Indirectly heated strong and robust emissive probe for dense and hot plasmas

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Electron-emissive probes have the advantage of measuring the plasma potential directly at the position of the probe with high reliability and temporal resolution. We present the development of two probes for high temperature and dense plasmas: An indirectly heated emissive probe and an emissive carbon fibre loop probe. The indirectly heated probe pin consist of LaB_6 of 1,5 mm diameter and 10 mm length. The pin is heated electrically on their rear ends while the protruding parts of the pins are heated by heat conduction. For the carbon loop probe the electrical current is driven through the entire carbon loop and therefore directly heated. A 10 mm long carbon roving with 5000 single, 7 µm thick fibres protrudes in to the measured plasma. The thermionic work function, the main parameter for electron emission, of LaB_6 is 2,7 eV and that of C 4,6 eV. Test measurements are carried out in a Double Plasma machine.

1. Introduction

We present the development of an electron emissive probe (EEP) suitable for high temperature and density plasmas.

Irving Langmuir was the first to describe how to derive the plasma potential from the current-voltage (*I*-*V*) characteristic of a cold probe. In 1923 he also mentioned EEPs for the first time [1].

Electrical probes have the advantage of measuring plasma parameters locally at the probe position. However, with a cold probe, the plasma potential can be deduced only indirectly from its floating potential, provided the electron temperature is known too, or from the "knee" of its *I-V* characteristic [2-7], i.e. from the transition of the electron current to the saturation region.

In contrast to that, EEPs are able to display the plasma potential directly by their floating potential with relatively high reliability. A necessary condition is that the electron emission current density is at least as high as the plasma electron saturation current. With a probe head carrying several EEPs, also electric fields and their fluctuations can be determined with higher reliability and accuracy than with cold probes.

In this contribution a detailed comparison of a strong and robust emissive probe with cold probes is carried out, where in the latter case the plasma potential is deduced from the *I-V* characteristic as described above [2-8]. With sufficient heating of the probe pin, the EEP's floating potential does indeed become more positive to eventually reach a value which agrees very well with the values for the plasma potential determined by cold probes [8-13].

2. Probe Design

Prototypes of such an EEP have been developed using a 1,5 mm diameter pin of LaB_6 and a 12 mm long carbon roving of 7 µm thick carbon fibres.

While the work function of LaB_6 is 2,7 eV [14], that of carbon is 4,6 eV [15]. The melting points of these two materials are 2482 K [16] (LaB_6) and 4023 K (C) [17]. Although carbon has the higher heat resistance, its high work function makes it necessary to heat it to much higher temperatures to emit a similar electron current density as LaB_6.

The probe tip of the LaB_6 emissive probe (LaBP) consists of a LaB_6 rod with a diameter of 1,5 mm and a total length of 10 mm. The rod is electrically heated through a carbon ring contact in the front and a molybdenum cylindrical holder at the rear end of the LaB_6-rod. Carbon is used for the contact ring since it is one of the few materials that sufficiently resist the heat load during the total measurement time without risk of oxidizing or melting. The inner heating circuit of the probe is partly isolated by ceramic tubes. The probe tip protrudes 3 mm from the isolation into the argon test plasma.

For the emissive carbon fibre probe (ECFP) a 12 mm long loop of carbon roving consisting of about 5000 single, 7 µm thick fibres is spliced 4 mm on both ends with thin copper wires [18]. The roving is bent and pulled into a double-bore alumina ceramic tube of 5 mm outer diameter so that only the pure carbon fibre loop protrudes. The two bores have a diameter of 1,5 mm each and are spaced 2 mm from each other. The rear ends of the roving-connected copper wires are further connected to electrical feedthroughs and thence to the measuring circuit. The probe loop protrudes 5 mm out of the ceramic tube into the plasma.

3. Experimental device (see Fig. 1)

The plasma is produced by a gas discharge in the 90 cm long, 45 cm diameter cylindrical vacuum chamber of the Innsbruck DP-machine (Double-Plasma Machine). At the ultimate background pressure of $p_{back} = 5\cdot10^{-6}$ mbar, argon is employed to the chamber to obtain the operating gas pressure. The two negatively biased 0,15 mm W filaments at the top of the chamber are separately heated, as indicated in Fig. 1. Adjusting the filament heating, a stable almost homogeneous plasma is created with the discharge currents $I_{discharge,1,2}$ from the filaments to the chamber wall adjusted to 200 mA each. By setting the chamber pressure between $2{,}0\cdot10^{-3}$ and $3{,}0\cdot10^{-3}$ mbar, an electron temperature T_e of 1 eV and a plasma density $n \approx 5\cdot10^{16}$ m^{-3} is attained.

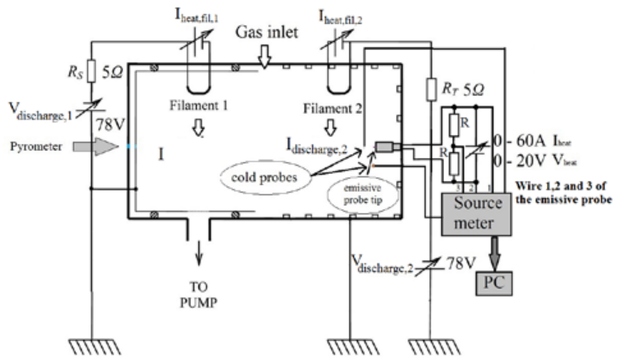

Fig. 1: Experimental setup for probe measurements in the DP machine.

Under the above-mentioned parameters, to compensate the plasma electron saturation current by the electron emission current from the probe tip, for LaB_6 temperatures between 1250 and 1750 K are needed; in case of C the necessary temperature range is 2000 to 2500 K. A 60 A-20 V power supply ensures the necessary power to heat the EEP tips to sufficient emission for both the 1,5 mm diameter LaB_6 rod and the C loop. A computer-controlled source meter is used to sweep the EEP at the connections wire 1, 2 and 3 (wire 3 only for the ECFP probe), as well as two cold probes to obtain *I-V* characteristics.

The probe heads with the above-described tips are in turns inserted 100 mm into the plasma on the axis of the vacuum cylinder. During heating, the probe tips reach temperatures up to 2500 K.

A pyrometer is aimed at the probe tip from outside the chamber through a quartz window, recording temperatures from 1263 to 3273 K. The two different cold probes are used to compare theirs with the results of the EEPs: one thin, 5 mm diameter brass disk mounted about 50 mm underneath the EEP tip and one 0,15 mm thin, 3 mm long cylindrical W probe mounted 40 mm directly in front of the EEP tip (cf. Fig. 1).

4. Results and discussion

The probe characteristics presented in Fig. 2 have been obtained using the LaB_6 probe and the voltage recorded at connection wire 2. For Fig. 3, the probe characteristics have been obtained using the ECFP probe and the voltage also recorded at connection wire 2. Both characteristics show the typical behaviour of EEPs [1, 9-14]: The emission current appears on the negative side of the characteristics superimposed on the ion saturation current, with increasing magnitude when the heating is raised. The electron saturation current, which should in principle remain unaffected by the electron emission, also shows a strong increase, in particular in case of the LaBP.

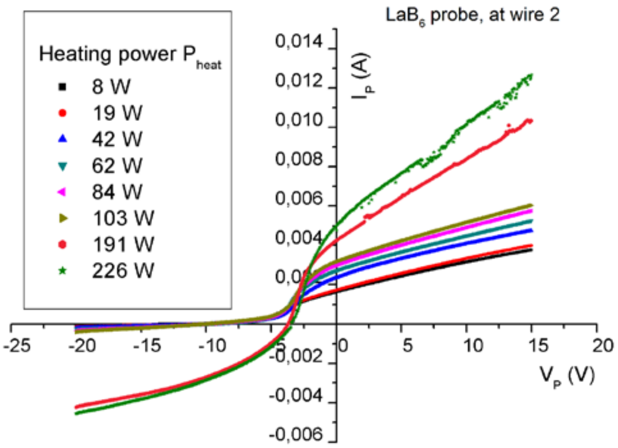

Fig. 2: *I-V* characteristics of the LaB_6 probe taken at different heating powers (cf. Fig. 4).

Such effects have been seen also in other cases of EEPs [19], but the reasons are not yet clear. On the other hand, this effect does not alter the principle property that the floating potential of the EEP is found very close to the plasma potential. Estimates show that even with C the average electron current density in high temperature and dense technical plasmas can be compensated by the electron emission current density, which is a prerequisite for the EEP to float on the plasma potential.

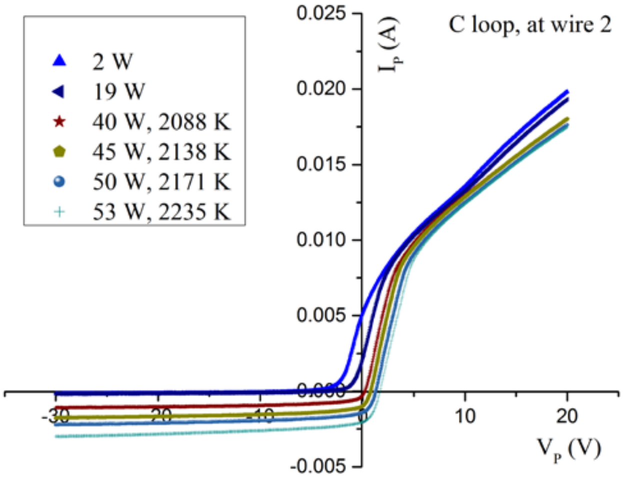

Fig. 3: *I-V* characteristics of the C probe taken at different heating powers (cf. Fig. 5)

The behaviour of the floating potential of the EEPs when heated is represented in Fig. 4 (LaBP) and Fig. 5 (ECFP) for the electrical wire connection 2. When the electron emission current of the probe tips approaches the plasma electron saturation current at the probe surface, the floating potential of the EEPs attains the actual plasma potential. If the electron emission of the probe is equal or greater than the value of the incoming plasma electron current density, the floating potential of the EEP stagnates more or less at the plasma potential, as seen in Fig. 3. The error bars in Fig. 4 and 5 represent $V_{heat}/2$, where V_{heat} (Fig. 5) is the heating voltage bias of the probe.

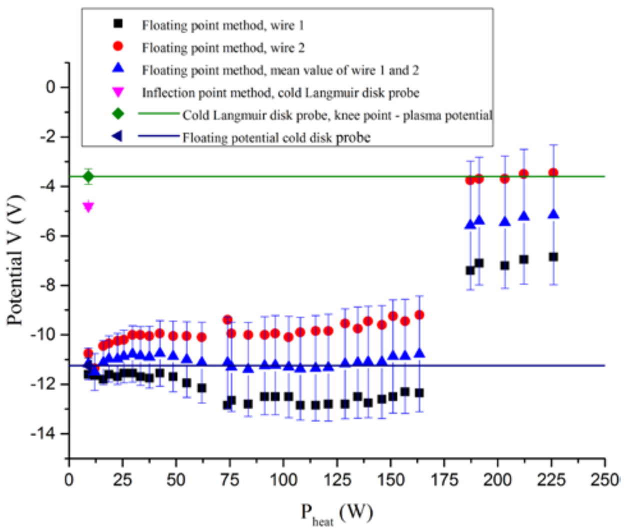

Fig. 4: Comparison of floating potential of the emissive LaB_6 probe with the plasma potential derived of the cold brass Langmuir disk probe.

The resistivity behaviour of the entire heating circuit of both probes is indicated in Fig. 6: The ohmic resistivity of both probes drops at the beginning of the heating process and settles at different values.

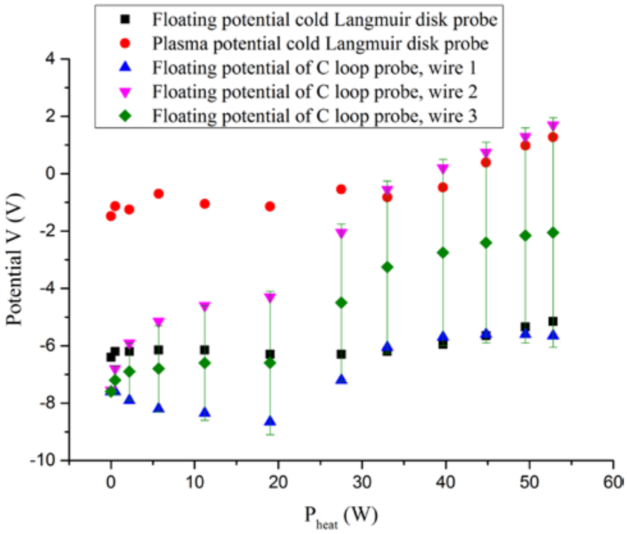

Fig. 5: Comparison of the floating potential of the emissive C probe with the derived plasma potential of cold Langmuir disk probe.

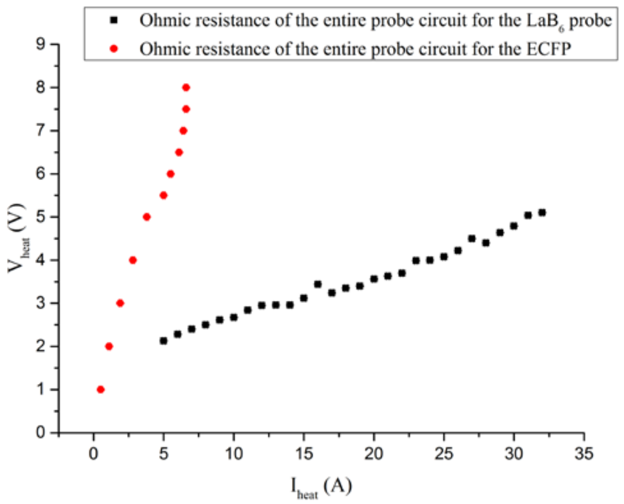

Fig. 6: The characteristic $V_{heat}(I_{heat})$ above symbolizes the ohmic resistance of the entire LaB_6 and C probe circuits during the heating process.

This can be better seen in Fig. 7, where the resistivity $R=V_{heat}/I_{heat}$ of both probes is plotted against the heating power $P_{heat}= V_{heat}\cdot I_{heat}$. The resistivity of the ECFP is by a factor of over 4 greater than that of the LaBP, lowering the necessary heating current I_{heat} to reach the plasma potential, even though C has a higher work function than LaB_6.

5. Conclusion

It has been demonstrated that an ohmically heated LaB_6 pin probe and a C loop probe can be used as

EEPs. In contrast to earlier directly heated probes [3] in our case we use a LaB_6 rod of 1,5 mm diameter and 10 mm length which is heated only on the rear part of its length, whereas the actual probe tip, protruding from the probe head into the plasma, is heated by conduction. The other probe type consisted of a C roving of 12 mm length, twisted together of 5000 C fibres, each 7 µm thick. The probe prototypes are capable of almost reaching the actual plasma potential in the chamber.

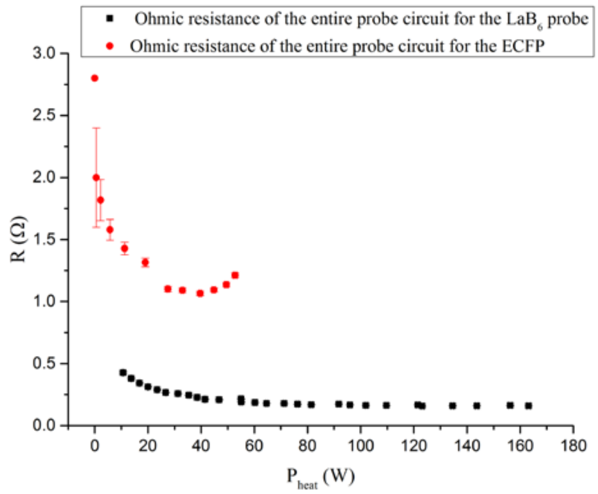

Fig. 7: Different representation of the data of Fig. 6 by this resistance-power characteristic: the resistance of the probe heating circuits $R = V_{heat}/I_{heat}$ decreases at the beginning with increasing heating power $P = V_{heat} \cdot I_{heat}$.

Due to the higher ohmic resistivity of C compared to LaB_6, lower currents are needed to heat the probe tip to necessary temperatures. Additionally, the highest electron emission of C is higher than of LaB_6, due to the much higher melting temperature.

The rather large uncertainties of the floating point technique indicated by the error bars in Fig. 1, resulting from the heating bias of the probes, can be ignored when measuring in high and dense plasmas. There the additional passive heating by the plasma can be used to keep the probe in the working temperature regime during insertion and measurement time.

The active heating of the probe ensures the correct temperature of the EEP tips during the entire measurement time. This measurement technique strongly reduces measurement errors regarding electron temperature fluctuations and strongly reduces measurement time scales (kHz to MHz) in technical and fusion plasmas.

Acknowledgement

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