DIVERTOR IMPURITY SEEDING EXPERIMENTS AT THE COMPASS TOKAMAK

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Abstract

Partial detachment is the desired regime for the baseline burning plasma scenario in ITER and next-step devices, as it allows to convert the majority of the energy carried by charged particles through the scrape-off-layer (SOL) and thus deposition of localized heat fluxes in the divertor region is avoided. The COMPASS tokamak is equipped with an open divertor and has a relatively short connection length, both factors being unfavourable for access to detachment. As such, it only allows to approach naturally detached operation at very high line-averaged densities (> $10^{20}$ m$^{-3}$), which are incompatible e.g. with maintaining the ELMy H-mode regime. In order to achieve the detachment at lower densities, impurities (such as nitrogen) should be injected into the plasma in the divertor region. A series of experiments with impurity injection in the range of 1-9×1020 molecules per second at different locations in the divertor were performed with the aim to cool the plasma and influence the particle and heat transport onto the divertor targets and provoke partial detachment. Previously reported results [M. Komm et al, EPS 2017, P1.118] were largely extended by injection of nitrogen at the outer divertor target.

1. INTRODUCTION

The power exhaust in the divertor represents one of the key challenges of contemporary fusion research, as the heat fluxes in large machines, such as ITER or DEMO, can easily exceed the material limits of the plasma-facing components (PFCs) and lead to their damage and reduced lifetime [1]. Most of the heat flux escaping from the last closed flux surface (LCFS) is carried along the field lines until it reaches the PFCs in the divertor. To overcome this issue of divertor overheating in ITER, the partially detached regime is envisaged in the baseline scenario for burning plasmas [2]. Detachment allows to convert a majority of the energy carried by charged particles into radiation and as such prevents localised deposition of the heat fluxes [3]. It is characterised by an electron temperature gradient along the field lines, as they pass from the scrape-off-layer (SOL) (upstream) to the divertor target (downstream) and significant power loss in the SOL. The temperature at the target is typically low (< 5 eV), allowing a significant population of neutrals to form in the divertor region and act as a cushion for the incoming plasma particles.

In general, there are two ways of achieving the detached regime - (i) by increasing the density until sufficient amount of collisions with charged and neutral particles leads to power dissipation and cooling of the downstream plasma, or (ii) by injection of selected impurities, often strong radiators, which also allows to remove the power by radiation. In this work, we will focus on the latter approach, and we will present results of impurity seeding experiments at the COMPASS tokamak, where access to detached operation is particularly difficult due to open divertor geometry and relatively short connection length. On the other hand, since COMPASS has a ITER-like plasma shape, which allows it to improve or formulate the related multi-machine scaling.

2. EXPERIMENTAL SETUP

The impurity was injected in a series of otherwise identical attached L-mode discharges ($I_p$ = -210 kA, $B_T$ = -1.38 T, $n_e$=5×10^{19} m$^{-3}$). After a series of comparative experiments with nitrogen and neon seeding, the nitrogen was selected as a more favourable impurity (allowing for a range of effects in the divertor without the risk of
disruptions) and all the experiments in this work refer to discharges with nitrogen seeding. The impurity particle flux was controlled by a pre-set waveform on a piezoelectric valve in the range of 1-9×10^{20} molecules per second. A typical waveform included a 10 ms pre-puff during which the valve was fully opened (to ensure that the valve actually opens), followed by a 100 ms constant puff at the desired particle flux, which was varied on a shot-to-shot basis. Two different seeding locations were used: at first nitrogen injection at the inner target (major radius R=469 mm) [4], later at the outer target (R=500 mm), outside the outer strike point. For reference in the future sections, we include the list of performed discharges in the summary Table 1.

<table>
<thead>
<tr>
<th>Discharge</th>
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</table>

3. EFFECTS OF THE SEEDING

3.1 Radiation measured by the visible cameras

The location of injection is in the field of view of the RIS system [5] - a pair of fast color cameras operating in the visible range. One camera was oriented with tangential field of view of the plasma, while the other was providing wide angle radial view. Both cameras operated at 2 kHz sampling frequency with full resolution (1280×1000 RGB pixels). It was possible to identify 3 different patterns of radiation during nitrogen injection, which are shown in Figs. 1 and 2. The piezoelectric valve was opened at $t=1100$ ms and after approximately 15 ms it was possible to detect a new source of radiation around the injection location (Fig. 1A). Later, this radiation became more toroidally uniform but was restricted to the HFS (Fig. 1B), even in the cases when the injection was located at the outer strike point. In addition, measurements by the second RIS camera (see Fig. 4) shows that the radiation is not limited to the inner target but extends up to the whole HFS SOL. In some discharges, where the amount of injected nitrogen was sufficient, there was an abrupt change of the radiation pattern and the radiation became centered around the private flux region (Fig. 1C). This transition was accompanied by a sudden change of temperature measured by the combined array of Langmuir and Ball-pen divertor probes [6] as shown in Fig. 3, for the discharge #13729 (HFS seeding $\Gamma N2 = 2.0 \times 10^{20}$ s$^{-1}$), where several such transitions were observed, since the amount of injected nitrogen was probably marginal with respect to detachment access. The pixel signal intensities (the total intensity from RGB channels was used) indeed follow this behaviour (patterns are labeled HFS and LFS in the figure) and at certain times exhibit low-frequency oscillations ($f \sim 1$ kHz), which according to RIS data are axisymmetric and resemble those measured at AUG[7].
Figure 1: Three different patterns of nitrogen radiation in discharge #13729 ($\Gamma_{N_2} = 2.0 \times 10^{20}$ m$^{-3}$) observed by RIS1 camera with marked locations of seeding, LFS and HFS pixels.

Figure 2: Three different patterns of nitrogen radiation in discharge #13729 observed by the RIS2 camera.

Figure 3: Pixel intensity at seeding location, HFS and LFS (top) and evolution of $T_e$ at LFS target (bottom). Background colors indicate radiation regimes shown in Figs. 1 and 2.
3.2 Spectroscopy measurements

The radiation of nitrogen was measured using a set of minispectrometers for visible (460-663 nm), near UV (247-473 nm), and infra-red (630-680 nm) ranges with resolution of 0.15, 0.17, and 0.23 nm, respectively [8]. The field of view is covering the edge plasma at the outer midplane but excluding the outer target, as shown in Fig. 4B. It was possible to identify several nitrogen lines in the measured spectrum (see Fig. 4A). The two lines of N III around 400 nm are likely to correspond to the blue color detected by the RIS cameras during the seeding. The most intensive line measured was N IV at 348.49 nm, which was used to estimate the nitrogen density. Since many other nitrogen lines were not covered by the minispectrometers (especially those emitted by higher ionization states of nitrogen), the resulting density of N IV, which was obtained by integration of the line emission, is strongly underestimated, which is consistent with the very low values obtained in this analysis - typically between 0.5 - 3.0 ×10^{12} m^{-3}. However, it can be seen that the qualitative behaviour of the radiation follows the amount of injected nitrogen as shown in Fig. 5A. The radiation exhibits a sudden increase at certain times, which within the precision of the measurement corresponds to transition times (marked by sharp drop of divertor temperature or increase of pixel intensity) visible in the output of visible cameras and probes (see Fig. 6).

![Figure 4: Nitrogen lines identified in the measured spectrum in discharge #15976 at t=1150 ms (a) and the field of view of the minispectrometers (b).](image)

![Figure 5: Density of N IV calculated from the radiation of N IV line at 348.49 nm evolving in time (a) and as a function of nitrogen content (b).](image)

3.3 Effects in the divertor

Figure 6 summarises the effects of nitrogen seeding on divertor temperature, pressure and heat flux, as measured by the divertor probes. The values plotted in the figures correspond to the maximum quantities within 2 cm outside the OSP. The electron pressure was calculated as

\[ p_e = (1 + M^2)n_e T_e \] (1)
where $M$ is the parallel Mach number, which was assumed to be equal to 1 at the target due to Bohm condition and equal to 0 upstream. The heat flux was calculated from the measured values of $T_e$ and $j_{sat}$. For simplicity it was assumed that the tiles were in ambipolar condition and so the parallel heat flux can be calculated as

$$q_{par} = \gamma j_{sat} T_e$$ (2)

The value of sheath heat transmission coefficient $\gamma$ depends on the ratio $T_i/T_e$ and the coefficient of secondary emission [9]. We assume that the secondary emission is negligible due to the small angle of incidence of the field lines with respect to the tile top surface (1-3°) [10] and that due to its high collisionality the plasma is isothermal, similarly to the conditions in MAST [11]. This yields value of $\gamma$ equal to 7. This approach neglects a number of details, which may be important under certain conditions, however in our analysis we will concentrate on such properties of the heat flux profiles, which are not affected by a possibly different value of $\gamma$.

The effects of the impurities are dependent on the location of the seeding. When the impurity was introduced at the HFS, it was always followed by an abrupt change of temperature (Fig. 6A) at the outer target, similar to behaviour which was observed at DIII-D[12]. For the highest amount of seeding, the discharge was ended prematurely due to a disruption due to mode locking of a tearing mode. When the nitrogen was seeded at the LFS, the effects in the divertor were generally more gradual (Fig. 6D-F). The abrupt response on the $T_e$ is still present but the relative magnitude of the drop is smaller and occurs at different times depending on the amount of nitrogen influx. At low seeding values there are no relaxations observed (unlike the case of HFS seeding, as shown in Fig. 6A-C), instead the target pressure and heat flux only gradually decrease. At highest amount of seeding there is still a disruption but it occurs only at the end of the flat-top phase.

Figure 6: Temporal evolution of $T_e$, $p_e$, and $q_||$ in the divertor for seeding at HFS (a-c) and LFS (d-f) measured by probes in the vicinity of the outer strike point.

### 3.4 Upstream and downstream pressure

The relatively small plasma cross-section and low edge temperature casted doubts whether the pronounced change in divertor parameters is due to nitrogen radiating in the SOL or whether the whole edge plasma is cooled. In order to distinguish between these two possibilities, the measurements of upstream and downstream pressures have to be compared. While the change of peak electron pressure at the outer target was monitored using the LP+BPP divertor probes, the upstream pressure was monitored by HRTS[13] at the position of separatrix calculated by magnetic reconstruction. Both upstream and downstream pressures were calculated using eq. 1.
It was observed that there is a significant drop of the downstream pressure following the injection of nitrogen and that the speed of the response and the magnitude of pressure drop can be controlled by the amount of injected nitrogen, as shown in Fig. 7. As expected the effect of nitrogen was not restricted to the divertor only but also affected the upstream pressure by reducing the power crossing the separatrix. When this pressure drop (visible e.g. in Fig. 7B) was taken into account, it became difficult to determine whether the effect of nitrogen in the SOL is more significant than in the confined region.

In order to resolve this issue, a new series of experiments was performed, where the effect of nitrogen radiation inside the separatrix was compensated by the application of NBI heating. The effect of auxiliary heating on the upstream profiles was generally not too pronounced, so maximum available power of 450 kW was delivered into the plasma. Fig. 8 shows a comparison of two discharges with identical amount of nitrogen seeding, where Fig. 8A was purely Ohmic and 8B was NBI-assisted. It can be seen that the upstream pressure recovers once the NBI heating reaches its peak value (at t=1135 ms). Note that the pressure decreases again for t > 1170 ms, which corresponds to a drop of signal from the neutron detector (gray line in Fig. 8B). This indicates that the absorption of the fast neutrals from the NBI systems is changing, however the exact underlying mechanism is not well understood. It may be related to a large sawtooth crash which develops at this time. The downstream pressure is not significantly affected by the application of NBI. The large pressure drop achieved in discharge #16282 is a clear demonstration of partial detachment.

4. CONCLUSIONS

Nitrogen seeding was proved to be an efficient tool for reduction of divertor pressure and heat flux in a series of dedicated L-mode discharges at COMPASS. The plasma response to the seeding is in general dependent on the
location of the seeding, with more favourable results being achieved with seeding in the vicinity of the outer strike point. The nitrogen radiation is not restricted to the divertor region but affects also the confined plasma, which results in considerable upstream temperature drop. This effect can be compensated by the application of additional heating, without a significant effect on the downstream pressure.

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was supported by projects Czech Science Foundation GA15-10723S, GA16-14228S, MYES Project #LM2011021 and IAEA CRP F13019 - Research Contract No. 22727/R0. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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