Emissive probe measurements of plasma potential fluctuations in the edge plasma regions of tokamaks

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The plasma potential Φ_{pl} and its fluctuations $\tilde{\Phi}_{pl}$ were measured by electron emissive probes in the edge plasma regions of two fusion experiments: the Instituto Superior Técnico Tokamak (ISTTOK) (Lisbon, Portugal), and the Czech Academy of Sciences Torus (CASTOR) tokamak (Prague, Czech Republic). Into ISTTOK, three emissive probes were inserted outside the last closed flux surface (LCFS) on different minor radii. In CASTOR, two emissive probes, poloidally separated, and two cold cylindrical probes, mounted on the same shaft, were used, which could be radially shifted outside and inside the LCFS. The advantages of a sufficiently emissive probe are that in principle Φ_{pl} and $\tilde{\Phi}_{pl}$ can be measured directly, without being affected by electron temperature fluctuations or drifting electrons. [DOI: 10.1063/1.1527258]

I. INTRODUCTION

A. Edge plasma turbulence and fluctuations

At the edge of a magnetically confined hot plasma, especially in the scrape-off layer (SOL), strong gradients of the charge-carrier densities $n_{e,i}$, of the plasma potential Φ_{pl} and of the electron and ion temperatures, $T_{e,i}$, drive a number of instabilities, which can lead to an enhanced radial loss of plasma across the SOL. Various effects like the fluctuation-induced flux or a gradient of the Reynolds stress play an important role in this context. To understand the actual mechanism of the turbulent transport through the SOL, a reliable and precise knowledge of Φ_{pl} and of $\boldsymbol{E}_{r,\theta}$, the radial and poloidal components of the electric field, respectively, and their fluctuations are vital. Also, for a comparison with theoretical models and numerical simulations, Φ_{pl} and $\boldsymbol{E}_{r,\theta}$ are the most important parameters.

B. Principle of emissive probes[1–7]

In order to measure the plasma potential in the edge region of a magnetized toroidal plasma directly and as precisely as possible, we have recently started to use electron emissive probes.[8,9] The floating potential of a probe, which emits electrons into the plasma, approaches the true value of the plasma potential Φ_{pl}, when the emission current I_{em} is increased by turning up the heating current of the probe. This follows from the formula for the floating potential of a heated probe (valid, however, only for a Maxwellian plasma and for probe voltages below the plasma potential, i.e., $V_p<\Phi_{pl}$)

$$V_{fl}=\Phi_{pl}-\mu T_e=\Phi_{pl}-T_e \ln\left(\frac{I_{es}}{I_{is}+I_{em}}\right), \tag{1}$$

with I_{es} and I_{is} being the plasma electron and ion saturation currents, respectively.

Equation (1) shows that for increasing emission current I_{em} the floating potential of the emissive probe grows and approaches Φ_{pl}. For $I_{em}=I_{es}-I_{is}$, V_{fl} attains the plasma potential. Indeed, also in a realistic experiment,[9] V_{fl} is observed to increase with the emission current, however, reaching a clear saturation for $I_{em}\cong I_{es}$, i.e., a further increase of I_{em} will not lead to a further growth of V_{fl}. This saturated value of V_{fl} is then considered to be a good approximation for Φ_{pl}. This result can, however, be falsified by a number of effects, among them the formation of a space charge around the emissive probe by the emitted electrons.[9–11] In the experiments, in order to produce a sufficient electron emission current up to $I_{em}\cong 250$ mA a heating current of 7.1–7.4 A was necessary.

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TABLE I. Main parameters of the two tokamaks used.

	Major radius [m]	Minor radius [m]	Magnetic field [T]	Working gas	Pulse length [ms]	Torial current [kA]	Working pressure [Pa]	Line averaged density [m^{-3}]	Edge plasma density [m^{-3}]	Core electron temperature [eV]	Edge electron temperature [eV]
ISTTOK	0.46	0.085	0.5	H_2	40	9	10^{-2}	$5-10\times10^{18}$	$5-10\times10^{16}$	80–220	10
CASTOR	0.40	0.085	1.0	H_2	30	10	10^{-2}	$0.5-2.5\times10^{19}$	$0.2-2\times10^{18}$	150–300	8–25

It is obvious that for $I_{em}=0$, from Eq. (1) we can calculate the electron temperature since $T_e=(\Phi_{pl}-V_{fl})/\mu$. Thus, if we measure V_{fl} of a cold probe and Φ_{pl} (by means of a sufficiently heated emissive probe) simultaneously, T_e can be inferred. In this case, $\mu=\ln(I_{es}/I_{is})$ depends also on the ratio between the effective areas of the probe for electron and ion collections.

II. EXPERIMENTAL SETUP

A. The Tokamaks

The experiments have been carried out in two European tokamaks, in the Instituto Superior Técnico Tokamak "ISTTOK" at the Nuclear Fusion Center, Instituto Superior Técnico in Lisbon, Portugal, and in the Czech Academy of Sciences Torus tokamak "CASTOR" of the Institute for Plasma Physics of the Czech Academy of Sciences in Prague, Czech Republic. Table I shows the main parameters of these two machines.

In ISTTOK, a poloidal limiter is used to determine the separatrix of the plasma ring. This limiter can also be biased to vary the space potential in the vicinity of last closed flux surface (LCFS). Usually a 50 Hz ac voltage 160 V_{rms} was applied to it.

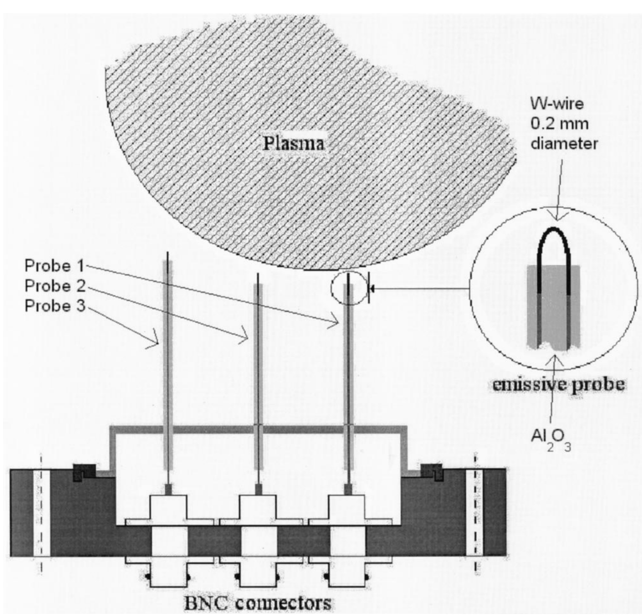

FIG. 1. Schematic of the three-emissive probe array inserted into the ISTTOK in Lisbon. The radial distances of the three probes from the plasma edge (defined by the limiter) are 1, 4, and 7 mm, respectively.

In CASTOR, the conditions near the LCFS could be modified by a radially movable electrode. Usually this electrode was put exactly at the radial position of the separatrix.

B. Emissive probe systems

The construction of our emissive probes has been described in detail in Refs. 7–9. The probes are able to produce an emission current up to 300 mA and are thus well suited also for higher densities than those shown in Table I.

In ISTTOK, two different probe arrangements have been used. For a number of measurements, the setup consisted of three fixed emissive probes. This is shown in Fig. 1. For preliminary results see also Ref. 8. The three probes are situated on the same poloidal meridian, but on different poloidal positions. The probe tips have different minor radii $r_1=86$ mm, $r_2=89$ mm, and $r_3=92$ mm. Thus, all three probes are outside the LCFS.

In CASTOR, a radially movable arrangement consisting of two emissive and two cylindrical (cold) probes has been used. The probe head is inserted in such a way that the two emissive probes are on the same poloidal meridian, with a poloidal separation $d=5.4$ mm between the probe tips. The cylindrical probes are located between the emissive probes, spaced toroidally by 5.6 mm, but displaced slightly to avoid mutual shadowing in the magnetic field. Usually one of the cold cylindrical probes was used to measure the ion saturation current and the other one was swept in order to record the current voltage (I-V) characteristics and to determine the average electron temperature. Figure 2 shows a schematic of this setup.

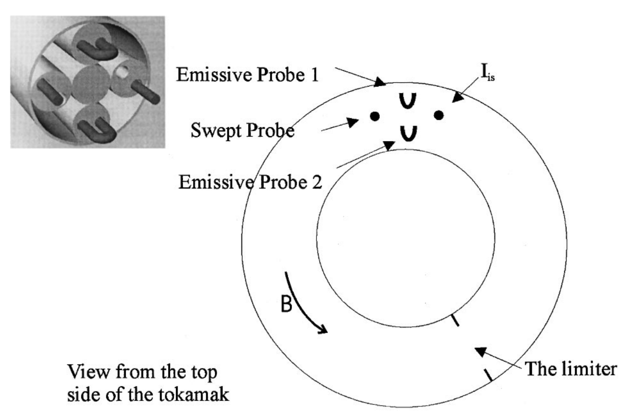

FIG. 2. Schematic of the experimental setup used in CASTOR in Prague. The inset shows the probe head which carries two electron emissive probes and two cylindrical cold probes.

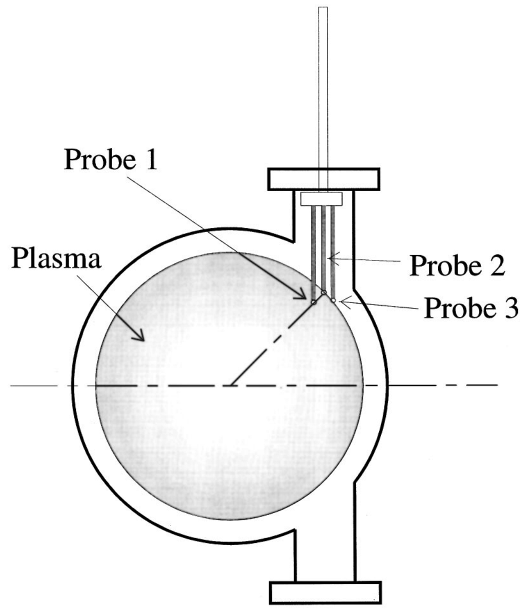

FIG. 3. Schematic of the experimental setup used in the ISTTOK in Lisbon. With this arrangement, the poloidal and the radial electric-field components and their fluctuations can be recorded simultaneously.

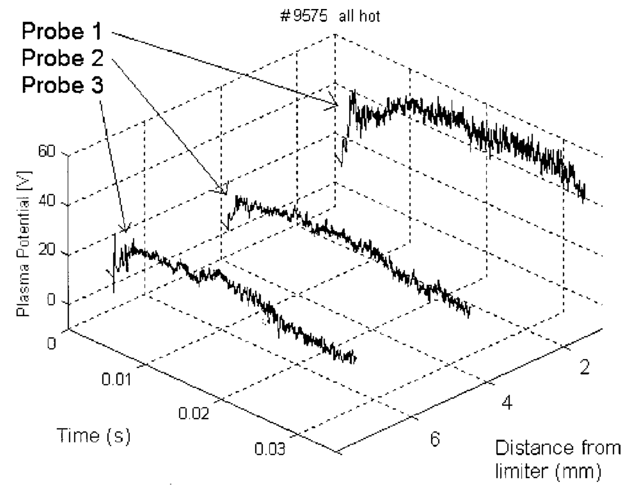

FIG. 4. Raw signal of the floating potential (which here corresponds to the plasma potential) from the three emissive probes (from ISTTOK) without limiter biasing. The probe positions are here given as the distances from the limiter.

The most recent measurements have been performed in ISTTOK with a vertically movable arrangement of three emissive probes, positioned in such a way that the radial and the poloidal component of the electric field in the edge region can be recorded simultaneously. The radial, respectively, poloidal spacing between the probes is 7 mm, respectively, 5.8 mm. This setup is laid forth in Fig. 3.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. ISTTOK—Stationary three emissive probe setup

We have measured the floating potential of the emissive probes on the three different positions simultaneously, thereby obtaining $\Phi_{\mathrm{pl}}(r_{1-3},t)$ for various plasma conditions. Thus, we have obtained a rough radial profile of the plasma potential, showing also the temporal evolution during each shot. Figure 4 shows the raw signals of the three probes versus time.

The radial profile shows a strong drop of the plasma potential in the SOL. Between $r_1=86$ mm and $r_2=89$ mm the plasma potential decreases from $\Phi_{\mathrm{pl},1}\cong 48$ V to $\Phi_{\mathrm{pl},2}\cong 18$ V. This corresponds to an electric field of $E_r\cong 10$ kV/m even without limiter bias. This value is in keeping with similar results of the CASTOR tokamak, but has been achieved there only with a dc limiter bias of $+100$ V.[9] The amplitude of the fluctuations also decreases between these two positions.

Figure 5 shows the probe signals when the limiter is biased with a 50 Hz ac voltage. As reference, the lowermost curve shows the current flowing to the limiter. For $V_{\mathrm{lim}}>0$, this means a strong electron current, we observe that $\Phi_{\mathrm{pl},1}$ is increased only slightly during this time. Also the other two probes show a slight increase of their floating potentials $\Phi_{\mathrm{pl},2,3}$, respectively. The fluctuation levels, however, show no considerable change for positive or negative limiter biases. Remarkable is the strong increase of the plasma density for $V_{\mathrm{lim}}>0$.

B. CASTOR—Radially movable double emissive/double cold probe setup

By recording the floating potential of one of the cold probes and that of a sufficiently emissive probe simultaneously, we have obtained a radial profile of the electron temperature (see Fig. 6). This was done by using the above relation $T_e=(\Phi_{\mathrm{pl}}-V_{\mathrm{fl}})/\mu$ with $\mu=2.04$.[9] The absolute value of the electron temperature, as well as the shape of its radial profile are in good agreement with that measured by the standard technique,[12] i.e., from the *I-V* characteristics of the single Langmuir probe.

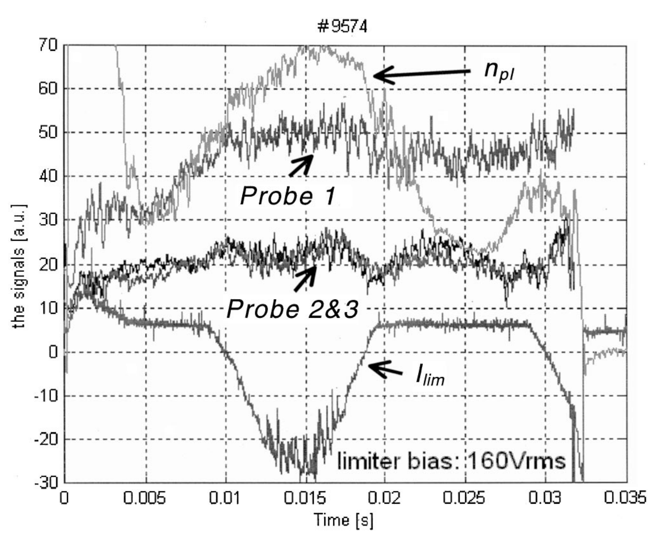

FIG. 5. Plasma potentials when the limiter was biased with a 50 Hz ac voltage of $V_{\mathrm{lim}}=160$ $\mathrm{V_{rms}}$. The lowermost curve shows the current flowing to the limiter; it is positive (ions) for $V_{\mathrm{lim}}<0$ and becomes (much more) negative for positive values of V_{lim} when electrons are attracted to the limiter.

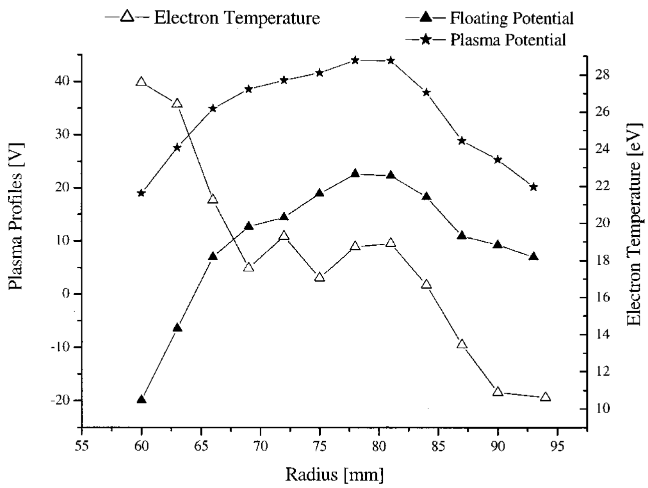

FIG. 6. Radial profiles of the plasma potential, of the floating potential of a cold probe, and of the electron temperature. The latter profile was calculated choosing $\mu=2.04$.

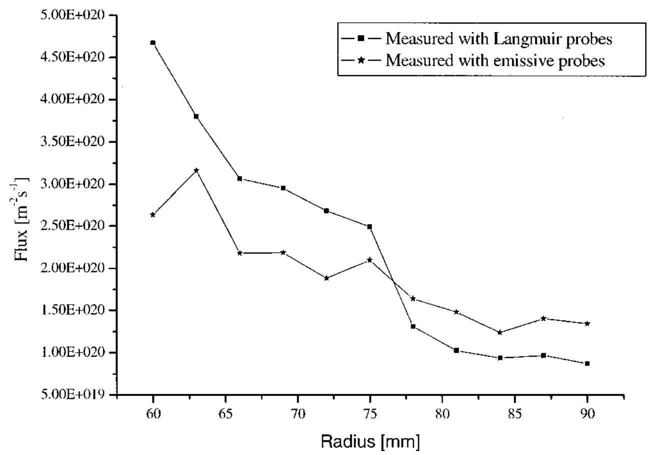

FIG. 7. Radial profiles of the fluctuation-induced flux; in this case, the emissive probes have been either not heated ("Langmuir probes" — squares) or heated to electron emission (stars). The radial position of the separatrix is at $r=78$ mm for this series of shots.

By measuring the fluctuations of the poloidal electric field $\tilde{E}_\theta=(\tilde{\Phi}_{\text{pl},1}-\tilde{\Phi}_{\text{pl},2})/d$ and the fluctuations of the plasma density $\tilde{n}_{\text{pl}}=\tilde{I}_{i,\text{sat}}$ simultaneously (with $I_{i,\text{sat}}$ being the ion saturation current to one of the cold probes—and by neglecting $\tilde{T}_e$ for this case), the radial fluctuation-induced flux $\tilde{\Gamma}_r=\langle\tilde{n}_{\text{pl}}\tilde{v}_r\rangle=\langle\tilde{I}_{i,\text{sat}}\tilde{E}_\theta/B_0\rangle$ could be derived, where B_0 is the external toroidal magnetic field. Figure 7 presents the average values of $\tilde{\Gamma}_r$ at several radial positions. The poloidal electric field E_θ was determined by the emissive probes, but in the case of solid square symbols the probes were not heated so that they acted as simple Langmuir probes. In the case of the star symbols the probes were emissive so that the plasma potentials were measured and thus a more realistic value of E_θ was obtained.

C. ISTTOK—Radially moveable three emissive probe setup

Our preliminary measurements with this probe array (see Fig. 3) have up to now delivered the Reynolds stress Re in two different positions, where the minor radius of probe 2 was taken as the reference coordinate. In both cases, all three emissive probes have been heated so that the plasma potentials $\Phi_{\text{pl},1-3}$ could be determined from the floating potentials of the probes. From these three values, $E_r=(\Phi_{\text{pl},1}-\Phi_{\text{pl},2})/d_{12}$, and $E_\theta=(\Phi_{\text{pl},3}-\Phi_{\text{pl},2})/d_{23}$ could be calculated with $d_{12}=7$ mm and $d_{23}=5.8$ mm being the respective distances between the probes.

The Reynolds stress is defined as $\text{Re}=\langle\tilde{v}_r\tilde{v}_\theta\rangle\cong\langle\tilde{E}_r\tilde{E}_\theta\rangle/B_0^2$. So from the above values we can determine this important parameter, which has a strong effect on the radial particle flux. Table II shows a summary of our measurements hitherto and a comparison with an analogous former measurement of Re in the ISTTOK, however, with cold probes.[13] As we can see, the values have a similar order of magnitude and the radial distance between the probes (7 mm in our case), may influence the value of the nonheated Reynolds stress at 80.32 mm minor radius. This radial position is near the velocity shear layer and around this position the radial correlation of the signals of the radial probes show a reduction, which is more pronounced than that of the correlation between the signals from the poloidal probes.

IV. CONCLUSION

We have succeeded to use electron-emissive probes in the edge region of smaller tokamak experiments in order to measure the plasma potential and its fluctuations directly. Our various probe arrays allow also the determination of the electric-field components in various desired directions.[8,9] Our probe design is simple and has a relatively long lifetime;[7] it can withstand the conditions in smaller tokamaks. We have not found any sign for an excessive evaporation of tungsten from the probe wire, or damage by sputtering. Since the emission current remains constant during an ISTTOK or CASTOR pulse, we can exclude an additional heating of the probe wire by the plasma, so that the effect of self-emission seems not to play a role.[14]

In spite of some demurs concerning the accuracy of the floating potential of a strongly emissive probe in terms of

TABLE II. Reynolds stress determined with the new three-emissive probe array in ISTTOK, once determined with heated (emissive) probes and once with the probes not heated.

Minor radius [mm]	Re[m^2/s^2], determined by means of the three emissive probes heated	Re[m^2/s^2], determined by means of the three emissive probes not heated	Re[m^2/s^2], determined by means of the three cold probes (Ref. 13)
74.82	-2.3×10^6	-4.9×10^6	$\cong-4\times10^6$
80.32	-0.86×10^6	-4.3×10^6	$\cong0.5\times10^6$

indicating the true value of Φ_{pl},[9–11] we believe that our method is able to deliver at least a better approximation for the plasma potential than the floating potential of a cold probe. Moreover, in any case the floating potential of an emissive probe shows a weaker dependence on drifting electrons and electron temperature fluctuations than a cold probe.

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