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Published in:
Nuclear Materials and Energy

**DOI:**
10.1016/j.nme.2017.02.020

Published: 01/01/2017

**Document Version**
Publisher's PDF, also known as Version of record

Please cite the original version:
Measurement of N⁺ flows in the high-field side scrape-off layer of ASDEX upgrade with different degrees of inner divertor detachment

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A rticle Info

Article history:
Received 14 July 2016
Revised 12 January 2017
Accepted 16 February 2017
Available online 9 March 2017

Keywords:
Impurity migration
Doppler spectroscopy
SOL flow
Divertor detachment

A bstract

Toroidal and poloidal flows of injected N⁺ ions were measured in the high-field side (HFS) scrape-off layer (SOL) of ASDEX Upgrade by Doppler spectroscopy with different degrees of HFS divertor detachment. In high-recycling conditions, the results suggest reversed parallel N⁺ flow away from the inner divertor in the near SOL close to the separatrix, while the flow is towards the inner divertor throughout the SOL in detached conditions. The measured poloidal N⁺ flows were directed away from the HFS divertor in the near SOL for all density cases. Divertor plasma oscillations, characterized by momentary peaking of the HFS target ion flux and decrease of the HFS SOL density, were observed slightly before the roll-over of the ion saturation current to the HFS target and lead to an increase in the N⁺ flow towards the HFS divertor. SOLPS and ERO simulations of the experiment predict entrainment below 50% between the velocities of N⁺ and D⁺ ions, suggesting that N⁺ ions are quantitatively a limited proxy for measuring D⁺ flows. ERO simulations show significantly higher entrainment for higher ionization states, e.g., N²⁺ and N³⁺.

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1. Introduction

Identifying plasma flows in the scrape-off layer (SOL) is essential for understanding material migration in the tokamak edge plasma. While SOL flows on the low-field side (LFS) of the plasma have been widely studied in several tokamaks [1], only few measurements exist on the high-field side (HFS). As the flow on the HFS has been observed to be stronger than on the LFS [2,3], and since it is considered responsible for material migration from the HFS wall to the HFS divertor, the HFS SOL is a specific region of interest for new experiments. Direct Langmuir probe measurements of the D⁺ flow have been performed in the HFS midplane region of Alcator C-Mod [2,4] and in the HFS divertor region of ASDEX Upgrade [5,6] and JT-60U [3], whereas indirect measurements by spectroscopy and camera imaging have been carried out in the HFS midplane region of ASDEX Upgrade and Alcator C-Mod with the help of methane and nitrogen injections [7–9].

In this contribution, HFS SOL flows of N⁺ ions, originated from an N2 injection, have been measured by Doppler spectroscopy in the visible wavelength range in the midplane region of ASDEX Upgrade in a similar fashion as in [7,8]. The flows were measured during L-mode discharges with varying degree of HFS divertor detachment to provide insight on the differences in flows under detached and high-recycling plasma conditions. The entrainment of the N⁺ ions with the background D⁺ plasma was studied by modelling the experiment with the SOLPS [10] and ERO [11] codes to assess, whether the N⁺ ions can be used as a representative proxy for measuring the D⁺ flows.

2. Experiment

The flow measurements were performed in six L-mode discharges (AUG shot numbers #32125, #32130–33, #32136) with plasma current, electron cyclotron resonance heating and ohmic heating of Iₚ = 0.8 MA, PₑCRH = 0.3 MW and Pₒₗₒₘₜ = 0.4–0.6 MW,
The discharges had a lower-single-null configuration with the ion $B \times V B$ drift towards the lower divertor, low triangularity of $\delta = 0.22$ and a gap of approximately 10 cm between the separatrix and the inner wall to ensure that flow data is obtained from a wide range across the SOL. The plasma geometry is presented in Fig. 1. To reach different degrees of HFS divertor detachment, the core electron density ($n_e$) was varied between the discharges. One discharge (#32125) was a density ramp within a range of $n_e = 2.0 - 6.0 \times 10^{19}$ m$^{-3}$, providing information on the evolution of the HFS divertor conditions with increasing density. Based on this discharge, different representative densities were selected for the remaining discharges, as presented in Fig. 2. The densities correspond to approximately 20–60% of the Greenwald density limit. The evolution of detachment was monitored by the target Langmuir probes [12], while the HFS SOL density was measured by Stark broadening of the Balmer lines in the divertor volume [13] and by reflectometry in the HFS midplane region [14]. The poloidal and toroidal locations of these measurements are shown in Fig. 1.

$N_2$ was injected into the plasma through a single valve in the inner heat shield 13 cm above the HFS midplane. Line-integrated emission of the injected nitrogen was recorded at different radial locations by seven toroidal and poloidal spectroscopic lines-of-sight (LOS) of the HFS edge charge exchange recombination spectroscopy (CXRS) system [15,16] throughout the discharges at temporal resolution of 2.5 ms. To provide a fully radially resolved profile, the plasma was swept radially by approximately 1 cm during the discharges. The contribution of recycled nitrogen in the LFS SOL close to the ends of the LOS was eliminated by subtraction of the background emission measured by separate toroidal and poloidal LOS not directly observing the injection. The geometry of the measurements is illustrated in Fig. 1.

3. HFS divertor conditions

When the core density is increased, the integrated total ion flux at the HFS target first increases, until it rolls over at $n_e = 4.0 \times 10^{19}$ m$^{-3}$ and starts to decrease, while the HFS strike-point electron temperature is always below 5 eV, as given by the target Langmuir probe data in Fig. 3a and b. This suggests that the vertical section of the HFS target plate ranged from high-recycling to detached conditions during the experiment.

The divertor spectroscopy data, presented in Fig. 3c for the density-ramp discharge #32125, shows spreading of a high-density front with $n_{e,SOL} = 2 - 5 \times n_{e,core}$ upwards from the HFS strike-point region with increasing core density, agreeing with earlier observations in ASDEX Upgrade and JET [17]. The coordinate $\Delta S$ measures the distance from the inner strike point along the target plate, corresponding to the end points of the divertor spectroscopy LOS, as illustrated in Fig. 1. Comparison of reflectometry data from discharge #32125 between the HFS and LFS midplane regions in Fig. 3d suggests that the high-density front extends all the way to the HFS midplane region: beyond the roll-over core density, the SOL density at the HFS midplane increases to 4–8 times higher values than at the LFS midplane. This finding is also consistent with earlier results from ASDEX Upgrade [18].

Divertor plasma oscillations, during which the HFS divertor returns momentarily from almost detached to attached conditions [19,20], were observed within a narrow density region at approximately $n_e = 3.7 \times 10^{19}$ m$^{-3}$ throughout discharge #32131. As shown in Fig. 4a, the oscillations appear as periodic increases in the target ion flux and cease moments after the neutral beam injection (NBI) blips, used for CXRS measurements at 0.5-s periods,
possibly due to a brief increase in the plasma density after each beam blip. The divertor oscillation cycle can thus be divided into two distinct states with high and low target ion flux, from here on referred to as high- and low-flux states. The high-flux state is characterized by a drop of an order of magnitude in the HFS divertor volume density and a 3–6-fold decrease in the HFS SOL midplane density, as suggested by the divertor spectroscopy and reflectometry data in Fig. 4b and c, respectively. The magnetic equilibrium data shows less than 2-mm variation in the HFS separatrix position during the oscillations, which has been taken into account in calculation of the R−Rsep coordinate. This indicates that the difference between the reflectometry profiles during the low- and high-flux states is not dominated by plasma movement but, together with the behaviour of the divertor volume density, is rather a sign of momentary disappearance of the HFS high-density front during the high-flux state. The return to attached conditions is evident in Fig. 4d and e in which both the target ion saturation current and electron temperature are shown to increase by up to an order of magnitude close to the strike point in the high-flux state.

4. SOL flows of N⁺ ions

The line-integrated SOL flow velocities of injected N⁺ ions were resolved from the Doppler shift of six N(II) lines within 460–465 nm, resulting from the 2s²2p³ ¹P→2s²2p³ ¹S transition. The studied N(II) lines were the same as illustrated in [8], while the N(III) lines in the studied spectral range were too weak for successful analysis. The radial intensity profiles of the N(II) emission, integrated over the width of the most intense line at 463 nm, are presented in Fig. 5 in toroidal and poloidal viewing directions. The

Fig. 3. Integrated total ion flux (a) and strike-point electron temperature (b) on the HFS divertor target as a function of the core electron density during the different discharges. Evolution and propagation of the HFS high-density front vertically in the divertor volume (c). The coordinate ΔS increases upwards from the strike point (ΔS = 0) along the target plate, and the white dashed line marks the roll-over density. Comparison of the HFS and LFS reflectometry data (d) shows an increase in the HFS SOL density also in the midplane region.

Fig. 4. During discharge #32131, the divertor plasma oscillations appear as periodic peaks in the time trace of the HFS target ion flux (a) and decreases in the divertor density (b). The green and magenta dashed lines illustrate the division to the high- and low-flux states during one oscillation cycle, and the coordinate ΔS is defined as in Fig. 2c. On the HFS midplane, the target ion flux peaks are connected to a decrease in the electron density (c). The grey region highlights the uncertainty of the radial position of the separatrix. Return to attached conditions is seen as significant increases in the ion saturation current (d) and electron temperature (e) on the HFS target. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. The radial profiles of the N(II) emission intensity as measured with toroidal (a) and poloidal (b) LOS during a radial plasma sweep. The grey regions highlight the uncertainty of the radial position of the separatrix.
profiles have been shifted radially to account for the uncertainty of the position of the separatrix, as will be discussed in Section 4.2. The figure shows that the emission peak shifts away from the separatrix with increasing density due to the parametric dependence of ionization and excitation on density. Thereby, the accuracy of the analysis in the vicinity of the separatrix suffers from low intensities at high densities, and in the subsequent analysis data has been omitted in regions where the intensity of the emission recorded by the signal LOS is less than 50% higher than that of the background LOS. Beyond this point, the fit of the background-corrected spectrum becomes unreliable due to decreased signal-to-noise ratio.

4.1. Measured toroidal and poloidal $N^+$ flows

At distances larger than 2 cm from the separatrix, co-current $N^+$ flows of approximately $2\sim10$ km$s^{-1}$ are observed at all core densities, increasing with the distance from the separatrix, as shown in Fig. 6a. Here, the co-current direction corresponds to a parallel flow direction towards the HFS lower diverter. The velocity profiles in Fig. 6a and b have been shifted radially similarly to the intensity profiles in Fig. 5. Closer to the separatrix, the results suggest reversal of the $N^+$ flow with velocities up to 7 km$s^{-1}$ in the counter-current direction, when the HFS diverter is in the high-recycling regime. The region of the reversed flow extends to approximately 2 cm from the separatrix at the lowest densities (#32130), while its width is roughly half of this in the medium density cases (#32131, #32132). At the highest densities (#32133, #32136), when the HFS diverter is in the detached regime, the results do not show reversed flows, and the co-current flow speed is increased in the far SOL by a factor of 2 in comparison to the low-density cases.

In the poloidal direction, the results of the spectroscopic analysis, presented in Fig. 6b, do not show noticeable differences between the different density cases. In the far SOL, i.e., $R_{sep}<2$ cm, the poloidal component of the $N^+$ flow is directed towards the HFS lower diverter at velocities below 1 km$s^{-1}$. Considering the pitch angle of the magnetic field, this flow magnitude is consistent with the poloidal component of the parallel $N^+$ flow, when compared to the magnitude of the toroidal component. In the near SOL, i.e., $R_{sep}>2$ cm, the poloidal flow is away from the HFS diverter, increasing up to 2 km$s^{-1}$ towards the separatrix. In this region, the direction of the poloidal flow is in contradiction with the toroidal flow component at high densities, hinting at a possible strong contribution of the cross-field $E_x \times B$ drift close to the separatrix. The measured poloidal velocities would correspond to a radial electric field of up to 7 kV$m^{-1}$ which is comparable to earlier observations in L-mode plasmas in the LFS SOL of ASDEX Upgrade [21,22]. However, it is noted that the uncertainties of the analysis cause a significant relative error in the poloidal velocities, which complicates both the interpretation of the flow direction and inferring the magnitude of the radial electric field.

The behaviour of the observed $N^+$ flows with varying density is similar to what was observed for $Cl^+$ ions in similar measurements during an L-mode density ramp in [7]. Even though the $N^+$ ions are not expected to be fully entrained in the $D^+$ flow, as will be shown in Section 5, the results are qualitatively consistent with earlier observations of parallel HFS SOL flows of $D^+$ in ASDEX Upgrade, Alcator C-Mod and JT-60U. In all these devices, the flow speed increases with distance from the separatrix [2,3,5,6]. Reversal of the flow close to the separatrix at low densities was also observed on the HFS midplane of Alcator C-Mod [2] and on the HFS divertor entrance of JT-60U [3]. In JT-60U, detachment of the HFS divertor was found to cancel the reversal in the near SOL and to noticeably increase the flow speed in the far SOL [1], agreeing with the behaviour of the $N^+$ flows in Fig. 6a. Increase in the far-SOL flow speed with increasing density was also observed in Alcator C-Mod, although generally the HFS flow was mostly found to be rather insensitive to the plasma density [2]. On the other hand, the observed increase in $N^+$ flows at high densities can also be largely due to improved frictional entrainment with the background $D^+$ flow.

The results of this work together with earlier results of $D^+$ flows suggest that detachment of the HFS divertor changes the poloidal pressure profile which mostly drives the HFS SOL flow. The reversal of the flow in the near SOL is commonly attributed to ionization of the neutrals recycled from the HFS target in a narrow region close to the separatrix causing the plasma pressure to exceed its upstream value, thus reversing the pressure-driven flow above the ionization region [23]. Such reversal was not observed in earlier measurements in the HFS divertor of ASDEX Upgrade [5,6], but the measurements were done below the X point, possibly being already below the strongly localized ionization region. The lack of reversal in detached conditions suggests shifting of the pressure peak from the HFS divertor region to above the HFS midplane.

4.2. Uncertainties of the measurements

The significant uncertainty of the position of the separatrix on the HFS of ASDEX Upgrade was compensated by radial positioning of the $N^+$ ion temperatures obtained from the Doppler broadening of the spectral lines. Fig. 6c shows the radial profiles of the $N^+$ temperature for each density case measured in both toroidal and poloidal viewing angles. For all densities, the data shows an increase from approximately 20 eV to 60 eV towards the separa-
4.3. Effect of divertor plasma oscillations on the N⁺ flows

The effect of the divertor plasma oscillations, which occurred during discharge #32131, was also observed in the measured flows. In Fig. 7a, the toroidal flow velocities measured during the high- and low-flux states of the oscillation cycle are presented separately, and a clear division in two branches is observed. In the high-flux state, the toroidal flow speed is observed to increase by approximately 2 km s⁻¹ with the largest effect close to the separatrix, where the direction of the flow changes from reversed to co-current. The small variation in the separatrix position during the oscillations is taken into account in calculation of the R-Rsep coordinate, eliminating the effect of plasma movement in interpretation of the results in Fig. 7. Fig. 7b shows the ion saturation current measured on the HFS target during both states, and the change in the flow direction can be seen to coincide with the region of the most significant increase in the ion saturation current in the high-flux state, mapping to within 1 cm of the separatrix at the HFS midplane. Together with the increased target ion flux and decreased HFS SOL density, shown in Fig. 4a–c, the results suggest increased parallel plasma transport in the high-flux state of the oscillations, pushing the high-density front down from the HFS midplane region to the HFS target. The effect is most dramatic close to the separatrix. The oscillations also shift the peak of the N(II) intensity profile by approximately 0.5 cm towards the separatrix in the high-flux state, as shown in Fig. 7c, which agrees with the density behaviour of the intensity profiles in Fig. 5.

5. Modelling of the N⁺ flows

The edge fluid code SOLPS 5.0 was used to predict the SOL conditions in the experiment on a 2-D grid by matching the predicted radial profiles of ne, Te and jee with the experimental profiles as closely as possible in the midplane and target regions. Drift terms were switched on for better representation of the HFS conditions [24,25], and atomic N injection was applied in the same location as in the experiment. Good correspondence has been obtained for ne and Te on the LFS midplane and ne on the HFS midplane, while the simulations overestimate the measured ion flux on the HFS divertor target by a factor of 10 at high densities after detachment. Since the poorly predicted plasma pressure distribution in the HFS SOL may affect the HFS flow, the background flow was used as a free parameter in the subsequent ERO modelling. Overestimation of the HFS target flux in SOLPS – especially at high densities – has been reported also earlier in, e.g., [24,26]. More recently, progress has been made to overcome the issue by improving the description of the HFS high-density front and the neutral conditions in the HFS divertor by adjusting the balance between the neutral and plasma fuelling with the help of additional convective transport in the LFS SOL [27]. No measurement data for Ti on the LFS and the ion temperature was approximated by using the same heat conduction coefficients for ions and electrons, leaving it also open for modifications in the ERO modelling.

Due to the parametric dependencies of the friction force between the nitrogen impurities and the main plasma (\(F_f \sim Z_{N^+}^2 V_{Te} n_{N^+} T_{e,i}^{-3/2}\)) [28], the entrainment of the N⁺ ions is expected to improve with increasing density. In this work, modelling of the experiment was restricted to discharges #32130 and #32136 to study two extreme cases of the density range. The parallel gradients of electron and ion temperatures at the HFS midplane were insignificantly small in the SOLPS solutions, leading to strong dominance of the friction force over the \(\nabla E_{e,i}\) forces in entrainment of the N⁺ ions.

The SOLPS results on the HFS midplane were extrapolated into background plasmas for the Monte Carlo particle transport code ERO which was used to model the N₂ injection by placing a 3D...
making the shapes of the $N^+$ temperature profiles coincide overcompensates the uncertainty of the separatrix position. On the other hand, the need to decrease $T_i$ in the low-density case to a level below the uncertainties of the $N^+$ temperatures in Fig. 6 can also indicate that entrainment of the $N^+$ ions with the $D^+$ flow is not purely frictional but the $\nabla T_{el}$ forces might also have a significant contribution.

The results show entrainment, i.e., ratio of $N^+$ and $D^+$ velocities, of 20–40% at high density and 10–20% at low density between the toroidal $N^+$ and $D^+$ flow magnitudes. The shapes of the $N^+$ and $D^+$ flow profiles are roughly similar with lower entrainment towards the inner wall, where the plasma density is decreased. In the low-density case, the region of reversed flow is approximately 1 cm narrower for $D^+$ than for $N^+$, which is an effect of line-integration of the $N^+$ velocity in the curved plasma. In the poloidal direction, radial electric fields of approximately 3 kV/m and 7 kV/m$^{-1}$ were required in the low- and high-density cases, respectively, to reproduce the measured velocities in the near SOL, supporting the experimental hypothesis made in Section 4.1. Overall, the results suggest that the line-integrated measurements with $N^+$ ions are qualitatively indicative for the $D^+$ flows, while the quantitative consistency could be improved by, e.g., considering $N^2+$ or $N^3+$ ions for which ERO predicted 2–5 times better frictional entrainment than for $N^+$, as shown in Fig. 9.

6. Conclusions

Flows of injected $N^+$ ions were measured in the SOL at the HFS midplane of ASDEX Upgrade by Doppler spectroscopy with different degrees of HFS divertor detachment. The results show reversal of the $N^+$ flow close to the separatrix in high-recycling conditions and flow towards the HFS divertor in the detached regime, suggesting shifting of the peak of the poloidal pressure profile from the HFS divertor to above the HFS midplane in detachment. In addition, divertor plasma oscillations at intermediate upstream densities were found to momentarily increase the plasma flow towards the HFS divertor, overcoming the reversal and pushing the high-density front back from the HFS midplane to the HFS target.

ERO simulations of the $N_2$ injection in the highest- and lowest-density cases of the experiment showed entrainment ratios of $v_{N^2}/v_{D^+} = 20–40\%$ and $\nu_{N^2}/\nu_{D^+} = 10–20\%$, respectively, between the flow velocities of $N^+$ and $D^+$. The results thus suggest that $N^+$ gives a qualitative indication of the $D^+$ flow but is quantitatively not suitable as a proxy for measuring its magnitude. To study the prospects of improved entrainment of higher charge states, new measurements have been performed with similar plasmas by
recording the emission of $N^2+$ ions. The analysis of this experiment will be reported elsewhere.

Acknowledgments

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 number 633053 [and from Tekes – the Finnish Funding Agency for Innovation under the FinnFusion Consortium]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Work performed under EUROfusion WP PFC.

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