PLASMA POTENTIAL MEASUREMENTS WITH EMISSIVE PROBES IN THE CASTOR TOKAMAK

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Abstract
Until recently, in experimental fusion devices only cold probes were used to determine the plasma potential, and their floating potential was assumed to be proportional to the plasma potential. However, drifting electrons or beams distort the current-voltage characteristic of a *cold* probe. In addition a cold probe is sensitive to electron temperature variations. These problems can be avoided by the use of *electron emissive* probes, since an electron emission current is fairly independent of the conditions in the surrounding plasma. We have used an emissive probe in the CASTOR tokamak in Prague, by which the plasma potential has been determined in the edge region of this device and even inside in last closed flux surface (LCFS). In this paper we present first results of our investigations.

1. Introduction

A reliable determination of the plasma potential Φ_{pl} and its fluctuations $\tilde{\Phi}_{pl}$ is essential in many plasmas. The confinement and stability of magnetised fusion plasmas and the radial transport across the **s**crape-**o**ff **l**ayer (SOL) is believed to be determined by the radial potential profile of the SOL and by the turbulent fluctuations present there. In fusion plasmas, as far as we know, hitherto only cold probes have been used for a determination of Φ_{pl}. Here we present an investigation where an electron emissive probe has been used not only in the edge plasma region of a small tokamak but also in a certain range inside the LCFS.

2. Drawbacks of cold (Langmuir) probes

Electric probes (or Langmuir probes) are very helpful for a quick localised determination of important plasma parameters: the electron and ion densities $n_{e,i}$, respectively, the electron temperature T_e and the plasma potential Φ_{pl}. The most accurate measure of Φ_{pl} is obtained from the "knee" of the current-voltage characteristic $I_p = I_p(V_p)$ of the probe. However, an exact theory of probes is very complicated. Therefore, the above mentioned plasma parameters can be subject to severe systematic errors. One of the gravest errors concerns the determination of the plasma potential, since it is usually assumed that the floating potential V_{fl} is a measure for Φ_{pl}. Indeed, in a plasma with Maxwellian velocity distribution functions of the ions and electrons the two values are proportional to each other through the relation $V_{fl} \cong \Phi_{pl} - f(T_e,T_i,...)$ where f is usually a function not only of $T_{e,i}$ but possibly also of other parameters. Since often not the absolute values but only the relative values of Φ_{pl} (or just of $\tilde{\Phi}_{pl}$) are of interest, it suffices to measure V_{fl} (or $\tilde{V}_{fl}$) of a cold probe. But if we want to register the temporal evolution of Φ_{pl} or a spatial profile of it, this method only works if we suppose that there are no temperature variations during the recording of V_{fl} or in the region where we measure V_{fl}, respectively.

An additional, often neglected fact is the following: Any sufficiently strong electron drift or an additional electron beam with an average drift velocity $\bar{v}_e$ will distort the current-voltage characteristic of a cold probe, in the simplest case by shifting it to the left by a voltage which corresponds to the mean kinetic energy of the drifting electrons $|V_s| = m_e \bar{v}_e^2 / 2e$. In such a case a determination of the plasma potential from the "knee" of the characteristic delivers an erroneous result, and of course, also the floating potential is no longer related to Φ_{pl} through the simple relation above.

3. The advantages of electron emissive probes

All the above mentioned problems can be circumvented when we use a probe, which emits an electron current into the plasma [1,2,3,4,5,6]. An electron emission current will be able to flow from the probe to the plasma as long as V_p is below the plasma potential Φ_{pl}, *irrespective* of the flow of plasma electrons and of electron temperature fluctuations. For $V_p \geq \Phi_{pl}$, the emission current drops and electron collection begins to determine the probe current. Usually simply the floating potential of the emissive probe is taken as a sufficiently accurate measure for the plasma potential.

An emissive probe is usually realised by a small loop of tungsten wire, carried by a double-bore ceramic tube, and heated by an external current so that the W-wire becomes emissive. Then the electron emission current density is given by the Richardson-Dushman formula $j_{ee} = AT_w^2 e^{-B_w/T_w}$, with A being the Richardson constant, and T_w the temperature and B_w a constant related to the work function of the wire material, respectively. For tungsten A = $6.012 \cdot 10^5$ A/m^{2}K^2 and $B_w = 5.256 \cdot 10^4$ K.

4. Emissive probe arrangement for the CASTOR tokamak

The CASTOR tokamak has a major radius of 0.40 m and a minor radius of a = 75 mm, the latter being determined by a metallic electrode. The background pressure is smaller than 10^{-7} mbar. Before each discharge, the chamber is filled with H_2 up to a pressure of around 10^{-4} mbar. Each shot has a duration up to 50 ms. The strength of the toroidal magnetic field on the minor axis is up to 1 T, the toroidal plasma current is typically 10 kA. The maximum attainable plasma density is 10^{19} m^{-3} and the electron temperature is in the range 80 – 220 eV. In the SOL the density drops to around $(0.5 - 1) \cdot 10^{17}$ m^{-3}, and T_e is on the order of 10 eV.

In CASTOR the emissive probe is mounted on a 68 mm long shaft by which it can be shifted radially. The range of movement is approximately $0 < r < 100$ mm (with r being the minor radius), i.e., the probe can be moved from the core plasma through the entire edge region. The probe shaft consists of a ceramic tube (Al_2O_3) with an oval cross-section of 1.4×2.3 mm outer dimensions and a length of 8 cm. The Al_2O_3 tube has two bores of 0.7 mm diameter each. Through them a 0.2 mm diameter tungsten wire is inserted in such a way that on one side of the tube (at the "hot end") a W-wire loop of an approximate total length of 6 mm is formed. Inside each bore, the W-wire extends at least 5 cm towards the other end (the "cold end") of the ceramic tube. Before the insertion, each W-wire is spliced twice with about 12 copper threads with diameters of 0.05 mm [4], except for the part that will form the actual emissive probe. In this way, inside the bores the W-wires are densely covered with a thin layer of Cu so that the conductivity of these parts is increased. This

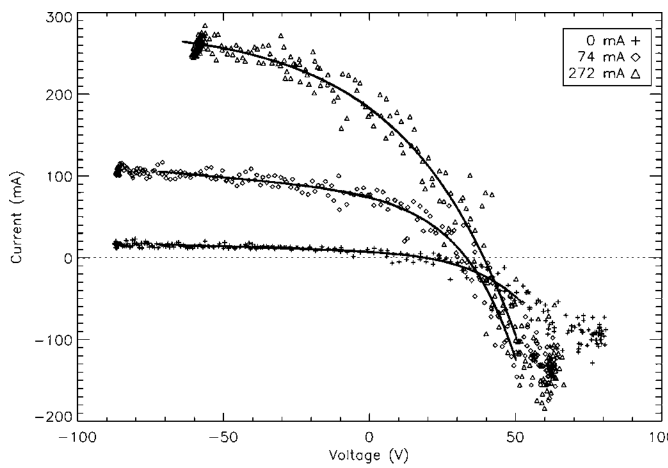

Fig. 1 Three typical probe characteristics for increasing probe heating current. The topmost curve with Iee = 272 mA is the characteristic for fully emissive probe so that its floating potential is approximately equal to Φpl.

treatment has the effect that only the exposed loop of the emissive probe is heated when a current is passed through the probe wire. The total resistance of such a probe is about 0.11 Ω. The plane of the probe loop is usually directed in such a way that it lies parallel to the magnetic field. Thus the effect of the Lorentz force on the loop wire is minimised.

5. Experimental results and discussion

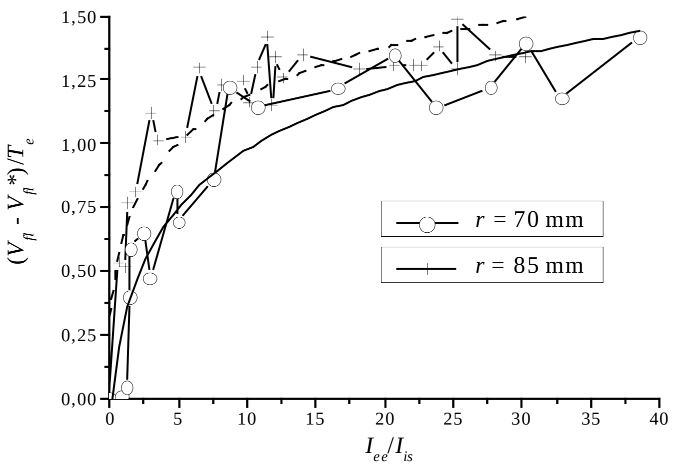

Fig. 2 Difference between the floating potentials of the cold probe (V_{fl}) and of the emissive probe (V_{fl}), normalised to the electron temperature, versus electron emission current, normalised to the ion saturation current I_{is} for two different values of the minor radius. The fittings are logarithmic.*

In the range around the floating potential, the total probe current I_p of an emissive probe is given by:

$$I_p(V_p) = I_e - I_{is} - I_{ee}, \qquad (1)$$

with $I_e = I_{e0}\exp\left[e\left(V_p - \Phi_{pl}\right)/k_B T_e\right]$ being the electron current (I_{e0} is the electron saturation current at Φ_{pl}), I_{is} is the ion saturation current and I_{ee} the electron emission current, given by the Richardson-Dushman formula above. From this the floating potential of the probe, for which $I_p(V_{fl}) = 0$, can be determined:

$$V_{fl} = \Phi_{pl} + \frac{k_B T_e}{e}\ln\left(\frac{I_{is} + I_{ee}}{I_{e0}}\right), \qquad (2)$$

From this the increase Δ of the floating potential with the electron emission can be derived:

$$\Delta = \frac{e\left(V_{fl} - \Phi_{pl}\right)}{k_B T_e} = \ln\left(\frac{I_{is} + I_{ee}}{I_{e0}}\right), \qquad (3)$$

Since always $I_{is} << I_{e0}$, we obtain $V_{fl} \cong \Phi_{pl}$ for $I_{ee} \cong I_{e0}$. From this we can derive that for a density of 10^{17} m^{-3}, $T_w \cong 2800$ K. At this wire temperature an emission current of typically 300 mA was achieved, for which a heating current of $I_{ph} \cong 6$ A was necessary. This simplified treatment is of course only applicable when both particle species have Maxwellian velocity distribution functions, whereas it has to be modified for drifting electrons.

In order to obtain probe characteristics, by means of a signal generator a sinusoidal voltage V_p from approximately -100 V to +100 V with a frequency of 1 kHz was applied to the emissive probe. In this way, during one CASTOR discharge of about 30 ms duration, about 30 probe characteristics were recorded with a sampling rate of 1 MHz. Fig. 1 shows three typical characteristics of the emissive probe for various heating currents. The solid lines are least square fits of the experimental points with the function given by:

$$I_p(V_p) = \left(I_{is} + I_{ee}\right)\left\{1 - \exp\left[-\frac{e\left(V_p - V_{fl}\right)}{k_B T_e}\right]\right\}\left\{1 - k\left[\frac{e\left(V_p - V_{fl}\right)}{k_B T_e}\right]^{3/2}\right\} \qquad (4)$$

where k is an additional fitting parameter. After fitting the experimental data to Eq. 4, from this curve the values of I_{is} and I_{ee} and T_e and the probe floating potentials V_{fl} are determined.

From Eq. 3 it is obvious that this value will increase with I_{ph}, and V_{fl} approaches a saturation value, which in the ideal case is identical to Φ_{pl}. This can be seen from Fig. 2, which shows $V_{fl} - V_{fl}^*$ (with V_{fl}^* being the floating potential of the cold probe) normalised to the

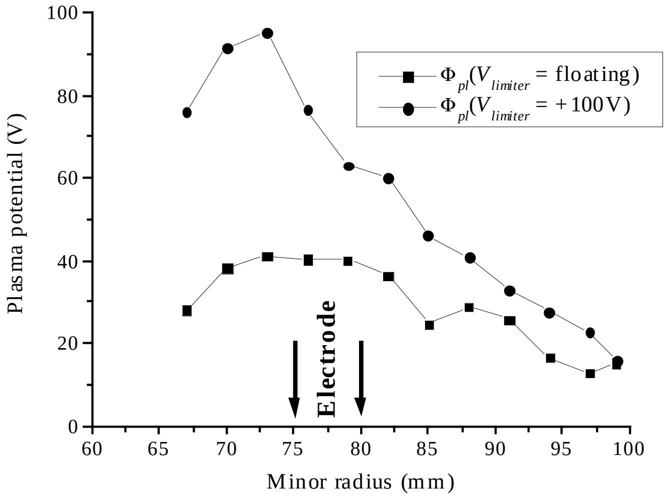

Fig. 3: Radial profile of the plasma potential for no bias on the electrode (squares) and for positively biased electrode (circles), as measured with the IEPP; r is the minor radius of the plasma torus.

electron temperature versus the electron emission current I_{ee}, normalised to I_{is}. The circles have been obtained for r = 70 mm, i.e., somewhat inside the LCFS; the crosses have been obtained for r = 85 mm, i.e., in the SOL. For $I_{ee}/I_{is} = I_{e0}/I_{is} \cong 15$ the value of $(V_{fl} - V_{fl}^*)/T_e$ approaches a saturation value which is $1.5T_e$ approximately for both radii. From this value the plasma potential in the two locations can be calculated. The fitting functions are logarithmic. An improved fitting shows the saturation more clearly.

We have also measured radial plasma potential profiles in the edge region of the CASTOR device in a range of $60 \leq r \leq 100$ mm. Fig. 3 shows such profile for two different conditions: the squares show the potential profile in normal conditions, while the circles show the profile when an electrode, inserted at r = 75 mm, was used to bias the edge plasma with +100 V [7]. In the latter case, the radial electric field is enhanced both in the SOL and in the core plasma, and the $\boldsymbol{E}\times\boldsymbol{B}$ velocity shear at the plasma boundary is increased. A very important observation is that the radial electric field is increased also inside the last closed flux tube and not only in the SOL. This is a very encouraging result about the possibility of actively changing the properties of the edge plasma through edge biasing also under experimental conditions where no large electrode can be inserted.

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References

[1] R.F. Kemp, J.M. Sellen Jr., *Rev. Sci. Instrum.* **37** (1966), 455; J.R. Smith, N. Hershkowitz, P. Coakley, *Rev. Sci. Instrum.* **50** (1979), 210.

[2] R.W. Motley, *J. Appl. Phys.* **43** (1972), 3711; H. Fujita, S. Yagura, *Jpn. J. Appl. Phys.* **22** (1983), 148.

[3] S. Iizuka, P. Michelsen, J.J. Rasmussen, R. Schrittwieser, R. Hatakeyama, K. Saeki, N. Sato, *J. Phys. E: Sci. Instrum.* **14** (1981), 1291.

[4] A. Siebenförcher, R. Schrittwieser, *Rev. Sci. Instrum.* **67** (1996), 849.

[5] M.A. Makowski, G.A. Emmert, *Rev. Sci. Instrum.* **54** (1983), 830.

[6] R. Schrittwieser, C. Avram, P.C. Balan, José A. Cabral, F.H. Figueiredo, V. Pohoaţă, C. Varandas, *Contrib. Plasma Phys.*, in print.

[7] G. Van Oost et al., *11th Int. Toki Conf. Plasma Phys. and Contr. Nucl. Fus. (ITC-11),* (Toki, Japan, 2000), to be published in J. Plasma Fus. Res. Series.