ELSEVIER

Journal of Nuclear Materials 241-243 (1997) 722-727

journal of nuclear materials

The separation of angle and size effects on Langmuir characteristics

A. Carlson *, V. Rohde, M. Weinlich, ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, Euratom Association, Garching, Germany

Abstract

Designing Langmuir probes which can survive the high power fluxes in current and future tokamak divertors is a difficult problem. Conventional probes, which are fixed and proud, will no longer be adequate in long pulse machines, even if they are carefully constructed and provided with extra thermal mass. Pop-up probes represent a fall back solution with generally unsatisfactory duty cycle. Flush mounted probes are the most robust solution, but their interpretation has difficulties which are different from, though not necessarily more severe than those of proud probes. Pop-up probes and a 'checkerboard' probe, both recently commissioned on ASDEX Upgrade, verify that flush mounted probes, when properly interpreted, yield the same results as proud probes. The latter also allow detailed studies of the physics of Langmuir probes at grazing field incidence, in particular the separation of angle and size effects. It is found that the angle of incidence has a large effect, independent of the projected area, for which no theoretical explanation is available.

Keywords: ASDEX-upgrade; Electric potential and current; Transverse transport; Sheath physics; Langmuir probe

1. The problem of high power densities

In order to survive the high power densities expected in a reactor and being studied in the current generation of tokamaks, limiters and divertor plates must be placed nearly parallel to the magnetic field. The Langmuir probes used to characterize these plasmas have traditionally had a 'proud' geometry, either as a protruding cylinder or as a dome, which is in many cases rapidly eroded. Three solutions have been suggested to this problem: A heat sink below the surface, reciprocating ('pop-up') probes, and a flush mounted geometry. Which solution is best depends sensitively on the effect of magnetic field angle on the $I-V$ characteristics. This is the central question to be pursued in this paper.

JET [1] has reported success with the first approach. Their design uses a graphite with a higher heat conductivity for the probe than for the divertor plate and takes advantage of a gap in the divertor tiles to provide space for a heat sink. Since the time between plasma discharges is long, it is possible to rely on radiative cooling of the heat sink. If the divertor of a future machine is made of better material and with smaller gaps, this approach will become less attractive. For the longer pulse lengths planned, a heat sink will provide no advantage, and active cooling with good thermal contact must be provided. The major drawback of this approach is thus the question of survivability in a very high power ($\gtrsim 20$ MW/m^2), long pulse ($\gtrsim 10$ s) divertor.

The second solution, pop-up probes, has been discussed informally for some time, but not yet implemented. By 'pop-up' we mean a reciprocating probe with a stroke length and time on the order of 1 mm and 10 ms, compared to 100 mm and 100 ms for reciprocating manipulators. It is necessary to invent a mechanism with such a stroke which will drive one or more electrodes out of a protected region behind a divertor tile or limiter into the plasma and back out again. The exposure time is limited by the high heat load resulting from the steep field angle. One of the most attractive mechanisms to use in the high field, high vacuum, poorly accessible environment of a tokamak is the force on a current carrying conductor running perpendicular to the toroidal magnetic field. We have implemented such a system and taken first measurements with it. Pop-up probes have a good survivability, but they require considerable operator attention and provide

---

* Corresponding author. Tel.: +49-89 3299 2205; fax: +49-89 3299 2580; e-mail: carlson@ipp-garching.mpg.de.

PII S0022-3115(96)00594-6

data for only a short fraction of a discharge (less than a second).

The third solution, flush mounted probes, has been pursued at ASDEX Upgrade. In contrast to the flush cylindrical probes used on some other experiments, the probes on ASDEX Upgrade are 30 or 40 mm long, so that the probe dimensions projected along the magnetic field are several times larger than both the ion Larmor radius and the Debye sheath thickness. Flush mounted probes are sometimes perceived as being more difficult to interpret than proud probes, but this is not necessarily the case [1,2]. With flush mounted probes, the geometrical continuity between probe and wall allows one to neglect lowest order Larmor radius effects and develop a theory to account for sheath effects [3,4]. Also, measurements of the particle and energy flux density to the divertor do not depend in lowest order on the field angle, as they do for proud probes. Finally, with flush mounted probes there is no mechanical perturbation of the plasma, so effects like increased recycling cannot play a role. Some doubts arise from fact that the ratio of electron to ion saturation current measured in ASDEX Upgrade is considered to be anomalously low, e.g., 4 or less, compared to many measurements with proud probes in other plasmas of 8 or above. This issue will be discussed below. Because they share the same geometry, flush mounted probes should be nearly as robust as the divertor plates themselves. For long pulse machines, good thermal contact must be ensured. We are actively developing electrically insulating thermal contacts for flush mounted probe elements for use in the Divertor II of ASDEX Upgrade, which will be installed in the coming year. The major drawback of flush mounted probes remains the question of the relation between grazing incidence, low values of the current ratio, and the interpretation of I–V characteristics.

2. The problem of angle, size, and electron current

The most systematic study to date of Langmuir probe characteristics at grazing angles of incidence was done using the tilting probe array (TPA) [2]. This was a plate with a number of 3 mm diameter probes flush mounted in the surface. The plate could be tilted from shot to shot. The ion saturation current was found to be, as expected, nearly proportional to cos ψ for $\psi \lesssim 85°$, where ψ is the angle between the surface normal and the magnetic field. The electron saturation current showed a very different behavior, so that the ratio of electron to ion saturation current dropped from about 5 at $\psi = 80°$ nearly down to 0.5 at $\psi = 90°$. A sizable increase in the floating potential and the fitted temperature were also reported for angles flatter than 85°. The authors of Ref. [2] conclude: ''Flush mounted probes in nearly tangential surfaces should be avoided...'' This conclusion is obvious, but, we believe, too conservative in light of the thermal benefits of flush mounted probes and newer procedures for analyzing their I–V characteristics. Since the publication of the TPA study, the importance of nonsaturation of the ion current has been recognized and a satisfactory theory developed [3,4]. If nonsaturation is accounted for, the ion saturation current and fitted temperature will both be reduced, improving the extraction of plasma parameters from I–V characteristics like those reported in [2]. Furthermore, fitting the data with a double probe characteristic [3,4], rather than simply ignoring the data above the floating potential, will also reduce the derived temperature and thus the anomaly reported.

3. The ASDEX Upgrade pop-up probes

In light of the open questions concerning the survivability of stationary probes and the interpretation of flush mounted probes, we decided to develop a pop-up probe design for ASDEX Upgrade. For redundancy (in the sense that one malfunction does not disable all probes), versatility (for use in surfaces of complex shape like the Divertor II of ASDEX Upgrade), and compactness, we chose a simple single pass $I_{\mathrm{drive}} \times B_{\mathrm{tor}}$ mechanism which drives only two probes. The design is shown in Fig. 1. It uses a

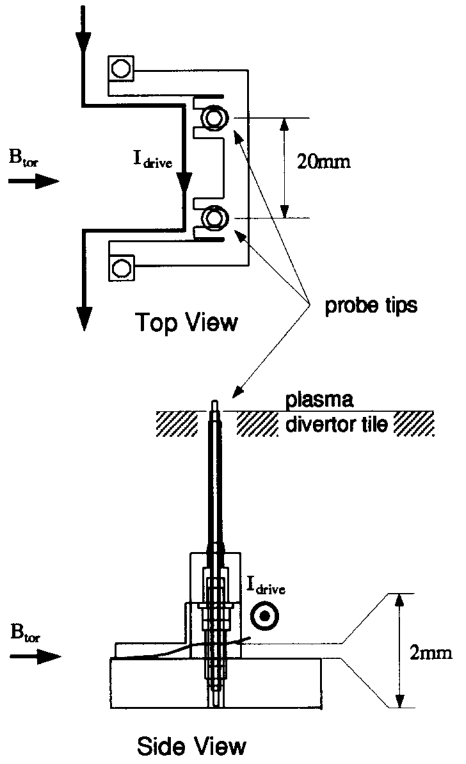

Fig. 1. The design of the pop-up probe. The probe is driven up by the interaction of the drive current in a U-shaped spring and the ambient toroidal field.

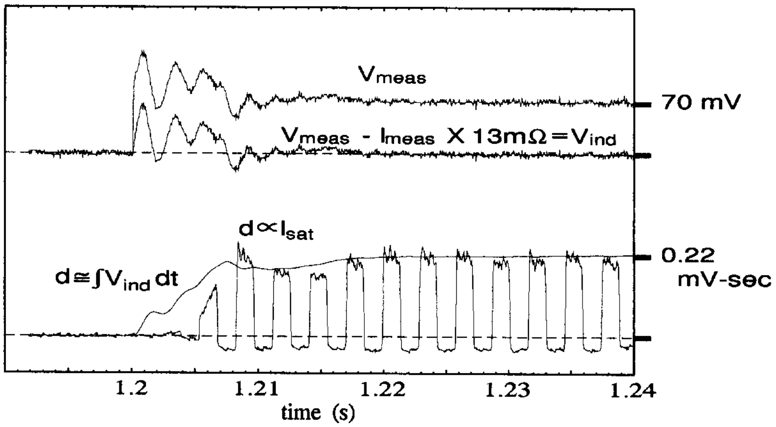

Fig. 2. Documentation of the motion of the pop-up probe. The measured voltage dropped across one pop-up drive mechanism and the same with the resistive contribution subtracted are plotted above. The integral of this quantity, which is proportional to the average displacement of the conductor and the probe current (driven by a triangular voltage), which, in saturation, is proportional to the displacement of the probe itself, are plotted below.

single, U-shaped piece of 0.1 mm copper–beryllium sheet which acts as conductor, passive return spring, and bearing (i.e., the flexibility of the metal is used to avoid the need for bearings). The probe holder, which weighs 2.3 g, is mounted on the spring and slides through vespel guides. The probe element is 0.9 mm diameter graphite. The stroke is 2 mm and the exposed position stabilizes in 20 ms when the drive current and toroidal field are about 5 A and 2 T, respectively.

The operation in situ is shown in Fig. 2 through the back voltage resulting from the motion in the toroidal field and the increase in the measured saturation current. The position calculated using the back voltage increases roughly linearly over 10 ms to full extension, rebounds somewhat, and comes to rest after about 20 ms. The position deduced from the probe saturation currents ($I_{sat} = j_{sat} \cdot$ width · exposed length) is similar, except that the initial motion is closer to constant acceleration than constant velocity. We believe that this discrepancy is due to internal bending of the conductor, which is also suggested by the oscillations seen on the back voltage signal.

An array of ten such probes (five driver mechanisms) was mounted in ASDEX Upgrade in the outer divertor plate about 0.6 m toroidally removed from an array of flush mounted probes. Simultaneous I–V characteristics from a pop-up probe and a flush mounted probe at nearly

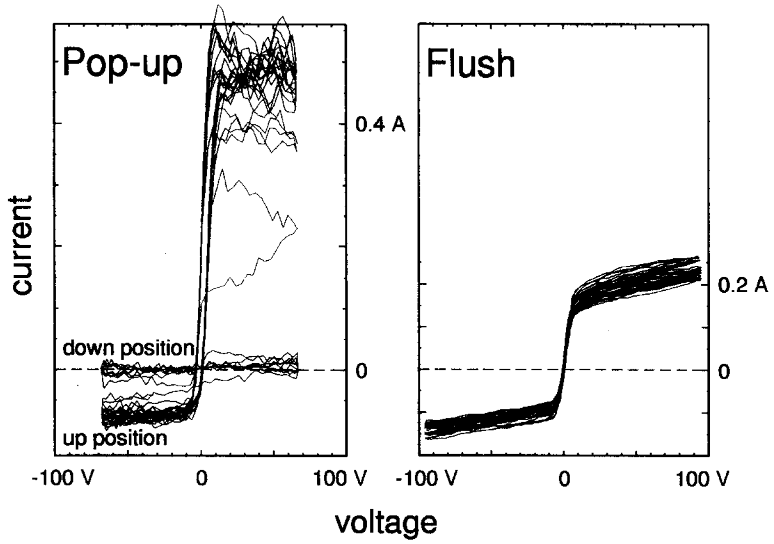

Fig. 3. Comparison of the I–V characteristics of a pop-up probe and that of a nearby flush mounted probe. The scales are chosen so that the ion saturation currents have the same height on the plots.

the same poloidal position are compared in Fig. 3. We see that the characteristic of the pop-up probe has the 'classical' form, while that of the flush mounted probe exhibits a low electron to ion current ratio and prominent nonsaturation. Nevertheless, when we analyze the flush mounted data using our standard procedures [3,4], which account for both these effects, we arrive at the same electron temperature as that found from the pop-up data, at least for those cases examined up to now. More exhaustive comparisons are planned, but the tentative conclusion is that flush mounted *I–V* characteristics can be interpreted as reliably as those from proud probes.

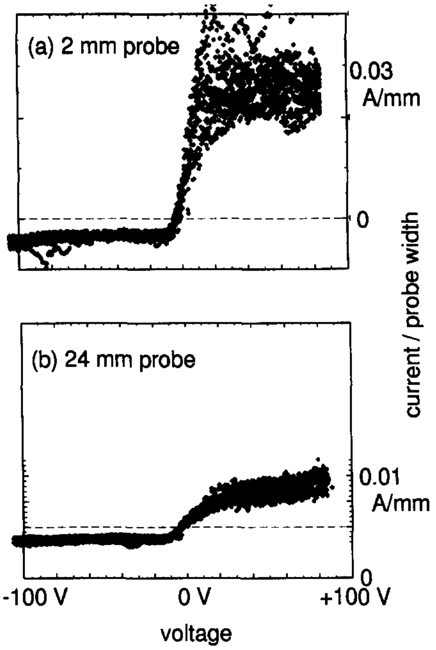

Fig. 5. *I–V* characteristics of a 2 mm (a) and a 24 mm (b) probe at one angle (about 75°). The vertical axis is the probe current divided by the probe width.

4. The checkerboard probe

A novel probe has been developed to investigate the independent effects of field angle and area on the *I–V* characteristics. It consists of a 3 by 5 'checkerboard' array of 15 abutting rectangular elements flush mounted with each other and with the edge of the probe, as shown in Fig. 4. This array is inserted into the scrape-off layer of ASDEX Upgrade on a manipulator and can be rotated about its axis during a discharge. The design was inspired by the tilting probe array but has three important innovations: The contiguous multiple elements allow the projected probe size to be varied by electrical reconfiguration in addition to tilting, the plasma conditions are held constant during the rotation by use of a fixed shield and letting the probe rotate about its center, and the checkerboard probe can be tilted during a discharge, which improves the comparability of the data as well as the experimental convenience. With the TPA, the positions of the probes and the leading edge of the plate changed as the plate was tilted. Because of the symmetry about grazing incidence, it was also not possible to tell from which direction the plasma being measured came.

Initial results have been obtained in two similar H mode discharges. The probe was held behind a limiter, and the angle ψ between the surface normal and the magnetic field varied over the course of one second from nominally

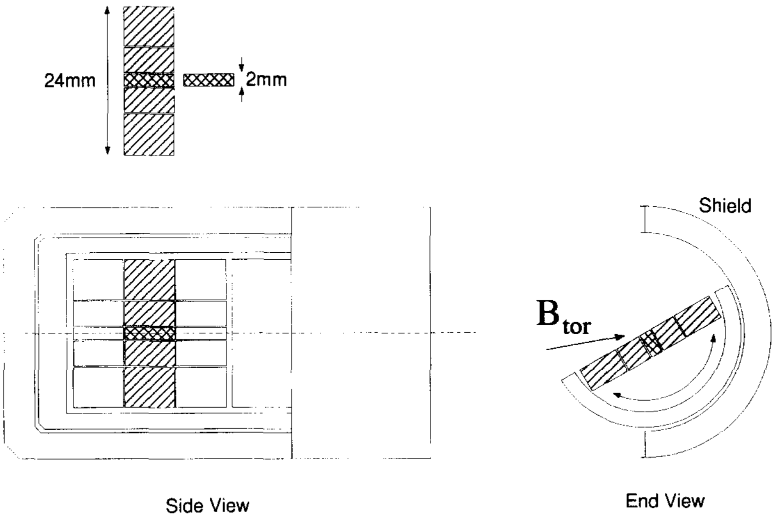

Fig. 4. The design of the checkerboard probe. The 15 probe elements are electrically independent. The probe is inserted near the midplane to a fixed radius and then rotated about its axis during the discharge.

55° to 115°, i.e., the probe started facing the plasma at a moderate angle, was rotated through the tangential position (90°), and ended facing the shield, not the plasma. Due to temporary mechanical difficulties, the absolute angles are not known reliably, but the constant speed of rotation should result in accurate relative angles. In one discharge (#7926) only the central element, 2 mm wide in the direction perpendicular to the axis of rotation, was connected to the voltage ramp, whereas in the other discharge (#7928) five adjacent elements were connected, resulting in a probe 24 mm wide.

In Fig. 5 we compare the *I–V* characteristics from these two configurations at the same, not too shallow angle (about $\psi = 75°$) and between ELMs. We see that the ion current densities are comparable, but the ratio of electron to ion current is about three times smaller for the larger probe. This is what would be expected from most mechanisms of cross field current transport [5–8]. Stated simply, if a large electron current is to flow, the electrons must find a way to get into the flux tube, or the ions must find a way to get out. This is easier to do if the flux tube is narrow, regardless of the details of the mechanism, which should lead to a larger current ratio for a smaller probe.

The behavior of the current ratio as a function of angle is shown in the top of Fig. 6. The ratio is seen to be constant for all angles sufficiently steep, and then to drop to a very low value (< 1) within several degrees of tangency. This is qualitatively the same behavior observed with the TPA. That this is related to the angle of incidence itself and is not simply a byproduct of the projected area, as has usually been assumed, can be seen by the fact that the pure size scaling reported above goes in the opposite direction and by the fact that the rate of change of the ratio with angle is nearly independent of size toward grazing incidence. Also shown in Fig. 6 are the fitted temperature and the floating potential. Both remain constant to within a few degrees of tangency, long after the current ratio begins to drop. This is especially clear for the 2 mm configura-

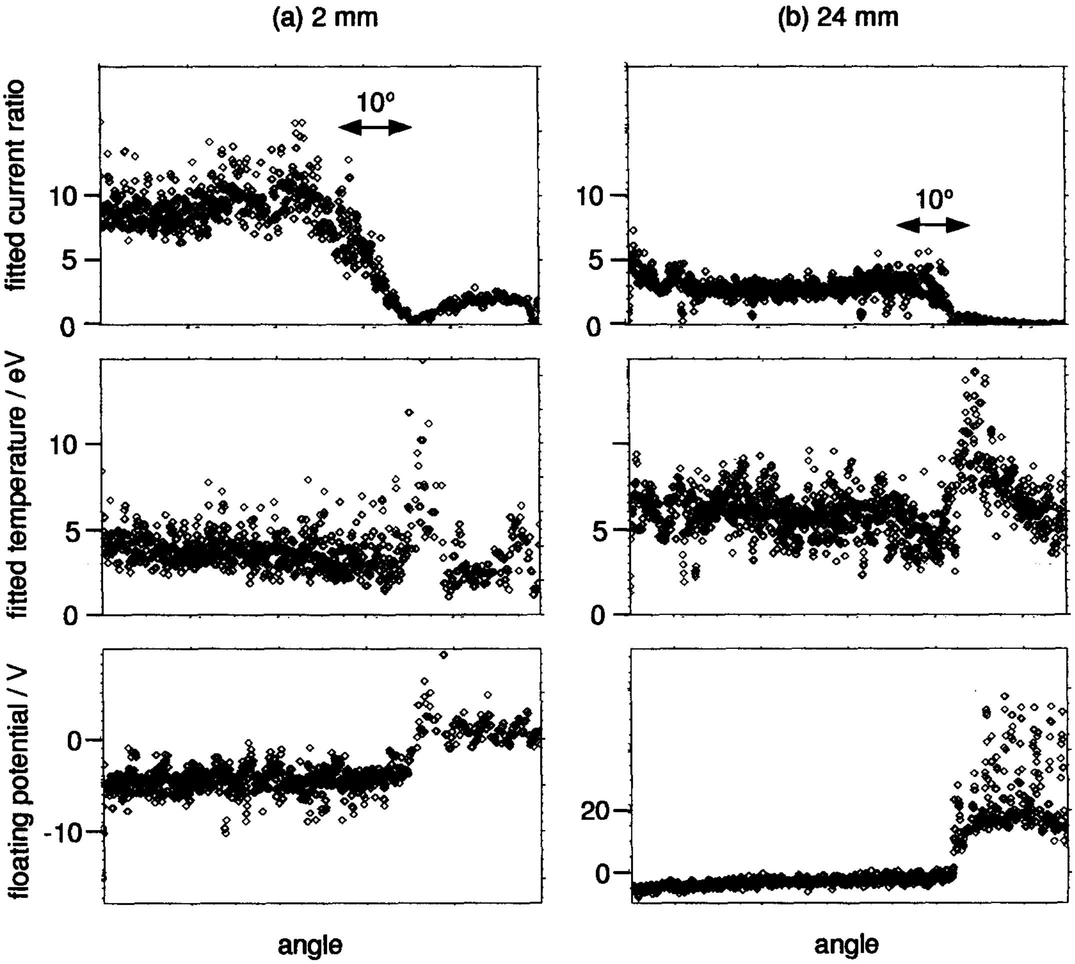

Fig. 6. The electron to ion saturation current ratio, the temperature fitted using a double probe model, and the floating potential for a 2 mm (a) and a 24 mm (b) probe as a function of angle.

tion. When the current ratio is near unity, fitting the part of the characteristic below floating with an exponential yields nearly twice the temperature indicated by the double probe model. The data of Fig. 2a clearly show that ignoring the data above floating can lead to large errors whereas using the double probe model results in temperatures which do not depend on the value of the electron saturation current.

5. Conclusions

A simple pop-up probe design has been found and its operation under tokamak conditions verified. If flush mounted probes cannot be made robust enough to survive in high power tokamak divertors, or if the interpretation of flush mounted probes should prove to be fundamentally ambiguous, these pop-up probes represent a reliable alternative. However, direct comparison of the temperatures calculated with pop-up and flush probes indicates that proud probes are not needed to make reliable measurements. Like any reciprocating probe, pop-ups have the disadvantages of complexity in construction and operation and a very low duty cycle.

A 15 element checkerboard probe head has been built and operated. This tool allows for the first time a clean separation of angle and projected size effects on Langmuir probe characteristics. Initial results indicate that the low current ratios seen with flush mounted probes are directly related to the shallow field angle, and not a byproduct of the small projected area. No mechanism has been proposed which can explain the effect of angle on the electron current. The essentially slab geometry of the checkerboard probe suggests that a truly three dimensional explanation is unnecessary, but a full two dimensional treatment will presumably be required. It is not yet possible to say whether identification of this effect will have significant consequences for our understanding of the plasma–wall interaction and divertor physics.

A flush mounted probe design has been chosen for use in Divertor II of ASDEX Upgrade. An interface with the divertor tiles is being sought, which is electrically insulating but thermally conducting. If this is successful, flush mounted designs may be the most useful approach for divertor probes in future high power, long pulse tokamak experiments.

References

[1] G.F. Matthews et al., Contrib. Plasma Phys. 36/S (1996).

[2] G.F. Matthews et al., Plasma Phys. Controlled Fusion 32 (1990) 1301–1320.

[3] M. Weinlich and A. Carlson, Contrib. Plasma Phys. 36/S (1996) 53–59.

[4] M. Weinlich and A. Carlson, Phys. Plasmas, submitted.

[5] P.C. Stangeby et al., J. Phys. D: Appl. Phys. 15 (1982) 1007–1030.

[6] K. Guenther and A. Carlson, Contrib. Plasma Phys. 34 (1994) 484.

[7] K. Guenther, 22nd EPS Conf. Contr. Fusion and Plasma Physics, Bournemouth (1995) p. 433.

[8] V. Rozhansky et al., Contrib. Plasma Phys. 36 (1996) 391–395.