Effect of the gas puff location on the divertor plasma properties in COMPASS tokamak

M Dimitrova1,2,5, M Tomes1,3, Tsv Popov2,4, R Dejarnac1, J Stockel1, J Adamek1, E Vasileva2, M Hron1, R Panek1 and the COMPASS team

1 Institute of Plasma Physics, Czech Academy of Sciences, Za Slovankou 3, 182 00 Prague 8, Czech Republic
2 Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, 72, Tsarigradsko Chaussee, 1784 Sofia, Bulgaria
3 Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
4 Faculty of Physics, St. Kliment Ohridski University of Sofia, 5, James Bourchier Blvd., 1164 Sofia, Bulgaria

E-mail: dimitrova@ipp.cas.cz

Abstract. Langmuir probes are used to study the plasma parameters in the divertor during deuterium gas puff injection on the high- (HFS) or low-field sides (LFS). The probe data were processed to evaluate the plasma potential and the electron temperatures and densities. A difference was found in the plasma parameters depending on the gas puff location. In the case of a gas puff on the LFS, the plasma parameters changed vastly, mainly in the inner divertor – the plasma potential, the ion saturation-current density and the electron temperature dropped. After the gas puff, the electron temperature changed from 10-15 eV down to within the 5-9 eV range. As a result, the parallel heat-flux density decreased. At the same time, in the outer divertor the plasma parameters remained the same. We thus concluded that using a gas puff on the LFS will facilitate reaching a detachment regime by increasing the density of puffed neutrals.

When the deuterium gas puff was on the HFS, the plasma parameters in the divertor region remained almost the same before and during the puff. The electron temperature decreased with just few eV as a result of the increased amount of gas in the vacuum chamber.

1. Introduction

The importance is well known of cooling the divertor region in the future thermonuclear reactors, such as tokamaks. The aim is to protect the plasma-facing components from the strong plasma’s heat fluxes. This is why a partial detachment is considered a mandatory regime for ITER operation [1], which can be achieved via different mechanisms – by increasing the plasma density, by increasing the number of puffed neutrals, or by impurity seeding. The impurity seeding studies in this respect started more than 30 years ago in many tokamaks, such as ASDEX [2], JT-60U [3], JET [4, 5], Alcator C-Mod [6], etc.

This report presents our experimental study on the influence of an additional deuterium gas puff on the high-field side (HFS) and on the low-field side (LFS) on the plasma parameters in the divertor...
region of the tokamak COMPASS [7]. The plasma parameters were estimated before and during the additional gas puff by means of the divertor probe system in the COMPASS tokamak [8, 9] during D-shaped, L-mode, deuterium plasmas.

The current-voltage (IV) probe characteristics measured were processed by the first-derivative probe technique (FDPT) [10], which is adapted to the conditions of strongly turbulent plasma and provides information on the poloidal distribution of the plasma potential and the electron energy distribution function (EEDF), respectively, the electron temperatures and densities. Using these data, the parallel heat-flux density distribution was calculated [9, 11] in the divertor region of the COMPASS tokamak before and during the gas puff.

2. Results and discussion

The probe measurements were performed in the COMPASS tokamak divertor region during discharges with an additional gas puff at 1160 ms (the cyan line at the second row of figure 1) on the HFS during discharge #16304 and on the LFS, discharge #16305. Figure 1 displays the main plasma parameters of the two discharges under plasma conditions typical for attached plasma: plasma current $I_{p} = 180$ kA at a toroidal magnetic field of 1.15 T and line-average electron density $n_{e}^{avr} = 4 \times 10^{19}$ m$^{-3}$.

It is seen that the discharges are very similar. The only difference is the increase of the H-alpha signal after the additional deuterium puff on the LFS (blue line at the fourth row of figure 1, #16305). This can be explained by the fact that the detector of the H-alpha is on the LFS; i.e., when the gas puff is on the same side the signal is higher.

The divertor probe system in the COMPASS tokamak consists of 39 single graphite Langmuir probes embedded poloidally in the divertor tiles. They are oriented along the magnetic field lines and provide profiles with a spatial resolution in the poloidal direction down to 5 mm [9]. The probes are swept with respect to the tokamak chamber wall by a triangular voltage $U_{p}(t) = +60 \div -160$ V with a frequency of 1 kHz.

Figure 2 shows the poloidal profiles of the plasma parameters determined from the IV characteristic using the FDPT. Figure 2a presents the floating potential, $U_{fl}$; figure 2b, the plasma potential, $U_{pl}$; and figure 2c, the ion saturation-current density, $J_{sat}$ for both discharges before (at 1120 ms) and during the additional deuterium puff (at 1175 ms). The positions of the strike points found from the
reconstruction of the magnetic surfaces by the Equilibrium FITing code (EFIT) are indicated by dashed lines in all figures below.

As the plots demonstrate, before the additional gas puff all profiles are the same for the discharge #16304 (empty black dots) for the HFS puff, and for discharge #16305 (empty red dots) for the LFS puff.

The floating potential $U_f$ (figure 2a) before the additional gas puff has positive values in the inner divertor ($0.39-0.42$ m) and in the private flux region (PFR) ($0.42-0.48$ m), and negative ones in the outer divertor ($0.48-0.55$ m). This is the well-known asymmetry in the COMPASS divertor [9].

During the additional gas puff, the $U_f$ on the HFS decreases in absolute values – more when the gas puff is on the LFS than when it is on the HFS. This tendency is reversed in the PFR. In the far scrape-off layer, the influence of additional gas puffing is negligible.

The changes in the plasma potential (figure 2b) in the inner divertor are similar (~20 V) to the changes of the floating potential when the additional gas puff is there. When the puff is on the LFS, the plasma potential in the inner divertor decreases by about 30 V. The plasma potential decrease is caused by the increased gas in the vacuum chamber. The effect of a higher line-average electron density in COMPASS has already been reported [12, 13]. The changes of the plasma potential in the outer divertor are smaller for gas puffs in both cases.

The ion saturation current density profiles are shown in figure 2c. When the gas puff is on the HFS, the changes in the $J_{sat}$ are negligible. When the gas puff is on the LFS, the plasma potential in the outer divertor decreases, but increases in the inner one.

Similar results were obtained using the second probe system in the COMPASS tokamak consisting of ball-pen probes (BPP) and rooftop-shaped Langmuir probe arrays [14]. The 2D profiles of the floating potential’s poloidal distribution measured by the Langmuir probes are presented in figure 3.

The positions of the inner and outer strike points are presented by solid lines. When the additional puff starts at 1160 ms, the changes, as seen in the figures, are more strongly expressed in the case of the LFS puff. There, the changes start almost simultaneously with the gas reaching the
vacuum chamber. An increase of the values is visible in the inner divertor, in the PFR and in the far scrape-off layer ($R = 500 – 540$ mm). This change lasts for about 50 ms, and then the potential slowly recovers to its initial values. The 2D figure for the HFS gas puff shows that the floating potential change occurs mainly in the inner divertor and in the PFR, but one can see that it starts later, about 5 – 10 ms after the puff.

The poloidal distributions of the electron temperature obtained, $T_e$, are shown in figure 4. As it is already mentioned above, under the conditions of plasma current $I_{pl}$ of 180 kA and $n_e^{avr} = 4 \times 10^{19}$ m$^{-3}$, the plasma is usually attached and the EEDF deviates from Maxwellian – besides thermal electrons, there exists a group of low-energy (cold) electrons and the EEDF can be approximated by a bi-Maxwellian one. The origin of the cold electron group was discussed in [15]. In the figure 4, the temperature of the thermal electrons is indicated by squares, and that of the cold electrons, by triangles. When the EEDF is Maxwellian, the electron temperature is indicated by stars.

Before the additional gas puff at 1160 ms, the poloidal profiles of the electron temperatures for both discharges are the same, as indicated by black and red empty symbols. When the puff is on the HFS, the temperature of the thermal electrons decreases as the strike points are approached, but the EEDF remains bi-Maxwellian on the HFS and the LFS. In the PFR, it changes to Maxwellian (black stars) with temperature below 9 eV. When the additional gas puff is on the LFS, the EEDF changes to Maxwellian (red stars) in the entire divertor, except in a region of 4 cm around the outer strike point in the outer divertor. The temperature of the cold electron group remains the same. We can thus conclude that a deuterium puff results in a cooling of the divertor mainly on the HFS. This is an important fact, as it provides guidelines on how to use gas puffs when impurity seeding is to be applied, e.g., with nitrogen or neon.
The electron density distributions (figure 5a, b) in general follow the changes of the $J_{\text{sat}}$. During the additional deuterium puffing, the electron density increases. When the puff is on the HFS, in both the inner and outer divertors the EEDF remains bi-Maxwellian, but the densities of the cold electron group increase significantly.

Figure 5. Poloidal distribution of a) the electron densities at gas puff on HFS (discharge #16304) and b) on LFS (discharge #16305) before (empty symbols) and during (solid symbols) the puff.

When the gas puff is on the LFS (figure 5 b), the EEDF become Maxwellian as the temperatures decrease, while the electron densities increase, except in a 4-cm interval on the LFS close to the outer strike point. In the far SOL and in the PFR, the electron densities are almost twice as high during the puff than before the puff (see the black solid stars in figure 5 b).

Using the data evaluated for the electron temperatures and $J_{\text{sat}}$, the poloidal profiles of the heat density [16] can be calculated (figure 6). It is seen that as a result of the LFS gas puff (solid red symbols), a practically flat distribution with a decreased heat flux is formed in the inner divertor region and around the inner strike point, which is the signature of a highly recycling or partially detached divertor at a higher plasma density.

Figure 6. Poloidal distribution of the heat flux before (empty symbols) and during (solid symbols) gas puffs on the HFS (discharge #16304, black symbols) and on the LFS (discharge #16305, red symbols).

The comparison with the results from an infra-red camera show a relatively good agreement in the HFS and far LFS, but the results from the two techniques in the interval of about 5 cm from the outer strike point in the LFS, (i.e. from 0.48 m to 0.53 m in figure 6) differ significantly. The data for the floating potential presented in figure 2 a and figure 3 show that it is negative in the near-strike point region. This is indicative of a lower sheath potential than usually assumed under floating conditions, with a larger than usual electron flux. This, as shown by Stangeby [16, 17], can lead to a significant increase of heat transmission factor (higher by a factor of 2 to 4, depending on the ratio $U_{\text{floating}} / T_e$), which could possibly be part of the explanation. There could also exist some toroidal asymmetries and/or shadowing. A deeper analysis of the problem will be subject of a future work.
3. Conclusions
The plasma parameters in the divertor were studied by Langmuir probes during an additional deuterium gas puff on the high- and on the low-field sides. It was found that there is a difference in the plasma parameters depending on the gas puff side.

In the case of an additional gas puff on the LFS, the plasma parameters changed vastly, mainly at the inner divertor – the plasma potential, the ion saturation-current density and the electron temperature dropped. After the gas puff, the electron temperature changed from 10-15 eV down to within the range 5-9 eV. As a result, the heat-flux density decreased. At the same time, in the outer divertor the plasma parameters remained the same. We thus concluded that using a gas puff on the LFS will facilitate reaching a detachment regime by increasing the density of puffed neutrals.

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