Comparative measurements of the plasma potential with the ball-pen and emissive probes on the CASTOR tokamak *)

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Received 31 January 2005

A novel approach to the direct measurement of the plasma potential in magnetized plasmas, using the so-called "ball-pen probe", was recently tested in the CASTOR tokamak. Comparison with the standard technique of plasma-potential measurement using the emissive probe is reported. It is found that the plasma potential determined by the emissive probe is systematically lower than that measured by the ball-pen probe. The difference is of the order of kT_e/e. A possible reason of this difference is the space charge occurring in the proximity of the emissive probe.

PACS: 52.70.Ds
Key words: tokamak, edge plasma, plasma potential, Langmuir probe

1 Direct measurement of the plasma potential in tokamaks

Up to now, emissive probes [1] and heavy-ion-beam probes [2] are used for direct measurements of the plasma potential in tokamaks. However, the more widespread use of these techniques is hampered by various technical problems and peculiarities in the interpretation of the measured data. Directly heated emissive probes are rather fragile and of limited lifetime and their exploitation on large-tokamak experiments is questionable. Indirectly heated emissive probes [3] are more robust, but they are still under development. The heavy-ion-beam probe is a complex diagnostic tool, suitable for the measurement of the plasma potential in the core plasma.

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*) Presented at the Workshop "Electric Fields Structures and Relaxation in Edge Plasmas", Nice, France, October 26–27, 2004.

Moreover, its spatial resolution is limited. In practice, a simple Langmuir probe is routinely used at the plasma edge for this purpose and the plasma potential Φ is deduced from the formula

$$V_{\mathrm{fl}} = \Phi - \left(\frac{kT_{\mathrm{e}}}{e}\right)\ln(R)\,, \tag{1}$$

where the floating potential V_{fl} and the electron temperature T_{e} are determined from the I–V characteristic of the single Langmuir probe; k and e denote the Boltzmann constant and elementary charge, respectively. The quantity $R = I^{-}_{\mathrm{sat}}/I^{+}_{\mathrm{sat}}$ represents the ratio of the electron to the ion saturation currents, which is not routinely measured. The main reason is that the magnitude of the electron saturation current is typically rather large, even at the plasma edge of tokamaks. When operating in this mode, the Langmuir probe is exposed to high power loads and can even be destroyed. Furthermore, as the determination of T_{e} requires measurements of the full I–V characteristics, this technique is not suitable for measurements with time resolutions in the range of 10^{-6} s, which are usually required to study the plasma turbulence in tokamaks. It has to be also noted that the theory of the electron branch of the I–V characteristics in magnetized plasmas is not yet fully developed, and measurements of the electron saturation current are still questionable. Therefore, the ratio R is usually estimated from the Langmuir probe theory of non-magnetized plasmas and its value is taken as $\ln(R) \approx (2.5\text{–}3)$ for hydrogen.

The basic idea of direct plasma-potential measurements by means of electric probes, however, by avoiding the above mentioned problems, is to adjust R to be equal to one by a proper experimental set-up of the probe. If this is achieved, the floating potential of the probe is equal to the plasma potential, as evident from Eq. (1). In this contribution a new method, the so called ball-pen probe [4] is compared to the standard approach that uses the emissive probe.

For the emissive probe, the ratio R is expressed as $R = I^{-}_{\mathrm{sat}}/(I^{+}_{\mathrm{sat}} + I_{\mathrm{ee}})$, where I_{ee} is the electron emission current. When the emission current balances the electron saturation current ($I^{-}_{\mathrm{sat}} \approx I_{\mathrm{ee}}$), the ratio R is adjusted to be close to one. The value of I_{ee} can typically be controlled by the intensity of the probe heating. Emissive probes are frequently used in low-temperature and non-magnetized plasmas (see e.g. [5]). An investigation using this technique in tokamaks is described in [1].

The alternative approach, which can be used only in magnetized plasmas, is the concept of the ball-pen probe (BPP) [4]. The probe is designed so that the ratio R can be modified by changing the collecting areas for electrons and ions, taking advantage of the fact that the Larmor radii of electrons and ions are rather different. The design of the BPP is shown in the schematic picture of Fig. 1.

The probe consists of a conically shaped collector, which is shielded by an insulating tube made of boron nitride.

The collector, which is movable inside the tube, is either completely shielded or partially exposed to the plasma. In the ideal case, when the collector is hidden inside the tube, only ions with sufficiently large Larmor radii can reach the collector surface and the collecting area for electrons is zero. Consequently, the ratio $R = 0$. When the collector is shifted outwards the electron current as well as R increase.

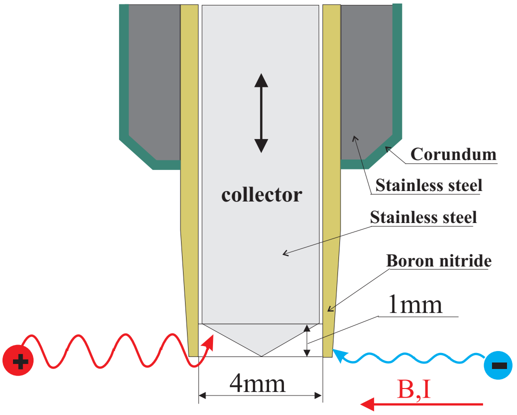

Fig. 1. Schematic picture of the ball-pen probe.

At a certain collector position, the electron and ion currents are expected to be balanced (i.e., $R = 1$). When the collector is fully outside the shielding tube, the probe operates as conventional single Langmuir probe and measures the floating potential V_{fl}.

Indeed, we have demonstrated in [4] that the ratio R can be significantly modified by moving the collector into the shielding tube. As is seen from Fig. 2, this ratio can be adjusted close to unity ($R \approx 1.1$) if the tip of the conical collector is located slightly inside the shielding tube at the position $h \approx -0.5\,\mathrm{mm}$. At this particular position, the floating probe potential $V_{\mathrm{probe}} = \Phi^{\text{ball-pen}}$ is significantly higher than the floating potential V_{fl}, which is determined with the collector fully exposed to the plasma ($h \approx +1.0$–$1.7\,\mathrm{mm}$). The normalized difference $\Delta = \ln R = (\Phi^{\text{ball-pen}} - V_{\mathrm{fl}})e/kT_{\mathrm{e}} \approx 2.3$ approaches the value predicted by the

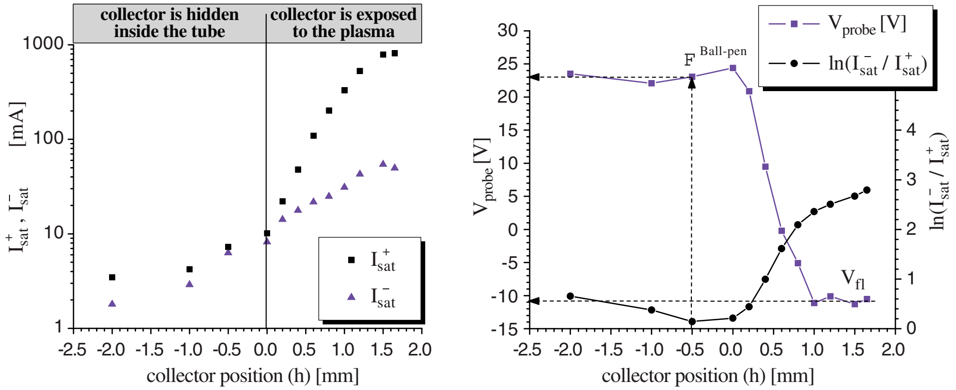

Fig. 2. Dependence of the BPP signals on the collector position. Left — electron and ion saturation currents. Right — the floating probe potential (V_{probe}) and $\ln(R)$. The figure is taken from [4].

theory. Consequently, the potential $\Phi^{\text{ball-pen}}$ measured at the position where R is minimum, is expected to be close to the plasma potential.

It should be noted that some experimental observations are not yet fully understood. At first, in contrast to predictions, the collected electron current is always higher than the ion one, even if the collector is completely hidden inside the shielding tube, as seen from the left panel of Fig. 2. The presence of electrons at $h < -1\,\text{mm}$ could be explained by the transport of plasma electrons across the magnetic field lines, partly due to collisions, partly due to an $E \times B$ drift. An alternative explanation might be that the collected electrons are produced inside the shielding tube by photo-ionization of the neutral gas or photoemission of electrons from the inner wall of the shielding tube. Another unexpected feature, observed with the collector hidden within the tube, is that the probe potential $\Phi^{\text{ball-pen}}$ is practically independent of the collector position for $h < 0$ mm. On the other hand, such findings would be beneficial for the practical use of the BPP in future, because a precise positioning of the collector inside the tube will not be required. Some additional experiments with slightly modified geometry are prepared for a better understanding of these unexplained features. In the next part of the article, measurements of the potential with both an emissive and a ball-pen probes at the plasma edge of the CASTOR tokamak are compared to each other.

2 Simultaneous measurements with ball-pen and emissive probes

Both probes are mounted on a manipulator, which allows their simultaneous radial movement on a shot-to shot basis. The arrangement of the combined probe head is shown in Fig. 3. The probes are spaced by 15 mm in poloidal direction, which is a sufficiently short distance to measure the floating and the plasma potential approximately at the same magnetic-flux surface in most cases. The ball-pen probe has been described in the previous section. The emissive probe consists of a ceramic tube (Al_2O_3) and a tungsten wire of 0.2 mm diameter. The wire is directly heated by an external DC power supply ($I_\text{h} \approx 7\,\text{A}$). As long as such a probe is not heated, it operates as a conventional single Langmuir probe and will be called "*cold*" probe in the text.

The voltage of the ball-pen and the emissive probe is swept to measure the I–V characteristics (triangular form, $f = 1\,\text{kHz}$, $\pm 100\,\text{V}$). Alternatively, the active parts of the probes (the wire and the collector) are kept floating. All signals are digitized at a sampling rate of 1 MHz. The comparative measurements were performed at the CASTOR tokamak (major radius = 40 cm, minor radius = 8.5 cm, $B_\text{T} = 1.3\,\text{T}$, $I_\text{P} = 10\,\text{kA}$). The probe head is inserted into the plasma from the top of the torus. At the plasma edge, the plasma density is $\approx 10^{18}\,\text{m}^{-3}$ and the electron and ion temperatures are in the range of 10 eV. The corresponding Larmor radii are $\rho_\text{i} \approx 0.5\,\text{mm}$ and $\rho_\text{e} \approx 0.01\,\text{mm}$, respectively.

I–V characteristics of the ball-pen and the emissive probe are shown in Fig. 4, where the probe-current densities are plotted versus the probe voltage. When the probes operate as conventional Langmuir probes (i.e., the "cold" emissive probe and

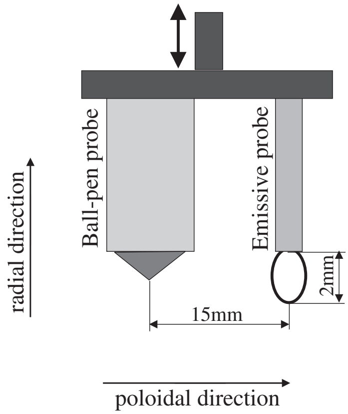

Fig. 3. The combined probe head (ball-pen and emissive probe) and its position with respect to the poloidal magnetic field.

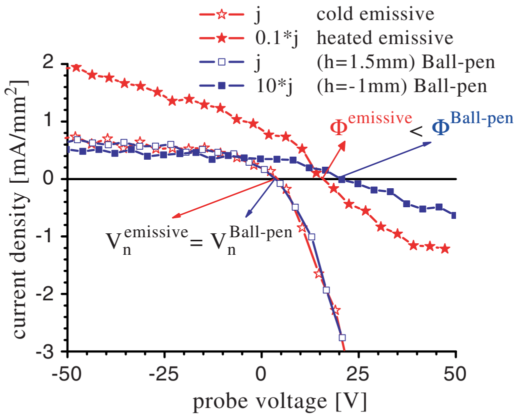

Fig. 4. Example of I–V characteristics of the ball-pen probe (solic squares) for two positions of the collector and of the cold and heated emissive probe (open stars).

the collector of the ball-pen probe are exposed to the plasma for $h = +1.5\,\mathrm{mm}$), their I–V characteristics are almost identical, as documented in the figure by open stars and squares, respectively. This indicates that both probes are located on the same magnetic surface.

The I–V characteristic of the sufficiently heated emissive probe ($j_{\mathrm{ee}} \approx j^{-}_{\mathrm{sat}}$) is plotted in the same figure (solid stars). As seen, the current of the ion branch of the characteristic ($j_{\mathrm{ee}} + j^{+}_{\mathrm{sat}}$) is significantly higher than in the "cold" case (by a factor of 20). As expected [1], the floating potential of the emitting probe increases up to the value Φ^{emissive}. The I–V characteristic of the ball-pen probe (solid squares), with the collector completely hidden inside the shielding tube ($h = -1\,\mathrm{mm}$), is also plotted. It is seen that the electron current of the BPP is significantly reduced, reaching roughly the same magnitude as the ion saturation current, which means that the ratio $R \approx 1$. The floating potential of the ball-pen probe increases up to the value $\Phi^{\mathrm{ball\text{-}pen}}$.

As evident from Fig. 4, the floating potential of the ball-pen probe is noticeably higher than that measured by the emissive probe. This is in contradiction to the simple theory mentioned above, which predicts that both potentials should be identical and equal to the plasma potential for $R \approx 1$.

The difference between $\Phi^{\mathrm{ball\text{-}pen}}$ and Φ^{emissive} appeared to be quite systematic. Figure 5 depicts the dependences of the floating potentials $V_{\mathrm{fl}}^{\mathrm{ball\text{-}pen}}$ on $V_{\mathrm{fl}}^{\mathrm{emissive}}$ and of the potentials $\Phi^{\mathrm{ball\text{-}pen}}$ on Φ^{emissive} as measured by the BPP and emissive probes for different radial positions of the probe head, respectively. In this particular case, not the full I–V characteristics were measured, but both probes were in the floating regime.

We performed two reproducible discharges for each radial position of the probe head. At first, the ball-pen and the emissive probe were operating as conventional

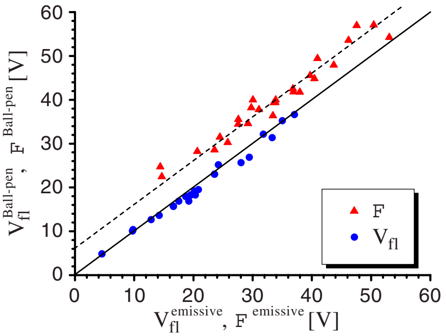

Fig. 5. Dependences of the floating potentials $V_{\text{fl}}^{\text{ball-pen}}$ on $V_{\text{fl}}^{\text{emissive}}$ (circles) and of the potentials $\Phi^{\text{ball-pen}}$ on Φ^{emissive} (triangles) as measured by the ball-pen and the emissive probe, respectively.

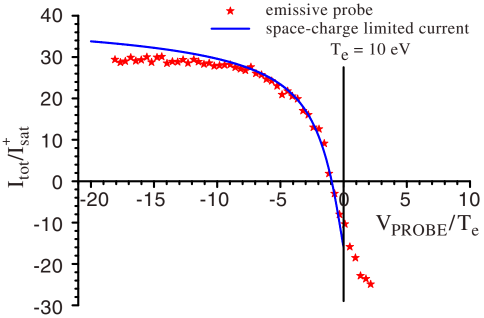

Fig. 6. Comparison of the I–V characteristic of emissive probe (stars) and the space-charge-limited current (solid line).

Langmuir probes (i.e., the emissive probe was not heated and the collector of the ball-pen probe was exposed to the plasma, $h = +1.5\,\text{mm}$) so that the floating potentials $V_{\text{fl}}^{\text{ball-pen}}$ and $V_{\text{fl}}^{\text{emissive}}$ were measured, respectively. We note that only data from discharges, where both probes provided almost the same value of the floating potential were plotted to be sure that the probes were located on the same magnetic surface. In the next discharge, the emissive probe was heated and the collector of the ball-pen probe was completely hidden inside the shielding tube ($h = -1\,\text{mm}$) so that the probes measured the potentials $\Phi^{\text{ball-pen}}$ and Φ^{emissive}.

It is evident from Fig. 5 that the potential $\Phi^{\text{ball-pen}}$ is proportional to Φ^{emissive}. However, the values measured by the emissive probe are systematically lower. The difference of both potentials, normalized to the electron temperature, was in the range of $(\Phi^{\text{ball-pen}} - \Phi^{\text{emissive}})e/kT_{\text{e}} \approx 0.68 \pm 0.2$, which was obtained by averaging all data plotted in Fig. 5. The electron temperature is deduced from the I–V characteristics, which were measured by the swept BPP operating as a conventional Langmuir probe.

3 Discussion

Let us first discuss the results achieved by the emissive probe: the simplest theory of the emissive probe, outlined above and discussed in [1] in detail, assumes that all emitted electrons are "absorbed" by the plasma even if the probe potential is equal to the plasma potential. However, as pointed out recently by Takamura et al. [6], for strong electron emission a negative space charge might form around the emissive probe. A virtual cathode is formed inside the probe sheath and does not allow the extraction of emission currents larger than the Child–Langmuir limit. As a consequence, the emission current depends not only on the temperature of the emitting wire, but also on the difference between probe voltage and plasma potential. Takamura has derived an analytical expression for the space-charge-limited current and confirmed it by kinetic simulations.

Figure 6 compares Takamura's model with the experimental data measured at the CASTOR tokamak. The space-charge-limited current, normalized to the ion saturation current, is plotted by the full line as function of the normalized potential $V_{\mathrm{probe}}e/kT_{\mathrm{e}}$ according to Eq. (47) in [6]. The potential V_{probe} is the difference between the probe voltage and plasma potential, the latter one is set to zero. The experimentally measured current of the emissive probe is also normalized to the ion-saturation current and the probe voltage is normalized to the electron temperature deduced from the I–V characteristic of the "cold" emissive probe ($T_{\mathrm{e}} = 10\,\mathrm{eV}$). Finally, the experimental data are shifted horizontally to get an agreement between the model and the experiment at $I_{\mathrm{tot}}/I^{+}_{\mathrm{sat}} = 0$.

As seen from Fig. 6, the agreement between the model and experiment is very good in a broad range of potentials, $-10 < V_{\mathrm{probe}}/T_{\mathrm{e}} < 0$. This is an indication that the assumptions of the model (the space-charge limitation of the emission current) are correct. The Takamura's model predicts that the floating potential of the emissive probe is approximately $1 \times kT_{\mathrm{e}}/e$ below the actual plasma potential. However, a lower value ($\approx 0.7 \times kT_{\mathrm{e}}/e$) results from the PIC simulations by Reinmüller [7] and recent experiments with laser-heated emissive probe by Madani et al. [3].

Let us focus now on the ball-pen probe. As documented in Fig. 2, the electron and ion currents cannot be completely balanced for the given design of the BPP. At the optimum position of the collector, the minimum ratio is about 1.1, which means that the potential $\Phi^{\text{ball-pen}}$ is lower than the plasma potential by a factor of approximately $0.1 \times kT_{\mathrm{e}}/e$ (assuming again that Eq. (1) is valid).

From this consideration and Takamura's model follows that the difference between the potentials of the BPP and the emissive probe should be $(\Phi^{\text{ball-pen}} - \Phi^{\text{emissive}})e/kT_{\mathrm{e}} \approx 0.9$. In the case of Reinmüller's PIC simulation this difference is rather lower, $(\Phi^{\text{ball-pen}} - \Phi^{\text{emissive}})e/kT_{\mathrm{e}} \approx 0.6$. However, both theoretical values are still inside the range of the experimentally observed difference, which is 0.68 ± 0.2. Despite the fact that it is not clear which theoretical model is closer to the experiment the potential of the BPP is still noticeably closer to the theoretical plasma potential than that measured by the emissive probe.

4 Conclusion

Comparison of the floating potentials measured by the ball-pen $\Phi^{\text{ball-pen}}$ and the emissive Φ^{emissive} probes has been performed on the CASTOR tokamak. Systematic measurements show that the potential $\Phi^{\text{ball-pen}}$ is higher than Φ^{emissive}, and therefore closer to the theoretical value of the plasma potential. This is in contrast to simple theoretical expectations, which predict that both probes should measure the same value, which is equal to the plasma potential. However, a space charge formed around the emissive probe could be partially responsible for this discrepancy. There are still a few features which are not yet understood. If in the future we can successfully demonstrate that the floating potential of the BPP is closer to the actual plasma potential than that measured by the emissive probe, it would mean that the potential fluctuations directly measured by the BPP could be less influenced by fluctuations of the electron temperature, which are not easy to measure. This is quite essential for measurements of potential fluctuations in the edge plasma of tokamaks.

We conclude that the BPP is potentially a well-suited diagnostic tool for routine measurements of the plasma potential in the edge plasma region of tokamaks, yielding sufficiently high spatial and temporal resolution. Furthermore, the BPP is a very robust construction, surviving even high power loads, so it could also be used in large-scale tokamaks. Full understanding of all observed features requires, however, further experiments (e.g. with different geometry of the probe head) and modeling.

Authors are indebted to L. Kryška, F. Jiránek, J. Zelenka, K. Rieger and M. Šatava for technical assistance with the experiments. Valuable discussions with J. Gunn and S. Kuhn are highly appreciated. The work was supported by the grants No: 202/03/0786 (GA ČR), probe construction and experiments in IPP Prague, and No. 2001-2056 (INTAS). This work has also been carried out within the Association EURATOM-ÖAW, and the support by the Fond zur Förderung der wissenschaftlichen Forschung (FWF,Austria) under grant No. P-14545 is acknowledged.

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