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Fluctuation measurements using a five-pin triple probe in the Joint European Torus boundary plasma

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A multi-probe system has been developed to investigate the importance of electron temperature fluctuations turbulent transport in the Joint European Torus boundary plasma. The compact five-pin triple probe has been designed to reduce the phase delay of fluctuations due to the finite pin separation in the standard triple probe technique, while still avoiding the effects of probe shadowing. This probe has been found to have advantages over the standard triple probe in the region close to the separatrix ($r-r_{\text{sep}}<0.01$ m), where the fluctuation wavelength is large. Importantly, results obtained with the probe support the standard estimation of cross-field particle flux, which ignores temperature fluctuations. They cannot be ignored, however, in the estimation of energy losses since measurements show that the conducted energy may be as large as the convected component. *© 2004 American Institute of Physics.* [DOI: 10.1063/1.1787578]

I. INTRODUCTION

It is well known that fluctuations are responsible for a significant portion of the particle loss rate in tokamaks. They may also account for a large part of the observed anomalous energy losses. For a complete estimate of the turbulent driven particle and heat transport, knowledge of the fluctuations in electron density, $\tilde{n}$, electron temperature, $\tilde{T}_e$, and electric field, $\tilde{E}$, are required. However, electron temperature fluctuations are in general difficult to measure and thus often ignored. The limited experimental results for $\tilde{T}_e$ that have been reported have demonstrated that $\tilde{T}_e/\overline{T}_e$ can be as high as, or even larger than, $\tilde{n}/\overline{n}$ in several devices (e.g., Ref. 1 and references within) bringing the evaluation of turbulent transport neglecting $\tilde{T}_e$ under question.

In recent years, turbulent transport has been studied in the plasma boundary of the Joint European Torus (JET) tokamak using a multiple-Langmuir probe system.[2] However, it should be noted that in some cases fluctuation fluxes appear too high to be consistent with global particle balance.[3] Poloidal asymmetries, large scale convective cells, the possible role of temperature fluctuations, and the disturbing effect due to the insertion of probe into the plasma[4] may account for these apparent inconsistencies. At present, this disagreement still remains as an open question. In an attempt to evaluate the importance of $\tilde{T}_e$ on the fluctuation induced transport in the JET boundary plasma, a five-pin triple probe technique has been developed which reduces the phase delay errors introduced by finite tip separations in the so-called standard triple technique.

In an earlier study using a method based on single Langmuir probe characteristics, temperature fluctuations in JET L-mode plasmas were found to be lower than those in density and potential.[5] It was also demonstrated that temperature fluctuations do not appear to be responsible for the large cross-field particle fluxes that are often measured in the JET edge plasma.

II. TURBULENT TRANSPORT PROBE SYSTEM

The new nine-pin probe head, of which the five-pin triple probe group is an integral part, is shown in Fig. 1(a). In addition to the five-pin group, located at the innermost radial position, four additional pins allow the determination of the parallel plasma flow and cross-field particle fluxes further out radially. To avoid pin self-shadowing the pins are oriented perpendicularly to the magnetic field lines. The probe head is mounted onto a fast reciprocating drive system that inserts the probe into the plasma vertically near the top, low-field side of the poloidal cross section at an angle of 75° with respect to the outer midplane. As for all JET probe system,[6] the turbulent transport probe body is manufactured in boron nitride, which has both excellent insulating properties (thus avoiding significant $\mathbf{J}\times\mathbf{B}$ forces) and a high thermal conductivity.

The schematic in Fig. 1(b) shows how, in the group of five-pins that constitutes the triple probe system, two poloidally separated pins are used to measure the floating poten-

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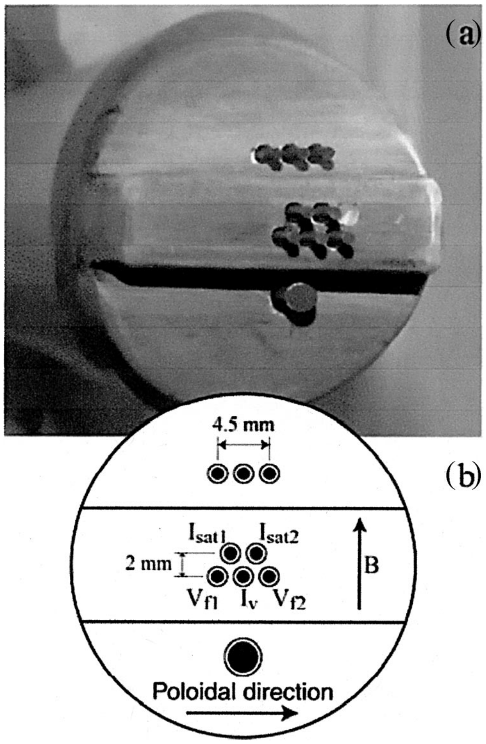

FIG. 1. Reciprocating probe head photograph (a) and pin layout (b).

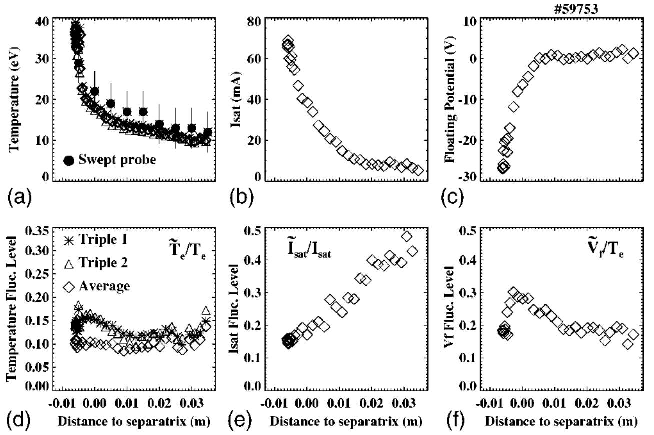

FIG. 2. Radial profiles of T_e, I_{sat}, and V_f and their fluctuation levels for L-mode discharge with $I_p=2$ MA, $B_T=2.4$ T. The temperature calculated using the swept single probe method is also shown for comparison [full symbols in Fig. 2(a)].

tial, V_f, with a second poloidally separated pair being used to measure the ion saturation current, I_{sat}. The remaining pin measures the current I_V, at a fixed voltage, V_{ap}, so that the electron temperature may be obtained using $T_e=(V_{\text{ap}}-V_f)/\ln(1-I_V/I_{\text{sat}})$. The value of V_{ap} is selected such that the three points in the characteristic $(V_f, I_{\text{sat}},$ and $I_{\text{v}})$ are significantly distinct. If this condition is not satisfied, the temperature cannot be determined or at best can be estimated only with large error.

The main disadvantage of the triple probe method is that measurement of the plasma parameters is not performed at the same position. As a result, the method cannot distinguish between a fluctuation in the parameters or its local gradient and can therefore only give an upper limit for $\tilde{T}_e$. The five-pin system partially compensates for this problem by measuring V_f and I_{sat} at poloidally symmetric positions with respect to the pin measuring I_V.

When the average values of I_{sat} and V_f are used in the determination of T_e, the phase delay in I_{sat} and V_f fluctuations is cancelled, improving therefore the accuracy of the $\tilde{T}_e$ measurement. It is important to note, however, that this method only cancels the phase delay of fluctuations with wavelengths larger than twice the average distance between pins. The range of poloidal wave numbers, k_θ, for which this method significantly increases the $\tilde{T}_e$ measurement accuracy, is therefore $|k_\theta|<9\ \text{cm}^{-1}$.

The principal difficulty in the development of this JET multiple-probe system was to avoid the effects of probe shadowing while reducing the effects of phase delay and decorrelation. Compared with the previous probe design,[2,3] the poloidal distance between pins has been reduced to 2.25 mm and their diameter to 1 mm. The resulting dimension of the five-pin probe array in poloidal direction, $\sim$5 mm, is smaller than the typical correlation length of fluctuations in the plasma parameters.

III. MESUREMENT OF FLUCTUATIONS

Figure 2 illustrates typical radial profiles on T_e, I_{sat} and V_f and their fluctuation levels obtained in a diverted L-mode discharge. Good agreement is observed between the temperature obtained from the triple probe method and that from the standard swept single probe method (shown as full symbols). In the present configuration, the temperature can be estimated at three locations: $T_{e1}=F(V_{f1}, I_{\text{sat1}}), T_{e2}=F(V_{f2}, I_{\text{sat2}})$ and the average value $T_{e,m}=F(V_{fm}, I_{\text{sat}m})$, where m denotes the average of the quantities measured at positions 1 and 2 [see Fig. 1(b)]. Evidently [Fig. 2(a)], the electron temperature profile does not depend significantly on the location of the calculation. This is not, however, the case for the electron temperature fluctuation level, which is significantly reduced $(\sim 35\%)$ close to the separatrix $(r=r_{\text{sep}})$ when signals are averaged. For $r-r_{\text{sep}}>0.01$ m this reduction is typically lower than 15%. This means that only close to the separatrix are there fluctuations with wavelengths larger than the distance between pins and which are cancelled when signals are averaged. This result may be explained by the poloidal phase velocity and hence the wavelength of fluctuations being close to zero in most of the scrape-off layer (SOL) and increasing only near the separatrix $(V_{\text{ph}}=w/k_\theta=w\lambda_\theta/2\pi$, where θ demotes the poloidal direction). In summary, it appears in JET ohmic and L-mode plasmas that the electron temperature fluctuation level is approximately constant across the SOL $(\tilde{T}/\tilde{T}\approx 0.1)$ and only close to the separatrix does the standard triple probe method significantly overestimate $\tilde{T}_e$. Concerning I_{sat} and V_f fluctuations levels, they show a typical radial profile;[3] the I_{sat} fluctuation level decreases as the probe is inserted into the plasma while for V_f the profile is roughly flat in the SOL, increasing near the separatrix.

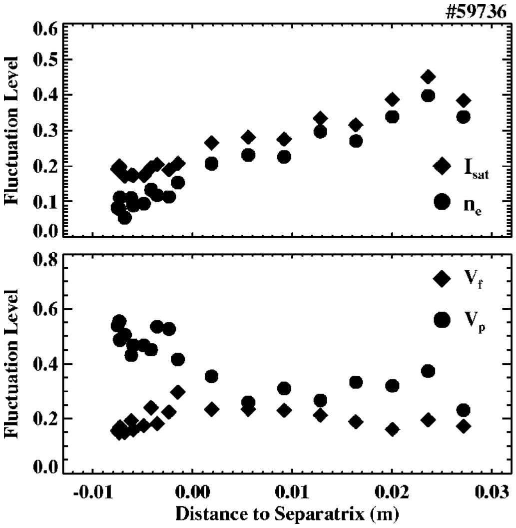

FIG. 3. Radial profiles of the fluctuation levels in I_{sat}, n_e, V_f, and V_p for L-mode discharge with $I_p = 1.9$ MA, $B_T = 2$ T.

IV. CONSEQUENCES FOR PARTICLE AND HEAT TRANSPORT

The fluctuation driven, cross-field particle and heat fluxes are given, respectively, by: $\Gamma_r = \langle \tilde{n}\tilde{E}_\theta \rangle / B$ and $Q_r = Q_{\mathrm{conv}} + Q_{\mathrm{cond}} = 3k\tilde{T}_e\Gamma_r/2 + 3n_e\langle K\tilde{T}_e\ \tilde{E}_\theta\rangle/2B$. Electron temperature fluctuations are often ignored and therefore density and plasma potential fluctuations are derived from the ion saturation current and floating potential fluctuations, respectively. Accounting for temperature fluctuations, the plasma potential and ion saturation current fluctuation levels may written as:[7] $\langle(\tilde{I}_{\mathrm{sat}}/\overline{I_{\mathrm{sat}}})^2\rangle \approx \langle(\tilde{n}/\overline{n})^2\rangle + \langle(\tilde{T}_e/\overline{T_e})^2\rangle/4 + \langle\tilde{n}\tilde{T}_e\rangle/\overline{n}\overline{T_e}$ and $\langle(\tilde{V}_p/\overline{V_p})^2\rangle \approx \langle(\tilde{V}_f/\overline{T_e})^2\rangle + \mu^2\langle(\tilde{T}_e/\overline{T_e})^2\rangle + 2\mu\langle\tilde{V}_f\tilde{T}_e\rangle/\overline{T_e^2}$ respectivley, where the brackets, $\langle\rangle$, denote time average and μ the sheath drop coefficient, which is assumed to be ∼3. Figure 3 shows the radial profiles of the I_{sat}, n, V_f and V_p fluctuation levels including the effects of $\tilde{T}_e$, again for a diverted L-mode discharge. Results show that $\tilde{I}_{\mathrm{sat}}/\overline{I_{\mathrm{sat}}}$ is a good approximation for $\tilde{n}/\overline{n}$, except in the region near the separatrix. On the contrary, the level of plasma potential fluctuations depends strongly on $\tilde{T}_e$ and, in general, its fluctuation level is larger than that of the floating potential. This is in good agreement with the results obtained from earlier analysis fluctuations using of the single probe characteristic method.[5]

The average electron temperature is determined at one location only and cannot therefore be used in the estimation of the poloidal electric field. Instead, E_θ has been evaluated using: $E_\theta \approx [V_{f1} + \mu T_{e1} - (V_{f2} + \mu T_{e2})]/d$, where d is the pin separation. Figure 4(a) illustrates the effect of temperature fluctuations on the particle transport for the same discharge shown in Fig. 3. The particle flux is only clearly affected by $\tilde{T}_e$ in the region close to the separatrix, being up to a factor of 2 larger when $\tilde{T}_e$ is included in the flux calculation. However, taking into account that in this region the standard triple probe method overestimates $\tilde{T}_e/\overline{T_e}$ by ∼50%, it can be concluded that the inclusion of temperature fluctuations does not appear to substantially influence the calculated cross-field particle flux.

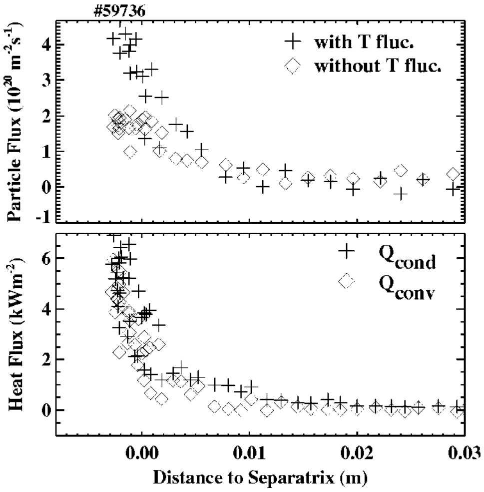

FIG. 4. Radial profiles of the (a) fluctuation driven particle (with and without accounting for electron temperature fluctuations) and (b) energy (convective and conducted) fluxes.

Recent measurements performed on the ISTTOK tokamak[8] with emissive probes have shown that, although the plasma potential fluctuation level is significantly higher than that of the floating potential (up to 40% higher), the derived fluctuation induced particle transport is not significantly affected by the inclusion of temperature fluctuations. Results tend to support, therefore, the standard estimation of cross-field particle flux, which ignores temperature fluctuations.

Figure 4(b) shows the energy flux radial profile separated into conductive and convectice components. Results show that the conductive component, which is proportional to temperature fluctuations, is significant, and may be as large as the covnected energy. In contrast to their small effect on the fluctuation induced particle flux, electron temperature fluctuation can be important for energy transport and therefore cannot be neglected.

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