ABSTRACT

In this contribution we report on various types of special probes which have been developed during the last few years at several European fusion experiments for the purpose to measure relevant plasma parameters in the edge plasma region. The rationale was that in particular the spatial structure and temporal evolution of the plasma potential and its derivative, the electric field, are decisive for the overall stability and in particular for the particle transport across the magnetic field. The probe types used were electron emissive probes, ball-pen probes, cold probes, and various combinations of these.
1 INTRODUCTION

Fluctuations in the edge region of a magnetized plasma cause radial transport and thereby a loss of plasma and energy, which leads to a reduction of the confinement time. To understand these mechanisms better, it is important to investigate the general structure of the plasma potential with as high as possible spatial and temporal resolution. Neglecting magnetic field fluctuations, the most important parameters are the electric field components in radial and poloidal direction and the electron temperature, in particular their fluctuations.

To measure the plasma potential directly, we used electron emissive probes and ball-pen probes. The electron temperature was determined from the difference between the floating potential of a cold probe and the plasma potential. Arrays of emissive or ball-pen probes and cold probes were used to measure the poloidal and radial electric field components and complex quantities such as the radial fluctuation-induced particle flux and the Reynolds stress.

Whereas in this paper the diagnostic tools are discussed, in another submission to this conference, a few remarkable results of the accompanying investigations are presented [1].

2 PROBES FOR DIRECT MEASUREMENTS OF THE PLASMA POTENTIAL

There are few diagnostic tools to determine the plasma potential $\Phi_{pl}$ with sufficient accuracy and spatial and temporal resolution. The least expensive and most easily to handle tool is the cold plasma probe (Langmuir probe). Usually the current-voltage characteristic ($I-V$ characteristic) of a cold probe is used to derive $\Phi_{pl}$ from the inflection point. Often the following relation between the floating potential $V_{fl}$ of a cold probe and the plasma potential is used:

$$\Phi_{pl} = V_{fl} + T_e \ln \left( \frac{I_{es}}{I_{is}} \right) = V_{fl} + \alpha T_e.$$  \hspace{1cm} (1)

This is a well-known result of cold probe theory (with $T_e$ being the kinetic electron temperature) (see e.g. [2]). The ratio of the electron to the ion saturation currents in $\alpha = \ln(I_{es}/I_{is})$ depends on $T_e$, but also on the effective areas for ion and electron collection, which in a strong magnetic field can differ. In typical tokamak edge plasmas $\alpha$ ranges between 2 and 3. In any case we always need to know $T_e$ for Eq. (1), and this is not always easily measured with sufficient reliability and temporal resolution, in particular in the edge region of a magnetically confined toroidal fusion plasma where there are strong gradients and fluctuations of $T_e$.

An additional important fact which is not always taken into account is that Eq. (1) is only valid for a Maxwellian plasma. As soon as there is a considerable electron drift or electron beam, this relation cannot be used anymore to calculate $\Phi_{pl}$ since the entire $I-V$ characteristic, and thereby also $V_{fl}$, shifts due to the drifting electrons.

2.1 Emissive probes

Emissive probes are able to emit an electron current into the plasma. Although already discussed by Langmuir [3], one of the first emissive probe was presented by Sellen et al. [4]. Since then emissive probes are standard tools in laboratory plasmas (see e.g. [2,5,6,7,8]), but only our group has started a few years ago to use them also in fusion experiments at higher densities and temperatures [2,7,8,9,10]. The emission current $I_{em}$ can be observed in the current-voltage characteristic as long as the potential on the probe surface is more negative than the plasma potential, irrespective of electron drifts or beams. In this case Eq. (1) becomes:
However, also this equation is only valid for a Maxwellian plasma. Since the plasma potential is constant, Eq. (2) shows that for increasing emission current $I_{em}$ (according to Richardson's emission law), the second term in Eq. (2) decreases, while the floating potential $V_{fl,em}$ of the probe increases. The second term vanishes for $I_{em} = I_{es} - I_{is}$, and $V_{fl,em} = \Phi_{pl}$. Thus when the emission current compensates the electron saturation current (minus the usually negligible ion saturation current), the floating potential of such a probe equals the plasma potential. In this case, the $I$-$V$ characteristic of the probe becomes symmetric, which is a requirement for $V_{fl,em} = \Phi_{pl}$. While Eq. (2) becomes more complicated in the case of electron drifts or beams, the general behaviour of an emissive probe is yet the same: for increasing emission current, the floating potential of the probe shifts towards higher values until it attains a saturated value, which is assumed to be close to $\Phi_{pl}$.

### 2.1.1 Emissive wire probe

The usual realisation of an emissive probe consists of a loop of tungsten wire with about 0.2 mm diameter and 6 mm total length, inserted into a suitable double-bore ceramic or boron nitride tube. Inside the bores the tungsten wire is spliced with a sufficient number of coppers threads so that a good electrical and mechanical contact is provided between tungsten and copper [2,6,7]. These two materials cannot be soldered or welded together, and any other way of connecting makes the construction more bulky. In this way only the exposed tungsten loop is heated when a current passes through the loop from an external power supply or battery.

Fig. 1 shows an arrangement of two emissive wire probes and two cold probes. The probe is inserted so that the two emissive probes measure $\Phi_{pl}$ at two positions on a poloidal meridian. From that the poloidal electric field component can be calculated. One of the cold probes is biased negatively to measure the ion saturation current, from which the ion density can be derived. The other cold probe is swept and the electron temperature is calculated from the $I$-$V$ characteristic [11].

![Figure 1: An arrangement of two emissive wire probes and two cold probes for simultaneous measurements of the poloidal electric field, the ion density and the electron temperature.](image)

Fig. 2 shows how this probe is inserted from top into the edge plasma region of the CASTOR tokamak in Prague. Ref. [1] shows examples of possible measurements with this arrangement, i.e., the radial fluctuation-induced particle flux and the electron temperature can be deduced from the data delivered by this probe system.
The main drawback of this conventional type of emissive probe is the inherent danger of melting when high emission currents are needed. This limits the emission current that can be produced by such a probe and thereby also the density and temperature of the plasma in which it is to be used. Therefore also the lifetime of such a probe is restricted. The necessity of an external power supply connected permanently to the probe reduces also the time response since the power supply has a high capacity.

2.1.2 Laser-heated emissive probe

Another way of heating an emissive probe was investigated recently, namely to heat a piece of LaB$_6$ or graphite by a laser [12,13,14] to sufficiently high temperatures for electron emission. As far as we know, this was attempted only once before [15].
outer diameter (see insert of Fig. 3). There were two reasons for the choice of LaB$_6$ and graphite as probe materials [16]: On one side, the work function of LaB$_6$ is low and therefore the electron yield is high even for low temperatures. Graphite, on the other hand, has a higher work function, but its absorption coefficient for laser light is very high. Therefore it absorbs the laser light much better, thus attaining higher temperatures for lower laser powers and also producing high electron emission.

The probe tip was heated from the front side through a quartz-glass window by an infrared high-power diode laser JenLas HDL50F from JenOptik, Jena, Germany, with a maximum laser power of 50 W at a wavelength of 808 nm. The laser beam is coupled into a fibre cable of 3 m length terminating in an output head, with which a focal spot of 0.6 mm diameter is produced in a distance of 20 cm. Fig. 4(a) shows typical current-voltage characteristics of such a probe, when it is inserted into the plasma of the VINETA helicon discharge at the IPP in Greifswald, Germany. Fig. 4(b) shows the corresponding increase of the floating potential with the laser power, i.e., with the temperature of the probe tip.

![Figure 4](image)

Figure 4: (a) $I$-$V$ characteristics of the LaB$_6$ probe with the laser power as parameter. The indicated electron temperature and plasma potential were determined from the cold characteristic (black curve) for no laser heating, i.e., $P_L = 0$ W. The apparent saturation of the emission current at 1 A on the left-hand side is due to the power supply used. (b) Floating potential of the probe versus laser power.

As we can see, the behaviour of this emissive probe is the same as that of a conventional emissive wire probe: For no heating, i.e., when the probe acts as cold probe, we obtain a usual cold probe characteristic, from which we can, for comparison, determine the plasma potential and the electron temperature, which here turn out to be $\Phi_{pl} \approx 10$ V and $T_e \approx 3.2$ eV, respectively. When the heating by the laser is turned on and electron emission starts, the emission current is superimposed on the ion saturation current, i.e., on the left hand side. For increasing heating the emission current increases too, while the floating potential of the probe shifts to the right-hand side until it reaches a saturation level, above which it will not grow further even though the emission is further increased. This value is considered to be the best available measure for $\Phi_{pl}$. We observe, however, that this value remains somewhat below (namely at around 6.2 V) the value taken from the cold characteristic (10 V). This effect that was recently related to the fact that the temperature of the emitted electrons is usually much lower than that of the plasma electrons [17,2]. This might lead to the formation of an electron space charge even around the floating emissive probe, which drags the probe potential down. This phenomenon is still under investigation.

Clear advantages of a laser-heated probe are that it cannot melt and can produce a much higher electron emission current than an emissive wire probe, making it suitable for hotter and...
denser plasmas. Moreover, the time response is also better since no external electric power supply is needed. A disadvantage is that the heating system is obviously more complicated. The development of a compact movable laser-heated emissive probe is under way.

2.2 Ball-pen probe (in combination with a cold probe)

A ball-pen probe consists of a cylindrical collector with a conical tip of 2 mm diameter, which can be moved up and down inside a screening tube of boron nitride [18,19]. In the design shown in Fig. 5, an additional Langmuir probe ring is mounted near the top of the BN tube. This acts as conventional cold probe to deliver the value of the floating potential [20]. The parameter \( h \) indicates the position of the collector relative to the tube, with \( h = 0 \) meaning that the collector tip lies exactly in the plane of the mouth of the tube.

![Schematic of the ball-pen/cold probe combination](image)

Figure 5: (a) Schematic of the ball-pen/cold probe combination. The conical collector can be shifted inside the boron nitride (BN) screening tube that acts as a shield for electrons. The Langmuir probe is made of 0.2 mm diameter tungsten wire. (b) Photo of the ball pen probe. In this case the ball-pen collector is fully exposed to the plasma.

The measurement of the plasma potential \( \Phi_{pl} \) by means of the ball-pen probe utilises the different electron and ion gyroradii in a magnetised plasma. Since the former are on the average much smaller, they are easily screened off by the BN tube, when the collector is withdrawn inside (Fig. 5(a)), while ions can still reach the probe collector. This principle was also used earlier for measuring the perpendicular ion energy distribution in a magnetic field [21]. However, in contrast to this method, where the electrons were screened off completely, in our case, by shifting the collector inside the BN tube, the effective collection area in particular of the electrons \( A_{p}^{e}(h) \) can be varied easily. In this case the quantity \( \alpha \) of Eq. (1) becomes:

\[
\alpha = \ln \left( \frac{j_{es}}{j_{is}} \right) = \ln \left( \frac{A_{p}^{e}(h)j_{es}}{A_{p}^{i}(h)j_{is}} \right),
\]

with \( j_{es, is} \) being the electron and ion current density, respectively.

Therefore, the electron current reaching the collector can be adjusted to almost the same absolute value as that of the ion current, with the same effect as in the case of an emissive probe, namely that \( \alpha \) become zero and \( V_{fl,bp} \equiv \Phi_{pl} \).
Figure 6: (a) $I$-$V$ characteristics for various collector positions. is negative when the collector is inside the shielding tube (see also Fig. 5(a)); (b) floating potential $V_{fl}$ (blue squares) and $\ln(I_{es}/I_{is})$ (black dots) with respect to $h$. The radial position of the probe head is at $r = 75$ mm inside the edge region of CASTOR.

Fig. 6 presents the analogous graphs as Fig. 4 for the laser-heated emissive probe with data that were also obtained in the edge plasma region of the CASTOR tokamak in Prague:

Fig. 6(a) shows the $I$-$V$ characteristics with $h$ as parameter, however, the current is normalized to the ion saturation current for $h > 0$ since it turned out that also the ion saturation is somewhat affected by the displacement of the collector. As we can see, for positive values of $h$, i.e., when the collector is completely out and the ball-pen probe acts as a normal Langmuir probe, the characteristic is conventional with the ion part on the left-hand side being much smaller in magnitude than the right-hand electron side. When the collector is withdrawn into the collector, i.e., for negative $h$, the electron branch of the characteristic drops while the floating potential moves to the right. For $h = -1$ mm, the characteristic is almost symmetric. Fig. 6(b) shows the corresponding values of the floating potential and of $\alpha = \ln(I_{es}/I_{is})$. Again we see that for negative $h$, i.e., about $-0.5$ mm, the floating potential increases from about $-11$ V to saturation at about $+23$ V. This latter value is almost equal to the plasma potential determined from the cold probe characteristic. At the same time $\alpha$ reaches its lowest value although it does not become completely zero.

Also in this case several features remain still to be clarified: As mentioned above, also the ion saturation branch of the characteristic drops for decreasing $h$. Moreover, the characteristic shows that even for very negative values of $h$, still ions and electrons can reach the probe collector, where both charge carrier species should be screened off completely.

In spite of these shortcomings the general trend [19] is that the saturated values of the ball-pen probe floating potential (for $h < 0$) are closer to the plasma potential (determined from the normal cold probe, for $h > 0$) than those of an emissive probe, where the saturated floating potential lies below the value determined by the unheated probe. The advantage of an emissive probe is its utility also for unmagnetized plasmas where a ball-pen probe would fail.

2.3 Multiple probe arrangements

Two probe arrays were already mentioned: In Section 2.1.1 a combination of two emissive and two cold cylindrical probes was presented (Fig. 1), and in section 2.2 the screening tube of the ball-pen probe carried an additional cold probe consisting of a tungsten wire ring which was fully exposed to the plasma (Fig. 5).

By the combination presented in 2.1.1 the poloidal electric field and its fluctuation were determined. Together with the fluctuations of the ion density, determined from the ion biased
cold probe, the radial fluctuation-induced particle flux could be calculated [1]. Another possibility was to derive the electron temperature from the data, namely from the difference between the plasma potential (measured with one of the emissive probes) and the floating potential of one of the cold probes (using Eq. 1). Also this is described in Ref. [1].

Also the combination of the ball-pen probe and the cold probe ring was used to measure the electron temperature directly with high temporal resolution from the difference between the plasma potential (by the ball-pen probe) and the floating potential (by the cold probe) [1].

A more sophisticated probe array was used in the ISTTOK (Instituto Superior Técnico Tokamak) in Lisbon, Portugal (see Fig. 7) [22,23]. The array consisted of three emissive probes, heated simultaneously, and one cold probe. From the corresponding differences between the plasma potentials measured by the three emissive probes, the radial and poloidal component of the electric field could be determined from the formulae:

\[ E_r = \frac{\Phi_{pl,1} - \Phi_{pl,2}}{d_{12}} \quad \text{and} \quad E_\theta = \frac{\Phi_{pl,3} - \Phi_{pl,2}}{d_{23}}, \]

respectively, (4)

with \( d_{12} \) and \( d_{23} \) being the respective distances between the probes.

This is a requirement to calculate the Reynolds stress (see Refs. in [1] and Ref. [24]), which under the assumption of purely electrostatic fluctuations reads:

\[ R_e = \langle v_r v_\theta \rangle \cong \frac{\langle E_\theta E_r \rangle}{B^2}. \]

(5)

Figure 7: Experimental set-up showing a segment of the cross section of the ISTTOK and the three emissive probes plus one cylindrical cold probe inserted into the edge region.

From the poloidal electric field fluctuations together with the fluctuations of the ion density determined by the negatively biased cold probe, also in this case the radial fluctuation-induced particle flux could be derived and compared with the Reynolds stress [22,23].

CONCLUSION

We have shown that various plasma probes, constructed according to the requirements of magnetized toroidal fusion experiments, can be used successfully even in such a plasma environment and we have obtained a number of interesting and far-reaching results. We would like to mention that fluctuation measurements with (cold) probes have in the meantime also been carried in larger experiments such as ASDEX Upgrade and JET [25,26].
Although in the forthcoming fusion experiment ITER such measurements cannot be directly carried out, our results from the presented fusion experiments will be relevant for a better understanding of the behaviour of the edge plasma phenomenology in general.

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REFERENCES


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