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# Edge Plasma Fluctuations Measurements In Fusion Experiments

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## ABSTRACT

We report on investigations on electrostatic fluctuations in the edge plasma region which have been carried out during the last few years at several European fusion experiments. Various methods and probe arrangements have been used to determine fluctuations of the plasma potential, the electric field and the electron temperature. Investigations were undertaken in ISTTOK (Instituto Superior Técnico TOKamak), Lisbon, Portugal, in CASTOR

(Czech Academy of Science TORus), Prague, Czech Republic, and the TJ-II Flexible Heliac at CIEMAT in Madrid, Spain.

## 1 INTRODUCTION

Fluctuations in the edge region of a magnetized plasma cause radial transport and thereby a loss of plasma and energy, which leads to a reduction of the confinement time. Radial particle transport due to large-scale electric field fluctuations [1,2,3] may account for a major part of the anomalous energy and particle losses observed [4,5,6,7,8,9,10]. In a toroidal plasma a counteracting effect may be related to a gradient of the Reynolds stress which might give rise to a sheared poloidal flow [11,12,13,14,15,16,17,18]. This can cause turbulent eddies to be tilted and elongated in the poloidal direction, thereby reducing the radial turbulent transport. This mechanism plays a key role in explaining the L-H transition [19,20,21].

In order to understand these mechanisms better it is of paramount importance to measure the electrostatic fluctuations in the edge region as comprehensively as possible. The most important parameters are the electric field components in radial and poloidal direction and the electron temperature, which should be measured in the edge region with the highest possible temporal and spatial resolution. These requirements reduce the number of usable diagnostics almost exclusively to probes of various types.

In our works various types of probes have been used for a direct determination of the plasma potential and various electric field components. The most important among them were (i) emissive probes [22,23,24,25] and (ii) ball-pen probes [26]. Whereas the first type of probe can be used in any plasma and is well known for a long time, the recently developed ball-pen probe works only in a magnetic field. For the measurement of electric field components and the electron temperature, various combinations of emissive or ball-pen probes and cold probes were used. From these parameters also the radial fluctuation-induced particle flux and the Reynolds stress [27] could be derived.

In this paper, a few typical experimental results on edge plasma fluctuation measurements are presented. Such investigations were carried out in ISTTOK (Instituto Superior Técnico TOKamak), Lisbon, Portugal, in CASTOR (Czech Academy of Science TORus), Prague, Czech Republic, and the TJ-II Flexible Heliac at CIEMAT in Madrid, Spain. The diagnostic tools are discussed in a work submitted also to this conference [28].

CASTOR and ISTTOK are large aspect ratio tokamaks with very similar dimensions, i.e., a major radius of 40 cm and a minor radius of 8 cm. They work with hydrogen and reach core densities of $10^{19}$ m$^{-3}$ and electron temperatures of 100 - 200 eV. In the edge region where we have carried out our investigations both parameters are about an order of magnitude smaller. TJ-II is a stellarator type device with an average major radius of 1.5 m and an averaged minor radius of 22 cm. The core density is $10^{20}$ m$^{-3}$ and the electron temperature about 1 keV. Also in this case the density in the edge region where the probes were used drops by one order of magnitude.

One of the objectives of this work was to prove the utility of probes for edge plasma measurements in various types of fusion experiments.

## 2 DETERMINATION OF THE ELECTRON TEMPERATURE AND ITS FLUCTUATIONS

As discussed in [28], in a purely Maxwellian plasma, consisting of electrons and single-charged positive ions, the following relation holds between the floating potential $V_{fl}$ of a cold probe and the plasma potential $\Phi_{pl}$:

$$\Phi_{pl} = V_{fl} + T_e \ln\left(\frac{I_{es}}{I_{is}}\right) = V_{fl} + \alpha T_e . \tag{1}$$

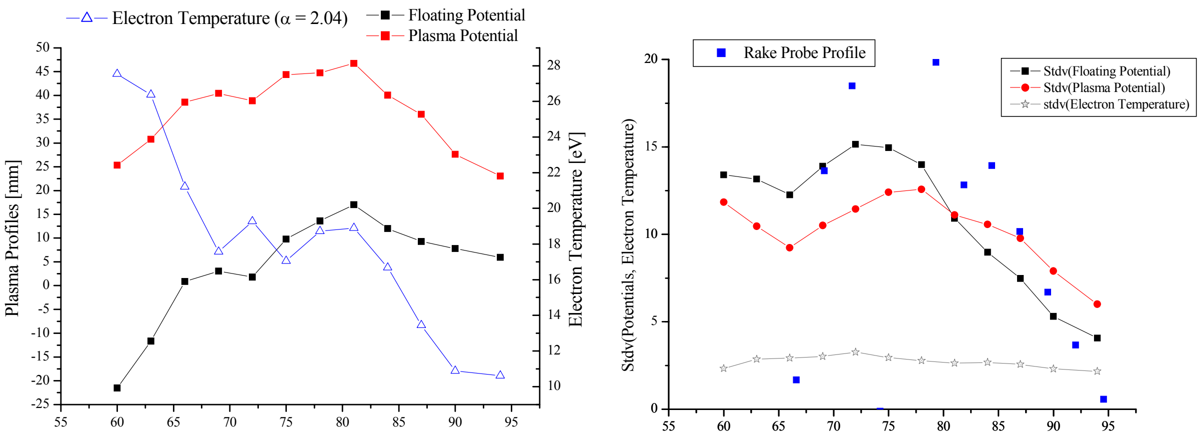
Here $T_e$ is the kinetic electron temperature and $\alpha = \ln(I_{es}/I_{is})$ is the ratio of the electron to the ion saturation current. In typical tokamak edge plasmas α depends on the magnetic field strength and ranges between 2 and 3.

If we have a possibility to measure $V_{fl}$ and $\Phi_{pl}$ simultaneously, we can use Eq. 1 to derive $T_e$:

$$T_e = \frac{\Phi_{pl} - V_{fl}}{\alpha} . \tag{2}$$

This has been done (i) with a combination of an emissive probe with a cold probe [29], and (ii) with a combination of a ball-pen probe and a cold probe [30].

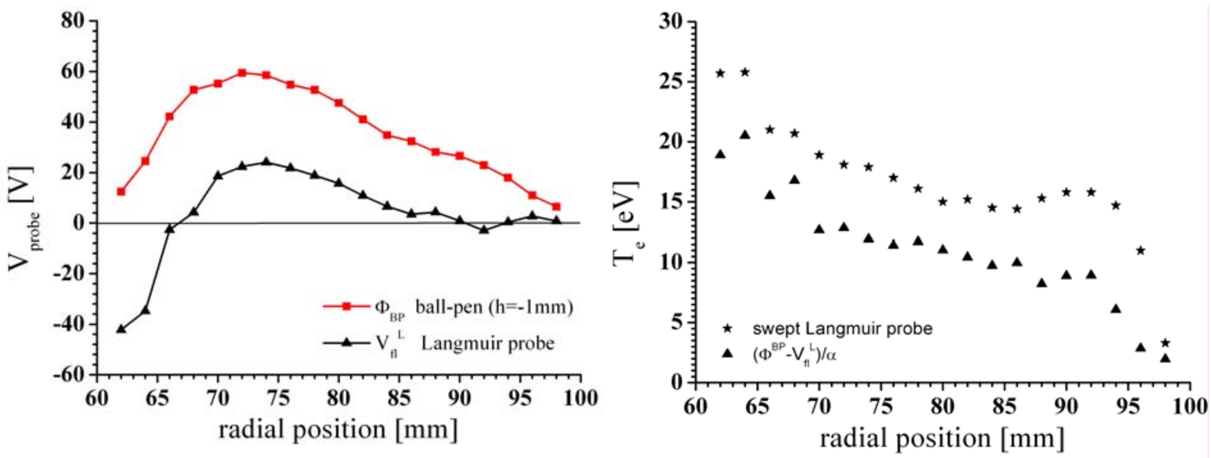
Fig. 1 shows a typical example of the radial profile of $T_e$ and of the standard deviation of $T_e$ in the edge region of the CASTOR tokamak [29]. The standard deviations of the potentials and of $T_e$ give us information on the fluctuations of these parameters in the edge plasma region. As we can see, the fluctuation level of $T_e$ is much smaller than that of the two potentials, which is obvious since the two latter quantities are related to each other (Eq. 1). It is remarkable that the standard deviation of the floating potential is larger than that of the plasma potential inside the **l**ast **c**losed **f**lux **s**urface (LCFS), whereas it is the other way around in the outer region. This finding has still to be resolved.




(a) (b)

Figure 1**:** (a) Radial profile of the electron temperature (open blue triangles), of the floating potential (solid black squares) and of the plasma potential (solid red squares) in the edge region of the CASTOR tokamak in Prague. (b) Radial profile of the standard deviation of the floating potential (solid black squares), the plasma potential (solid red squares) and of the electron temperature (grey stars) in the same region. The solid blue squares show the standard deviation of the floating potential measured simultaneously by a rake probe, but this is ignored here. The radius of the LCFS is 80 mm.

Fig. 2 shows recent results from measurements with a combination of a ball-pen with a cold probe [30], where the collector of the ball-pen probe was retracted inside the screening tube so that its floating potential also corresponded to the plasma potential [28]. The cold probe was in this case a tungsten wire ring around the screening tube. By comparing Fig. 1 (a) with Fig. 2 we see a very similar behaviour of all three parameters, which we take as an additional corroboration of the usefulness of both types of probes, emissive and ball-pen, as diagnostic tools for the direct determination of the plasma potential. However, Fig. 2 also shows $T_e$ determined from the *I-V* characteristics of the cold probe, and we see that these latter values of $T_e$ are usually larger by up to 5 eV than those determined using Eq. (2). The discussion of this discrepancy is still pending, but it is known that the determination of $T_e$ from a probe characteristic can lead to somewhat higher values, depending on how far up into the electron retarding field region the evaluation is drawn.




(a) (b)

Figure 2**:** (a) Radial profile of the plasma potential $\Phi_{pl}$ (red squares), measured with the ball-pen probe, and of the floating potential $V_{fl}$ of the Langmuir probe-ring (black triangles) in the edge region of the CASTOR tokamak. (b) Radial profile of the electron temperature calculated using Eq. (1) with $\alpha = 2.89$ (black triangles) and determined from swept Langmuir probe (black stars). In this case the LCFS was at $r = 75$ mm.

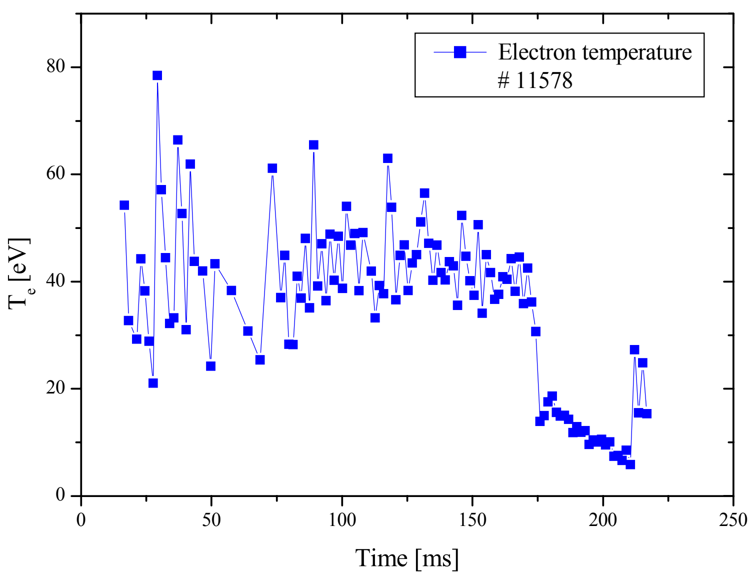



Figure 3**:** Temporal evolution of the electron temperature in the edge region of TJ-II in Madrid. Starting for $t = 175$ ms also neutral beam heating was turned on.

Also triple probes can be used to measure the electron temperature [31]. This was also done in the edge region of the flexible heliac TJ-II at CIEMAT in Madrid. The plasma is produced by **e**lectron **c**yclotron **r**esonance **h**eating (ECRH), while starting by $t = 175$ ms additional heating by **n**eutral **b**eam **i**njection (NBI) was applied. Fig. 3 shows an example of the temporal evolution of the electron temperature during a discharge. As we can see, $T_e$ shows a rather strong drop of more than 20 eV after NBI was switched on.

## 3 MEASUREMENTS OF THE FLUCTUATION-INDUCED RADIAL PARTICLE FLUX

Under the assumption that in the edge region of the described experiments magnetic fluctuations can be neglected, the radial particle flux $\Gamma_r = \langle \tilde{n}_{pl} \tilde{v}_r \rangle$ is driven mainly by fluctuations of the poloidal electric field $\tilde{E}_\vartheta$ through the action of the $\tilde{\boldsymbol{E}}_\vartheta \times \boldsymbol{B}$ drift; $\tilde{n}_{pl}$ are the density fluctuations, and the fluctuating radial velocity is thus $\tilde{v}_r = \tilde{E}_\vartheta / B_0$. Therefore the flux becomes:

$$\Gamma_r = \langle \tilde{n}_{pl} \tilde{v}_r \rangle \cong \left\langle \tilde{n}_{pl} \frac{\tilde{E}_\vartheta}{B_0} \right\rangle \tag{3}$$

The poloidal electric field was determined by two emissive probes inserted into the edge region of CASTOR on a poloidal meridian [28]. From the difference of their floating potentials (which under strong electron emission are equal to the plasma potentials) divided by their distance (5 mm), $E_\vartheta$ could be deduced. The density fluctuations were determined from those of the ion saturation current, recorded by a negatively biased cold probe nearby the two emissive probes.

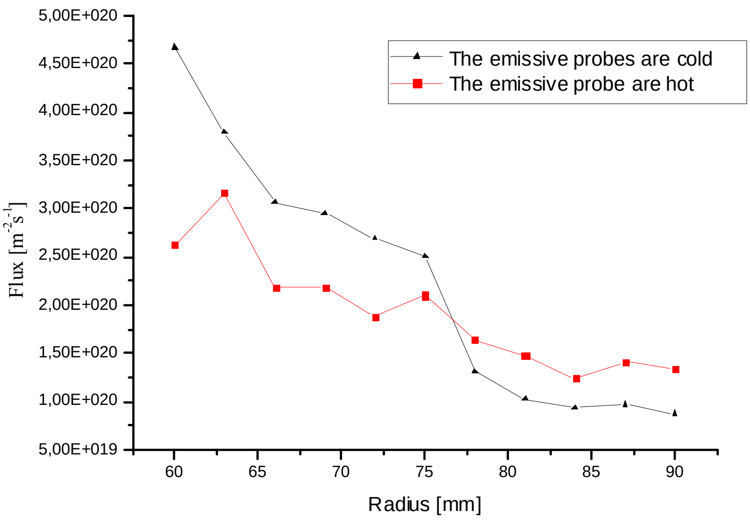



Figure 4**:** Radial fluctuation-induced particle flux measured by two emissive probes and one cold probe in CASTOR. The red solid squares show the results when the emissive probes were heated so that their floating potentials were assumed to be equal to the plasma potentials. In the case of the solid black triangles the probes were not heated. The radius of the LCFS was 80 mm.

Measurements of this kind were performed in CASTOR [29]. Fig. 4 shows the results of such an investigation. The red squares show the more reliable results since they have been obtained with both emissive probes heated. In the case of the black triangles the probes were not heated so that they were acting as normal cold probes. However, in this case the real poloidal electric field could only be deduced if there were no difference of the electron temperatures between the two probes and no major temperature fluctuations. Since the "flux" measured with the cold probes (black curve) differs considerably from the flux determined with the probes being emissive (red curve), we can easily see that this was not the case here. We have therefore to conclude that there are considerable differences and fluctuations of $T_e$ in this region.

It is, however, interesting to note that there is again (cf. Fig. 1(b)) a pronounced difference between the region inside and outside the LCFS: whereas the real flux (determined with the probes being emissive) is smaller inside the LCFS, it is vice versa outside. This effect needs still to be investigated.

With an arrangement of several conventional cold pin probes, the flux was also determined in TJ-II. Fig. 5 shows a part of these results.

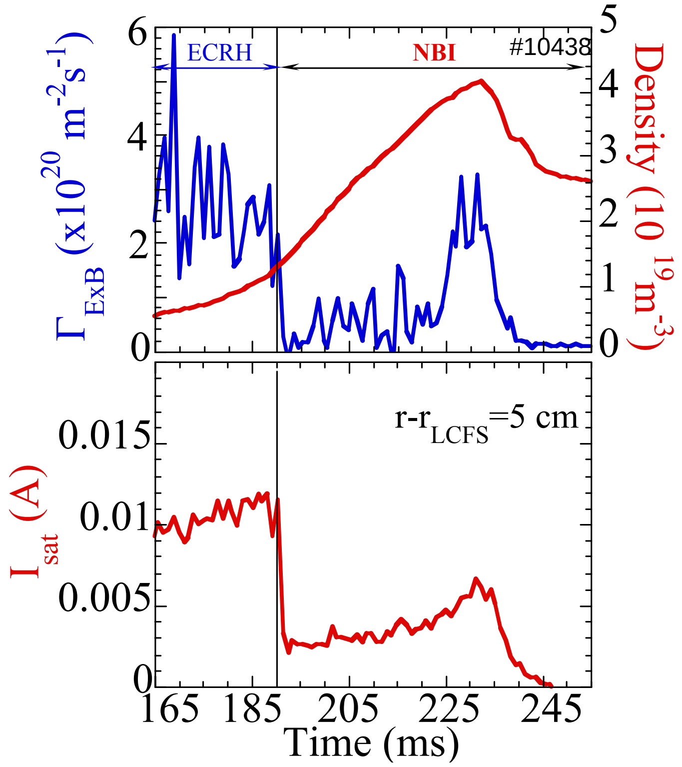


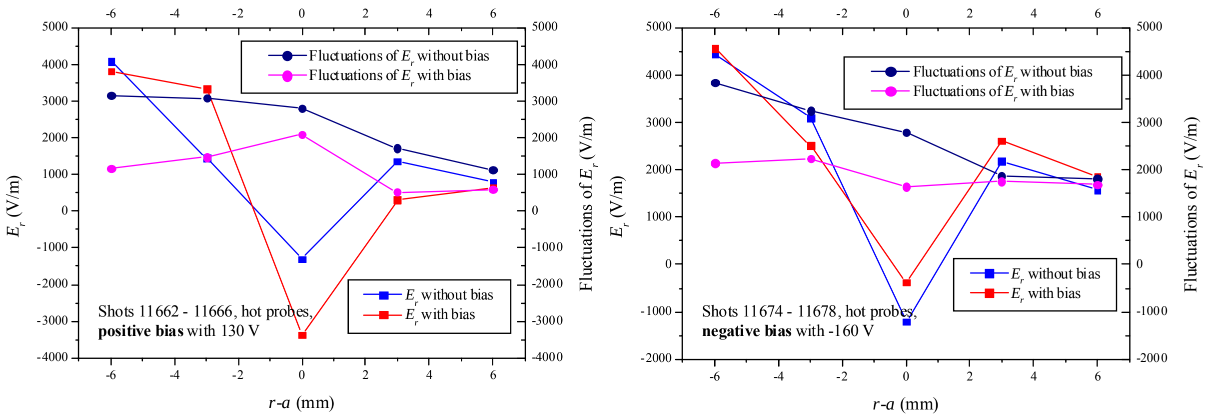

Figure 5**:** Upper graph: temporal evolution of the radial fluctuation-induced particle flux (blue line) and of the electron density (red line), as determined by Thomson scattering, in the edge region of TJ-II (5 cm outside the LCFS) for normal ECRH and NBI heating. The latter was turned on for $t$ = 190 ms. Lower graph: temporal evolution of the ion saturation current.

We notice that with the start of the NBI for $t$ = 190 ms the flux first drops, whereas the density increases. But close to the maximum density, for $t \cong$ 230 ms the flux strongly increases. The reason is that here the maximum density due to NBI approaches the intrinsic density limit of TJ-II.

## 4 MEASUREMENTS OF THE RADIAL ELECTRIC FIELD

Recently in the edge plasma region of ISTTOK, Lisbon, the radial electric field and its fluctuations were measured with a combination of two conventional emissive wire probes, set apart radially by a distance of 3 mm. A few preliminary results are shown in Fig. 6. These measurements were carried out in ISTTOK in order to get more evidence of localized radial dc electric fields which can drive poloidal fluxes due to the effect of the $\boldsymbol{E}_r\times\boldsymbol{B}$ drift.

During each shot of about 30 ms length the edge plasma was biased for 2 ms by means of an indirectly heatable circular tantalum plate of 20 mm, covered with $LaB_6$. The plate, with the axis parallel to the plasma current, was inserted into the edge region so that no perturbation of the discharges was observed, i.e., the center of the plate was at $r \cong 70$ mm, whereas the LCFS was at $a \cong 78$ mm. When this electrode was biased negatively, it was heated indirectly to emit an electron current into the plasma. The current drawn from the plasma (for positive bias to around +130 V), or emitted into the plasma (for negative bias to around −160 V), respectively, was up to 20 A.




(a) (b)

Figure 6**:** (a) Radial profiles near the LCFS (at $a$ = 78 mm) of the dc radial electric field without (blue squares) and with (red squares) positive edge biasing (with 130 V), the circles show the fluctuation levels of the radial electric field without (black circles) and with edge biasing (pink circles). (b) Same for negative bias (with −160 V with emissive electrode).

First of all it is remarkable that in all cases (without and with bias, positive or negative) the radial dc electric field (the squares in Fig. 6) passes through a minimum for $r - a = 0$, i.e., at the LCFS and becomes even negative, i.e., it is pointing inwards. On both sides, for $r - a \neq 0$ the field is positive (directed outwards). The consequently following poloidal flows $v_\vartheta$ in the edge region must therefore be strongly sheared. The effect of biasing is not very strong: a positive bias (Fig. 6(a)) leads to a reduction of $E_r$ outside the LCFS. Inside we observe the contrary effect. A negative bias with electron emission from the electrode (Fig. 6(b)) leads to a slight increase of $E_r$ outside the LCFS. Also in this case the trend appears to be inverse inside.

More obvious is the effect of biasing on the fluctuation levels of $E_r$: in both cases the fluctuation are suppressed, especially inside the LCFS. Outside the effect becomes weaker.

## CONCLUSION

We have shown that a number of very interesting and far-reaching results can be obtained by using various plasma probes in the edge region of smaller fusion experiments. We would like to mention that fluctuation measurements with (cold) probes have in the meantime also been carried in larger experiments such as ASDEX Upgrade and JET [32,33].

Our results show that the stationary and the fluctuating parts of the plasma potential and, derived from that, of various electric field components can be determined with arrangements of emissive probes and ball-pen probes. Together with cold probes also the radial fluctuation-induced particle flux and even the Reynolds stress can be determined.

We are confident that our results are sufficiently general so that they also will bear significance for larger fusion machines where probes cannot be used anymore.

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