A probe-based method for measuring the transport coefficient in the tokamak edge region *)

J. Brotánková, J. Adámek, J. Stöckel

Institute of Plasma Physics, Ass. Euratom/IPP.CR, AS CR, Prague, Czech Republic

E. Martines

Consorzio RFX, Associazione Euratom/ENEA sulla Fusione, Padova, Italy

G. Popa, C. Costin

Association EURATOM-MEdC, Faculty of Physics, Al. I. Cuza University, Iasi, Romania

R. Schrittwieser, C. Ionita

Association EURATOM-ÖAW, Institute for Ion Physics and Applied Physics, Leopold-Franzens University Innsbruck, Austria

G. Van Oost

Department of Applied Physics, Ghent University, Belgium

L. van de Peppel

Hogeschool Rotterdam, Rotterdam, Netherlands

Received 26 October 2006

A new method for measuring the diffusion coefficient in the edge plasma of fusion devices is presented. The method is based on studying the decay of the plasma fluctuation spectrum inside a small ceramic tube having its mouth flush with a magnetic surface and its axis aligned along the radial direction. The plasma fluctuations are detected by an electrode, radially movable inside the tube.

In the experiment described herein, which was performed in the edge region of the CASTOR tokamak, the electrode measured the floating potential. The experimental arrangement is the same used for the direct plasma potential measurements according to the "Ball-pen probe" [1], which design is based on the Katsumata probe principle.

When the electrode protrudes from the tube, the measured signal shows the floating potential fluctuations of the plasma. Retracting the electrode into the tube, the signal power spectrum displays a decay. This decay is different for different frequencies, and is exponential. Assuming a mainly diffusive behaviour of the plasma inside the tube, the spectrum decay length can be used to derive a value of the diffusion coefficient.

The measurement were performed at different radial positions in the CASTOR edge region, so that a radial profile of the diffusion coefficient was obtained. Typical values of D are of $2 - 3\mathrm{m}^2/\mathrm{s}$, consistent with expectations from the global particle balance. The radial profile shows a tendency of the diffusion coefficient to increase going deeper into the plasma.

*) Presented at the Workshop "Electric Fields, Structures and Relaxations in Edge Plasmas", Roma, Italy, June 26-27, 2006.

PACS: 52.25Xz, 52.55.Fa, 52.70.-m
Key words: toroidal plasma, tokamak, plasma diagnostics, plasma probes, power spectra, diffusion

1 Introduction

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.

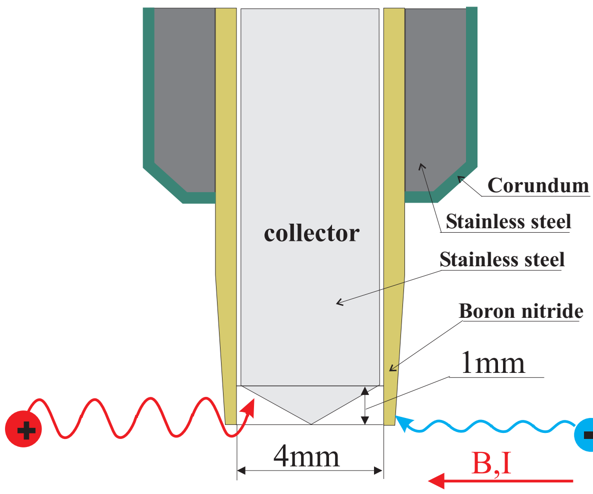

Fig. 1. Schematic representation of the ball-pen probe.

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.

2 Theory

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.

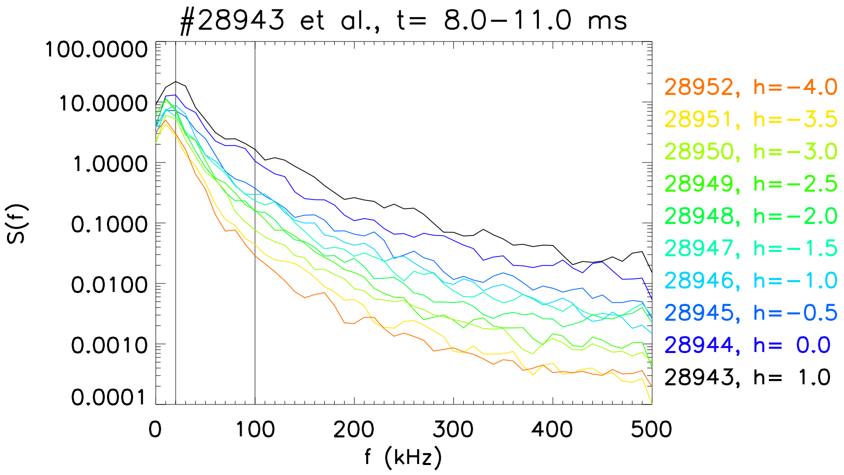

Fig. 2. Fluctuation power spectra for different collector position h[mm].

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

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

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 $D \approx 1$ 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 $1/L^2$:

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

3 Evaluation of transport coefficient

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.

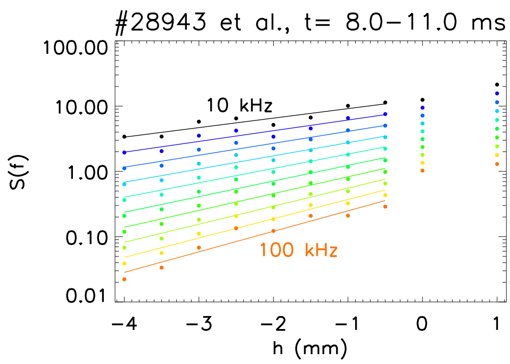

Fig. 3. Evaluation of transport coefficient: radial decay of spectrum at 10 different frequencies.

It is worth noting that of crucial importance in applying this procedure is the degree of smoothing applied in the power spectrum computation. As explained in any spectral analysis textbook (and too often disregarded by scientists) a statistically meaningful evaluation of a power spectrum requires the estimation of an ensemble average [3]. This is usually obtained dividing the signal in a number N_s of equal length segments, usually called slices, computing the Fourier transform of each of them, and averaging them together. The value of N_s determines both the statistical error on the spectrum and the frequency resolution: a small N_s results in a spectrum affected by large statistical uncertainty ("noisy") but well resolved in frequency, while a high value gives a more precise evaluation, but can lead to the loss of features which are well localized in frequency. A trade-off between these two situations has to be found, based on the type of spectrum to be analysed. In the present situation, where no fine scale features are of interest, it is appropriate to use a rather large number of slices, so as to obtain a smooth spectrum, well suited for an exponential fit. On the other hand, if N_s is chosen to be too large, there may not be enough independent frequency points to which the procedure can be applied. In our analyses we chose N_s to be such that ten frequency values between 10 kHz and 100 kHz are available for the analysis.

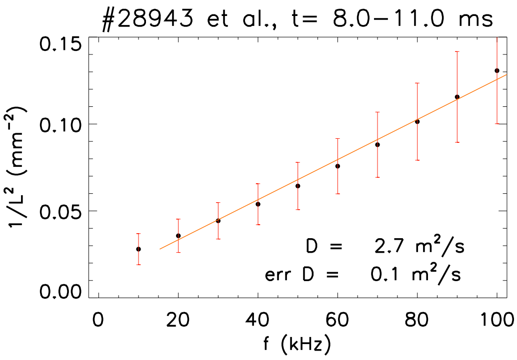

Fig. 4. Evaluation of transport coefficient: dependence of $1/L^2$ on the frequency.

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 $1/L^2$ as function of f to evaluate D, although a more refined analysis procedure needs to be developed.

Also, in some cases (mainly in the deeper positions of the plasma column), the method fails: the decay of the spectrum with h (Fig.4) is not clear, thus the exponential fits don't work. A possible explanation could be that in these cases the transport is dominated by convection due to radially propagating coherent structures (blobs). This phenomenon requires further investigation.

4 Results and conclusions

A radial profile of the diffusion coefficient in the CASTOR edge plasma is shown in Fig.5. Each point is the result of the analysis procedure described above, and is obtained from a set of discharges where the probe was fixed, and the collector position was changed on a shot-to-shot basis (black points). 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 (red line). This latter quantity was multiplied by an arbitrary constant equal to 1/8. We observe that the measured diffusion coefficient increases moving from the edge toward the core, and that it tracks very well the Bohm diffusion coefficient profile.

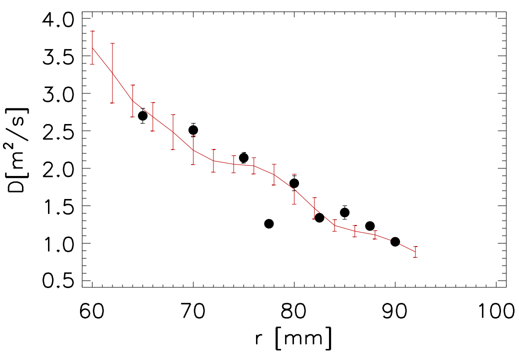

Fig. 5. Radial profile of the measured diffusion coefficient (black points) compared with the Bohm one (red line).

This work presents a novel method for measuring the diffusion coefficient in the edge plasma. The resulting diffusion coefficient values show a good agreement with the Bohm model. It is worth to remark, however, that the method is based on the assumption of a diffusive behaviour of the plasma itself, and that this assumption is challenged by recent work showing that transport in the tokamak edge is mostly due to radially propagating turbulent structures [4, 5]. Therefore, further analysis will be required to clarify the relationship between these results and current works, especially to assess the possible influence of processes taking place inside the shielding, in particular due to the boundary conditions.

This work was carried out within the Associations EURATOM-IPP.CR, -ENEA, -MedC, and –ÖAW and was supported by project GA AV B100430601 of the Grant Agency of AS CR, and by INTAS Grant 2001-2056.

References

[1] J. Adámek, J. Stöckel, M. Hron, J. Ryszawy, M. Tichý, R. Schrittwieser, C. Ionita, P. Balan, E. Martines, G. Van Oost, *Czechoslovak J. Phys.* **54** (2004), C95-C99.

[2] J. Adámek, J. Stöckel, I. Ďuran, M. Hron, R. Pánek, M. Tichý, R. Schrittwieser, C. Ionita, P. Balan, E. Martines, G. Van Oost, *Czechoslovak J. Phys.* **55** (2005), 235-242.

[3] J. S. Bendat, A. G. Piersol, *Random Data, Analysis and Measurement Procedures*, 2nd Edition, John Wiley and Sons, 1986.

[4] J.A. Boedo et al.: *Phys. of Plasmas* **10** (2003) 1670.

[5] P. Devynck, J. Brotankova, P. Peleman, M. Spolaore, H. Figueiredo, M. Hron , G. Kirnev , E. Martines, J. Stockel, G. Van Oost ,V. Weinzettl, *Phys. of Plasmas 13*, 102505 (2006) .