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Direct measurement of the plasma potential in the edge of ASDEX Upgrade using a self emitting probe

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Abstract

In this paper we present first measurements of the plasma potential close to the separatrix in ASDEX Upgrade using a self emitting tip. The probe was inserted into the edge plasma of AUG using the midplane manipulator. Assuming Maxwellian plasmas, the observations agree with the predicted voltage drop in the plasma sheath, $V_{pl}^{ps} - V_{fl} = 2.5T_e$, where V_{pl}^{ps} is the plasma potential at the presheath boundary and V_{fl} the floating potential. Applying this technique a rapid change of the plasma potential was observed close to the separatrix during Ohmic discharges. From the gradient we derive a radial electric field E_r of about -5 kV/m close to separatrix. Further out the field strength changes sign and we find up to $+7$ kV/m in the SOL.

Keywords: ASDEX Upgrade; SOL plasma; Langmuir probe; Electric potential and current; radial electric field

1. Introduction

A classical method to determine the plasma potential is to use an emitting probe [1]. The basic idea is to force the probe to emit as many electrons as it collects. Under this condition the probe will float at a potential very close to that of the surrounding plasma. For technical reasons it is difficult to use an auxiliary heated probe tip in a tokamak, but a Langmuir probe moving into the central plasma is sufficiently heated by the plasma. Approaching the separatrix the probe tip is reaching temperatures above 2500 K and, therefore, begins to emit electrons. If the power load exceeds a certain limit the zero-current potential of the probe changes from floating to plasma potential. This condition holds until the probe is sufficiently cooled by thermal conduction as it moves backwards. Meanwhile, the radial profile of the plasma potential can be observed. In Ohmic L-mode discharges it peaks close to the separatrix and the amplitude of the peak scales with the local electron temperature. Using this profile a radial component of the electric field up to $+7$ kV/m and -5 kV/m could be estimated outside and inside the separatrix, respectively.

2. Self emitting probes

2.1. The principle

The usual method to derive the plasma potential V_{pl} by using the turning point of the I–V characteristic of a Langmuir probe does not work in a strongly magnetized plasma. Due to the magnetic field the probe characteristics are strongly affected by the return current, which changes the shape of the electron branch significantly. Alternatively, one can measure the floating potential V_{fl} and add the sheath potential (approximately three times the electron temperature T_e) to get an estimate of V_{pl}. This method has two disadvantages: (i) the evaluation assumes a Maxwellian electron distribution function, which may not be established especially near the separatrix. (ii) the evaluation of T_e in a tokamak plasma is strongly affected by fluctuations, thereby restricting the accuracy. Applying probe techniques, the method of choice for measuring V_{pl} is the emitting probe. A surface in a plasma will collect more

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electrons than ions, due to the higher thermal speed and will be charged negatively. If the probe emits electrons its potential will get more positive until an amount of electrons is emitted that compensates for the difference between electron and ion saturation current. Now the probe will float near V_{pl}. Usually, an electrically heated wire is used as the emitting electrode but, unfortunately, this simple method is difficult to apply in a tokamak due to the $j \times B$ force on the current carrying wire.

The energy flux to a floating surface in a plasma is

$$P = I_{sat}/e(\gamma k T_e + E_{rec}), \qquad (1)$$

with I_{sat} the ion saturation current, γ the sheath transmission factor and E_{rec} the recombination energy. Therefore, a probe reaching the core plasma of a tokamak will be strongly heated and, finally, if the temperature is high enough, will emit electrons. This technique of a self emitting probe was first proposed by Hershkowitz [2]. The current density of emitted electrons could be estimated using Richardsons law,

$$j_{em} = 1.20 \cdot 10^6 \frac{A}{m^2} \frac{T^2}{K^2} \exp(-W_a/kT), \qquad (2)$$

with T the body temperature of the tip and W_a the work function (4.2 eV for carbon). A probe considered to monitor V_{pl} requires an electron emission comparable to the electron saturation current. For carbon as the tip material and conditions of the ASDEX Upgrade plasma near the separatrix a temperature of about 2500 K is necessary which is below the sublimation point of carbon.

2.2. The temperature of the probe tip

Whether or not such a tip can be heated to the required temperatures was investigated using a simple model describing heat conduction along a 1D-tip. The very front of the tip is heated by a time dependent energy flux calculated from the local plasma parameters taken from experiment. The far end is in contact with a heat reservoir of constant temperature and radiative losses are included. A Monte Carlo technique [3] was applied to solve the time-dependent 1D heat transfer equation

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C} \frac{\partial}{\partial x} \kappa \frac{\partial T}{\partial x} + S, \qquad (3)$$

where ρ is the density; the heat capacity $C(T)$ and the heat conductivity $\kappa(T)$ are functions of the temperature. $S(x, t, T)$ is the source function which includes both the power input (see Fig. 1a) and the radiative losses assumed to be proportional to T^4 (Stefan Boltzmann law). The time evolution of the temperature of the length element representing the tip of the probe, which is in contact with the plasma, is calculated.

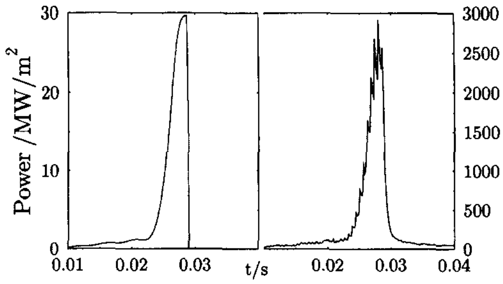

Fig. 1. Power flux to the probe tip (a) and calculated temperature (b). At $t = 0.029$ s the power flux is set to zero to get an estimate of the time for relaxation.

The results presented in Fig. 1b demonstrate that an emitting mode of operation can be reached when the probe approaches the separatrix.

Because Richardsons law depends very strongly on the temperature of the probe tip we can use the onset of emission to estimate this temperature. By varying the sheath transmission factor we fit these data to the measured onset of emission. So we estimated the appropriate sheath transmission factor to be about 7.

2.3. The potential

The potential profile along field lines in front of a probe is rather complicated and the underlying physics is still under discussion. It is well established, that if the probe emits more and more electrons, the emitted current will finally be space charge limited. Because of this limitation it is impossible in our situation to get a potential much higher than the plasma potential. Therefore, we assume that the probe still collects ions and Bohms criterion has to be fulfilled. This requires a presheath to accelerate the ions and, consequently, only the potential drop in the Debye sheath will vanish using an emitting probe. It follows that this probe would float at the potential V_{pl}^{ps} of the boundary between presheath and sheath. For the determination of this potential we use one dimensional models, because the magnetized plasma reveals a very pronounced anisotropy. Although there are different theories concerning different distribution functions of the ions entering the sheath, Bissell [4] showed that there are only small differences concerning the potential under discussion. Assuming a pure hydrogen plasma and $T_e = T_i$, one would expect:

$$V_{pl}^{ps} = V_{pl} - 0.6 T_e \quad \text{(eV)}$$
$$V_{fl} = V_{pl}^{ps} - 2.5 T_e \quad \text{(eV)}. \qquad (4)$$

It can be summarized that a moving Langmuir probe can be used to measure V_{pl} near the separatrix of a tokamak. Moving inward the cold probe measures V_{fl}, moving outward the hot probe measures V_{pl}^{ps}. The comparison of T_e derived from Eq. (4) with results from other techniques proves that the probe emits enough electrons. Eq. (4) then allows one to determine V_{pl}.

3. Experiments

We use the midplane manipulator of ASDEX Upgrade to expose the probe. A pneumatical drive was used to move a probe head, fully made of carbon, 100 mm towards the plasma within 100 ms. By adjusting the initial position the depth of penetration could be varied [5]. Using two pins of the probe we measured the V_{fl} and complete I–V characteristics simultaneously. The data are fitted with an asymmetric double probe characteristic to get electron density and temperature, floating potential and the ratio of electron to ion saturation current [6].

A typically observed potential profile is shown in Fig. 2. The cold probe starts outside the plasma and moves inwards monitoring V_{fl}. Near the separatrix the electron temperature rises and, consequently, V_{fl} reaches very low values. Meanwhile, the thermal load on the probe rises (Eq. (1)) and the probe gets hot. Due to Richardsons law (Eq. (2)) the current emitted by the probe rises very rapidly with temperature. As the emitted current is comparable with the electron saturation current the current–zero potential jumps to V_{pl}^{ps}. Then the probe turns back, continuously emitting and monitoring V_{pl}^{ps}.

As a check of the method we compare T_e obtained from potential differences using Eq. (4) with T_e evaluated from full I–V characteristics and results of the independent ECE diagnostic. The profiles are plotted in Fig. 3 versus magnetic coordinates to allow a comparison of the differently located diagnostics. The accuracy of reconstruction of this magnetic coordinate ρ_{pol} is within 1 cm or $\Delta\rho_{pol} = 0.008$. From this we can conclude that the probe emits enough electrons to reach V_{pl}^{ps}.

Additionally, we get information on the electron distribution function near the separatrix. V_{fl} is predominantly determined by the high energy part of the electron distribution function, whereas the evaluation of probe characteristics uses mainly the low energy part. Therefore, differences in the differently obtained values of T_e close to the separatrix may easily be caused by a hot component of electrons, penetrating from the core plasma.

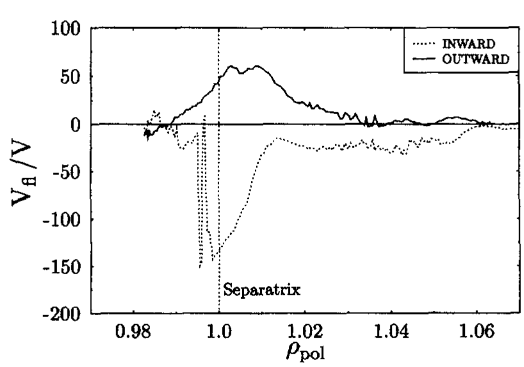

Fig. 2. Measured potential during a whole stroke of the emitting probe. The dashed line indicates V_{fl}, the solid V_{pl}^{ps}, versus magnetic flux coordinates $\left(\rho = \sqrt{(\psi_o - \psi)/(\psi_o - \psi_s)}\right)$.

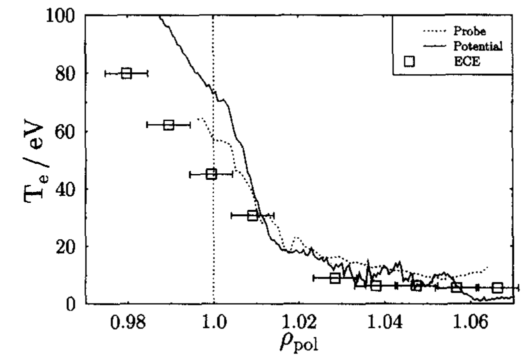

Fig. 3. Comparison of electron temperature profiles measured by ECE, Langmuir probe characteristics and those obtained from potential difference using Eq. (4).

In cases where V_{fl} switched to V_{pl}^{ps} before the turning point of the probe movement, we use an extrapolation of V_{fl}. As shown by the ECE diagnostic the radial T_e profile is linear at the separatrix, so we use a linear extrapolation of V_{fl}. Again we check this extrapolation by a comparison with the temperatures from the ECE diagnostic.

4. Results and discussion

4.1. The plasma potential near the separatrix

As discussed above the potential measured by the emitting probe has to be corrected using Eq. (4) to get V_{pl}. This correction mainly changes the potential within the separatrix. V_{pl} for an Ohmic L-mode discharge is shown in Fig. 4. Moving inward from the edge to the core V_{pl} changes only slightly. Reaching the region connected with the divertor via magnetic field lines the potential rises and reaches a maximum of 100 V near the separatrix position. Deeper inside the plasma the potential decreases and ap-

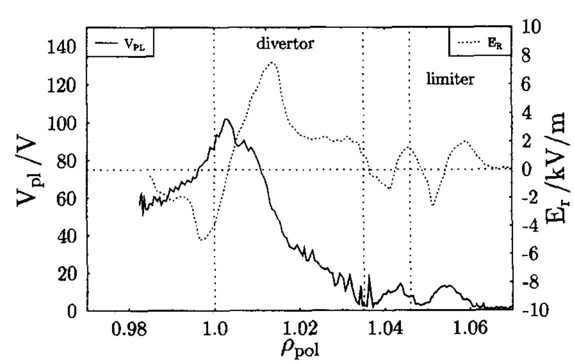

Fig. 4. Plasma potential V_{pl} and derived radial electric field E_r for an Ohmic L-mode discharge ($n_e = 2.1 \cdot 10^{19}$ m^{-3}, 600 kA). The dotted vertical lines indicate the position of a limiter, the divertor region and the separatrix, respectively.

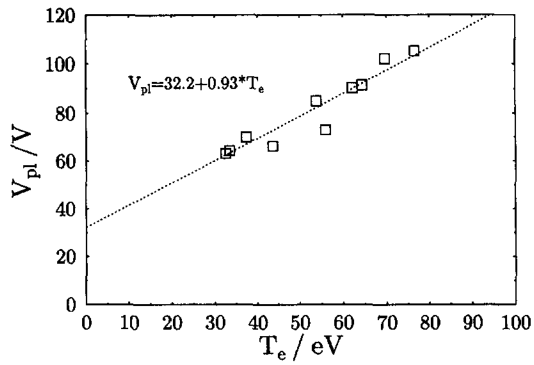

Fig. 5. Height of the potential peak versus T_e at the separatrix position for Ohmic 600 kA discharges.

proaches a constant value of 50 V with respect to the divertor plates.

We have done systematic studies on V_{pl} in Ohmic L-mode discharges (600 kA) having different central densities. By changing the plasma density T_e is varied at the separatrix position and Fig. 5 shows that the height of the V_{pl} peak near the separatrix varies linearly with this temperature.

4.2. The radial electric field

From the potential profile we can derive the radial electrical field $E_r = \delta V_{pl}/\delta r$. It rises in the divertor region and has a maximum of $+10$ kV/m outside the separatrix position. Near the separatrix the radial electric field changes sign and falls to values of -5 kV/m inside the separatrix. Further inside the electric field increases.

In D–IIID spectroscopic investigations using the $V \times B$ drift velocity of He II to derive E_r were done [7]. Only the two peak values inside and outside the separatrix are measured. Typically -15 kV/m inside and $+5$ kV/m outside the separatrix were found in Ohmic L-mode discharges. We find only -4.9 kV/m inside the separatrix and $+6.7$ kV/m outside the separatrix. From the distance of the two channels $\mathrm{d}E_r/\mathrm{d}r = 750$ kV/m^2 in D–IIID could be derived, which is in close agreement with the value of $\mathrm{d}E_r/\mathrm{d}r = 880$ kV/m^2 derived using our method in ASDEX Upgrade.

The change of sign in the electric field can be explained within the frame of: Outside the separatrix the plasma is directly connected with the divertor. Here the much faster electrons will leave the plasma leaving the ions behind. This is the typical behavior of a sheath. The potential will be adjusted to compensate the electron movement, i.e., one would expect a positive potential outside the separatrix. On the other hand due to the larger poloidal Larmor radius in a magnetized plasma it is much easier for heavy particles to cross the separatrix. This enhanced ion diffusion is suppressed by the negative E_r-field thus establishing an ambipolar total flux.

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