Measurements Of Fluctuations With Probes In The Edge Region Of Various Toroidal Plasmas

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Abstract. We report on investigations of 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 at ISTTOK (Instituto Superior Técnico TOKamak), Lisbon, Portugal, at CASTOR (Czech Academy of Science TORus), Prague, Czech Republic, and at the TJ-II Flexible Heliac at CIEMAT in Madrid, Spain.

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INTRODUCTION

Fluctuations in the edge region of a toroidal plasma cause radial transport and loss of plasma. Radial particle transport due to strong electric field fluctuations[1] may account for a major part of the anomalous energy and particle losses.[2,3] A counteracting effect may be the Reynolds stress, a gradient of which might cause sheared poloidal flows.[4,5,6,7,8,9] This can cause turbulent eddies to be tilted and elongated poloidally, thereby reducing the radial turbulent transport. This mechanism plays a key role in explaining the L-H transition.[10,11,12]

For these phenomena the most relevant parameters are the radial and poloidal electric field components $\boldsymbol{E}_{r,\theta}$ and the electron temperature T_e. We have used various types of probes for a direct determination of the plasma potential Φ_{pl} and of $\boldsymbol{E}_{r,\theta}$. Among them were (i) emissive probes[13,14,15,16] and (ii) ball-pen probes.[17] Ball-pen probes work 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[18] and the Reynolds stress[19] could be derived. Such investigations were carried out on ISTTOK (Instituto Superior Técnico TOKamak), Lisbon, Portugal, on CASTOR (Czech Academy of Science TORus), Prague, Czech Republic, and on the TJ-II Flexible Heliac at CIEMAT in Madrid, Spain.

PLASMA POTENTIAL PROBES AND A FEW RESULTS

There are few diagnostic tools to determine the plasma potential with sufficient accuracy and spatial and temporal resolution. The least expensive and most easily to handle tool is the cold probe (Langmuir probe). Usually the well-known relation $\Phi_{pl} = V_{fl} + T_e\ln(I_{es}/I_{is}) = V_{fl} + \alpha T_e$ between the floating potential V_{fl} of a cold probe and Φ_{pl} is used.[14] However, for this we need to know T_e; and also the ratio of the electron to the ion saturation currents in $\alpha = \ln(I_{es}/I_{is})$ depends on T_e. In typical tokamak edge plasmas $\alpha \cong 2 - 3$. The electron temperature is not easily measured with sufficient reliability and temporal resolution, in particular in the edge region of a magnetically confined toroidal fusion plasma where there are strong gradients and fluctuations of T_e. An additional often ignored fact is that the relation $\Phi_{pl} = V_{fl} + \alpha T_e$ is *only* valid for a Maxwellian plasma. As soon as there is a considerable electron drift or electron beam, the entire *I-V* characteristic, and thereby also V_{fl}, shifts to the left due to the drifting electrons.

Emissive Probes

Although emissive probe were discussed by Langmuir in the 1920-ies,[20] one of the first such probe was presented by Sellen et al.[21] Since then emissive probes are standard tools in laboratory plasmas,[13,14,15,22,23] but only our group has started to use them also in fusion experiments.[13,14,15,16,19] The emission current I_{em} can be observed as long as the probe potential is more negative than the plasma potential, irrespective of electron drifts or beams. In this case, however, also only in a Maxwellian plasma, the above relation becomes:

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

Eq. (1) shows that for increasing I_{em} the second term decreases, while the floating potential $V_{fl,em}$ of the probe increases. The second term vanishes for $I_{em} = I_{es} - I_{is}$, and the $V_{fl,em} = \Phi_{pl}$. Thus when the emission current compensates the electron saturation current (minus the usually negligible ion saturation current), the floating potential of such a probe equals the plasma potential.

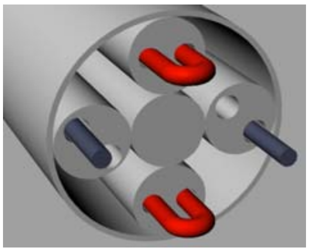

FIGURE 1. Two emissive probes and two cold probes for simultaneous measurements of the poloidal electric field, the ion density and the electron temperature in CASTOR.

Emissive Wire Probes

The usual realization of an emissive probe consists of a loop of tungsten wire, inserted into a suitable double-bore ceramic tube. Inside the bores the tungsten wire is spliced with a sufficient number of coppers threads.[13,14,23] In this way only the exposed tungsten loop is heated when a current passes through the loop from an external power supply or battery.

Fig. 1 shows an arrangement of two emissive wire probes and two cold probes used in CASTOR. The probe is inserted so that the two emissive probes measure Φ_{pl} at two positions on a poloidal meridian. From that $\boldsymbol{E}_\theta$, including its fluctuations can be calculated. One of the cold probes is biased negatively to measure the ion saturation current, from which the ion density can be derived. The other cold probe is swept and the electron temperature is derived from the *I-V* characteristic.[18] With such a probe system we have also the possibility to measure V_{fl} and Φ_{pl} simultaneously. Therefore we can derive T_e directly: $T_e = (\Phi_{pl} - V_{fl})/\alpha$. This gives us the opportunity to measure also electron temperature fluctuations up to high frequencies, which is not possible by the normal method to sweep the probe voltage.

Another possibility of such a probe arrangement is the determination of the radial particle flux $\Gamma_r = \left\langle \tilde{n}_{pl} \tilde{v}_r \right\rangle$ driven mainly by fluctuations of the poloidal electric field $\tilde{E}_\theta$ by the action of the $\tilde{\boldsymbol{E}}_\theta \times \boldsymbol{B}$ drift. Thus the fluctuating radial velocity is $\tilde{v}_r = \tilde{E}_\theta / B_0$ and $\tilde{n}_{pl}$ are the density fluctuations. Therefore the flux is:

$$\Gamma_r = \left\langle \tilde{n}_{pl} \tilde{v}_r \right\rangle \cong \left\langle \tilde{n}_{pl} \frac{\tilde{E}_\vartheta}{B_0} \right\rangle \tag{2}$$

FIGURE 2. Photo of the probe system of ISTTOK, consisting of three emissive probes and one cold probe to measure the radial and poloidal electric field and the ion saturation current simultaneously.

Measurements of this kind were performed also on ISTTOK[24] with the probe arrangement shown in Fig. 2. It consists of three emissive probes and one cold cylindrical probe, allowing a simultaneous determination of the radial and poloidal electric field and of the density. With this system in principle also the Reynolds stress

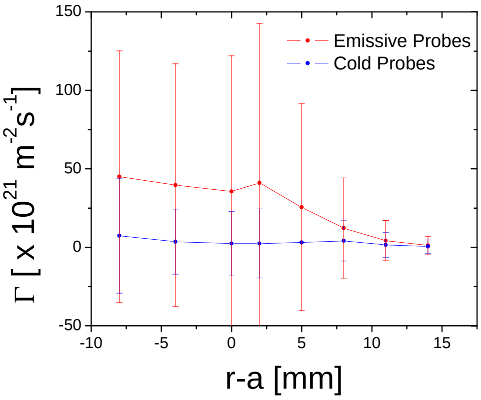

FIGURE 3. Radial fluctuation-induced particle flux measured by the system shown in Fig. 2 in the edge region of ISTTOK; red dots and line: emissive probes were heated; blue dots and line: probes were not heated. The radius *a* of the LCFS was 80 mm..

$$R_e \cong \langle \tilde{v}_r \tilde{v}_\theta \rangle \cong \frac{\langle \tilde{E}_\theta \tilde{E}_r \rangle}{B^2} \tag{3}$$

can be determined under the assumption that also the poloidal fluctuating velocity is due to the drift $\tilde{\boldsymbol{E}}_r \times \boldsymbol{B}$.

Fig. 3 shows the radial fluctuation-induced particle flux determined according to Eq. (2) in the edge region of ISTTOK. In general it turns out that the fluctuations of V_{fl} (measured with the probes not heated) are considerably smaller than those of Φ_{pl} (measured with heated probes). Consequently also the turbulent particle flux measured with the emissive probes is significantly larger than that measured with cold probes, since in the latter case also temperature fluctuations are superimposed. These results indicate that temperature fluctuations are correlated with density fluctuation but not with those of the floating potential. This also suggests that in the ISTTOK edge plasma temperature fluctuations are important for the estimation of the particle flux and therefore the standard method based on cold probe measurements is not valid.

Laser-Heated Emissive Probe

Another way of heating an emissive probe was investigated recently, namely to heat a piece of LaB_6 or graphite by a laser to sufficiently high temperatures for electron emission.[25,26] Something similar was attempted only once before.[27]

Small cylindrical pieces of 2 mm diameter and heights of 4 mm of LaB_6 or graphite were used as probe tips. The electrical connection was made with an Mo wire of 0.2 mm diameter wound around the probe tip. The tip was heated from the front side through a quartz-glass window by an infrared high-power diode laser JenLas HDL50F from JenOptik, Jena, Germany, with a maximum laser power of 50 W at 808 nm. The laser beam is coupled into a fiber cable of 3 m length ending in an output head, with which a focal spot of 0.6 mm diameter is produced in a distance of 20 cm. It turned out that the behavior of such a probe is the same as that of a conventional emissive wire probe, but it has several advantages such as longer lifetime and higher electron yield.

Triple Probes

Also triple probes can be used to measure the electron temperature.[28] This was 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. 4 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.

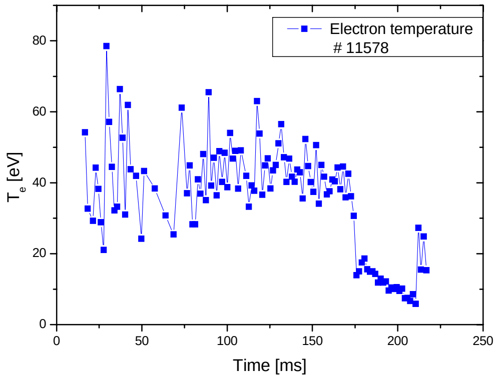

FIGURE 4. Temporal evolution of the electron temperature in the edge region of TJ-II in Madrid. Starting for $t = 175$ ms also neutral beam heating was turned on.

Ball-Pen Probes

A ball-pen probe consists of a cylindrical collector with a conical tip of 2 mm diameter, which can be moved up and down inside a screening tube of boron nitride.[29,30] In Fig. 5 an additional Langmuir probe ring is mounted on the BN tube. This acts as conventional cold probe to deliver the floating potential similar to the above-described method.[31] The parameter h indicates the position of the collector relative to the tube, with $h = 0$ indicating that the collector tip lies exactly in the plane of the mouth of the tube. The measurement of the plasma potential Φ_{pl} by means of the ball-pen probe utilizes the different electron and ion gyroradii in a magnetized plasma. Since the former are on the average much smaller, they are easily screened off by the BN tube, when the collector is withdrawn inside (Fig. 5(a)), while ions can still reach the probe collector. When the magnitudes of the electron and ion saturation currents are equal, the floating potential of the collector becomes equal to Φ_{pl}.

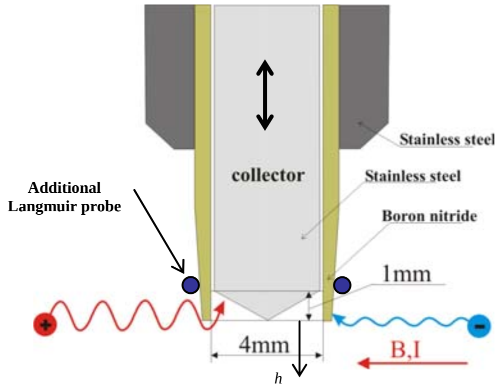

FIGURE 5. Ball-pen probe for direct measurements of the plasma potential in a magnetized plasma.

CONCLUSION

We have shown that with special probes also in toroidal fusion experiments the plasma potential and its fluctuations can directly be measured, which makes it possible to derive also further important parameters characterizing various features of edge plasma turbulence, among them the radial fluctuation-induced particle flux and the Reynolds stress.

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