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A new probe-based method for measuring the diffusion coefficient in the tokamak edge region

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Transport in tokamaks is still an unsolved problem, although its understanding is essential for the design of new machines and of a fusion reactor. The evaluation of transport coefficients in tokamak plasmas is therefore of paramount importance, since it allows to validate different models. In this contribution we present a novel method for a direct estimation of the diffusion coefficient in the tokamak edge.

Our method is based on the use of a novel type of probe, called "ball-pen probe" which was developed to obtain a direct measurement of the plasma potential [1,2]. The probe, which is based on the Katsumata probe concept, consists of a movable collector with a conical tip housed inside an insulating boron nitride shielding, as shown in Fig. 1. The collector can be moved radially, and adjusted so as to collect equal fluxes of ions and electrons, thanks to the shadowing effect of the shielding. When such condition is reached, and the collector is floating, the collector potential will be equal to the plasma potential.

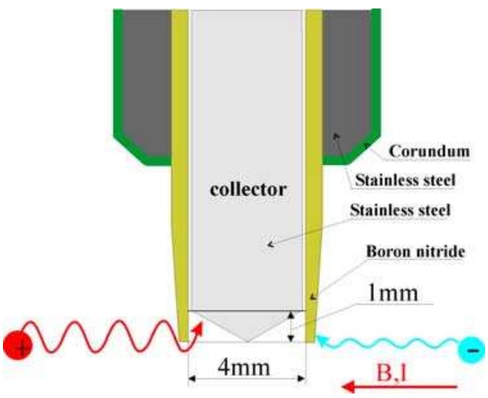

Fig.1 Schematic representation of the ball-pen probe.

We used the same probe in a different way, namely measuring the collector potential fluctuations for different values of the collector radial position h and studying the spatial decay of the fluctuation power spectrum. The same technique was also applied with the collector in the ion saturation current regime. The measurements were performed in the edge region of the CASTOR tokamak (R = 0.4 m, a = 0.085 m), in discharges having a toroidal magnetic field, B =1.2 T, and a plasma current I_p = 10 kA.

An example of power spectra, measured with the probe at r = 65 mm, for several values of the collector position h ($h > 0$ means that the collector tip is protruding from the shielding, while $h < 0$ means that it is hidden inside it) is shown in Fig. 2. It can be clearly observed that the spectrum decays as the collector is pulled inside the shielding, and that this decay is faster for higher frequencies than for lower ones.

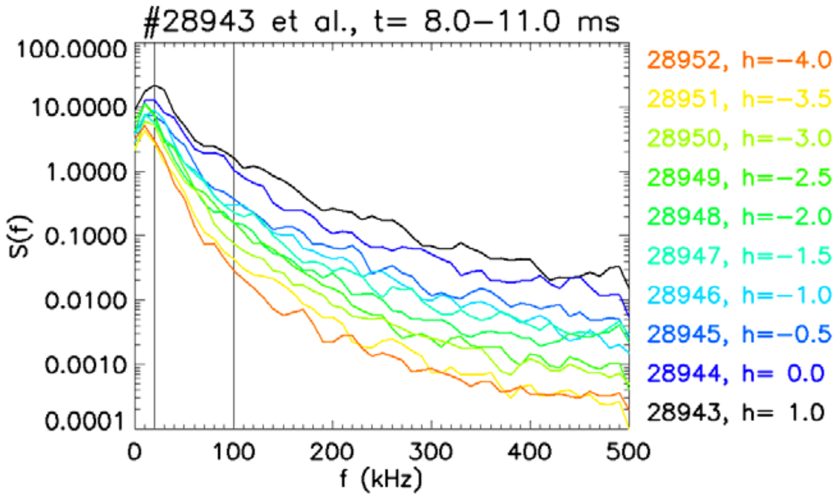

Fig. 2 Fluctuation power spectra for different collector position h *[mm]*.

In order to interpret the observed spectral decay, we have developed a simple model. The model is based on the assumption that the penetration of the plasma inside the boron nitride shielding is purely diffusive. Therefore, any plasma quantity n(x,t) can be described by a simple diffusion equation of the kind

$$\frac{\partial n}{\partial t} = D\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right) \tag{1}$$

where x represents the radial coordinate, previously marked as h, y is the poloidal coordinate (we assume uniformity with respect to the toroidal coordinate z). Since we are interested in the radial dependence, we Fourier-transform Eq. (1) with respect to y and t, obtaining

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

where $g(x)$ is the Fourier-transform of n for given wave number k and angular frequency ω. The solution of this second order differential equation with complex constant coefficients is of the form

$$g(x) = g_0 \exp[(\alpha + i\beta)x] \tag{3}$$

where

$$(\alpha + i\beta)^2 = k^2 - i\omega / D \tag{4}$$

that is

$$\begin{aligned} \alpha^2 - \beta^2 &= k^2 \\ \alpha\beta &= -\omega / D \end{aligned} \tag{5}$$

We now use the assumption that $k^2 << \omega/D$. This is justified for the frequencies we wish to analyse (below 100 kHz), since the typical experimental dispersion relation for turbulence in the CASTOR edge is $\omega \approx kv$, with $v \approx 3$ km/s, while $D \approx 1\ \mathrm{m^2/s}$. Under this assumption, we find the approximate solution

$$\alpha^2 \approx \beta^2 \approx \omega / 2D\,. \tag{6}$$

Thus, the function *g(x)* has an exponentially decaying part with a decay length $\sqrt{2D/\omega}$. The decay length of the power spectrum, which is a quadratic quantity, will be $L = \sqrt{D/2\omega}$. This implies the following linear relationship between the frequency *f* and $1/L^2$:

$$f = \frac{D}{4\pi L^2}\,. \tag{7}$$

The decay length *L* is evaluated by taking, at a fixed frequency *f*, the power spectrum for different values of *h*, and plotting them in logarithmic scale. An example of this procedure is shown in Fig. 3, where different sets of points, corresponding to different frequencies, are shown. It is seen that all sets display a good exponential decay, confirming the initial hypothesis of a diffusive process.

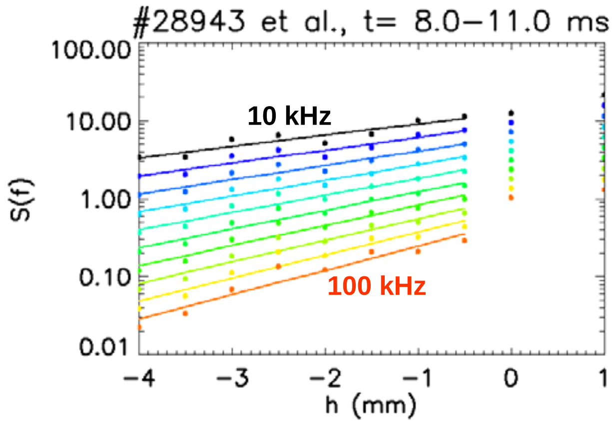

Fig.3 Radial decay of spectrum at 10 different frequencies.

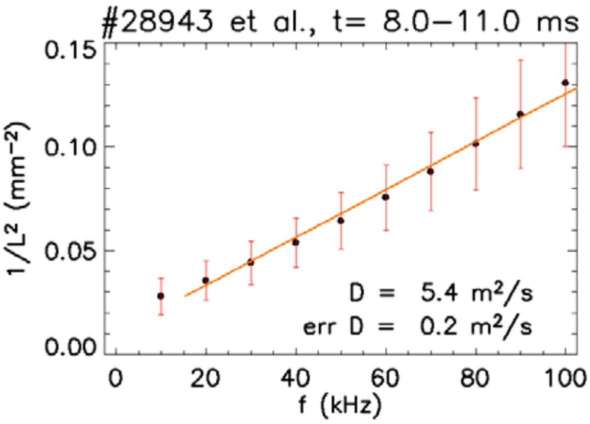

Fig.4 Dependence of $1/L^2$ on the frequency.

It is worth noting that for this procedure the degree of smoothing applied in the power spectrum computation is of crucial importance. In our case, where no fine scale features are of interest, it is appropriate to average over a rather large number of slices of the original signal, so as to obtain a smooth spectrum, well suited for an exponential fit.

The exponential fits of the sets of points displayed in Fig. 3 yield some values of the decay length *L*. Since each set was deduced at a particular frequency, we obtain a decay length *L(f)* as a function of frequency. In Fig. 4 we show the dependence of $1/L^2$ on *f*. As predicted by the model developed above, the dependence is a straight line going through the origin. The gradient of this line is equal to $4\pi/D$, so that the diffusion coefficient can be evaluated. The obtained value is of the order of 1 m^2/s, which is consistent with previous estimates of D in the CASTOR edge.

It is worth mentioning that in several cases the dependence of $1/L^2$ on f turns out to be a straight line, which does however not pass through the origin. This behaviour could be due to the approximation introduced in solving the differential equation for g. In such cases, we have used the gradient of the line to evaluate D, although a more refined analysis procedure needs to be developed.

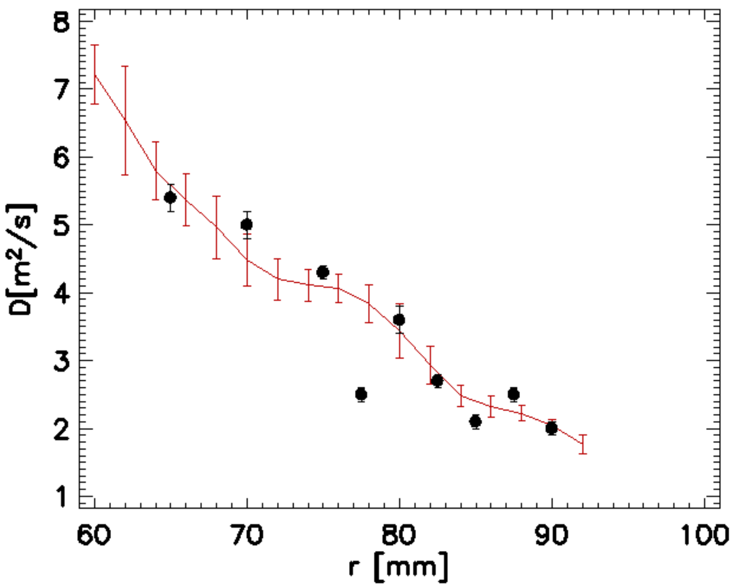

Fig.5 Radial profile of the measured diffusion coefficient (black points) compared with the Bohm one (red line).

A radial profile of the diffusion coefficient in the CASTOR edge plasma is shown in Fig. 5 (red line). Each point is the result of the analysis procedure described above, and is obtained from a set of discharges where the probe was held fixed, and the collector position was changed on a shot-to-shot basis. The values of the Bohm diffusion coefficient, obtained using the toroidal magnetic field values and the electron temperature measured with a Langmuir probe, are plotted in the same graph. This latter quantity was multiplied by an arbitrary constant equal to 4. We observe that the measured diffusion coefficient increases moving from the edge towards the core, and that it tracks very well the Bohm diffusion coefficient profile. This gives a further motivation to assume that the measured values are indeed representative of the properties of the main plasma, although further analysis will be required to assess the possible influence of processes taking place inside the shielding, in particular due to the boundary conditions.

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