Charles University in Prague

Faculty of Mathematics and Physics

BACHELOR THESIS

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Measurement of the Plasma Potential by Means of the Ball-Pen and Langmuir Probe

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Study programme: Physics
Specialization: General Physics

Prague 2011

I would like to thank to everybody who supported me during the last days of writting my bachelor thesis. Special thanks belong to my supervisor prof. RNDr. Milan Tichý, DrSc., who despite being very busy never underspent on time dedicated to helping me with experimental device adjustments, consulting the measured results, offering me participation in conferences, and finally assisting me with finalization of my thesis.

I declare that I carried out this bachelor thesis independently, and only with the cited sources, literature and other professional sources.

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Název práce: Měření potenciálu plazmatu pomocí ball-pen a Langmuirovy sondy

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Abstrakt: Ball-pen je unikátní sonda vyvinutá před několika lety na Ústavu fyziky plazmatu Akademie věd ČR. Její prvotní použití bylo přímé měření potenciálu plazmatu v tokamaku CASTOR. Následně byla testována také na několika dalších Evropských tokamacích i jiných vysokoteplotních zařízeních. Cíle této bakalářské práce jsou primárně experimentální. Z dostupných materiálů byla zkonstruována ball-pen sonda uzpůsobená pro měření v nízkoteplotním plazmatu válcového magnetronu. Přestože se jeho parametry výrazně odlišují od vysokoteplotních zařízení, podařilo se ukázat, že hlavní principy měření s Ball-pen sondou zde stále platí.

Klíčová slova: ball-pen sonda, potenciál plazmatu, magnetron

Title: Measurement of the Plasma Potential by Means of the Ball-Pen and Langmuir Probe

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Abstract: The ball-pen probe is a unique probe recently developed at the Institite of Plasma Physics in Prague. It has been designed for direct measurement of plasma potential at the CASTOR tokamak. It has also been succesfully tested on several other high-temperature plasma devices in Europe. The aims of the bachelor work are primarily experimental. A ball-pen probe has been constructed from available materials, which is suitable for measurement in the low-temperature plasma of a cylindrical magnetron. Although its parameters are much different from those in high-temperature plasma devices, the main principle of measurement with ball-pen probe has been proven to apply also in this brand-new conditions.

Keywords: ball-pen probe, plasma potential, magnetron

Contents

Preface

Plasma diagnostics represents an independent branch of plasma physics, as it is employed on one side in all fields of plasma research, from various kinds of gas discharges, through lasers to the development of thermonuclear fusion reactors, and on the other side in number of technological applications, e.g., thin layer plasma deposition and surface modification, most of which appertain to low temperature plasma. In this field, one of the oldest and most often used methods is probe diagnostics, having its origins in the works of Irving Langmuir and his co-workers from the early twenties.

The basic type of probe, now called Langmuir probe, has a fairly simple structure, which allows us to construct whole arrays of them, obtaining good spatial resolution without the necessity of moving mechanism. However, the interpretation of data measured in real conditions is considerably intricate. The method is based on evaluation of the current-voltage characteristics of the probe, which serves as indirect determination of many essential plasma parameters, one of them being the potential of the unaffected plasma in the place of the probe, so-called *space potential* or *plasma potential*.

The motivation for the direct measurement of the plasma potential lies in the fact it can give temporal fluctuations with much better resolution and also in its simple application to technological practice. Emissive probe is one of the special probes derived from the Langmuir probe, which has been developed for plasma potential direct measurement. Unlike Langmuir probe, this is a probe of a rather fragile construction, which substantially constrains its lifespan and scope of usage. Moreover, the act of emitting electrons brings usually bigger influence on the measured plasma than just passively collecting them by a regular cold probe. In particular, the emitted electrons typically have a much lower temperature than the plasma electrons, so that their mean flux towards the plasma is smaller than the mean flux of plasma electrons towards the probe. What arises is that the probe is surrounded by a sheath of electrons, whose space potential systematically lowers the measured value of plasma potential.

A different approach is offered by the concept of so-called *ball-pen probe*, a novel probe designed by Jiří Adámek and his co-workers. Instead of compensating the flux of plasma electrons to the probe by emission, it is reduced through shielding of the probe collector by a ceramic tube. A limitation is that it requires the presence of magnetic field, which introduces an anisotropy into the charged particles' movement and prevents most of the electrons from getting inside the tube placed perpendicularly to the magnetic field direction.

1. Literature review

1.1 Probe diagnostics of the plasma potential

The Langmuir probe diagnostics is in general based on collecting a small part of plasma particles by a metal electrode and measuring the electric current that arises. Let us denote the measured probe current simply by I, for it serves as the basis of other notations. The part of the probe current, which the incident electrons are responsible for, is so-called *electron current* I_e; it is possitive in our convention with the orientation of I being from probe towards plasma (often referred to as the technical direction). In the same fashion, the possitive ions (which we consider as the only kind of ions in our assumption) bring a negative *ion current* I_i to the probe.

As a matter of course, the measured current is dependent on the potential V_p applied to the probe, namely on the difference between V_p and the plasma potential Φ. It is worth mentioning that all considered potentials are defined with respect to the grounded wall of the vacuum chamber. The potential difference $(V_p - \Phi)$ is the source of an electric field attracting and repeling the charged particles, which gives rise to a layer of space charge layer surrounding the probe, a so-called *sheath*. Therefore, the inevitable perturbation of plasma by the probe measurement is the least when $V_p = \Phi$ [1]. In this case, the only current the probe collects is due to the random thermal motion of electrons and ions, with the mean velocities v_e resp. v_i:

$$v_{e,i} = \sqrt{\frac{8k_B T_{e,i}}{\pi\, m_{e,i}}}, \tag{1.1}$$

where k_B is the Boltzmann constant, m the respective particle mass and T its temperature, under the assupmtion of Maxwellian velocity distribution. From the expression above it is clear that ions have a much lower mean velocity than electrons due to their mass, even if the temperature of both kinds is similar; on top of that, also T_i is mostly smaller or much smaller than T_e. Since the electron and ion current are proportional to these mean velocities, there will be a strong imbalance between the respective currents leading to a nonzero total probe current while the probe potential being equal to plasma potential:

$$I\Big|_{V_p=\Phi} \gg 0$$

This fundamental aspect of plasma behaviour brings a lot of complication to probe measurements. In order to maintain the probe at the plasma potential, the extra electrons that are collected by the probe have to be drained from it by an electrical circuit. If we disconnect the probe, i.e., leave it *electrically floating*, the electrons cumulate and bias the probe negatively with respect to the plasma potential. At the same time, the negatively biased probe is already repelling part of the electron thermal current, which is now about to be balanced with the ion current. As soon as the bias of the probe fully compensates the inequality of the electron and ion mean velocities, the amount of incident electrons is the same as of ions and the probe potential remains at a value called *floating potential*, denoted as V_{fl}. The difference between the floating potential and the plasma potential is proportional to the electron temperature and is given by: [1]

$$V_{fl} = \Phi - \frac{k_B T_e}{e} \ln\left(\frac{I^-_{\mathrm{sat}}}{I^+_{\mathrm{sat}}}\right), \tag{1.2}$$

where I^-_{sat} and I^+_{sat} are so-called *electron saturation current* resp. *ion saturation current*. Their ratio is often denoted as

$$R = \frac{I^-_{\mathrm{sat}}}{I^+_{\mathrm{sat}}} \tag{1.3}$$

and it quantifies the above mentioned imbalance between collection of electrons and ions in a way, in which it can be measured. The electron resp. ion saturation current represents the probe current in the case when the probe is biased enough to repel all of the particles of the other kind, in which case only the electron resp. ion current is collected by the probe. A common assumption is that the attracting effect of the probe field is not very strong, compared to the repelling, so that when increasing the probe potential V_p above a certain value, the probe current I remains almost the same and equals the electron saturation current, and the same with the ion saturation current.

The above mentioned implies that direct measurement of the Langmuir probe potencial, i.e., connecting the probe to a circuit with voltmeter, won't give us the value of plasma potential Φ but the floating potential V_{fl}, if we assume that we have an ideal voltmeter which doesn't draw any current. If we want to measure the plasma potential by a Langmuir probe, we have to do it indirectly, i.e., to aquire the whole current-voltage characteristics and then to evaluate it. The possible methods to achieve this are mentioned in [2]: "In accordance with the works of Luijendijk and van Eck and Herrmann and Klagge the space potential is most accurately determined as the probe voltage at the zero-cross of the second derivative of the total probe current. Other methods, such as the method of tangents, estimation from the position of the maximum of the second derivative or from the probe voltage corresponding to the floating potential etc. are less accurate and not commonly used.”

Because of the difficulties with the plasma potential measurement, a great effort has been devoted to development of various probes, which would be able to measure the plasma potential directly, i.e., which would have their floating potential equal to Φ. The equation (1.2) shows that this would be accomplished by compensating the imballance between the electron and ion saturation current somehow.

One approach to this is given by *emissive probes.* The idea is that the collector of the probe is heated by an electrical circuit to a temperature sufficient for the electron emission to occur. Since the electron emission current I_{em} has the opposite direction to the current of incident electrons, it adds to the ion current I_i. The relation (1.2) is then altered in the following way [1]:

$$V_{fl} = \Phi - \frac{k_B T_e}{e} \ln \left(\frac{I^-_{\mathrm{sat}}}{I^+_{\mathrm{sat}} + I_{\mathrm{em}}} \right) . \tag{1.4}$$

As soon as the emission current is large enough to compensate the electron saturation current, Φ can be measured as the floating potential of the emission probe.

The so-called *ion-sensitive probes* bring different conception: instead of introducing a new kind of current that compensates the electron current, they try to reduce the electron current itself. This is done by optimizing the probe geometry to make it harder for the electrons to reach the probe collector. One of the probes of this kind is the ball-pen probe, which surpasses the others in exceptionally simple construction.

1.2 The Ball-Pen probe

The ball-pen probe conception has originally been publicated in 2004 as “A novel approach to direct measurement of the plasma potential” [3], not yet mentioning the name *ball-pen.* The principle of the method is decribed as the reduction of the electron saturation current to the same magnitude as that of the ion saturation current. I.e., to adjust the ratio R to be equal to one, in which case the floating potential V_{fl} is equal to the plasma potential Φ (1.2). “ This goal is attained by a shield, which screens off an adjustable part of the electron current from the probe collector due to the much smaller gyro–radius of the electrons.” [3] The scheme of the probe head is on the Figure 1.1. The ‘shield’ is realised by an isolating tube

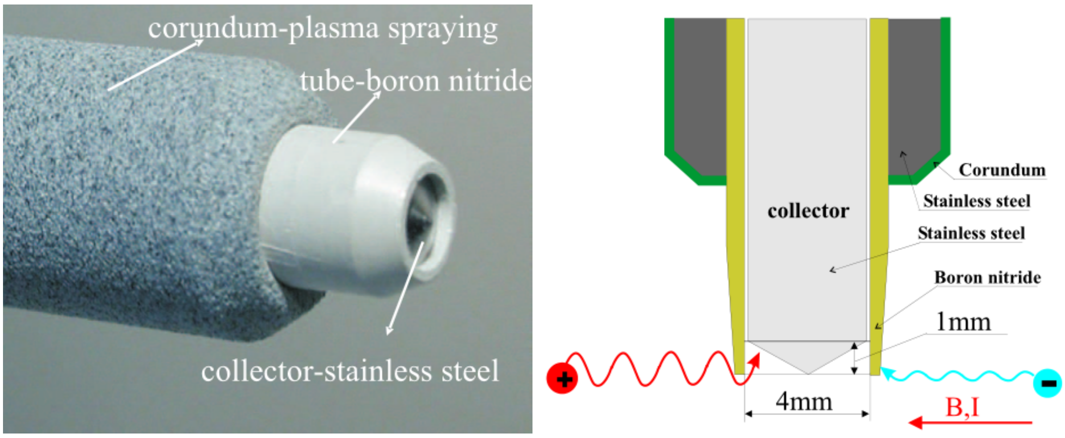

Figure 1.1: The photo and schema of the first realisation of the ball-pen probe, as they were published in the original literature. [3]

made of boron nitride, in which a movable stainless steel collector is hidden to an arbitrary depth. I.e., the collector can be either completely shielded or partially exposed to the plasma. An assumption was made, that for a certain collector position, the ion and electron current will be ballanced and $\ln R$ will equal zero. How it has been fulfilled, we can see on the Figure 1.2.

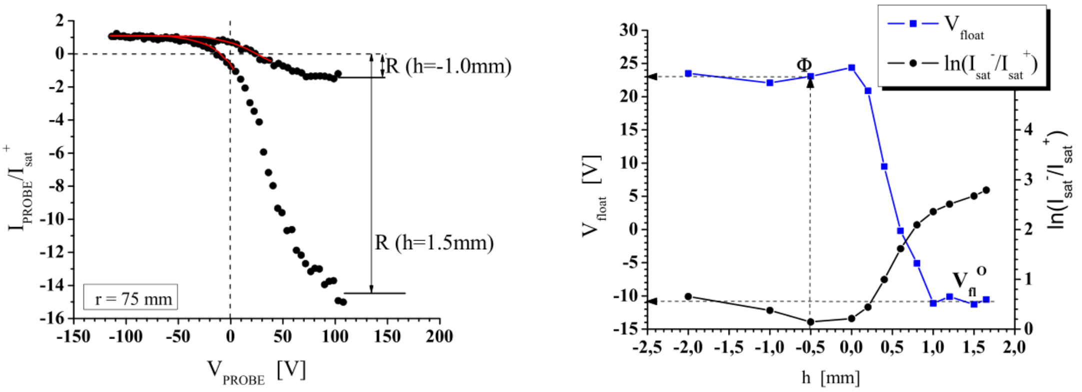

Figure 1.2: Left hand side – example of an I–V characteristics for two different collector positions. The h value is negative for collector position hidden inside the shielding tube. Right hand side – variation of the floating potential V_{fl} and $\ln(R)$ with respect to the collector position. [3]

In the following years, a lot of further investigations have been made, e.g. in 2005, the plasma potential measured by ball-pen probe has been systematically compared to the one measured by emissive probe at the same time [4]. The comparative measurements took place on the CASTOR tokamak in Prague and they have shown, that the potential by ball-pen is higher than by emissive probe. As the latter is decreased by the influence of emitted electrons' space charge, the ball-pen's potential is believed to be closer to plasma potential.

2. Experimental set-up

2.1 The main parameters of the experiment

The measurement took place in a cylindrical magnetron installed in the plasma physics laboratory of the Department of Surface and Plasma physics, MFF UK[1]. The geometry of this device is sketched in the schema on the Figure 2.1. The water-cooled stainless steel cathode with the outer diameter of 10 mm is conductively connected to a pair of disc-shaped limiters, which enclose the discharge volume to the length of 110 mm. The grounded anode of the same material has the inner diameter of 60 mm; from the edge of the limiters it is isolated by special teflon insulators. The discharge voltage, **376 V** in our case, is provided by a high-voltage DC source, which is connected to the cathode in series with a stabilising resistor of approximately 1 kΩ. The discharge current of **75 mA** was measured by a common multimeter as the voltage across a 1 Ω resistor (dropped out from the scheme on Fig. 2.1) that is connected in between the grounded anode and the power supply for better safety — there's not any high voltage on this resistor's terminals.

The electrodes are surrounded by a high-vacuum chamber, which is connected to an oil-free evacuating system with a primary piston pump and a turbomolecular pump. The ultimate pressure we achieved before the measurement was ca. $\mathbf{5 \cdot 10^{-3}}$ **Pa**, according to the used Penning vacuum gauge. For pressures above 1 Pa, a Piranni vacuum gauge is installed, which however isn't suitable for measurement during the experiment in **argon** since the value depends on the working gas composition. Instead, the MKS Baratron is used, which performs a relative pressure measurement based on the principle of membrane. Its output voltage is measured by a voltmeter; the zero level is adjusted at the ultimate pressure and then it is capable of giving us the value of the working pressure. In our case it was **2.3 Pa**, as a result of the balance between the continuous pumping and the inflow of argon, which was adjusted by a MFC flow controller to **0.75 sccm**.

The magnetic field of **40 mT** has axial direction and is generated by a couple of identical water-cooled coils, each with 5000 turns, placed symmetrically to achieve a maximum homogeneity. From the same reason, the space between them is just as wide as necessary for the vacuum ports, one of which was used for the ball-pen probe.

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[1] abbreviation for Faculty of Mathematics and Physics of the Charles University in Prague

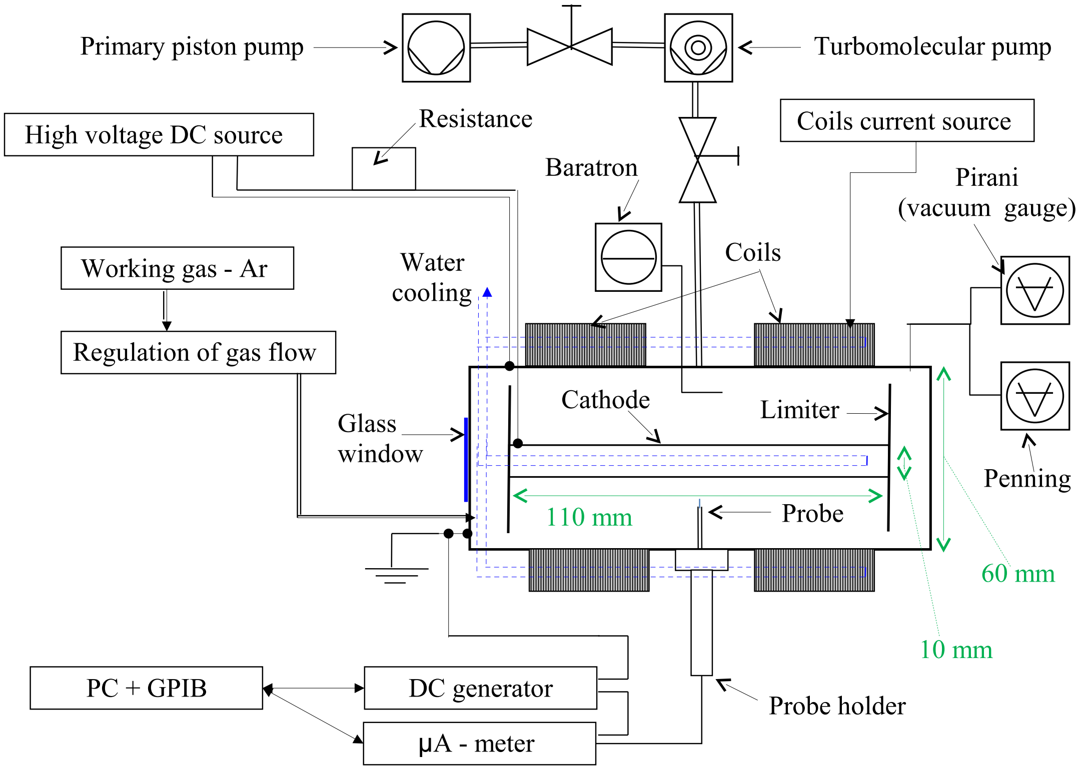

Figure 2.1: The simplified schematic picture of the experimental set-up. [5]

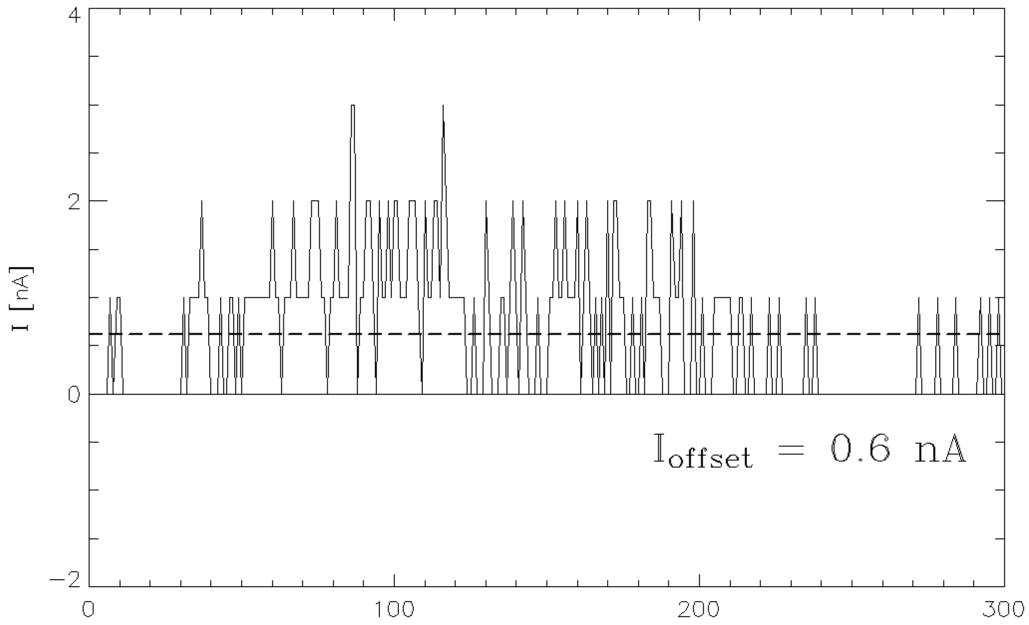

Figure 2.2: The measured "zero signal" from the μA-meter.

2.2 Diagnostic system

The DC voltage for the probe current-voltage charasteristics was supplied by Siemens PC-Instrument Precision Voltage/Current Calibrator B3050. Among other applications, it is suitable as a voltage transmitter for testing and calibrating analog and digital instruments, which should mean we are dealing with a very precise device. It includes a highly-stable reference voltage source, an A-D converter and a power amplifier which can be operated either as a constant current or constant voltage source. The output is galvanically isolated from the instrument socket (standby).

As a disadvantage of the used power source can be considered quite a small maximum voltage range: from –30 to +30 V. In our experiment, we wanted to measure down to the voltage of –40 V, so we used a preload of –10 V. This was realised by connecting one 10 V battery in series with the power source. Of course, this didn't actually enlarge the voltage range; it was only shifted. So the final measurement range was **–40 to +20 V**.

The probe current was registered using the Siemens PC-Instrument Multimeter B3220. As the name itself prompts, both instruments belong to the same Siemens system, which was designed for remote-controlled operation through the GPIB (IEEE 625) interface. Like the Calibrator, also this Multimeter turned out to be very precise, which was particularly useful for us when measuring with the deeper positions of the collector. The maximum current of the probe characteristics was in these cases lower than 100 nA, whereas the minimal recognizable current by the Multimeter was 1 nA. That means that we were measuring close to the sesitivity limit and some considerable offset of the measured current could be expected. In addition, the correct value of the zero current was essential for determining the value of floating potential from the characteristics. For this reason, we have measured the value of offset current with the Multimeter being disconnected from the circuit (on Figure 2.2).

2.3 Ball-pen probe construction

The probe **collector** has to be made of a special non-magnetic stainless steel, which is of particular importance in the case of the ball-pen probe. A ferromagnetic collector would deform the field lines of the originally homogeneous magnetic field in such a way that the electrons would be dragged into the shielding tube, which obviously is contradictionary to the principle of the ball-pen probe.

What we utilised was manufactured as a stainless steel welding electrode, but its material and diameter of **2.4 mm** were suitable for our needs.

For the **ceramic shielding**, we used a tube from Degussit®, as it is commercially available in a variety of dimensions so that we could choose the one that had its inner diameter approx. corresponding to the collector. There is one more intricate thing about the probe construction. Since the magnetron's cathode is exposed to the bombardment of the ions accelerated by the cathode fall, there is a considerable amount of metal particles dispersed in the plasma, which are about to settle on any available surface. This phenomenon is called *magnetron sputtering* and it is a widely used technique to deposit thin films on the surface of any object inserted into technological magnetrons. In the case of our ceramic tube, there will be a subsequently growing conducting layer on the surface of all its parts exposed to plasma. To prevent this newly formed surface from being conductively connected to our collector, it is necessary to 'hide' the point of contact between the collector and the tube sufficiently far away from plasma. This was fulfilled by lathe turning of a ca. two-centimetre edge part of the collector to the diameter of **1.8 mm** (see Figure 2.3). Another common approach to deal with the 'sputtering issue' is to use a pair of co-axial ceramic tubes, the outer one overhanging the inner one.

The collector is connected to the rest of the measuring circuit via an electric feed-through. The probe holder includes a single **linear motion feed-through**, which means that only one kind of motion can be provided. Because our measurement requires having the collector moveable with respect to the ceramic tube, we aren't able to move the probe as a whole, with respect to the magnetron chamber. This is the reason why we could not measure the radial dependency, although it was requested in the annotation of this bachelor thesis.

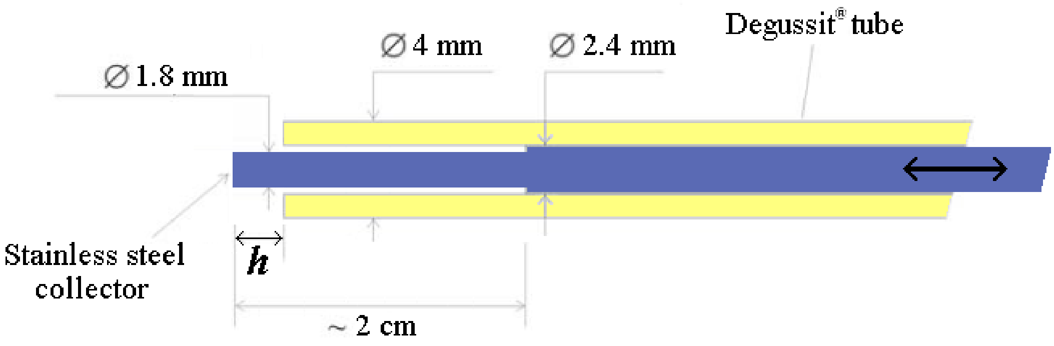

Figure 2.3: The detail of the used ball-pen probe head. The definition of the position h of the movable collector is illustrated.

3. Results

3.1 The definition of saturation currents

In the ball-pen probe's 'domestic conditions', e.g., in the tokamaks and other high-temperature plasma devices, the ion saturation current I^+_{sat} and electron saturation current I^-_{sat} really do saturate — their value remains almost constant or there is just a little growth with respect to the increasing of the probe bias. This happens thank's to the fact, that the sheath around the probe is very thin. The quantity

$$R = \frac{I^-_{\text{sat}}}{I^+_{\text{sat}}}$$

is then well-defined and it makes a good sense to compute how R alters when changing some parametres of probe.

Unfortunately, this is not nearly the case when dealing with low-temperature plasma of our magnetron. After looking at the Figure 3.1 we can doubt, whether we can even talk about any saturation. We will keep the term 'value of saturation current', although it is not clear yet, if there is some single value we can assign to it. As well, we'll need the quantity R, no matter what exactly it should mean — a mere look at the Figure 3.2 shows that the ratio R between the saturation currents definitely *is* changing with the probe parameter h. So there is a clear motivation for having some definition of the quantities I^-_{sat} and I^+_{sat} in order to be able to measure quantitatively the decrease of the ratio R.

The solution may be found in the way of characteristic evaluation from the times of pre-computer science, when a ruler with a pencil were the fundamental fitting tools. Each of the saturation currents are approximated by a straight line in the best-fitting range, then the lines are extended to the so-called transition or electron acceleration region (red lines on Fig. 3.1). Their points of intersection with the y-axis could come to one's mind, which is regrettably of no physical importance, since the position of the vertical axis is dependant on the reference electrode's particular choice. The only point with a symmetric relationship to both ion and electron current is the plasma potencial Φ, so we draw a vertical line (green dashed on Fig. 3.1) at this special voltage and intersect both fitted lines. This method of saturation currents estimation is used e.g. in [6] and probably also in any of older publications concerning probe diagnostics.

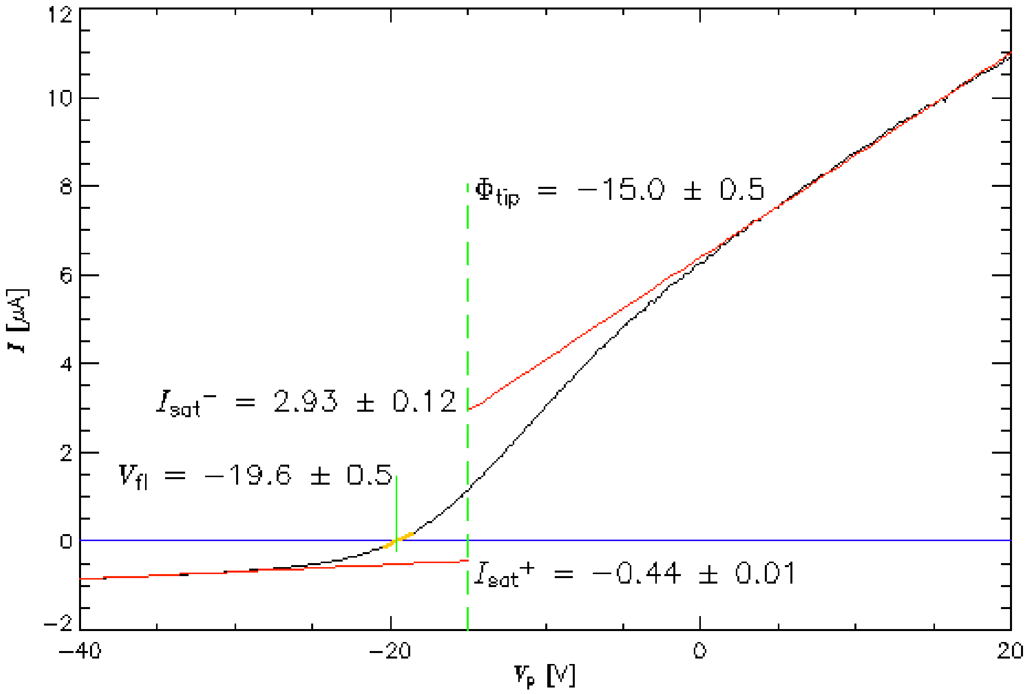

Figure 3.1: The evaluation of the single probe characteristics. Estimation of the electron saturation current I_{sat}^{-} and the ion saturation current I_{sat}^{+}.

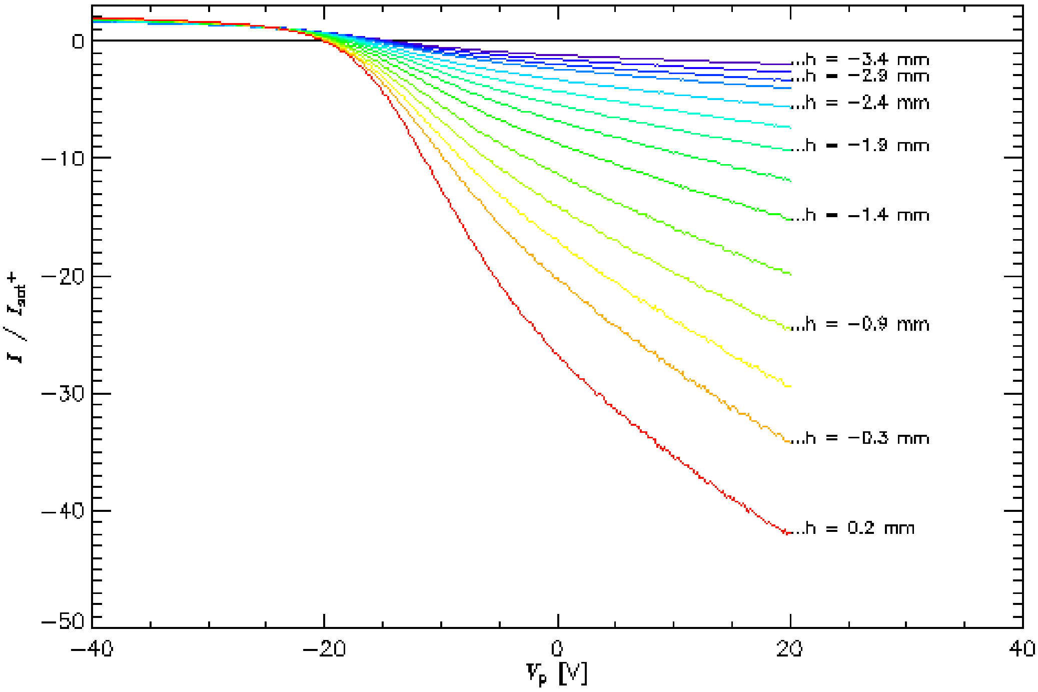

Figure 3.2: Ball-pen probe characteristics normalized with respect to the ion saturation current, defined as in Fig. 3.1. The saturation currents imbalance is being reduced through insertion of the collector deeper inside the dielectric tube. For definition of h see Fig. 2.3.

3.2 Estimation of the plasma potential

Once we have defined the necessary quantities, the data evaluation can become a simple routine. In the method described above, however, we have made a silent presumption that the value of plasma potential is known so that we can use it for the characteristics evaluation. Because we will get the plasma potential not sooner than after the evaluation of all characteristics, we need at least an initial guess or estimation from other method. For this purpose, a classical Langmuir probe would be suitable, from which we can get the plasma potential as the voltage corresponding to the inflection point of its current-voltage characteristics.

For computing the plasma potential by the mentioned method of inflection point, we can also use the characteristics of the ball-pen probe with the collector being fully exposed to plasma, e.g., with the parameter $h > 0$. It is right to mention that the dimensions of our ball-pen probe are much different from those typical for a Langmuir probe. If we were to evaluate all the main plasma parametres from its characteristic, further considerations would have to be made concerning the partial nonfulfilment of the basic assumptions of the Langmuir theory. Therefore, we restrict ourselves to estimation of the plasma potential, while taking into account that its accuracy can be somewhat lower than it would be for a thin Langmuir probe. However, if we used a separate Langmuir probe, it could never be placed to the same position as the ball-pen probe, which would lead to a much greater impreciseness.

3.3 Evaluation of measured characteristics

From inflection points of several characteristics of the ball-pen probe with collector being outside of the ceramic tube, the plasma potential was estimated to

$$\Phi_{\mathrm{tip}} = (-15.0 \pm 0.5)\,\mathrm{V}$$

Using this value, the electron and ion currents have been evaluated by linear fitting, as shown on the Figure 3.1. Their errors come from the standard deviations of the fitted parameters as well as from the Φ_{tip} uncertainty.

The floating potential V_{fl} was estimated from the point of intersection of the x-axis and the measured characteristics. Due to the certain noise on the experimental data, another line had to be fitted in the short range around the expected value of V_{fl} in order to mark the cross point correctly (orange line on Fig. 3.1). This fit also served for the error estimation.

Finally, we could evaluate the ratio R for individual characteristics in order to confirm the fulfillment of the relation between the floating potential V_{fl} and the plasma potential Φ (1.2). Let us mention this equation once more at this place:

$$V_{fl} = \Phi - \frac{k_B T_e}{e} \ln \frac{I^-_{\text{sat}}}{I^+_{\text{sat}}} = \Phi - \frac{k_B T_e}{e} \ln R$$

The floating potential is supposed to be linearly dependent on the value of $\ln R$. We corresponding plot is on the Figure 3.3. As we see, most of the computed points fulfil the relation. The horizontal error-bars show us the influence of the uncertainty of the initial plasma potential estimation, vertical errors are caused by the floating potential evaluation.

The point where $\ln R$ reaches zero, i.e., where the characteristics is considered as symetric, is our final estimation of the plasma potential by ball-pen probe. Within the determined errors, it corresponds with the estimation by the inflection point evaluation.

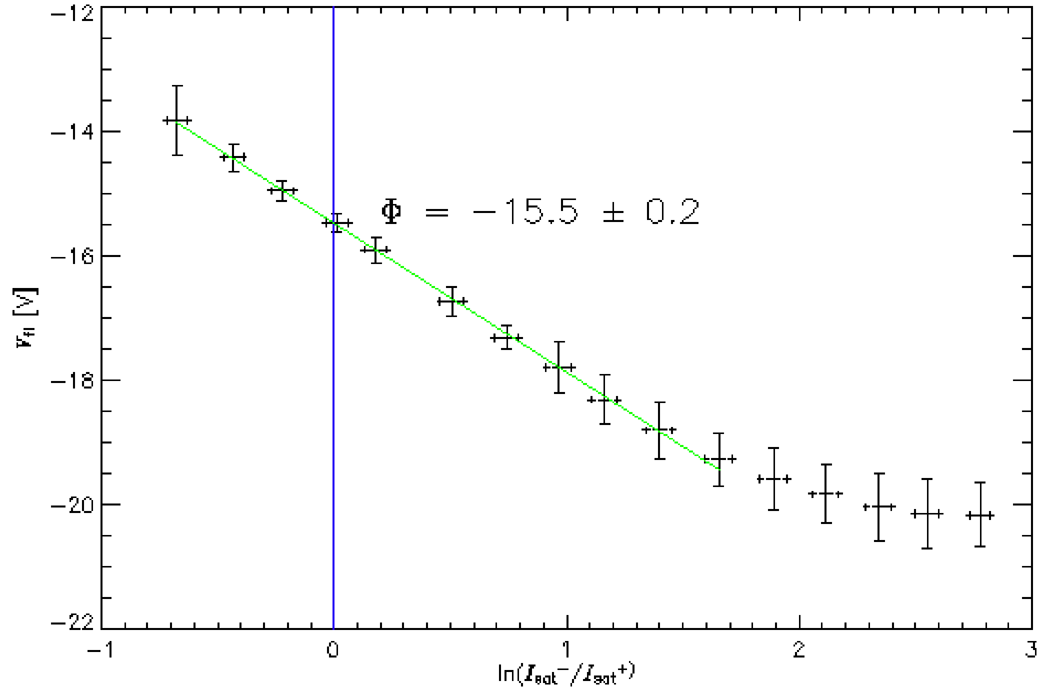

Figure 3.3: Dependence of the collector floating potential on the logarithmic ratio of the saturation currents.

Conclusion

Our aim was to explore the possible scope extension of a recently designed ball-pen probe to a brand new field of usage — to the low-temperature plasma. So far, ball-pen probe has been successfully operated in several tokamaks and other high-temperature devices throughout Europe. From these, the cylindrical magnetron used in this experiment has far different plasma conditions. In particular, the magnetic field, which is essential for the ball-pen probe principle, is only in the order of 10 mT here, while in tokamaks it is two degrees of order higher.

In spite of such a big difference in the plasma parametres, we succeded to show that the main principle of the measurement with ball-pen probe remains. It is possible to compensate the lower magnetic induction by a deeper insertion of the probe collector inside the shielding tube. The measured current in bigger depths is of a very low magnitude, which forms high demands on the measuring electronics' precision. The Siemens PC-Instrument set with multimeter B3220 turned out to be well suited for this task, as its offset current is lower than 1 nA.

The Figure 3.2 represents the main result of our experiment: that the magnitude of the electron current is significantly decreased with the collector being inserted inside the ceramic tube, enough to reach the hoped-for symetric current-voltage characteristics. At the same time, the floating potential of the probe is increasing towards the plasma potential, which fulfils the basic theory for the ball-pen probe measurement. The floating potential in the characteristics, which is considered as the most symetric, corresponds to the plasma potential measured by Langmuir probe.

We have proven that we were able to measure the plasma potential by the ball-pen probe. If we leave the collector in the position h corresponding to the most symetric characteristics, the plasma potential can be measured directly as the floating potential. However, for different plasma conditions, the proper position h might have to be estimated again from the probe characteristics. To uncover if the ball-pen probe is suitable for direct plasma potential measurement without the collector movement within a certain range of plasma parametres, further experimental research is necessary.

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List of Abbreviations

I	probe current in the technical direction (from the probe to plasma)
I_e	electron current — the electron part of the probe current
I_i	ion current — the ion part of the probe current
V_p	potential applied to the probe
Φ	plasma potential (space potential)
v_e, v_i	mean velocity of the thermal motion of electrons resp. ions
m_e, m_i	mass of an electron resp. ion
T_e, T_i	temperature of electrons resp. ions
k_B	Boltzmann constant
V_{fl}	potential of a floating (i.e. electrically disconected) probe
I_{sat}^{-}	electron saturation current
I_{sat}^{+}	ion saturation current
I_{em}	emission current
R	the ratio between electron saturation and ion saturation current
h	the height (length) of the part of the ball-pen's collector which juts out of the dielectric tube