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MASTER

TIME-RESOLVED MEASUREMENTS OF HYDROGEN AND DEUTERIUM FLUXES IN THE ASDEX PLASMA BOUNDARY

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NOTICE and the ASDEX-Team

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Abstract

Hydrogen and deuterium fluxes parallel to the toroidal magnetic field were measured in the plasma boundary of ASDEX using graphite collector probes. Time resolution of the order of 100 ms can be obtained by rotating the cylindrical probes behind an aperture during the discharge. The trapped amount of hydrogen was determined by subsequent thermal desorption; in the analyses of deuterium the $D(^3\text{He}, p)^4\text{He}$ nuclear reaction was used. Both methods yield quantitative results. Measurements were done for limiter and divertor discharges in the range of 4 to 20 cm outside the limiter or separatrix. The time distributions show a maximum flux at the beginning and ~~and~~ the end of the discharge. The relatively lower flux during the plateau phase of the discharge is in the range of 10^{15} to $2 \times 10^{17} \text{ cm}^{-2} \text{ sec}^{-1}$, depending on the radial probe position; the maximum values are higher by a factor of 5 to 50. During neutral hydrogen injection, an additional maximum can be observed. The radial $1/e$ -decay length is about 0.9 cm in front and 0.4 cm behind the fixed limiter. The results are compared with independent measurements in ASDEX and other plasma machines.

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Introduction

Measurements of hydrogen ion fluxes and energies in the plasma scrape-off zone are important for the understanding of transport phenomena in this layer, of the recycling behaviour of the plasma particles at the wall or limiter and to estimate impurity production rates due to ion sputtering. The time dependence of the ion flux and its radial decay from the plasma boundary have to be measured and ion energies must be evaluated. The influence of limiter, divertor, neutral injection and plasma parameters such as density and current are important.

Results will be presented for different plasma conditions in the Garching tokamak ASDEX. From the decay length the diffusion coefficient will be determined, flux and energy will be used to estimate surface erosion by sputtering.

Experimental

The method for measuring the ion flux involves hydrogen trapping in PAPYEX carbon stripes. Carbon is known to retain impinging energetic hydrogen ions very effectively and extensive calibration data are available /1,2/.

The amount of retained hydrogen is analysed without breaking the vacuum using thermal desorption and de-

tection in a quadrupole mass spectrometer / 3/. In the analysis of deuterium the nuclear reaction $D(^3\text{He}, p)^4\text{He}$ has been used for analysis / 4 /. From the retained amount of hydrogen and its dependence on the number of identical shots, the impinging hydrogen flux and the mean hydrogen energy are determined / 5 /. The experimental set-up is schematically shown in Figs. 1 and 2.

Figure 1 shows the probe system. The probes consist of carbon stripes mounted on a cylinder rotating behind a fixed aperture. The time resolution depends on rotational velocity and was chosen to be typically 0.6 sec. In the case of thermal desorption (upper probe) the $50 \times 4 \text{ mm}^2$ stripes can be heated by direct current flow and are positioned behind a $40 \times 4 \text{ mm}^2$ slit. The solid angle seen by the stripes is nearly 2π . The probes can be retracted together with the apertures into a separate chamber, where the hydrogen can be desorbed and analysed using a quadrupole mass spectrometer. In the case of the nuclear reaction technique (lower probe) a set of ~~the~~ ^{six} stripes ^{is} are mounted on the circumference of the cylinder and rotated behind 4 ^{circular} mm apertures. The solid angle in this case is about 0.6 sterad. After transport^{ing} the stripes in air to the 2.5 MeV accelerator the nuclear reaction analysis is done together with Rutherford backscattering analysis of impurities / 6 /.

Results were obtained for discharges with poloidal limiter, double null divertor, single null divertor and toroidal limiter operation / 7/. Figure 2 shows the typical position of the probes with respect to the plasma and the limiters in which most of the reported data were obtained. Both probes were positioned about 11 cm from the plasma separatrix and regarding the magnetic field lines they were in the shadow of the toroidal limiter, a movable and a fixed poloidal limiter, as indicated. The flux tube to the next limiting structure, however, is very different in both cases. In the case of the upper probe the length of the flux tube to the closest limiter is about 280 cm, while the foremost apertures of the lower probe sample $\frac{3}{4}$ a flux tube of a full large circumference of about 10 m. The probes were electrically connected to the vacuum vessel. The plasma parameters for the reported series of discharges are given in Tab. 1.

Results

a) Time dependence of hydrogen flux

The time dependence of the flux of hydrogen ions parallel to the magnetic field lines shows typically a strong initial peak followed by a low plateau phase and a final peak at the end of the discharge. Figure 3 shows a typical example at a position of 6 cm from the separatrix.

The retained amount of hydrogen is shown for an accumulated number of 1, 2 and 4 divertor discharges. From the ^{saturation} behaviour the temperatures of the ions can be estimated to ^{be} 200 eV in the initial peak and 50 - 60 eV in the plateau phase. The final peak does not show a systematic behaviour.

For deuterium discharges with hydrogen neutral injection an additional peak in the deuterium flux is measured during the injection phase. Figure 4 shows a comparison of discharges with and without neutral injection with all other discharge parameters unchanged (see table 1) the probe being at similar distance from the plasma boundary. For the same position from the plasma boundary the hydrogen flux increases by a factor of 10 during neutral injection, the energy increases at least by 50 % (see discussion of Fig. 8).

b) Dependence on distance from plasma boundary

The hydrogen or deuterium flux decreases exponentially with increasing distance from the plasma boundary with a typical decay length of 0.8 to 1 cm. Figure 5 shows the decay for the different times during ^{the} ~~a~~ typical divertor discharge. It can be seen that during all the different phases of the discharge, i.e. the initial peak, the neutral injection, the plateau phase and the final peak, roughly the same decay length is observed.

At distances larger than 17 cm, where the flux tube is cut-off by the fixed limiter at 60 cm, a much faster decay can be observed. Towards ~~to~~ the plasma the distribution levels off due to saturation of the trapped deuterium. This can also be seen from the ratio of trapped deuterium for one discharge to two discharges. From this saturation level an ion temperature of 50 eV can be determined for the initial peak, while in the plateau and end phase the temperature can be estimated to (20 ± 10) eV. During neutral injection a lower limit of 30 eV can be deduced.

At what distance does T_i depend on distance?

Figure 6 shows a comparison of the initial peak from the both probes using the nuclear reaction analysis. From the data of the carbon stripes behind the extended slit in the upper probe a background level of $1 \cdot 10^{15}$ D/cm² sec had to be subtracted, which probably results from the flux of charge exchange neutrals out of the plasma. On the stripes from the lower ^{probe} (behind the separate apertures, which do not allow direct sight to the plasma column, the background level was about 10^{14} D/cm² sec. The result shows a lower trapped amount of deuterium on the upper probe without signs of saturation up to 3 discharges, and a much shorter decay length of about 0.4 cm. Figures 7 and 8 show a collection of all measured hydrogen ion fluxes and energies in the ASDEX boundary layer obtained from the surface probes. For comparison also data from the ExB probe are given / 8 /.

Discussion

Similar time dependence for the hydrogen ion flux as shown in Figs. 3 and 4 are observed at different other plasma experiments /9-13/ (DITE, PLT, PDX). The initial and final peaks can be explained by the poor confinement in these phases. Also during neutral injection the increased flux may be explained by the loss of confinement, which is also deduced from other observations /14/, ~~and ASDEX Team.~~

The high initial flux, which can exceed the plateau flux by 2 orders of magnitude together with the high ion energies observed during this phase, may contribute more to surface erosion and impurity generation by sputtering of limiters or divertor plates than the ion flux during the rest of the discharge /15/. Time resolution is therefore ^{very desirable} ~~a stringent~~ requirement in the measurements of the hydrogen flux as well as the impurity flux /6/.

The measured mean ion energies are much higher than the electron temperature in the plasma boundary layer of about 5 eV. They represent the energy of the ions impinging onto the sample and have to be corrected for the energy gain in the Langmuir sheath in front of the target which is of the order of 3 kTe for singly charged ions. After correction the measured ion temperature close to the separatrix or limiter still exceeds by far the electron temperature and approaches the electron temperature only close to the wall. Similar mean ion energies and fluxes have, however, been measured at other large tokamak devices /15/.

It has to be mentioned that the methods used for ion detections are very sensitive to ion energies above 50 eV, while ions with temperatures close to electron temperatures of 5 eV are not detected. If the trapping mechanism as found for energetic ions, still hold at these low energies, the saturation value will be at about 10^{14} D/cm² and therefore below the background levels from energetic neutrals. It is therefore possible that the measured flux does not represent the majority of plasma ions in the boundary plasma. The flux and energy of the detected hydrogen ions agrees, however, well with similar measurements at other plasma experiments / 15/. For estimates of impurity sputtering rates only the energetic ion flux contributes.

The decay length of the ion flux is strongly dependent on the poloidal position of the probe. This can be seen in Fig. 6: The upper probe, being closer to the plasma boundary but positioned at a distance of 280 cm to the next limiting surface, measures much lower fluxes and only half the decay length compared to the lower probe, positioned at about 1000 cm from the next limiting surface. This is probably the entrance slit to the divertor. A simple model /8,16,17/ of the scrape-off layer yields the relation $\delta = \sqrt{4 D_{\perp} L / v_{\perp}}$, where $D_{\perp}$ is the diffusion perpendicular to the magnetic field lines, $v_{\perp}$ is the

ion velocity parallel to the field lines and L the length of the flux tube. With v_{ii} calculated from the measured ion temperature for both positions a diffusion coefficient D of 1000 to 1500 $\text{cm}^2 \text{sec}^{-1}$ can be calculated, values typical for Bohm-diffusion in the turbulent plasma edge /18/. The different decay lengths seen in Fig.7 may therefore be the result of different positions towards the next limiting structure.

The steep decrease of the ion flux and energy behind the fixed limiter leads to a much lower flux of energetic ions at the wall compared to the energetic charge exchange neutrals. ~~They~~ ^{the neutral flux has} have been measured independently to ^{be} about $2 \cdot 10^{15} \text{H}^+/\text{cm}^2 \cdot \text{sec}$ depend ^{ing} on electron density and temperature /19/ which agrees well with the background on the thermal desorption probe. The energy of the charge exchange neutrals represent ^{the} central plasma temperature and is ^{much} ~~far~~ higher than the ion temperature measured. The impurity production due to particle fluxes in ^{the} case of divertor discharges will therefore be dominated by wall sputtering due to charge exchange neutrals and sputtering of the divertor plates by plasma ions /15/.

Table 1

	1. series	2. series	3. serie
	# 1906-08, 2101 229-32, 2916-23	# 3856-66	# 4667-7
Large radius R [cm]	1650	1650	1652
Small radius r	40	40	35
discharge type	double null divertor in H ₂	single null divertor in D ₂	single r divertor D ₂
toroidal field B _T [kG]	22	22	22
plasma current J _p [kA]	250	400	325
electron density $\bar{n}_e$ [cm ⁻³]	$3 \cdot 10^{13}$	$4 \cdot 10^{13}$	$2 \cdot 10^{13}$
Neutral injection [MW]	-	1 beam line 1.2	2 beam 2
Central electron temperature T _e [eV]	600	800 1200 during NJ	800 1300 during
Central ion temperature Ti [eV]	450	1050 during NJ	2700 during
H ⁺ flux at fixed limiter [cm ² sec ⁻¹]	$1.5 \cdot 10^{16}$	$2 \cdot 10^{16}$	$4 \cdot 10^{16}$
H ⁺ energy at fixed limiter [keV]	10	10	10

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Figure Captions

- Fig. 1 Schematic Diagram of the carbon probe assembly on ASDEX
- Fig.2 Schematic Cross Section of the ASDEX torus for an single null divertor discharge with toroidal stainless steel limiter (1). The fixed poloidal limiters(2) and the movable poloidal limiter (3) are projected into the plane of carbon probes. The separatrix (4) and the magnetic field line (5) which is touching the divertor entrance slits (6), the toroidal limiter and inner poloidal limiter are shown.
- The insert shows enlarged the thermal desorption probe (upper probe) and the stationary probe (lower probe).
- Fig.3 Trapped flux of hydrogen for one, two and four divertor discharges as function of discharge time measured using the thermal desorption probe.
- Fig.4 Comparison of the trapped flux of deuterium for divertor discharges with and without neutral injection measured by nuclear analysis of the collectors of the lower probe. The time dependence of plasma current and electron density is shown for comparison. At a time of 1.4 sec the density decreases as result of closing the gas inlet valve.
- Fig.5 The dependence of the trapped fluence of deuterium on the distance from the separatrix for the different phases of discharges shown in Fig.4.
- Fig.6 The dependence of the fluence of deuterium trapped in the initial phase of the discharge on distance from the separatrix for the probes both analysed using the nuclear reaction technique. The position of the fixed limiter with respect to both probes is indicated.

Fig.7 A collection of the measured fluxes of plasma ions in the boundary layer of ASDEX as a function of the distance from the separatrix. For each measurement the fixed limiter may be at a different position towards the probe.

Fig.8 A collection of the average ion energies of plasma ions in the boundary layer of ASDEX as a function of the distance from the separatrix.

SCHEMATIC DIAGRAM OF THE CARBON PROBE
ASSEMBLY MOUNTED ON ASDEX

ASDEX

H-Flux in PLASMA BOUNDARY

Distance from SEPARATRIX : 6cm

Divertor Discharges