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Published in:
Nuclear Materials and Energy

DOI:
10.1016/j.nme.2019.03.024

Published: 01/05/2019

Please cite the original version:

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Assessment of particle and heat loads to the upper open divertor in ASDEX Upgrade in favourable and unfavourable toroidal magnetic field directions

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ARTICLE INFO

Keywords:
ASDEX Upgrade
Upper single null
Scrape-off layer
Divertor detachment
Drifts

ABSTRACT

Pairs of ASDEX Upgrade L-mode discharges with the toroidal magnetic field, B T, in the forward and reverse directions have been used to study the impact of neoclassical drifts on the divertor plasma conditions and detachment. The evolution of the peak heat flux and the total power loads onto both the outer and the inner targets depends significantly on the toroidal field direction: increasing the core plasma density affects mainly the heat loads in the B T < 0 (unfavourable) direction, whereas increasing the plasma current has a larger impact on the heat loads for B T > 0 (favourable). Ion saturation current measurements show similar trends to those of the IR heat flux data. These discrepancies are not only caused by drifts but also by different levels of radiated power in the core, thus the power across the separatrix, P sep, is not constant within the entire dataset. Finally, at I p = 0.8 MA, a significant reduction of the peak heat flux is observed at both targets for both field directions. On the other hand, at I p = 0.6 MA, a reduction of the peak heat flux is only observed for B T < 0 at the outer target. Additionally, the onset of particle detachment is only observed at the outer target for B T < 0 with I p = 0.8 MA.

1. Introduction

Drifts are considered to play a critical role in the Scrape-Off Layer (SOL), divertor plasma transport and detachment. The onset of detachment is a reduction of both the particle and heat fluxes with respect to their maximum value in an upstream collisionality scan. Understanding and controlling detachment is fundamental for the operational feasibility of future devices.

The toroidal field direction in which the ion V VB drift [1] points towards the active divertor is called favourable (B T > 0, Fig. 1 (a)). The opposite field direction is unfavourable (B T < 0, Fig. 1 (b)). They are called favourable and unfavourable with respect to the L–H transition power threshold being lower or higher, respectively. The typical flow pattern of the V VB drift [1] for the two directions of the magnetic toroidal field is also shown in Fig. 1, but it may vary under certain plasma conditions, c.f. [2].

Previous studies of the effect of drifts in different machines (AUG [3–6], CMOD [7], JET [8], DIII-D [8], JT60-U [9]) reported similar observations with respect to the asymmetries of the inner and outer target temperatures and densities. In favourable field direction, a hotter, less dense outer target with respect to the inner target is usually observed, while in unfavourable field direction the asymmetry between inner and outer targets is reduced.

2. Experimental setup

A set of discharges were performed in the upper, open divertor of ASDEX Upgrade during its 2017 experimental campaign. The corresponding shot numbers are presented in Table 1. The database consists of pairs of shots with both toroidal field directions for which the same plasma conditions (plasma core density and current as well as input heating power) were maintained as similar as possible. The plasma core density is measured with the interferometer LOS H1. Because of the lack of tilt of the upper divertor tiles, when reversing the toroidal field...
direction, the plasma current direction remained unchanged and thus the helicity was reversed. The tilt of the surface normal of the divertor targets with respect to the impact angle of the magnetic field in the poloidal plane is expected to reduce the neutral communication across the private flux region between the two divertors.

Electron Cyclotron Resonance Heating (ECRH) with a power of $P_{\text{ECRH}} = 0.5 \text{ MW}$ was applied for all cases except those labelled with * in Table 1, which only received $P_{\text{ECRH}} = 0.3 \text{ MW}$. Additionally, Neutral Beam Injections (NBI) blips were used in order to obtain Charge Exchange Recombination Spectroscopy (CXR) measurements with $P_{\text{NBI}} = 2.5 \text{ MW}$ at a blip duration of 12 ms. These NBI blips in addition to the ECRH and the Ohmic heating caused an L–H transition in some discharges, especially in favourable toroidal field direction. The occasional L–H fluctuations and the lack of a pumping system close to the upper divertor degraded the level of density control in some discharges.

Infra-red thermography provides the reconstruction of the heat flux onto the targets based on temperature measurements. The heat flux distribution is calculated from these temperature data using an implicit solving scheme of the THEODOR code (2D heat equation solver) [3,10,11]. Fig. 2(a) shows the thermal emission as received by the cameras in a typical USN plasma.

The heat flux profiles data are collected along the upper inner and outer target plates (yellow lines in Fig. 2(a)). The position of the lines are preserved for different discharges. The outer target (right-hand side) consists of an special tile for IR measurements. There, the heat flux is toroidally symmetric and a single radial line can be used to characterise it. On the other hand, at the inner target (left-hand side), the heat flux is localized toroidally and poloidally around leading edges [12], which is a hotter, glowing region that receives larger heat loads due to geometrical effects (lack of tilt of the target components). The leading edge changes from one end of the tile to the other when the toroidal magnetic field and thus the helicity are reversed.

The lines of sight (LOS) of the bolometry system [13] are shown in Fig. 2(b). The tomographic reconstruction of these data can be used to analyse radiation patterns of the plasmas. The upper divertor of AUG was displaced up and down by 2 cm, which caused the strike line to cross two different probes. A large divertor volume is desirable as more volumetric processes might occur. However, displacing the X-point further down would realign most LPs to the private flux region (PFR) where their utility is limited.

### 3. Experimental results

#### 3.1. Core plasma density scan

The evolution of the profiles of the heat flux onto the targets with increasing core plasma density and $I_p = 0.8 \text{ MA}$ is presented in Fig. 3 according to profile lines in Fig. 2(a).

In the transition from low to medium core density with $I_p = 0.8 \text{ MA}$ (Fig. 3) and $B_t > 0$, the heat flux onto the outer target does not change significantly ($\approx 5\%$) but the peak at the inner target is reduced by 45%. In contrast, in the case of $B_t < 0$, the peak heat flux increases for both inner and outer targets by a factor 2.5. At high density, the peak power to the targets was observed to be reduced to very low values comparable to the measurement uncertainties.

In Fig. 4, the power to the divertor, $P_{\text{div}}$, follows a similar trend (within uncertainties which are very large for high density cases) to

### Table 1

Pairs of L-mode plasmas in forward and reverse toroidal field directions with different plasma conditions (plasma core density and current). *: $P_{\text{ECRH}} = 0.3 \text{ MW}$ instead of $P_{\text{ECRH}} = 0.5 \text{ MW}$. **: No $I_{\text{n,pp}}$ data. ***: No IR data.

| $|B_t| = 2.5 \text{T}$ | $n_{\text{H}} [10^{21} \text{m}^{-3}]$ | 2.5 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 |
|--------------------------|----------------|------|------|------|------|------|------|
| $I_p = 0.6 \text{ MA}$   | $B_t < 0$      |       | 34303* | 34623** | – | – | – |
|                          | $B_t > 0$      |       | 34302*** | – | 34624** | – | – |
| $I_p = 0.8 \text{ MA}$   | $B_t < 0$      |       | 34314 | 34312 | – | 34505*** | 34616** | 34503*** |
|                          | $B_t > 0$      |       | 34306 | 34311 | – | 34507*** | 34618** | – |
| $I_p = 1.0 \text{ MA}$   | $B_t < 0$      |       | 34309 | – | – | – | – |
|                          | $B_t > 0$      |       | 34308 | – | – | – | – |
that of the peaks of the heat flux profiles. Here, \( P_{\text{div}} = 2 \pi R \int q \, ds \) with \( R = 1.5 \) m being the average major radius and \( q \) the heat flux density measured by the IR camera. The error bars correspond to the integral of upper and lower values of the uncertainty in the profiles of Fig. 3. Additionally, the absolute value and the in/out difference might not be correct because toroidal symmetry cannot be assumed. Nonetheless, the trends for each divertor are more certain.

At a lower plasma current, \( I_p = 0.6 \) MA (Fig. 5), the inner target heat flux profile is already low and flat at low density for \( B_T > 0 \), indicating a power detached target. For the outer target, when the core density is increased from low to medium levels, the peak of the heat flux raises by a small amount, 20\%. In the \( B_T < 0 \) direction, however, the peak of the heat flux in the medium density range drops by 50\%, even as the value of \( P_{\text{div}} \) increases by 5\% (Fig. 6). Although the heat flux increases along the entire profile at the inner target, the uncertainty of the measurements is considerable.

This apparent disparity of the effect of increasing plasma core density depending on the magnetic field direction is not a power detached target. For the outer target, when the core density is increased from low to medium levels, the peak of the heat flux raises by a small amount, 20\%. In the \( B_T < 0 \) direction, however, the peak of the heat flux in the medium density range drops by 50\%, even as the value of \( P_{\text{div}} \) increases by 5\% (Fig. 6). Although the heat flux increases along the entire profile at the inner target, the uncertainty of the measurements is considerable.

This apparent disparity of the effect of increasing plasma core density depending on the magnetic field direction is not a
consequence of drifts exclusively. Considering the total heating power, $P_{\text{heating}} = P_{\text{ohmic}} + P_{\text{ECRH}}$, and the total radiated power within $\rho_{\text{pol}} < 0.95$, $P_{\text{rad}} < 0.95$, then the power crossing the separatrix can be approximated by $P_{\text{sep}} = P_{\text{heating}} - P_{\text{rad}} < 0.95$. In Fig. 8, it is shown that $P_{\text{sep}}$ does not remain constant for different plasma conditions.

At medium current, $I_p = 0.8 \text{ MA}$, $P_{\text{sep}}$ values for both toroidal field directions are similar within the medium to medium-high density range. At high density, a 30% increase is observed for both field directions. However, at low density, $P_{\text{sep}}$ for $B_T < 0$ is 30% lower than for $B_T > 0$. From low to medium density, the quantity $q_{\text{load}}/P_{\text{sep}}$ increases by $\sim 60\%$ instead of a factor of 2.5. Estimations of the tungsten core radiation are obtained with a grazing incidence spectrometer for VUV by calculating the fractional abundance of different tungsten ionisation states and the emissivity [14]. In Fig. 9, it is shown that $P_{\text{rad, W}}$ in unfavourable direction is up to a factor of 5 larger than in favourable direction. The reason for this significant difference in tungsten radiation is yet to be understood.

Additionally, since radiation outside of the core increases when the core density is increased from medium to high values, most of it occurring within the inner divertor volume for $B_T > 0$ (Fig. 7), the stronger effect on the inner target compared to the outer target may be partially explained.

For the cases at $I_p = 0.6 \text{ MA}$, the amount of power crossing the separatrix is 30% lower in the low density range than in the medium density range. However, in this case, the tungsten radiation is rather similar in both field directions. The 0.2 MW difference might be explained by the fact that, for those cases, $P_{\text{ECRH}} = 0.3 \text{ MW}$ instead of $P_{\text{ECRH}} = 0.5$ as for the rest of the database, as previously explained.

Taking into account the net heating power and subtracting from it the total radiated power from the tomographic reconstructions, the integrated heat loads observed by the IR system only capture the total radiated power from the tomographic reconstructions, the integrated heat loads observed by the IR system only capture

3.2. Plasma current scan

In the plasma current scan at low density, neither the peak heat flux (Fig. 10) nor the power onto both inner and outer targets (Fig. 11) did change significantly for the $B_T < 0$ direction. On the other hand, for the $B_T > 0$ direction, the peak heat flux increased up to a factor of 8 at the outer target and up to a factor of 4 at the inner target. However, only the outer target $P_{\text{net}}$ increases significantly across the entire scan (up to a factor of $\sim 6$).

In Fig. 12, the tungsten radiation is up to a factor of 6 higher for the $B_T < 0$ direction compared to the $B_T > 0$ direction. This result is similar to the trend observed in the core plasma density scan. Because Ohmic heating also increases with increasing plasma current, the resulting $P_{\text{sep}}$ does not change within uncertainties. On the other hand, for $B_T > 0$, the small increase of tungsten radiation within the entire plasma current scan cannot compensate the enhancement of Ohmic heating and thus the amount of power crossing the separatrix doubles. It should be noted (again), that the low current, low density cases for both field directions had a lower ECRH power.

3.3. Ion saturation current

The data of the ion saturation current measured by the Langmuir probes on the outer target for $I_p = 0.8 \text{ MA}$ are presented in Fig. 13. The data have been taken from the entire strike line sweep, excluding events such as NBI blips or strong variations of density (±5% of the requested $n_{\text{HI}}$ value). Some profiles have been shifted within equilibrium uncertainties ($\Delta n_{\text{pol}} = 0.001$).

In the unfavourable direction, the peak of the ion saturation current increases by a factor of 2.5 when going from low to medium density. At
high density, the peak ion saturation is reduced by ~33%, indicating the onset of particle detachment. At the highest density, further reduction of the overall $I_{sat}$ profile is observed.

In the favourable field direction, the peak of the ion saturation current doubles in the transition from low to medium-high density but the onset of particle detachment is not observed.

In the plasma current scan (Fig. 14), the ion saturation current does not change significantly within statistical uncertainties for $B_T < 0$. On the other hand, for $B_T > 0$, the peak of the profile increases up to a factor of 6 at $I_p = 1.0$ MA compared with $I_p = 0.6$ MA.

The results of the ion saturation current measurements are in agreement with the trends of the IR data. Significant reduction in the peak heat flux and total power to the targets is triggered at lower densities with respect to the onset of particle detachment.

4. Conclusions

As observed in previous studies, outer and inner target heat loads are more balanced in the unfavourable toroidal field direction with respect to the favourable field direction, in which the heat load to the outer target can be up to a factor of 4 larger than to the inner target.

At medium plasma current, increasing plasma core density from low to mid values increases the heat flux to the targets mainly in the unfavourable direction, while for favourable direction only a small reduction of the inner target heat flux is observed. For high densities, significant reduction of the peak heat flux and total power to the target plates is observed at both targets for both field directions. In the density scan at low plasma current, such reduction in power is only observed at the outer target in the unfavourable direction at medium densities.

In addition, increasing plasma current also increases significantly the heat flux to the targets in the favourable field direction while the heat flux in the unfavourable direction remains unchanged within error bars.

In these plasmas, the effect of the toroidal magnetic field direction on the evolution of the heat flux profiles was observed to be not only an effect of drifts but it is also influenced by the power crossing the separatrix. Here, $P_{sep}$ is rather constant for medium to medium-high densities but different for most of the low density plasmas, except $B_T > 0$ with $I_p = 0.8$ MA. Plasmas at low density have a reduced $P_{sep}$ due to two different issues: tungsten radiation for $B_T < 0$ with $I_p = 0.8$ MA and lower ECRH power for $I_p = 0.6$ MA in both field directions. The tungsten core radiation in the unfavourable direction is, in general, much larger than in favourable direction, and this observation is not yet understood.

The ion saturation current data of the outer target show similar trends as those of the IR measurements. Particle detachment is only observed at the outer target in the unfavourable field direction for $I_p = 0.8$ MA. The reduction in heat flux and power is triggered at a lower plasma core density than the onset of particle detachment, which is in line with observations of previous studies.
Acknowledgement

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 has been supported by the Academy of Finland, grant no. 285143.

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