport in the tokamak edge, has been started within the EU fusion community using state-of-the-art numerical codes [11-14] to unveil the physics behind the SOL dynamics. The validation of these simulations results with, in the first step, experimental measurements in the simplest configurations is a crucial point for the understanding of SOL plasma dynamics and predictive simulations of future devices. The COMPASS tokamak is part of this numerical-experimental validation, especially with its access to highly-resolved measurements of poloidal asymmetry only accessible thanks to the new PP system.

In this paper, the PP system developed for the COMPASS tokamak (design and commissioning) is described in section 2. First measurements of the J_{sat} profiles in the COMPASS SOL measured by one TP mounted on the upper PP and by a single Langmuir tip mounted on the horizontal reciprocating manipulator are presented in section 3. The vertical manipulator was not available at that time since it was out of the vacuum vessel for a massive upgrade. The two PPs were commissioned separately by the only one specific power supply available at the IPP Prague, a KEPCO 36V-12A, therefore only one PP could be used at a time. The upper PP was chosen to be compared with the horizontal manipulator for these J_{sat} radial profile measurements. The general conclusion is presented in section 4.

2. The COMPASS pecker probes: design and commissioning

The equation describing the coil rotation (equation (9) in [8]) is solved numerically in order to identify the main feature of the PP dynamics and to optimize the coil geometry. The dimensions of the COMPASS PP are limited by the space available in the tokamak port where it is installed. As an example, a photograph of one of the two PPs is shown in figure 2 before its installation inside the chamber. The PP is fixed on the bottom flange which is screwed to the tokamak port. The carbon shield faces the plasma and the coil itself and the mechanical support structure are hidden inside the port. The optimized design of the COMPASS PP system gives the following: coil length $L^{coil} = 64$ mm, coil internal radius $R^{coil,intern} = 24$ mm, length of the lever arm $L^{lever\ arm} = 76$ mm, total

motion. As described in [8], “upon application of a voltage V , the torque $\tau_{coil} = \mu B \cos \theta$ causes the coil to rotate to align the magnetic moment $\mu = NIA$ with the total magnetic field B ”, with N and A being the total number of windings and the cross-section of the coil, respectively, with I being the total current in the drive circuit. The schematic of the PP system principle taken from [8] is reproduced in figure 1. The two PPs are equipped with identical tunnel probe (TP) heads allowing simultaneous fast DC measurements of the absolutely calibrated ion-current density J_{sat} and the electron temperature T_e [9,10]. Since the two TPs are mounted back-to-back, it is also possible to retrieve the parallel Mach number $M_{//}$ using the two independent J_{sat} measurements on both the ion and electron sides. As a matter of fact, thanks to the current advancement of numerical techniques and computational capabilities, first-principle simulations of SOL turbulence are now reaching predictive capabilities. A recent joint effort,

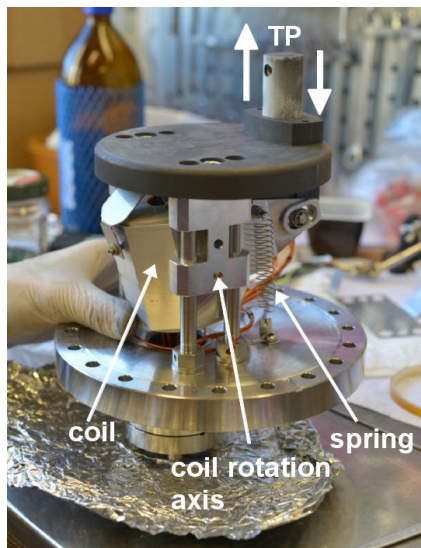


Figure 2. Photograph of one of COMPASS PPs before being installed in the vessel.

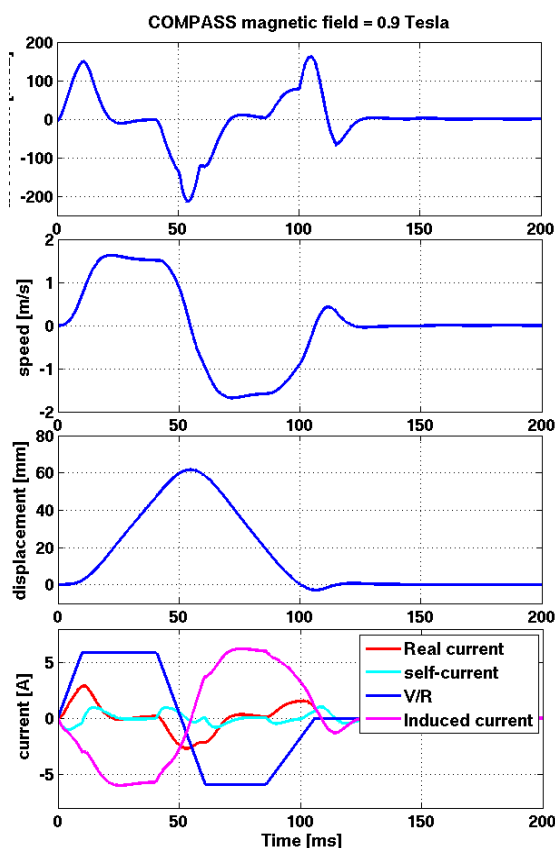


Figure 3. Simulation results for COMPASS PP with $N = 420$ & $B_T = 0.9T$. From top panel: acceleration, speed and displacement of the probe. The bottom panel shows the different currents in the system.

resistance of the system $R^{tot} = 2.6 \Omega$. Therefore, only the number of windings N of the coil needs to be estimated for the COMPASS toroidal field value $B_T = 0.9 T$ at the PP location, i.e., at the low field side, in order to have a moving speed of $\sim 1 \text{ m/s}$ and to keep an acceleration around 100 m/s^2 . As explained in [8], the linear probe speed is proportional to the current in the circuit induced by the probe rotation (equations (20)-(22) in [8]). The induced current is simply the difference between the real current, as it would be measured by an Ampere-meter, and the theoretical current V/R^{tot} . The probe position is obtained by simply integrating the speed from the beginning of the reciprocation. A current due to the self-inductance of the coil is also present in the system. This current is generally of low intensity and can be neglected [8]. The response of an optimized system for COMPASS PP with $N = 420$ windings is shown in figure 3. Predictive calculations show that the acceleration is slightly higher than originally wanted, but still acceptable. The optimum voltage to be applied to the PP is $V^{opt} = 15.6 \text{ V}$. A positive

voltage moves the probe inside the plasma and by reversing the polarity of the applied voltage, keeping the same magnitude, the probe is retracted back to its parking position. For a smooth landing, the voltage is slowly decreased towards zero in the middle of its way back. It can be seen that the current due to the coil self-inductance is indeed negligible.

The two PPs were installed and commissioned in the COMPASS tokamak in April and July 2015, respectively. Figure 4 shows the measured currents (*top panel*) in the coil of PP#2, the bottom PP (the one located at -47.5° with respect to the outer mid-plane) and the displacement of the probe (*bottom panel*) calculated as the integral of the speed, which is directly proportional to the measured induced current, during the vacuum discharge #10481. The currents are compared to the predictive currents from the solution of equation (9) in [8] for the same applied voltage of 15.6 V . Note that the current is different from the expected value $V/R^{tot} = 15.6/2.6 = 6 \text{ A}$. This is because the total resistance is changing from shot to shot due to heating of the wires. To avoid this uncertainty, the total resistance is measured before each movement as V/I when the probe is at parking position and the system is in steady state; in this case during the time interval $1045 < t < 1060 \text{ ms}$ in figure 4. In this particular discharge, the resistance was $R^{tot} = 2.9 \Omega$. Calculations are made without (*thin dashed curves*) and with (*thin curves*)

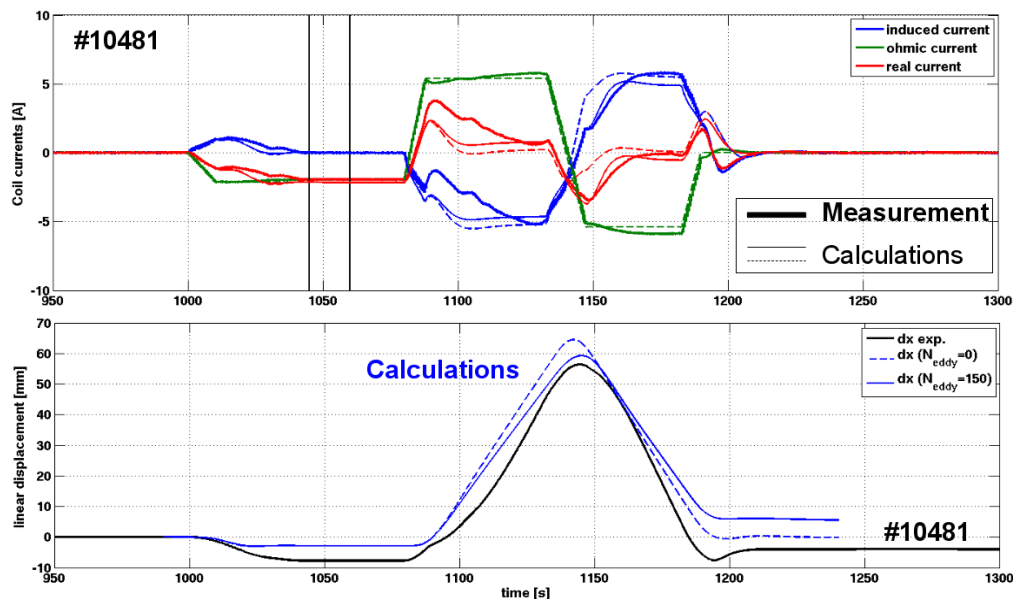


Figure 4. Comparison of measured currents in the PP#2 coil (top panel) and of the resulting probe position (bottom panel) with simulation results without and with eddy currents, characterized by the equivalent windings number N_{eddy} . Here, $N_{eddy} = 0$ (thin dashed curves) and $N_{eddy} = 150$ (thin full curves).

an estimate of eddy currents flowing into the system. As it is well explained in [8]: “For an eddy current to flow in a closed loop inside a moving conductor, there must be a time varying magnetic flux through its cross section. This can occur if a component of the object’s velocity is parallel to the gradient of a spatially non-uniform magnetic field, or if it rotates about an axis that is not parallel to a magnetic field”. Therefore, eddy currents must flow in the PP conducting structure. They can be expressed “as being due to the back electro-motive force in a second, unbiased copper coil of the same geometry as the drive coil, with a number of windings N_{eddy} ” [8]. It can be seen in figure 4 that the eddy currents with an equivalent winding number $N_{eddy} = 150$ are affecting the response of the system and that the consequent simulated currents are closer to measured currents than without eddy currents (*top panel*). Even if the probe position seems to be too damped on its way back to parking compared to reality (*bottom panel*), the curve with $N_{eddy} = 150$ is closer to the real movement of the probe. This number is an optimum number found for best matching with experimental curves. Simulations with larger numbers of equivalent windings start to strongly diverge from the experimental curves. In general, one observes a very good agreement between the experimental measurements and the simulation results, which makes us being confident in our simulations and in understanding which type of currents dominate the probe motion.

3. First simultaneous poloidal measurements in COMPASS using the pecker probe system

The first simultaneous poloidal measurements in COMPASS were made using only one PP and the horizontal reciprocating manipulator (HRCMP), which is 135° toroidally separated. At present, only one power supply (KEPCO 36V-12A), specific for the PPs, is available at IPP Prague. Therefore, only one PP can be powered at a time. For the comparison with the HRCMP, we chose the top PP#1, which is located at $+47.5^\circ$ with respect to the outer mid-plane. The PP#1 is equipped with two TPs mounted back to back, each of them looking at either the ion- or the electron-side of the plasma. Each TP is biased negatively by a biasing voltage $V^{bias} = -200$ V in order to collect the ion saturation current, I_{sat} . Due to a failure in the power line to the TP at the electron-side, only the data from the ion-side will be presented here. The COMPASS TP consists of a hollow conducting cylinder, the “tunnel”, of 6 mm in

diameter and in length, and a conducting “backplate” at one end, which is electrically insulated from the tunnel. The tunnel axis is parallel to the magnetic field and the plasma flows into the open orifice.

The ion saturation current is distributed and measured on both collectors; their sum gives the total I_{sat} . The advantage of the TP is to be immune to sheath expansion effects due to its concave geometry. Indeed, due to its shape, it provides an absolutely calibrated measurement of the parallel ion current density [9,10]. The resulting J_{sat} is simply: $J_{sat,TP} = I_{sat,TP}/r_{TUN}^2$, r_{TUN} being the tunnel radius.

The HRCP is equipped with a classical Langmuir probe of cylindrical shape with dimensions $L^{LP} = 1.5$ mm and $r^{LP} = 0.45$ mm. In first approximation, the collecting area of the LP is taken as the geometric area of the probe, i.e., its projection along **B**. The measurements presented in this paper

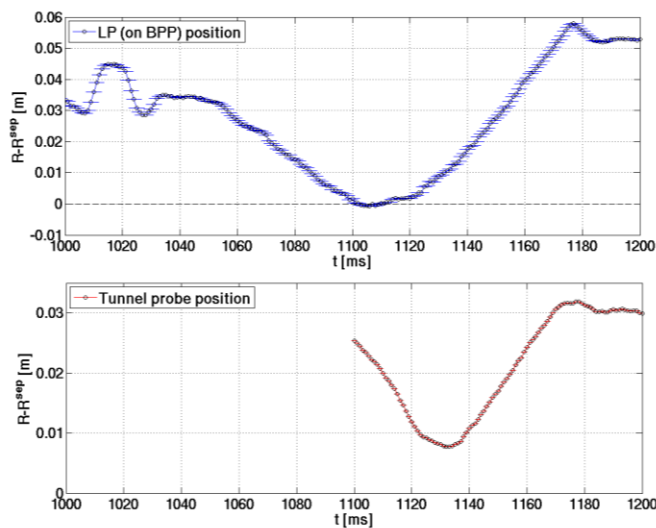


Figure 5. HRCP (top panel) and TP (bottom panel) positions as a function of time during shot #9788.

were performed in the diverted ohmic discharge #9788. Both reciprocations were made during the steady-state of the discharge with a constant plasma current $I_p = 200$ kA and a line averaged density $n_e = 4 \times 10^{19} \text{ m}^{-3}$. Figure 5 shows both the LP (*top panel*) and the TP (*bottom panel*) positions with respect to the separatrix in time. It is seen that the two manipulators do not reach the same absolute radial position. The HRCP goes 10 mm deeper in the plasma and reaches the separatrix. The two probes are also not synchronised. The deepest position occurs at different times, for the HRCP being ~ 30 ms earlier than for the PP. Figure 6 (*left*) shows the magnetic reconstruction of the equilibrium in shot #9788 at the time

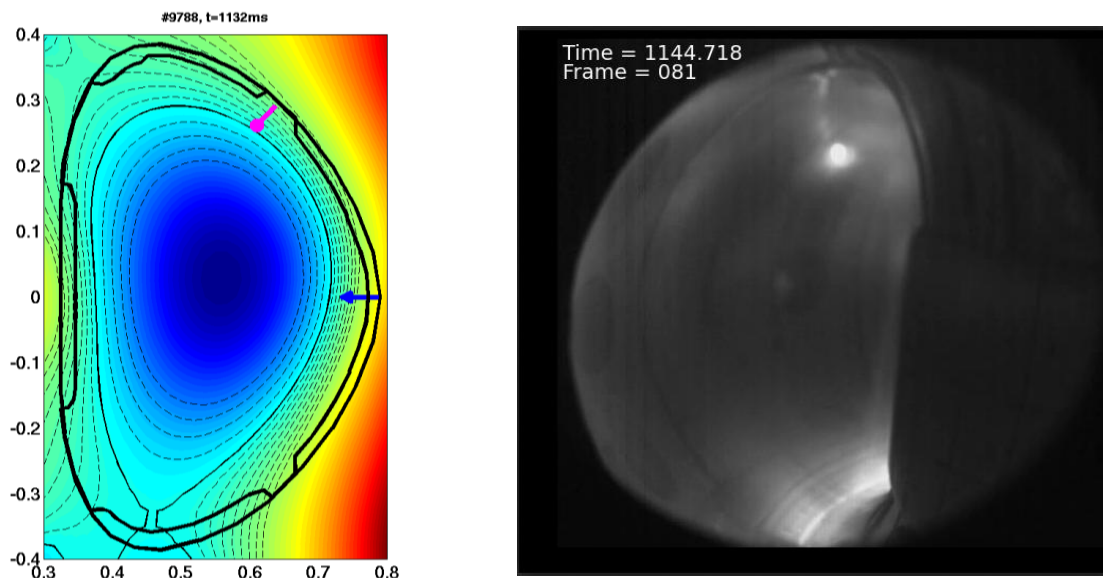


Figure 6. (Left) Magnetic reconstruction of the COMPASS equilibrium during shot #9788 at the time of the TP deepest insertion in the plasma. The PP and HRCP positions are marked by a pink dot and a blue arrow, respectively. (Right) a snapshot from the tangential, fast visible camera shows the PP interaction with the plasma later on during its way back to parking position.

$t = 1132$ ms corresponding to the maximum insertion of the PP. The positions of both the PP and the HRCF are marked with a pink dot and a blue arrow, respectively. On the right side of figure 6, a snapshot from the tangential, fast visible camera shows the PP interaction with the plasma later on during its way back to parking position.

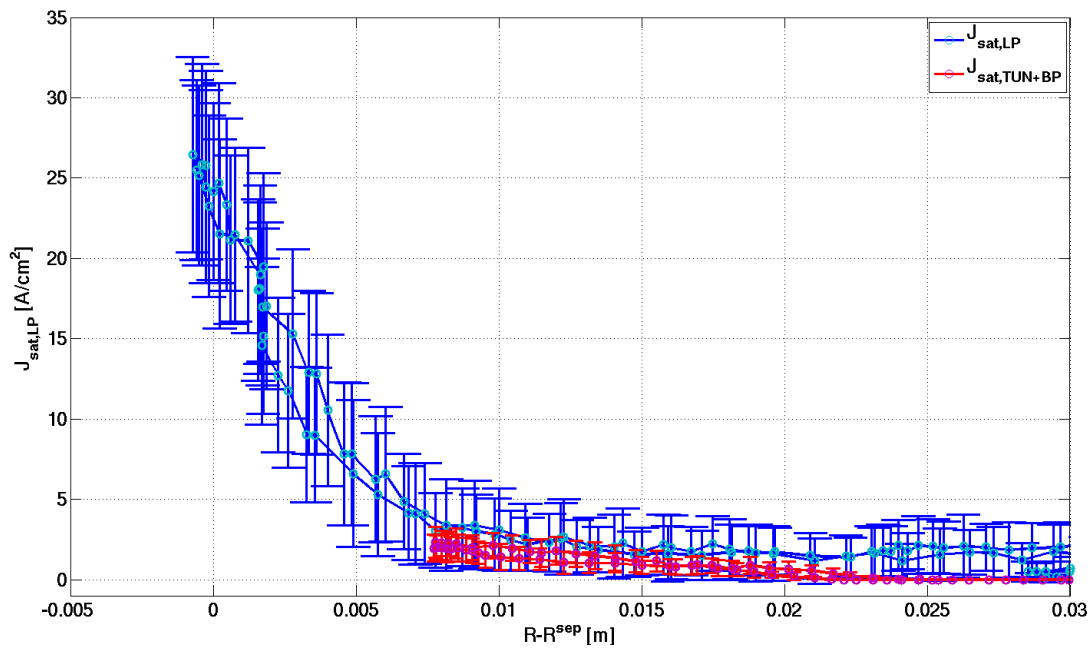


Figure 7. Radial profiles of the ion saturation current density measured by the TP mounted on the PP and the LP mounted on the HRCF. The distance to separatrix for the TP data is mapped to outer mid-plane.

Radial profiles of the ion saturation current density measured by both probes are presented in figure 7. In the case of the PP, the distance to separatrix is mapped to the outer mid-plane. It can be seen that $J_{sat,TP}$ is lower by 35-40% compared to $J_{sat,LP}$. This might be due to a poloidal asymmetry; however, it is well known that small (and even bigger) LPs are prone to sheath expansion effects [15]. It has been demonstrated experimentally that the collecting area of such probes are from 2 to 4 times larger than their geometrical projection along \mathbf{B} [16]. In our case, if we assume $J_{sat,TP}$ to be the real value of the ion current density, the underestimation of the LP collecting area is by a factor 1.6. However, the TP backplate is prone to secondary electron emission (s.e.e.) from ion bombardment. In the case of the tunnel, this effect is cancelled by the fact that every electron emitted is immediately re-collected by the tunnel. For the backplate, the situation is the opposite. Every electron leaving the tunnel follows field lines which are parallel to the tunnel surface. The backplate s.e.e. rate is unfortunately unknown, but can be as high as 80% [17]. Consequently, the current measured at the backplate is overestimated, which tends to increase the difference between $J_{sat,TP}$ and $J_{sat,LP}$ and to increase the error on the LP collecting area. Interestingly, it can be seen that the level of fluctuations is lower for the TP measurements than for the classical LP. It can be explained by the TP measuring the true J_{sat} fluctuations, whilst the LP is contaminated by the sheath expansion current, which depends on other plasma parameters such as the electron temperature, making it impossible to distinguish between density and temperature fluctuations [10]. The results reported in this paper are the very first results obtained by the PP system on COMPASS proving its functionality. This paper is a basis for future publications with all the COMPASS manipulators fully functional in the very near future.

4. Conclusions

The Institute of Plasma Physics in Prague has a long tradition of probes measurements in tokamaks since 1980's; this expertise continues now with the COMPASS tokamak. In order to increase the poloidal coverage by probes, two new in-situ, linear reciprocating manipulators, the pecker probes, have been designed, installed and commissioned in COMPASS, bringing to four the number of poloidal measurement points together with the two existing reciprocating manipulators. The pecker probes are located at $\pm 47.5^\circ$ with respect to the outer mid-plane in the same poloidal cross-section, 135° away for the two reciprocating manipulators in the toroidal direction. The pecker probe system is based on the rotation of an energized coil in the tokamak total magnetic field. Predictive simulations of the COMPASS pecker probes are in good agreement with the measurements. Each pecker probe is equipped with two identical tunnel probes, mounted back-to-back, allowing fast measurements of the absolutely calibrated ion current density, the electron temperature and the parallel Mach number. First measurements of the ion saturation current density at two poloidal locations are presented here. The comparison is only between one pecker/tunnel probe and a classical Langmuir probe mounted on the horizontal reciprocating manipulator because only one power supply for the pecker probe coil was available at that time and the vertical reciprocating manipulator was out of the machine for upgrade. The measurements confirmed the problem of sheath expansion around small convex Langmuir probes. A second power supply to power the two PPs at the same time has been purchased, so that in a near future a full poloidal coverage with four measurement points will be performed in COMPASS. This paper presents the very new pecker probe system installed in COMPASS and proves its functionality before future more complete studies of simultaneous multi-poloidal characterization of the SOL unveiling the physics behind SOL dynamics.

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