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## 1 Introduction

Cross-field transport of particles and energy is a major issue in magnetized fusion-relevant plasmas, due to its relevance for plasma confinement and for the consequent fusion energy balance. This issue is still mostly unresolved, due to the fact that the main drive of the transport is turbulence, a largely unsolved problem both in neutral fluids and plasmas. Indeed, the design of the subsequent generations of fusion devices has been based over the years on empirical scaling laws for the energy confinement times, and the ITER experiment soon to be built in France is no exception in this respect. Also in many instances of non-fusion magnetized plasmas the cross-field transport is not fully understood: examples of this are the transport of electrons across the magnetic trap in magnetron sputtering devices used for thin film deposition or in Hall thrusters for space propulsion.

It is clear that, in order to gain a better understanding of the transport mechanisms in magnetized plasmas, accurate measurements are important, as they allow to validate or reject different theories. In general, a local measurement of the transport, as described by particle or energy flux, is required for a careful comparison with theory. In the case of turbulence-driven fluxes, statistical techniques exist which allow to evaluate these fluxes from turbulence measurements. This is however not an easy task, involving the measurement of several quantities, and an intrinsic uncertainty due to the fact that Langmuir probes measure the plasma potential only indirectly and time-resolved temperature with difficulty.

In this paper we present a new probe-based technique for a direct evaluation of the local value of the diffusion coefficient in a turbulent magnetized plasma. The technique, which is based on the analysis of the turbulence spectra decay length in a particular geometry, assumes from the very beginning a diffusive behaviour of the plasma, featuring proportionality between particle flux and density gradient, as in Fick's law. It is thus clear that

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the technique may fail in situations where such proportionality is not respected. On the other hand, it is worth to stress that no hypothesis is made about the process driving the transport, and in particular this process need not be collisionality: on the contrary, the presence of turbulence is crucial for the technique to work, and the diffusion process may well be due to the effect of the turbulence itself.

A preliminary version of the technique had already been described [1]. Here we improve it, by introducing the dependence of the wavenumber on the frequency: in the previous version, the wavenumber had been neglected. In this way, a three-parameter model has been derived, which allows a better fit of the experimental data than the previous one. Furthermore, we show an application in the edge region of the CASTOR tokamak, which yields the dependence of the diffusion coefficient on the magnetic field strength. The paper is organized as follows: in section 2 a description of the probe used for the evaluation is given; in section 3 the data analysis technique is illustrated; in section 4 we show results of the data analysis, including the dependence of the diffusion coefficient on the magnetic field; finally, in section 5 conclusions are drawn.

## 2 Probe layout

The technique for measuring the diffusion coefficient is based on the use of the so-called ball-pen probe, which was originally developed as a tool for a direct measurement of the plasma potential. The basic idea underlying the ball-pen probe concept is to have a probe geometry such that the ion and electron currents collected by the active electrode are equal. If this can be achieved, the floating potential of the probe $V_{fl}$ is interpreted as the plasma potential $\Phi$.

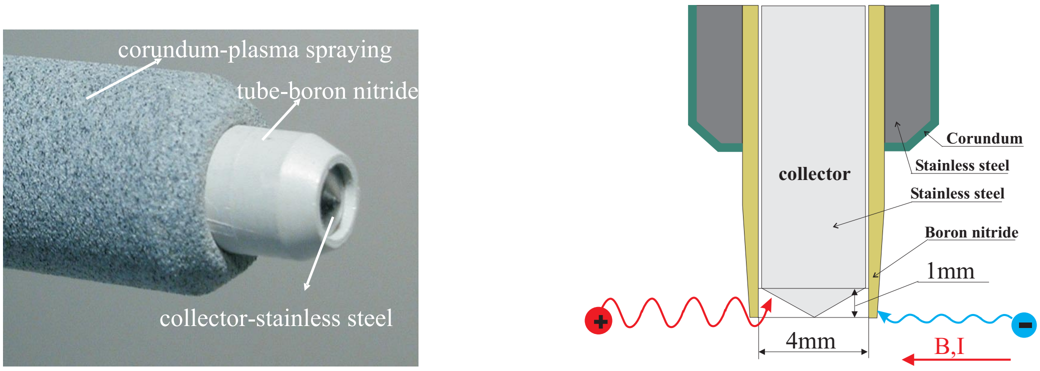

**Fig. 1** Left - Picture of novel probe. Right - Positioning of the probe head with respect to the toroidal magnetic field lines. (Online colour: www.cpp-journal.org).

The probe head, shown in fig. 1, is designed to modify the ratio $R$ of the electron and ion current. It consists of conically shaped define h as the position of the collector, which is shielded by an isolating tube of boron nitride. The collector is movable inside the tube and it is either completely shielded or partially exposed to the plasma. In the ideal case, when the collector is hidden inside the tube, as shown in fig. 1, only ions with sufficiently large Larmor radius reach the collector surface. In this case the collecting area for electrons is negligible. When the collector is shifted toward to the plasma the electron current increases. The value of the ratio R is changing with the position of the collector. The position of the collector is described by the h parameter. In fig. 1 the collector is in the reference position where h is equal to zero. The h has a positive or negative value when the collector is partially exposed in the plasma or completely hidden inside the tube, respectively. In the following, it will be shown how this probe can be used to evaluate the diffusion coefficient.

## 3 Data analysis technique

The basis of the technique presented herein is the continuity equation, expressing the conservation of mass

$$\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{\Gamma} = 0 \tag{1}$$

where $n$ is the plasma density and $\Gamma$ is the particle flux. It is assumed that no source term is present, thanks to the fact that the density decays quite steeply inside the probe shaft As stated in the introduction, the main assumption underlying the data analysis is that of a purely diffusive density behaviour as far as the cross-field transport is concerned. We will therefore write the particle flux as

$$\mathbf{\Gamma} = \mathbf{\Gamma}_{\parallel} - D\nabla_{\perp}n. \tag{2}$$

In the usual treatment of the Scrape Off Layer (SOL) of fusion machines or of other plasmas bounded by conducting walls, the parallel component of the flux is dominant over the cross field one. However, the present situation is substantially different, due to the fact that the shaft is made of a dielectric material, and also to the fact that ions penetrate more easily inside the shaft, due to their larger Larmor radius [2–4]. As a consequence, one can expect that a positive charge is deposited on the inner wall of the shaft, and this reduces the ion parallel flux to very low levels. We will therefore, to a first approximation, neglect the parallel flux, and will assume that only the perpendicular components survive.

In the following we assume for simplicity a slab geometry, with the z-axis aligned along the magnetic field, the x-axis representing the radial direction, and the y-axis in the third direction, which in a tokamak will be almost poloidal. We will assume that the section of the ball-pen probe shaft is not circular, but rectangular, with one side along the z direction and the other along the y direction. We take the side aligned along z to have a length $2L$. In this coordinate system, the two non-negligible components of the ion flux are

$$\Gamma_x = -D\frac{\partial n}{\partial x} \qquad \Gamma_y = -D\frac{\partial n}{\partial y} \tag{3}$$

We shall assume that the diffusion coefficient $D$, which is the quantity that we wish to evaluate, is constant and uniform in the region inside the shaft, and that its value is the same as in the plasma immediately outside of the shaft.

The continuity equation becomes

$$\frac{\partial n}{\partial t} - D\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right) = 0. \tag{4}$$

Let us now Fourier-transform this equation with respect to $y$ and $t$. Calling $g(x)$ the Fourier transform for a given angular frequency $\omega$ and wavenumber $k$, we have

$$-i\omega g - D\left(\frac{d^2 g}{dx^2} - k^2 g\right) = 0. \tag{5}$$

We now seek a solution of the form

$$g(x) = g_0 \exp[(\alpha + i\beta)x]. \tag{6}$$

Substituting, one obtains the characteristic equation

$$-i\omega = D(\alpha + i\beta)^2 - Dk^2. \tag{7}$$

This complex equation is equivalent to the two real equations

$$\alpha^2 - \beta^2 = k^2 \qquad 2\alpha\beta = -\frac{\omega}{D} \tag{8}$$

Evaluating $\beta$ from the second one and substituting into the first one the following equation for $\alpha$ is obtained:

$$\alpha^4 - k^2\alpha^2 - \frac{\omega^2}{4D^2} = 0. \tag{9}$$

The only solution leading to a real value for $\alpha^2$ is

$$\alpha^2 = \frac{1}{2}\left(k^2 + \sqrt{k^4 + \frac{\omega^2}{D^2}}\right). \tag{10}$$

Let us now consider the power spectrum of a plasma quantity measured inside the shaft. This should be the density, but it is possible to use instead the floating potential, which is readily measured. This is justified by the fact that density and plasma potential are related by Boltzmann's relation, which for small fluctuation amplitudes can be linearized giving a proportionality between the two quantities. The further assumption that the temperature fluctuations are sufficiently small to be neglected leads to the possibility of using the floating potential. We assume that, for a given frequency $\omega$, the spectrum decays moving deeper into the shaft with a decay length $\lambda(\omega)$ (we shall see that this is indeed the case most of the time). The actual value of $\lambda$ is obtained by fitting the power spectrum, computed at a certain frequency, expressed as a function of the collector position $h$, by an expression of the type $A\exp(h/\lambda)$. Since the power spectrum is a quadratic in $g$, the decay length of $g$, which is $\lambda' = \alpha$, will be related to $\lambda$ by $\lambda' = 2\lambda$.

We thus get

$$1/\lambda^2 = 4\alpha^2 = 2\left(k^2 + \sqrt{k^4 + \frac{\omega^2}{D^2}}\right) \tag{11}$$

In general, the wavenumber $k$ will depend on the frequency according to some dispersion relation. We can make different hypotheses concerning the functional form of $k(\omega)$. We chose to assume a linear dispersion relation for the plasma turbulence of the type $\omega = \omega_0 + kv$, as is often done in the edge of fusion plasmas, where the Doppler effect due to the plasma rotation is dominant over the turbulence phase velocity. Substituting, we obtain

$$1/\lambda^2 = 2\left[\left(\frac{\omega-\omega_0}{v}\right)^2 + \sqrt{\left(\frac{\omega-\omega_0}{v}\right)^4 + \frac{\omega^2}{D^2}}\right]. \tag{12}$$

Thus, the experimental values for $\lambda$ can be fitted with a three-parameter function, obtaining values for $D$, $v$, $\omega_0$.

## 4 Results

A set of power spectra obtained for different values of the collector position $h$ at a fixed probe position are shown in fig.2.

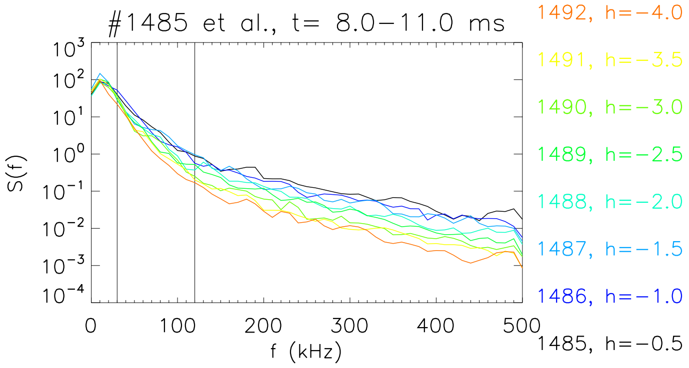

**Fig. 2** Power spectra of the fluctuation on the collector in different position of $h$. (Online colour: www.cpp-journal.org).

It is possible to see that in the frequency range 30-120 kHz the power decays as the collector is retracted inside the shaft. At larger frequencies, this effect is partially lost because in the most retracted positions the power spectrum goes below the noise level. In order to better show the decay, the same data are plotted in fig.3, where the spectrum value at fixed frequency is plotted as a function of $h$, each curve representing a different frequency in the range 30-120 kHz. This figure clearly shows that the decay is exponential to a very good degree. In the same figure the curves resulting from exponential fits of the form $A\exp(h/\lambda)$ are shown. From each fit a value of the decay length $\lambda$ corresponding to that particular frequency is obtained. These $\lambda$ values are shown in fig.4, where they are plotted as a function of frequency. In the same picture the curve resulting from the three-parameter fit given by equation (12) is plotted, demonstrating that the agreement is very good. A linear fit, corresponding to the version of this model described in [1] is also plotted. One can see that in this case the old model does not describe the data accurately, and indeed this was the motivation for refining the model. The old version of the model predicted a straight line passing through the origin, while in many cases, as in the one shown in fig. 4, this does not happen.

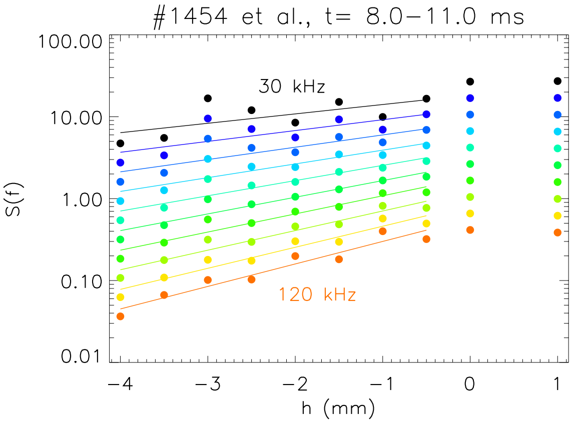

**Fig. 3** Radial decay of spectrum at different frequencies. (Online colour: www.cpp-journal.org).

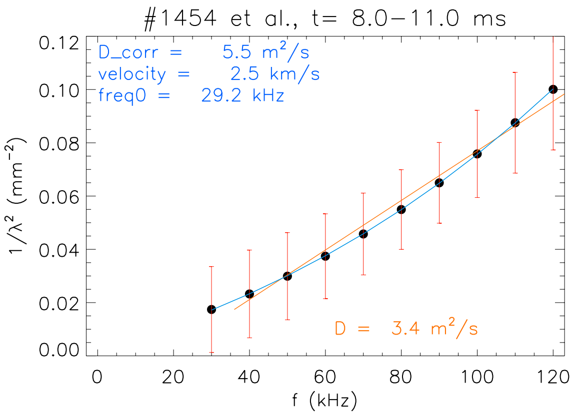

**Fig. 4** Dependence of $1/\lambda^2$ on the frequency with two different fits: The red one is the linear fit from the old method, the blue one is the three-parameters fit from the new method. (Online colour: www.cpp-journal.org).

The fitting of the data shown in fig. 4 with expression (12) yields three parameters: the diffusion coefficient $D$, the turbulence phase velocity $v$ and the frequency $f_0 = \omega_0/2\pi$. For the case shown in the figure, the resulting values are $D = 5.5$ m$^2$/s, $v = 2.5$ km/s and $f_0 = 29.2$ kHz. It is worth noting that $v$ is comparable to the edge poloidal rotation speed, confirming that the linear relationship between frequency and wavenumber in the laboratory reference frame is mainly due to the Doppler effect induced by the plasma rotation. The $f_0$ value can be regarded as a typical turbulence frequency in the plasma reference frame.

The procedure has been applied to a set of CASTOR discharges which were performed at three different levels of the toroidal magnetic field (1.1 T, 1.35 T, 1.5 T). For each magnetic field value, the probe was placed at three different radial positions: two inside the SOL ($r = 75$ mm and $r = 85$ mm) and one just beyond the Last Closed Flux Surface, inside the confined plasma region ($r = 65$ mm). $T_e$ ranges from 10 eV at 90 mm to 42 eV at 57 mm [5]. For each radial position of the probe, an $h$ scan was performed on a shot-by-shot basis. The resulting diffusion coefficient values are plotted in fig. 5. Notice that the diffusion coefficient increases as the magnetic field is reduced, as one would expect from the fact that the field confines the plasma. Furthermore, for a given $B$ value, the diffusion coefficient becomes larger going toward the confined plasma. The absolute values of $D$ was compared with estimations of $D$ from balance of the particle flows in perpendicular and longitudinal directions [6]. These estimations were made for $B_{tor} = 1.3$ T and show $D \simeq$5-11 m$^2$/s, which is in agreement with the fig. 5 for $B_{tor} = 1.35$ T. For the low magnetic field, however, the temperature and density profiles are not available.

The velocity and $f_0$ values resulting from the fits do not show any clear dependence on the parameters of the experiment ($B$,$r$). The velocity is in the range of $2 - 5$ km/s, the frequency $f_0$ varies between $30 - 80$ kHz. A rather large scattering of these values may be due to a shot-to-shot variation of these quantities. Anyway, it is worth noting that all the values are reasonable, giving further confidence on the suitability of the method.

An important question to be discussed is the confidence level of the diffusion coefficient values obtained by this technique. In order to get an appraisal of it, we tried to change some parameters entering the procedure, such as the length of the time window used for power spectrum evaluation and the frequency range over which the exponential decay is computed. The general result was that not all the values of these parameters yield sensible values for $D$, $v$ and $f_0$. In the cases when sensible values are obtained, a typical variation of the order of 30% of the resulting values can be obtained. This is the result of several effects, such as the statistical error on the power spectrum evaluation, which is expected to improve if longer time records with a stationary plasma behaviour can be recorded, and the imperfect shot reproducibility. This 30% can be regarded as a rough estimate of the

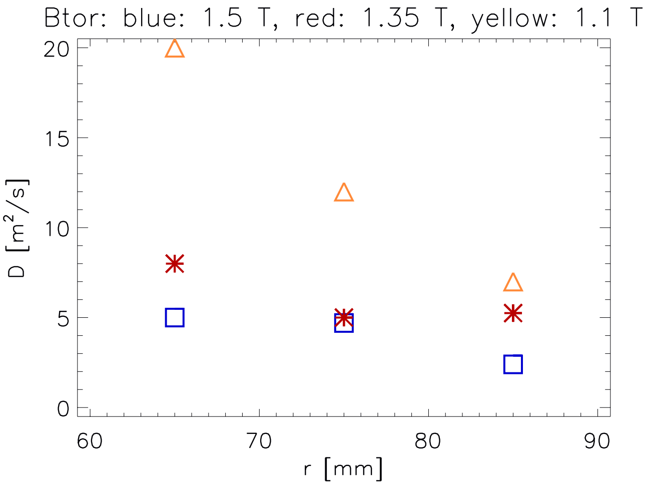

**Fig. 5** Radial profile of the diffusion coefficient for three different values of the magnetic field: 1.1 T (yellow triangle), 1.35 T (red asterix), 1.5 T (blue square). (Online colour: www.cpp-journal.org).

uncertainty level on the data shown in fig. 5, thus a better way of evaluating this error is required. Work is under way in this direction.

## 5 Conclusions

We have presented a probe-based technique for evaluating the diffusion coefficient in the edge region of a fusion plasma or in another turbulent magnetized plasma. The method is based on the decay of the turbulence power spectrum inside a dielectric tube oriented in such a way to allow mostly ions to enter, thanks to their larger Larmor radius, according to the Katsumata probe principle. The data shown in this paper reveal that the power spectrum indeed decays exponentially inside the tube, at least for a certain frequency range. By evaluating the decay length, an estimate of the diffusion coefficient can be obtained. Such an estimate has been shown to have the expected dependence on the magnetic field. While the statistical uncertainty of the estimate resulting from the method is still not easy to evaluate, the results presented herein are encouraging. A check of the method in other fusion devices or in other kinds of magnetized plasmas would be worthwhile, in order to verify its general applicability.

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