A Radially Movable Laser-Heated Emissive Probe

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Emissive probes are standard tools in laboratory plasmas for the direct determination of the plasma potential. Usually they consist of a loop of refractory wire heated by an electric current until sufficient electron emission. We have developed and investigated various types of emissive probes which were heated by a focused infrared laser beam. Such a probe has several advantages: higher probe temperature without evaporation or melting and thus higher emissivity and longer lifetime, no deformation of the probe in a magnetic field, no potential drop along the probe wire, faster time response. The probes are heated by an infrared diode laser with 808 nm wavelength and an output power up to 50 W.

Keywords: emissive probe, plasma potential, floating potential, laser-heated emissive probe, emission current.

1. Introduction

In a conventional Maxwellian plasma the plasma potential Φ_{pl} can be determined by cold plasma probes (Langmuir probes), but only indirectly. Either the first derivative of the current-voltage (IV-) characteristic is used to indicate the value of Φ_{pl} or the following well-known relation between the floating potential V_{fl} and Φ_{pl} is used (see e.g. [1,2]):

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

with T_e as the electron temperature and $I_{es,is}$ as the ion and electron saturation current, respectively. In typical tokamak edge plasmas with hydrogen, $\alpha \equiv \ln(I_{es}/I_{is})$ is typically $\cong 2$ [1] while in a low pressure magnetized argon plasma $\alpha \cong 4.2$. However, for applying Eq. (1) to find Φ_{pl} we need to know T_e. In addition, as soon as there is a considerable electron drift or electron beam, the entire IV-characteristic, and thereby also V_{fl}, shift to the negative side due to the kinetic energy of the drifting electrons (see e.g. [2]), and Eq. (1) is no longer applicable.

From Eq. (1) we see that always $V_{fl} < \Phi_{pl}$. This is due to the fact that in a conventional plasma the mass of the negative charge carriers, the electrons, is much lower than that of even the lightest positive ion. This fact is also the reason for the well-known strong asymmetry of the current-voltage characteristic. However, by a sufficient electron emission current I_{em} from the probe into the plasma, the floating potential $V_{fl,em}$ of an *emissive* probe can in principle be made equal to the plasma potential. In this case for a Maxwellian plasma, Eq. (1) becomes:

$$\Phi_{pl} = V_{fl,em} + \frac{T_e}{e}\ln\left(\frac{I_{es}}{I_{is} + I_{em}}\right) \tag{2}$$

Equation (2) shows that for increasing I_{em}, the second term decreases, while the floating potential $V_{fl,em}$ of the probe approaches Φ_{pl} until finally for $I_{em} = I_{es} - I_{is}$ we attain $V_{fl,em} = \Phi_{pl}$, i.e., it suffices to measure the emissive probe's floating potential to obtain the plasma potential. We emphasize that for sufficiently high electron emission such a probe works also in case of electron drifts or beams in the plasma, and is thus the most important diagnostic tool to detect strong potential variations in a plasma, for instance with double layers and other nonlinear potential structures.

When the floating potential of an emissive probe $V_{fl,em}$ attains exactly the value of Φ_{pl} there is no sheath around the probe. However, under certain conditions, deviations between $V_{fl,em}$ and Φ_{pl} were seen. Often it was observed that above a certain emission current no further increase of $V_{fl,em}$ could be achieved but a saturated value $V^*_{fl,em}$ was attained which lay below the value of $\Phi_{pl,cold}$ (by which we understand the value derived in the conventional way from the cold probe characteristic), in particular in plasmas with electron temperatures in excess of a few eV [1]. This effect was ascribed to space charge effects around the floating emissive probe [3], and recently the effect was investigated in detail [4,5].

However, by avoiding or at least reducing the effect of the electron temperature and its fluctuations in Eq. (1) and (2), respectively, the floating potential of an emissive probe delivers a more reliable measure of Φ_{pl} than a cold probe [6].

Two methods were reported to measure the plasma potential with an emissive probe:

(i) The floating point method as described above [7].

(ii) The inflection point method at low emission or zero emission approximation [8].

Only more recently emissive probes were also used in

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toroidal fusion experiments (see e.g. [1,6,9,10]).

Here we report on a radial moveable laser-heated probe which was tested in VINETA [11]. The VINETA plasma is produced by a helicon discharge with an RF power of 2 kW creating densities up to about 10^{19} m^{-3} and an electron temperature between 3 and 5 eV. The confining magnetic field is in the range of 100 mT and the neutral Ar-pressure around 0.2 Pa. The plasma column diameter is around 10 cm and the maximum density is reached in the center.

2. Basic considerations

Although superior to cold probes for a direct determination of the plasma potential, conventional emissive probes, consisting of a loop of a refractory metal, heated by an electric current, have certain drawbacks:

(i) short lifetime because the wire evaporates and eventually melts,
(ii) therefore also a limited emission current,
(iii) therefore the emission current has to be readjusted frequently since the wire becomes constantly thinner due to evaporation,
(iv) mismatch between the necessity to use a refractory metal as probe wire (like e.g. tungsten) and the normally high work function of such metals, which restricts the emission,
(v) in a magnetic field possible bending of the probe wire due to the Lorentz force,
(vi) slow time response since the probe needs two cables with a finite cable capacity for connecting it to the heating power supply,
(vii) a voltage drop across the wire due to the heating current.

In order to avoid these disadvantages of a conventional emissive wire probe we have developed a system to heat the probe tip indirectly. In this case the actual probe consists of just a little piece of graphite or LaB_6 connected by one wire. Such a system can reduce or avoid the above listed disadvantages, since:

(i) a piece of LaB_6 or graphite can be heated to much higher temperatures before damage occurs, therefore the electron emission can be stronger and the lifetime much longer,
(ii) no heating current flows through the probe, therefore there is no danger of deformation in a magnetic field,
(iii) the time response is better since, with just one connecting wire and no power supply, the capacity of the probe is lower,
(iv) the surface of the probe piece is an equipotential area.

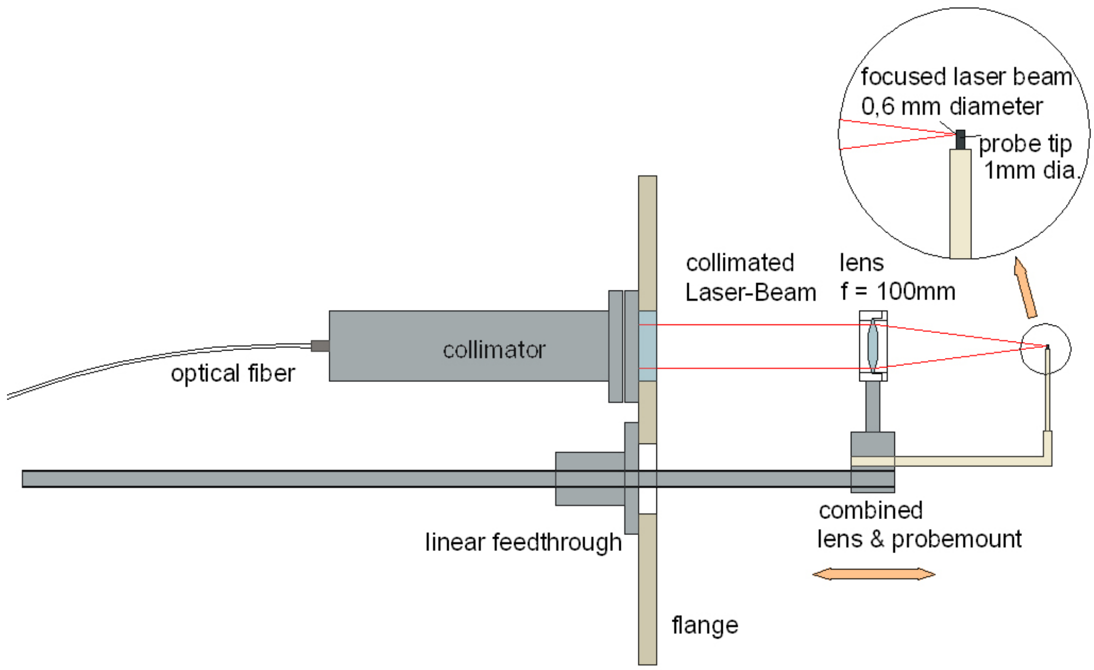

Fig. 1: Schematic of the radially moveable laser-heated probe.

Our emissive probe is heated by a water-cooled diode laser type JenLas HDL50F from the company JenOptik, Jena, Germany, with a maximum output power of 50 W and a wavelength of 808 nm. The laser beam is coupled into a conventional glass fiber cable of 3 m length that terminates in the collimator (see Fig. 1).

3. Probe construction

Figure 1 shows the set-up of our most recent type of laser-heated probe [12]. Inside the collimator, which is fixed directly on a quartz window of VINETA, the laser beam exiting and diverging from the fiber cable, is collimated by a first lens into a parallel beam of about 20 mm diameter. After penetrating the quartz window, inside the vacuum chamber the parallel beam is focused by a second lens onto the probe pin consisting of a cylindrical piece of LaB_6 of 1.5 mm diameter and 3 mm length. The diameter of the focus is about 1 mm. The probe is mounted mechanically stable on the same shaft as the second lens so that the distance between them is constant. Thus the probe shaft can be moved radially over a range of about 10 cm while the laser beam focus stays constantly centered on the probe pin and the heating is stable. Any deviation of the laser beam focus from the lateral centre of the probe pin leads to a lesser heating and the emission is insufficient.

With the Richardson constant of LaB_6 being $A^*_{LaB_6}$ = 29×10^4 A/m^{2}K^2 and the work function $W_{LaB6} = 2.66$ eV [13], for a temperature of typically 2100 K theoretically an electron current density of about $j_{em} \cong 5.4\times10^5$ A/m^2 is emitted under field-free emission conditions. The emitting surface A_{em} of our probe pin with the above mentioned dimensions is 16 mm^2. Thus in principle we could achieve an emission current of $I_{em} \cong 8.6$ A. The average electron current density in the scrape-off layer (SOL) of ASDEX Upgrade with an electron temperature of $T_e \cong 5$ eV and a SOL density of $n_{e,SOL} \cong 10^{18}$ m^{-3} amounts to $j_e = -n_e e(2k_B T_e/\pi m_e)^{1/2} \cong -1.2\times10^5$ A/m^2. Thus such a probe would be suitable even for direct measurements of Φ_{pl} in the SOL of the tokamak at IPP Garching even in the H-mode.

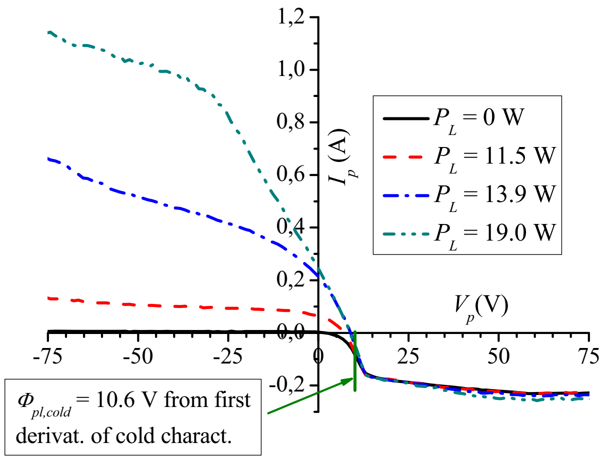

Fig. 2: Current-voltage (*IV*-) characteristic of the laser-heated emissive probe with increasing laser heating power P_L for radial position $r \cong -15$ mm. The vertical line indicates the value of $\Phi_{pl,cold}$ derived from the first derivative (black line).

4. Results and discussion

Figure 2 shows a set of current-voltage characteristics of the LaB_6 probe pin for increasing laser heating power P_L taken at a radial position of $r \cong -15$ mm, i.e. near the center of the VINETA plasma column. Figure 3 shows the increase of the floating potential $V_{fl,em}$ of the probe with P_L where also the value of $\Phi_{pl,cold}$ is indicated. See also Fig. 4.

The probe characteristics of Fig. 2 show the typical behavior of an emissive probe: The black solid line shows the characteristic of the unheated probe behaving exactly like a cold probe with a low floating potential of $V_{fl} \cong 1.6$ V. For increasing heating we observe the emission current I_{em} superimposing on the ion saturation current on the left-hand side of the characteristic. At the same time the floating potential of the emissive probe $V_{fl,em}$ shifts to the right-hand side, until above about 14 W it saturates at $V^*_{fl,em} \cong 9.2$ V, i.e., even though we further increase the probe heating and thereby the emission current, $V^*_{fl,em}$ does not further grow.

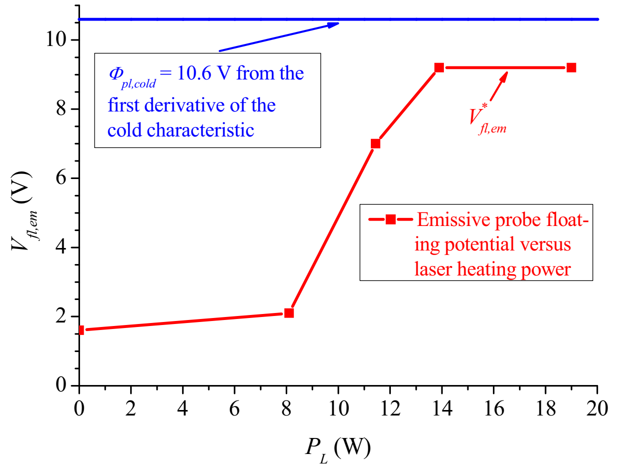

Fig. 3: Floating potential of the laser-heated probe versus laser heating power P_L. The horizontal blue line shows the value of $\Phi_{pl,cold}$ as derived from the first derivative of the cold characteristic in Fig. 2 (see also Fig. 4).

In a Maxwellian plasma it is in principle sufficient to adjust the saturated emission current to about the same value as the magnitude of the electron saturation current to attain an approximate equality of $V_{fl,em}$ and Φ_{pl}. Here we have increased the emission current to much higher values to find out what maximum emission current we could achieve at all. For these plasma parameters and a laser heating power of just 19 W we could already produce an emission current of about 1.2 A. We have even reached currents of more than 2 A, this being on the order of magnitude which we have calculated above.

Figure 2 delivers us a value of $\Phi_{pl,cold} \cong 10.6$ V. With the electron temperature also derived from the cold characteristic as $T_e \cong 6.4$ eV, the difference between $\Phi_{pl,cold}$ and $V^*_{fl,em}$ is about 0.2 T_e. Thus also in this case we find that $V^*_{fl,em}$ is somewhat smaller than $\Phi_{pl,cold}$, however this deviation is considerably smaller than those observed and derived earlier, where differences between 0.6 T_e and T_e were found [1,3,14]. We note that in another recent work an excellent agreement between $\Phi_{pl,cold}$ and $V^*_{fl,em}$ was found [15]. We note that the value of $T_e \cong 6.4$ eV is higher than the usually observed electron temperature in VINETA, which is probably due to the fact that our probe was not compensated against the rf of the power supply [12].

Figure 4 shows radial profiles of $V_{fl,em}$ across the VINETA plasma column for three values of the laser heating power P_L. Also shown are the radial profiles of $\Phi_{pl,cold}$ and the electron density $n_e(r)$, which was determined from the electron current at the inflection point of the cold IV-characteristics. These values of $n_e(r)$ appear low due to the well-known effect that in a magnetized plasma the probe's electron saturation current is always smaller than in a unmagnetized plasma of the same density. Therefore $n_e(r)$ gives only a qualitative impression of the radial density profile. The actual center of the plasma column is slightly right-shifted compared to the geometrical center.

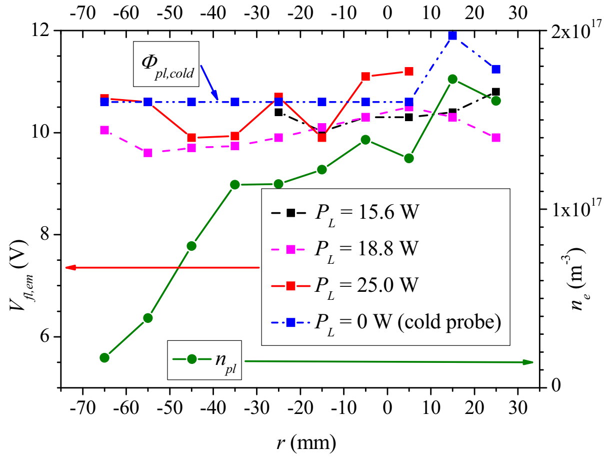

Fig. 4: Radial profile of the emissive floating potential $V_{fl,em}$ for three values of the laser heating power P_L. Also shown are the radial profiles of $\Phi_{pl,cold}$ and of the electron density n_e as determined from the electron current in the inflection point of the IV-characteristics.

Figure 4 offers further details of the behavior of our emissive probe: Like in Fig. 3, we see that above a laser heating power of $P_L \cong 14$ W $V_{fl,em}$ is practically constant. However, for $P_L \cong 25$ W, $V_{fl,em}(r)$ lies in general slightly higher than the other two profiles and shows stronger deviations from the mean value. On the other hand $\Phi_{pl,cold}(r)$ is flat for $-65 < r < +5$ mm. It is surprising to discern that not only the deviation between $\Phi_{pl,cold}$ and $V_{fl,em}$ is very small (as already mentioned above for the IV-characteristic at $r \cong -15$ mm – see Fig. 2 and 3), but also that sometimes we find even that $V_{fl,em} > \Phi_{pl,cold}$.

5. Conclusion

We have succeeded to develop a laser-heated emissive probe which can produce very high emission currents which would be sufficient even for the SOL of tokamaks such as ASDEX Upgrade in the H-mode. Our probe can be shifted radially over a range of about 10 cm without deviation of the laser beam focus form the probe so that the probe temperature and thereby the emission current are stable. As for the deviation between the saturated emissive floating potential and the plasma potential, and in spite of recent comprehensive investigations [4,5] still some questions remain open.

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