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Diagnostics of magnetized low temperature plasma by ball-pen probe

Jiří Adámek,
Matěj Peterka,
Tomaž Gyergyek,
Pavel Kudrna,
Milan Tichý

Abstract. The ball-pen probe is an innovative electric probe for direct measurements of the plasma potential in magnetized hot plasma. This probe is based on the Katsumata probe concept. The ball-pen probe can adjust the ratio $I^{-}_{\mathrm{saturat}}/I^{+}_{\mathrm{saturat}}$ of the electron and ion saturation currents to be equal to one and therefore the ball-pen probe characterization becomes symmetric. If this is achieved, the floating potential of the ball-pen probe is equal to the plasma potential in Maxwellian plasma. We show the application of a ball-pen probe in slightly magnetized low temperature plasma.

Key words: ball-pen probe • magnetron

J. Adámek
Institute of Plasma Physics AS CR, v.v.i.,
3 Za Slovankou Str., 18200 Prague 8, Czech Republic

M. Peterka, P. Kudrna, M. Tichý✉
Faculty of Mathematics and Physics,
Charles University in Prague,
3 Ke Karlovu Str., 12116 Prague 2, Czech Republic,
Tel.: +420 221 912 305, Fax: +420 284 685 095,
E-mail: milan.tichy@mff.cuni.cz

T. Gyergyek
Faculty of Electrical Engineering,
University of Ljubljana,
25 Tržaška Str., 1000 Ljubljana, Slovenia

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Introduction

The most widely used electric probes in low temperature plasmas are the Langmuir probes. They are constructed of a simple and small electrodes of various shapes and exposed directly into the plasma as floating or biased probes. From the probe's current voltage characteristics many plasma parameters can be found. If the plasma is magnetized the interpretation of the Langmuir probe data becomes more complicated. Recently, a specially designed probe, so-called ball-pen probe [4], has been developed for direct measurements of the plasma potential in magnetized hot plasma because the conventional method of the plasma potential determination using the Langmuir probe in such a plasma must be combined with the electron temperature measurements.

In a tokamak edge plasma, the plasma potential Φ is routinely calculated from the floating potential V_{float} of the Langmuir probe and the electron temperature T_e determined of the I–V characteristics of the swept probe using the following equation:

$$V_{fl} = \Phi - \left(\frac{k_B T_e}{q_0}\right)\ln(R) \tag{1}$$

The quantities k_B and q_0 represent the Boltzmann constant and the elementary charge, respectively. The quantity $R = I^{-}_{\mathrm{saturat}}/I^{+}_{\mathrm{saturat}}$ expresses the ratio of electron and ion saturation current, respectively. The ball-pen probe can adjust the ratio R to be equal to one and therefore its floating potential is equal to the plasma potential, as follows from Eq. (1).

The ball-pen probe consists of a metallic collector, which is shielded by an insulating tube; the probe head itself must be oriented perpendicular to magnetic field lines. Figure of the ball-pen probe, its detailed description and experiments performed so far can be found in previous works [1–4, 6–8, 12, 15]. For its simplicity and rugged construction, the ball-pen probe is subject to intensive 3-D PIC modeling [13, 14].

We show in our contribution the application of a ball-pen probe in two experimental systems: in cylindrical magnetron at the Charles University in Prague and in linear magnetized plasma device at the Jožef Stefan Institute in Ljubljana. We have used a ball-pen probe with a movable collector accommodated within a ceramic shielding tube. The results of both experiments indicate that the ball-pen probe might be applicable also for the diagnostics of weakly magnetized plasma and low ion temperature $T_\mathrm{i} < 1$ eV.

Experimental arrangement

The cylindrical magnetron in Prague consists of a cylindrical cathode mounted coaxially inside of the cylindrical hollow anode. The diameters of the cathode and anode were 10 and 60 mm, respectively. The length of the discharge volume was 110 mm. Typical discharge current was 75 mA and the discharge voltage around 400 V. The homogeneous magnetic field in the range from 10 up to 50 mT was within the investigated discharge volume parallel with the common axis of the system. The ultimate pressure achieved by the oil-free pumping system was of the order of 10^{-3} Pa. During the operation, the working gas argon slowly flew through the system with a typical flow rate below 1 sccm. Typical plasma density ranges from 10^{16} up to 10^{17} m^{-3}. The below described experiments were performed in argon at a pressure of 2.4 Pa, discharge current 75 mA and magnetic field 40 mT. For more detailed description of the experimental system see, e.g. [11]. The ball-pen probe was at a fixed position approximately in the middle between the cathode and the anode.

The main part of the linear magnetized plasma device in Ljubljana is a stainless steel tube about 1.5 m long and 17 cm inner diameter. Plasma is confined by axial magnetic field created by the magnetic field coils with the maximum induction up to 0.4 T. The plasma is created by a discharge from hot cathode W/Th filaments, which are heated by direct current. Thermally emitted primary electrons are accelerated by a discharge voltage 40–50 V and plasma is created by impact ionization. The discharge current was between 120 and 400 mA. In measurements described in this work the magnetic field was adjusted between 7 and 20 mT. The ball-pen probe was inserted from the side, about 1 m from the hot cathode source and could be moved in the radial direction. Prior to experiments the chamber was evacuated down to ultimate pressure below 10^{-4} Pa. Then argon was leaked into the vacuum system. The argon pressure was kept between 0.01 and 0.5 Pa. The resulting plasma had the electron temperature approximately 2 eV and the ion temperature approximately 0.1 eV. The typical plasma density was between 10^{14} and 10^{15} cm^{-3}. For more detailed description of the system see, e.g. [10].

The ball-pen probe used in Prague and Ljubljana was constructed in a way that enabled the movement/shift of the collector. Instead of boron nitride as decribed in [4] we used Degussit® tube of 4/2.4 mm in outer/inner diameter to shield the collector made of non-magnetic stainless steel. The position of the probe collector with respect to the tube edge will be denoted as *h*.

Results of experiments

The main aim of our effort was to prove that the ball--pen probe is able to operate also at comparatively low magnetic fields. At first, we present the results from the cylindrical magnetron system in Prague. Since we had the possibility of measuring Φ by operating the ball-pen probe with an extended collector, i.e. as a Langmuir probe, we could use the ion current linearly extrapolated to the plasma potential I^{+}_{saturat} as a normalizing factor. At the same time, we could calculate $R = I^{-}_{\text{saturat}}/I^{+}_{\text{saturat}}$ using as I^{-}_{saturat} the linearly extrapolated value of the electron saturated current to the plasma potential. Example of a set of normalized ball-pen probe characterization with *h* as a parameter is given in Fig. 1a. In Fig. 1b we see the dependence of the floating potential on the ratio *R* in a semilogarithmic scale. In accord

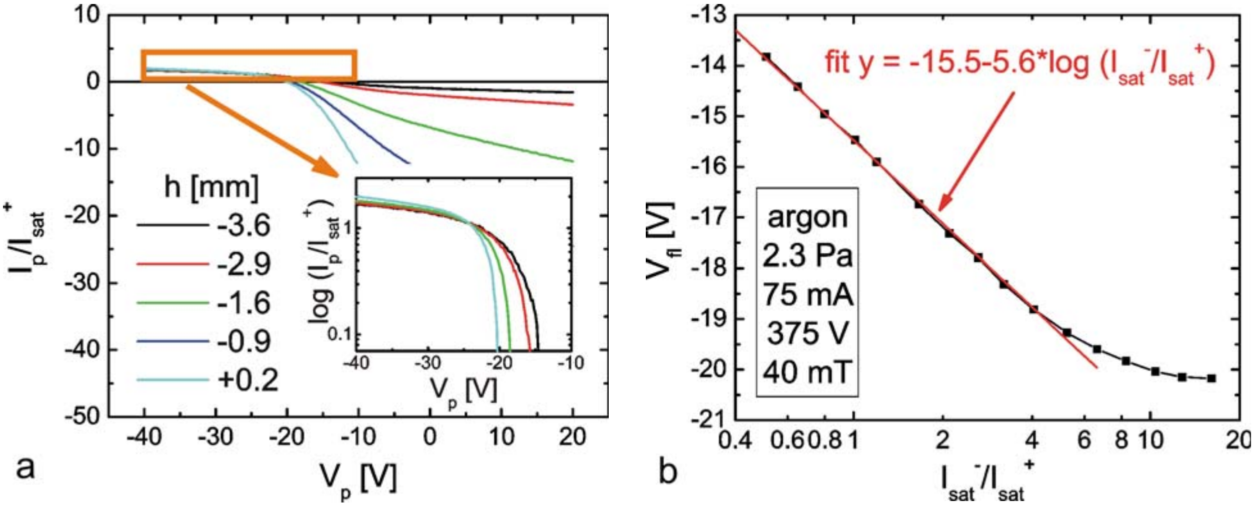

Fig. 1. (a): Normalized I–V characteristics at different depths *h* of insertion/extension of the ball-pen probe collector. The insert shows clearly the shift of the floating potential. (b): Dependence of the ball-pen probe floating potential on the ratio $I^{-}_{\text{saturat}}/I^{+}_{\text{saturat}}$.

with Eq. (1), the dependence should be linear. The Eq. (1) was, however, derived under the assumption of constant saturated electron and ion currents that is not the case in low temperature low density plasma. That is the probable reason why for large R the dependence deviates from the linear one.

The plasma potential determined by a conventional way from the ball-pen probe operating as a Langmuir probe, i.e. for positive h, was approximately –10 V while V_{float} amounted to around –20 V. These data well agree with those published in [11] that were taken in the same system under similar conditions. Looking at Fig. 1b, we infer that extrapolation of the red line down to $R = 0.1$ gives approximately –10 V, however, at $R = 1$ we arrive in Fig. 1b on the ordinate axis at around –15.5 V. Such a discrepancy cannot be explained by the method for obtaining the I^{-}_{saturat} and I^{+}_{saturat} described above. The most probable explanation suggest the results of the work [5] where it has been shown that in the same system in similar conditions the electron energy distribution function (EEDF) is not Maxwellian. Consequently, Eq. (1) does not hold. An attempt has been made in [5] to approximate the EEDF by the so-called "standard" distribution introduced in [16] of the form $f^{*}(\varepsilon)$ = const. $\sqrt{\varepsilon}\exp(-\varepsilon^{k}/k\varepsilon_p^{k})$, where $k \geq 1$ is the distribution parameter, ε_p is related to the voltage equivalent V_p of the so-called "effective temperature" by $\varepsilon_p = q_0 V_p$. The equivalent of Eq. (1) for the standard electron energy distribution is as follows:

$$V_{\text{float}} = \Phi - \varepsilon_p \sqrt[k]{k.\ln(R)} \tag{2}$$

The parameter k was estimated in [5] to be approximately 2. Since we use in Fig. 1b linear extrapolation, we should therefore extrapolate to lower value of $I^{-}_{\text{saturat}}/I^{+}_{\text{saturat}}$ simple calculation for $k = 2$, gas argon, $k_B T_e = \varepsilon_p = 1$ eV and $T_i = 300$ K arrives at around $I^{-}_{\text{saturat}}/I^{+}_{\text{saturat}} = 0.14$. Extrapolated value of the red line in Fig. 1b gives us at this value the ordinate around –11 V. We can conclude that the V_{float} value measured by the ball-pen probe in the cylindrical magnetron system and, in the conditions described above, is close to that measured by Langmuir probe.

In the linear magnetized plasma device it was possible to perform experiments at much lower pressure because of using the hot cathode as an electron source. At such low pressure in argon the EEDF is typically of the "double temperature" form, see e.g. [9], i.e. with the EEDF body having comparatively low temperature and the EEDF "tail" having much higher electron temperature. One cannot therefore expect that the difference between the Φ and V_{float} will obey Eq. (1); V_{float} will be much more negative because of the current due to faster electrons.

Since in this system were installed both the ball-pen as well as the Langmuir probe we could directly compare the Φ measured by both diagnostics. Both probes were located approximately at the axis of the experimental system. At a pressure of 0.12 Pa, 100 mA discharge current and 7 mT magnetic field the Φ measured by both the probes (ball-pen with extended collector) was around + 1.4 V, while the floating potential amounted to approximately –42 V. In Fig. 2a we see the measured ball-pen probe characteristic with an extended collector; the floating potential V_{float} being –41.8 V. From the second derivative zero-cross, the value Φ has been estimated as 1.4 V. It is clear that at higher retarding potentials the probe current is almost solely determined by the higher energy "tail" of the EEDF. From the difference between Φ and V_{float}, the higher electron temperature is estimated as approx. 8 eV.

In Fig. 2b we plotted the dependence of the floating potential of the ball-pen probe on the depth of collector insertion. Apart from expected rise of the floating potential with increasing collector insertion, we see a local maximum on the curve around $h = 0$. That phenomenon we are, at present, unable to explain. However, for a sufficiently deep insertion we see in Fig. 2b that the floating potential of the ball-pen probe approaches to zero potential, i.e. quite close to the plasma potential Φ determined from the Langmuir probe data.

Summary and conclusions

After the ball-pen probe has been successfully applied in fusion devices we attempted to utilize it in the low

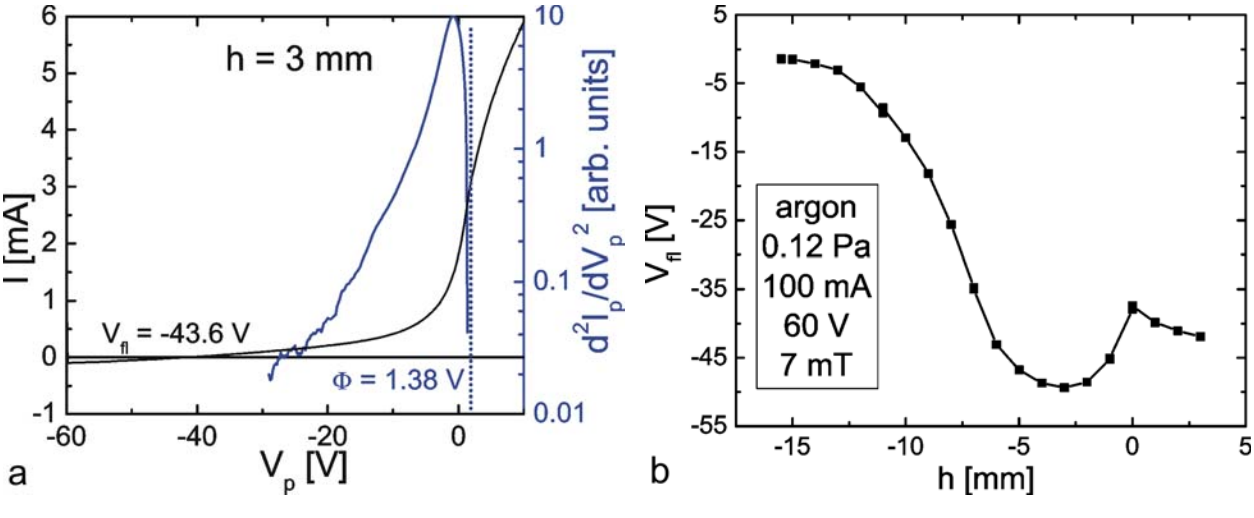

Fig. 2. (a): Characteristic of the ball-pen probe with collector extended by 3 mm (black line) and its second derivative in a semilogarithmic scale (blue line). Note the "double temperature" character of the second derivative. (b): Dependence of the ball-pen floating potential on the depth of collector insertion/extension.

temperature slightly magnetized low pressure magnetized plasma. We employed the ball-pen probe for measurements of the plasma potential at different experimental conditions: in the system in Prague at a magnetic field of 40 mT and an argon pressure of around 3 Pa and in the system in Ljubljana at a low magnetic field of around 7 mT and a very low argon pressure of around 0.1 Pa. We experienced that for sufficiently deep insertion h the floating potential of the ball-pen probe approached in both cases quite well to the "true" plasma potential Φ determined from the Langmuir probe measurements.

It has to be noted, however, that the determination of the ball-pen floating potential requires sensitive measurements. When the collector is inserted deeper into the ceramic tube both the electron and the ion currents become reduced down to the fraction of μA range.

It can be concluded that the presented experiments indicate that the ball-pen probe can be successfully applied for "direct display" of the plasma potential also in low temperature slightly magnetized low pressure plasma.

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