Journal of Nuclear Materials 313–316 (2003) 1114–1118

www.elsevier.com/locate/jnucmat

Angular dependence of the floating potential in a magnetized plasma

B. Koch *, W. Bohmeyer, G. Fussmann

Max-Planck-Institut für Plasmaphysik, Bereich Plasmadiagnostik, Mohrenstr. 42, Berlin D-10117, Germany

Abstract

The experiments presented in this work are part of an extended investigation aiming to understand the angular dependence of energy and particle fluxes in magnetized plasmas. Here we concentrate on measurements of the floating potential U_f as a function of angle under various conditions (n_{pl}, T_e, B) and for a number of ion species (H, D, He and Ar). A pronounced reduction of U_f is experimentally observed at oblique incidence. It is found that the magnitude of this reduction correlates with the Debye length while the normalized angular dependence remains similar under all conditions investigated.

PACS: 52.40.Hf
Keywords: Plasma-wall interactions; Plasma sheath; Oblique magnetic field; Floating potential

1. Introduction

In what follows we report on measurements of the floating potential as a function of angle under various conditions and for a number of ions. This potential is of crucial importance in all kind of plasma boundary interactions. In particular it is well known that a considerable fraction of the energy flux to a surface exposed to a plasma is transported by the kinetic energy the impinging ions gain within the sheath potential [1]. A reduction of this potential therefore causes a decrease of the energy influx beyond the mere reduction of the electron and ion particle fluxes. The floating voltage U_f is directly linked to the ratio of ion to electron flux density, but in addition it depends on the electron temperature (T_e) as well as other parameters. It adjusts itself to ensure the balance of electron and ion flux at the surface by repelling one species (usually the electrons) and attracting the other.

The physics of the plasma sheath at oblique incidence in strong magnetic fields have been subject for intensive theoretical considerations for a long time [1–4]. It is, for example, vital for the interpretation of data acquired by flush mounted probes [5,6]. However, most theoretical results can only be made available by numerical calculations.

At moderate magnetic fields like the ones used at the plasma generator PSI-2 or similar facilities, a further complication arises from the fact that the gyro radii of the ions can be of the same order of magnitude as the size of the probes.

In contrast to such complications occurring in a theoretical treatment the floating potential (U_f) is readily obtained experimentally. In this work we present data obtained under various experimental conditions at moderate magnetic fields $B \approx 0.1$ T. The corresponding Hall-parameters ($h_{e,i} = \omega_{e,i}^{gyr} \tau_{e,i}^{col}$) are of the order of 1300 for electrons and range from about 0.4 (Ar) to 32 (H) for the ions. This means that the electrons are always well magnetized whereas this is only marginally true for the heavy ions. It should be noted, however, that solely the magnetic confinement of the electrons is essential since the ions are coupled to them by electric fields in any case. A considerable variation of the Debye length λ_D

---

* Corresponding author. Tel.: +49-30 20366 119; fax: +49-30 20366 181.
E-mail address: bernd.koch@ipp.mpg.de (B. Koch).

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01547-7

for different gases (H, D, He and Ar) could be achieved by varying the density by almost three orders of magnitude (10^{15}–10^{18} m^{-3}) while the electron temperature T_e was kept rather constant ($T_e = 1$–4 eV). Although the ion temperature could not be measured directly, it is known from previous measurements [7] that it is approximately $2/3\,T_e$. Finally, the magnetic field was varied in the case of argon to reveal the expected dependencies on the electron and, in particular, ion gyro radii ($B = 0.05$–0.1 T).

2. Experimental setup

Our experiments were conducted at the PSI-2 plasma generator, a stationary high current arc discharge confined by an axial magnetic field. The plasma is produced between a heated LaB_6 cathode and a hollow anode made from molybdenum. The plasma generated in this region streams along the magnetic field lines through a differential pumping stage into a target chamber where it is used for all kind of experiments including plasma–wall interaction studies and tests of various plasma diagnostics [8].

The measurements presented below were also performed in this target chamber region by inserting a turnable flat probe into the center of the plasma column. A molybdenum plate immersed in a flat BN isolation was used for this purpose. The axis of rotation is coinciding with the probe surface to avoid vertical shifting of the probe during rotation (Fig. 1). Effects of a vertical gradient of the plasma potential were estimated by positioning the probe at $\alpha = -90°$ and moving it vertically. The measured potential changes were small compared to observed angular dependencies. By using a step motor driven rotational feed through a high angular resolution was obtained. *U–I* characteristics were taken by applying a sweeping voltage while scanning the probe at a constant speed (resolution 0.7°/*U–I* characteristic for scans from $\alpha = -100°$ to $\alpha = +100°$, 0.07°/*U–I* characteristic for scans in the vicinity of $\alpha = \pm 90°$). Additionally the floating potential was measured by means of a high impedance voltage recorder (resolution determined by step motor, $\Delta\alpha \approx 0.01°$). The electron temperature was evaluated from the characteristics obtained at $\alpha \approx 0°$. In order to eliminate changes in the overall potential structure of the plasma due to the rotating probe the floating potential is given with respect to the plasma potential U_{pl}. The latter is determined from the knee of the *U–I* characteristic. Since U_{pl} could not be determined at angles close to $\alpha = \pm 90°$ a polynomial fit was applied for interpolation.

Additionally a simple double probe was used to measure radial profiles of electron temperature and density in front of the turnable probe to assure homogeneity of the plasma parameters.

3. A basic model

It is beyond the scope of this work to present a fully satisfying theory explaining the measurements. Nevertheless, some basic considerations may be helpful to understand the results.

The floating potential is characterized by an ambipolar flux to the surface:

$$j_i(U_f) + j_e(U_f) = 0. \tag{1}$$

Applying the well known relations for $U < U_{pl}$, $j_i(U) = j_i^{sat} = \text{constant}$ and $j_e(U) = j_e^{sat}\exp(eU/kT_e)$ (Boltzmann relation), valid for normal incidence $\alpha = 0°$, U_f is found from the equation

$$\frac{eU_f}{kT_e} = \ln\left(\frac{j_i^{sat}(\alpha)}{j_e^{sat}(\alpha)}\right), \tag{2}$$

yielding explicitly for $\alpha = 0°$

$$\frac{eU_f}{kT_e} = \frac{1}{2}\ln\left(\left(2\pi\frac{m_e}{m_i}\right)\left(1 + \frac{T_i}{T_e}\right)\right). \tag{3}$$

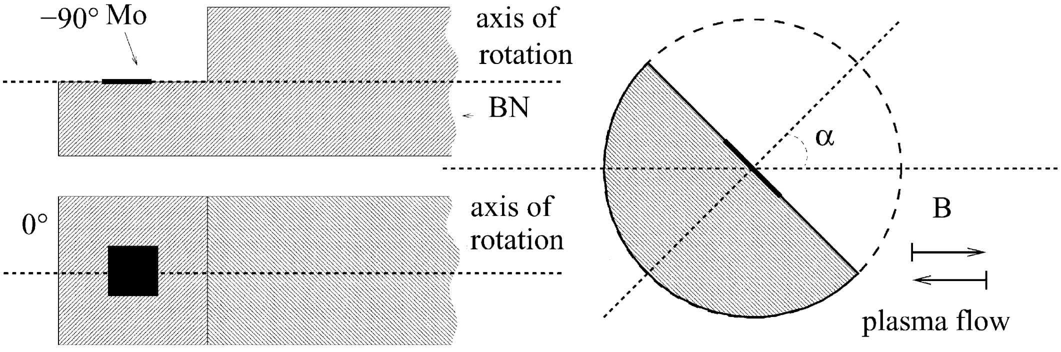

Fig. 1. Draft of the probe head as seen from the direction of the plasma column at $\alpha = -90°$ and $\alpha = 0°$ as well as a side view indicating the direction of the magnetic field B and the plasma flow.

In order to obtain an expression for the angular dependence of the floating potential an assumption for the angular dependence of $j_{\rm i}^{\rm sat}$ and $j_{\rm e}^{\rm sat}$ is needed. As a basic ansatz we will use a cosine dependence, taking into account the projected area of the probe perpendicular to the magnetic field, combined with a constant fraction β_k to account for particles reaching the surface at oblique incidence due to gyration and possibly diffusion across the magnetic field.

$$j_k = j_k^{\rm sat}(0°)(\beta_k + (1-\beta_k)\cos\alpha) \quad k = {\rm i},{\rm e}. \qquad (4)$$

Inserting (4) into (2) we obtain the desired function $U_{\rm f}(\alpha)$. The reduction of the floating potential $\Delta U_{\rm f}(\alpha) = U_{\rm f}(\alpha) - U_{\rm f}(0°)$ as a consequence of rotating the probe to oblique incidence should thus solely depend on the ratio of the constant fractions of the electron and ion flux at the angle α. This ratio in turn should depend on the characteristic lengths of the magnetized sheath: the ion and electron gyro radii $r_{\rm i}$, $r_{\rm e}$ and the Debye length $\lambda_{\rm D}$.

However, the model outlined above suffers from two severe limitations: First, in the case of large $r_{\rm i}$, the angular dependence used in Eq. (4) does not give the proper values for the ion flux at intermediate angles. Second, the assumption of the Boltzmann relation for the electron flux breaks down at $\alpha \to \pm 90°$. An improvement may be achieved by solving Eq. (1) by invoking refined models $j_{\rm i}(U,\alpha)$ and $j_{\rm e}(U,\alpha)$ or using functions obtained from fits of the experimental data.

4. Experimental results

In the scope of this work a large amount of experimental data has been collected. As an example we show the $j(U)$ characteristics for hydrogen in Fig. 2. It is found that even at $\alpha = 0°$ the characteristics do not show the $j_{\rm e}^{\rm sat}/j_{\rm i}^{\rm sat}$ ratio expected from the mass ratio. Furthermore, although $j_{\rm e}^{\rm sat}/j_{\rm i}^{\rm sat}$ tends to follow the mass ratio it also depends on other parameters. Apart from observing a general reduction of the particle fluxes we find a further reduction in the $j_{\rm e}^{\rm sat}/j_{\rm i}^{\rm sat}$ ratio at oblique angles ($\alpha = \pm 90°$) as well as pronounced non-saturation effects. As to be seen from Fig. 2, the deviations from saturation are different for ion and electron currents.

Fig. 3 depicts measured values of the floating potential as a function of the incidence angle. The reduction of $U_{\rm f}$ for different ions under comparable conditions is shown in Fig. 4. The theoretical value of $U_{\rm f}$ for $\alpha = 0°$ according to Eq. (3) (assuming $T_{\rm i}/T_{\rm e} = 2/3$) is also included in the figure as a horizontal line. As to be seen this value agrees well with experimental data. The magnitude of the reduction of $U_{\rm f}$ shows a clear trend with the ion mass, i.e. the ion gyro radius $r_{\rm i}$ ($r_{\rm i} = m_{\rm i}\sqrt{2kT_{\rm i}/m_{\rm i}}/(eB)$). For heavy ions the floating potential becomes even positive with respect to the plasma potential (see Fig. 3). Similarly, the extend of the angular range in which the reduction is observed depends on this parameter. While in case of hydrogen the reduction starts at about $\alpha \approx 60°$ for argon it changes already at $\alpha \approx 20°$. Closer inspection of the results shown in Fig. 4 suggests that the function $\Delta U_{\rm f}(\alpha, m_{\rm i}n_{\rm pl}, T_{\rm e})$ could be written as a product $\Delta U_{\rm f} = f(\alpha)g(m_{\rm i}n_{\rm pl}, T_{\rm e})$ with $f(\alpha)$ being a unique function of the angle and g containing all parameters specific to the ions and the plasma conditions. In order to reveal this dependency, the difference between the floating potential at oblique incidence and for the perpendicular case, i.e. $\Delta U_{\rm f}(\pm 90°) = U_{\rm f}(\alpha = \pm 90°) - U_{\rm f}(\alpha = 0°)$, was examined under various conditions. Although it was not possible to vary all plasma parameters involved in an independent manner, some useful combinations could be real-

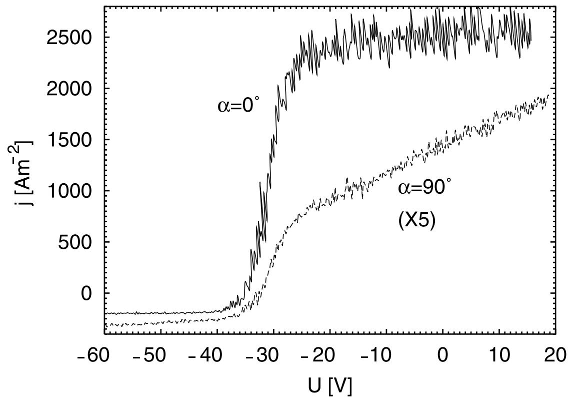

Fig. 2. Probe *U–I* characteristics for H at $\alpha = -90°$ and $\alpha = 0°$. Please note the different scale for the $\alpha = -90°$ case.

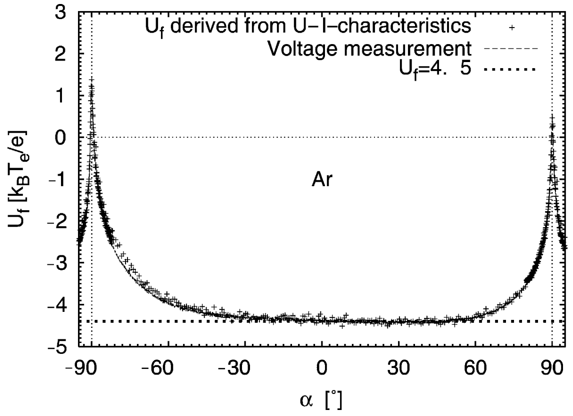

Fig. 3. Floating potential determined from the zero crossing in the *U–I* characteristic for Ar as a function of the angle between the surface normal and the magnetic field. The horizontal line indicates $U_{\rm f}$ according to Eq. (3).

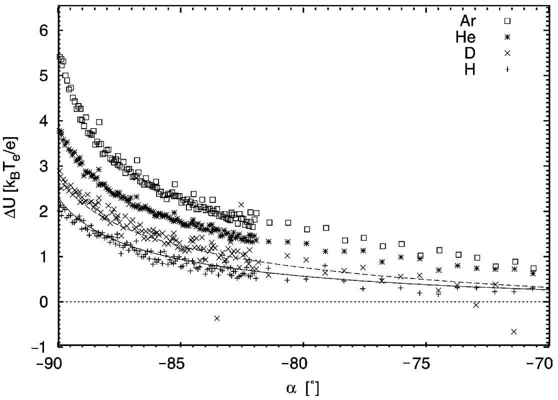

Fig. 4. Floating potential for Ar, He, D and H as a function of the angle between the surface normal and the magnetic field. The lines indicate the dependency expected by the basic model from Section 3 with Eq. (4) approximating the measured values for $j_i^{sat}(\alpha)$ and $j_e^{sat}(\alpha)$ for H ($\beta_i = 0.2$, $\beta_e = 0.02$) and D ($\beta_i = 0.4$, $\beta_e = 0.02$).

ized. In a first series of experiments we focused on variations of the Debye length $\lambda_D = \sqrt{\epsilon_0 k T_e/(n_{pl}e^2)}$ by keeping the temperature nearly constant, hence changing the ratio of ion gyro radius to the Debye length. This ratio turned out to be an important parameter involved in all plasma boundary and shielding problems [9]. Furthermore, different magnetic field strengths were applied in case of argon ($B = 0.067$ T to $B = 0.094$ T) yielding a considerable change in the gyro radii while keeping the other plasma parameters almost constant. Finally, the magnetic field configuration was changed on a larger scale resulting in two measurements using a low magnetic field ($B = 0.051$ T) with moderate plasma density and a high magnetic field ($B = 0.103$ T) with a comparatively high plasma density. Considering only the measurements from the first series of experiments, a dependence on the gyro radii was suspected which, however, could not be confirmed by the results from the magnetic field variations. The only dependence common to all measurements is with respect to the Debye length λ_D. Fig. 5 shows this dependence using a logarithmic scale for λ_D. While the applicability of a linear fit may be questionable in the case of the H and D, the He and Ar data show a clear functional dependence with $\ln \lambda_D$.

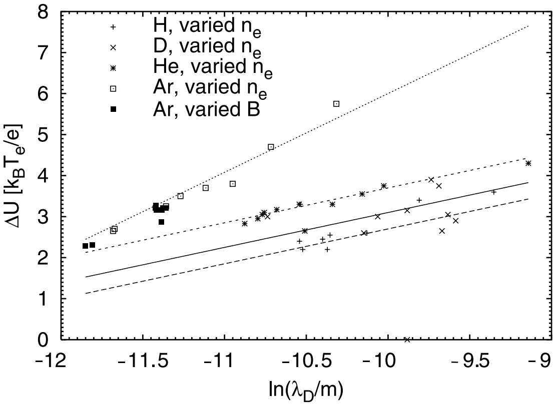

Fig. 5. Voltage difference between the floating potential at $\alpha = \pm 90°$ and $\alpha = 0°$ vs. $\ln(\lambda_D)$ for H, D, He and Ar. The measured values are linearly fitted by: $y = mx + n$ with $m = 1.92$ for Ar and $m = 0.85$ for He, for D and H the slope indicated is the same as for He. Ar values were acquired at different densities (empty squares) and different magnetic fields (filled squares).

5. Summary

The floating potential U_f has been carefully measured with a high angular resolution as a function of the angle α between the surface normal and the magnetic field. It is found that the floating potential is substantially decreased at oblique incidence and may even become positive with respect to the plasma potential. Probe measurements show good saturations for both j_e^{sat} and j_i^{sat} at $\alpha = 0°$. However, at $\alpha = \pm 90°$ we observe pronounced non-saturation with different slopes for j_e^{sat} and j_i^{sat} (see Fig. 2). Experimental parameters (T_e, n_{pl}, B, m_i) were varied in a wide range in order to study the correlation between characteristic lengths (λ_D, r_e, r_i) and the reduction of U_f. In the case of H and D the reduction of the floating potential can be quantitatively reproduced combining an angular cosine dependence of the particle fluxes due to the projection of the probe area perpendicular to $\vec{B}$ with a fractional flux $\beta_{i,e}$ remaining at oblique incidence due to gyration effects. However, for He and Ar the description is not satisfactory. Normalizing the angular profiles of the floating potential in the following manner $(U_f(\alpha) - U_f(0°))/(U_f(\pm 90°) - U_f(0°)) := f(\alpha)$, the function $f(\alpha)$ is found to be largely independent of all plasma parameters and the ion species. Assessment of the experimental data suggests that $\Delta U_f = U_f(\alpha) - U_f(0°)$ is a function of α and the Debye length only. The reason for this is subject of ongoing investigations.

References

[1] P.C. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, IOP, 2000.
[2] R. Chodura, Phys. Fluids 25 (9) (1982).
[3] I.I. Beilis, M. Keidar, Phys. Plasmas 5 (5) (1998) 1545.
[4] U. Daybelge, B. Bein, Phys. Fluids 26 (6) (1981).
[5] M. Weinlich, A. Carlson, Phys. Plasmas 4 (6) (1997) 2151.
[6] A. Carlson et al., in: Proc. 20th EPS Conf. Control. Fusion and Plasma Phys., 1993.

[7] O. Jensen, Messungen der Ionentemperatur und Stroemungsgeschwindigkeiten in einem Plasma mit linearer Magnetfeldkonfiguration. Diplomarbeit, Humboldt-Universitaet zu Berlin, 1998.
[8] H. Behrend et al., in: Proc. 21st EPS Conf. Control. Fusion and Plasma Phys., 1994, p. 1328.
[9] D. Naujoks, Technical Report 8/18, IPP, 2001.