# Poloidal structure of the turbulence and the turbulent flux during edge plasma biasing in the Castor tokamak

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**Abstract :**

The poloidal structure of the turbulence and the turbulent particle flux in the scrape off layer (SOL) of the CASTOR tokamak are analysed by means of a poloidal ring of 124 probes distributed uniformly along the whole poloidal circumference. Fluctuation measurements are performed in standard ohmic regime as well as in discharges when a biased electrode is inserted either into the SOL or deeper into the confinement region. It is found that in both the cases, a strongly sheared radial electric field is created in the SOL, which de-correlates the density and radial velocity fluctuations and reduces their levels. Consequently, the turbulent flux is reduced. However, no phase shift is observed between density and radial velocity fluctuations. When the electrode in localized in the confinement region, all the above effects are less pronounced because of a smaller shear. In addition, the increase of the ExB velocity at biasing leads in both cases to the formation of oscillations in the temporal correlation function. These oscillations are specifically associated to the poloidal mode (m=q), which is created for a limited time and rotates poloidally. This mode does not modify the phase between density and radial velocity fluctuations and has no further effect on the turbulent flux.

## 1. Introduction

Many papers describe the impact of biasing on the edge fluctuations and associated transport. Shearing of the turbulent eddies by the sheared radial electric field [1] is widely accepted to be the dominant mechanism for the de-correlation of the structures and reduction of turbulent flux. When such a shear is formed in the confinement region, it leads to the formation of a transport barrier and to an improved confinement [2,3]. Such mechanism has been studied in detail in numerous machines [4] with the restriction that only a limited range of poloidal angles is investigated. Moreover, most of the turbulence studies in the SOL consider effects occurring in the r/θ plane and neglect any parallel or toroidal effects while the SOL itself is really 3 dimensional because the magnetic field lines are not closed. In particular, the effect of the parallel connection lengths is never taken into account because no information is available about them. For example, it is found in some devices that a time periodicity exists in the turbulent signals at some radial locations [5,6,7] but no information on its full poloidal extent is known and one can only speculate about the nature of such mechanism. In this paper it is found that in fact time periodic events in the SOL can be related to the geometry of the plasma, the long parallel connection lengths and also to the poloidal propagation speed of the turbulence. We analyse here the turbulence in the SOL of the CASTOR tokamak at many poloidal positions measured simultaneously thereby revealing some effects generated by the geometry of the system.

## 2. Experimental arrangement:

The tokamak CASTOR and biasing schemes are described elsewhere [8]. In present experiments, the parameters of the plasma are the following: R=0.4m, =0.058 m, Bt=1 T, Ip=7 kA, <ne>=1×10 $^{19}$ m$^{-3}$, duration of the quasistationary phase of the discharge is 20 ms. The edge safety factor is around q(a)=8. The poloidal structure of the the edge turbulence is investigated with a poloidal ring of 124 probes covering the whole poloidal perimeter with a spatial resolution of 3 mm. The poloidal ring represents in fact a poloidal limiter of 58 mm of radius on which the probes are fixed. To measure the turbulent flux, the probes are alternatively in the floating potential and ion saturation regime. The number of 1 MHz synchronized acquisition channels (32) allows to measure the flux at 15 poloidal positions on one quadrant of the poloidal ring. In measurements described here, the flux is measured on a quadrant situated on the bottom low field side of the machine. A rake probe located at the top of the machine, composed of 16 probe tips is also used to measure the radial profiles of floating potential in the SOL with a resolution of 2.5 mm. A massive graphite electrode inserted from the top of the machine at another toroidal angle is used to apply the positive 100 V bias for a time limited to 2 ms in the middle of the plasma current plateau. This electrode can be inserted at different radial positions allowing to bias the SOL or the confinement region.

## 3. Turbulence properties in ohmic regime:

In this section, we present some basic information about the nature of the turbulence in CASTOR. For this purpose we use 32 floating probes, uniformly distributed around the full poloidal section. The plasma column is approximately centered and all the probes are located in the proximity of the shear layer.

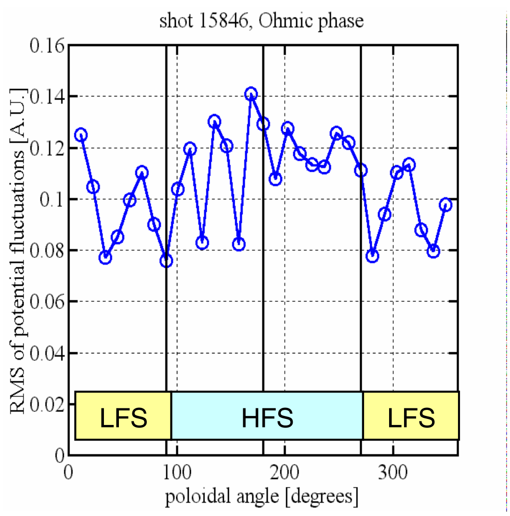



**Figure 1:** *RMS of floating potential fluctuations measured on 32 tips equi-distributed around the poloidal limiter during the ohmic phase of the discharge.*

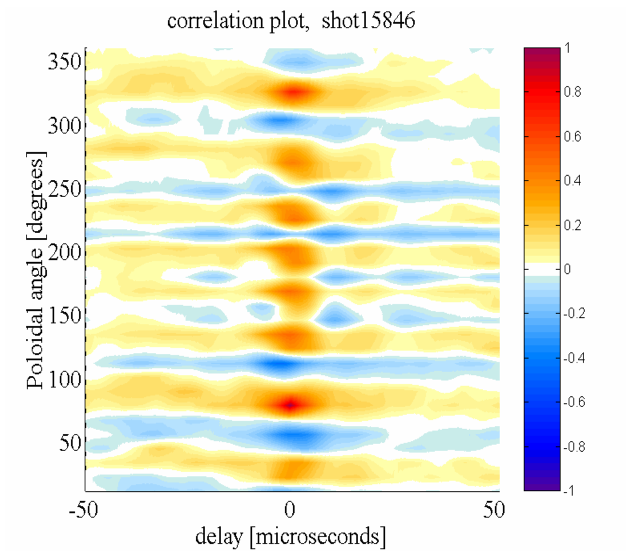



**Figure 2***: Temporal correlation plot of the potential fluctuations on the poloidal ring of probes during the ohmic phase. The reference probe is taken at 80°.*

Figure 1 shows the root mean square (RMS) value of potential fluctuations as a function of the poloidal angle. As seen, the level of fluctuations is in average the same on high field side (90° -270°) and low field side (270° -90°) of the torus. This indicates the absence of any ballooning effects in the SOL, which are expected to create a strong asymmetry between high and low field side. The lack of clear ballooning effect is also observed in the SOL of other tokamaks such as HYBTOK-II [10] or TF-I [11]. However, a rather high aspect ratio of the

CASTOR, R/a=7, is not favourable for the observation of such ballooning. Therefore any general conclusion can not be drawn regarding its existence.
Figure 1 also shows a poloidal modulation of the RMS values of the potential fluctuations. The periodicity is found to correspond to the edge safety factor, which is q=8 in this case. A similar periodicity in the mean value of the floating potential and its RMS value is observed, when the biasing electrode is inserted into the SOL and an explanation is suggested in [9]. However, in the described experiment, the electrode was unbiased and pulled out of the SOL. Therefore, the underlying physics of this observation is not clear and this result must be further analysed.

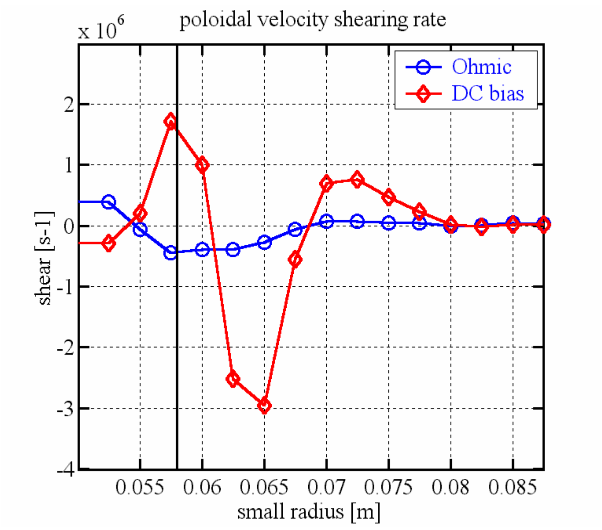
In Figure 2, the spatial-temporal correlation function of floating potential fluctuations is plotted. It is seen in the figure that the reference probe is either correlated or anti-correlated with all remaining probes distributed along the poloidal ring. The level of correlation is high. The poloidal mode number is 8, which is again in the range of the edge safety factor $q$. This correlation pattern can be explained by the position of the probes in the proximity of the last closed flux surface where the helical magnetic field lines are still closed. The helicity of the field lines around the torus will allow to the same turbulent structure reappear q times in the poloidal section. The observed poloidal periodicity corresponds in fact to the parallel continuity of the turbulent structure around the tokamak. The fact that the correlation extends all around the poloidal circumference demonstrates that the turbulence remains correlated over 23 m along the field lines.

Another interesting feature seen in Fig. 2 is that all the correlation patterns are not inclined in the (θ,t) plane, but parallel to the time axis. This indicates that there is no poloidal propagation of the turbulence. In this case, the correlation functions only reflect the lifetime of the turbulence, which is found to be of the order of 100 μs. The lack of poloidal velocity of fluctuations in a region where the ExB velocity is also null indicates that if the turbulence has any phase velocity (such as the one which is expected for a wave instability), it must be extremely small. Therefore, the SOL turbulence is convected by the ExB velocity and that there is probably no additional phase velocity involved in its propagation. Such a conclusion imposes strong constraints on the nature of the instability underlying the turbulence and points towards an instability of the flute type.

## 4. Edge biasing

*4a) Biasing electrode is located in the SOL.*
Measurements described in this section are performed in the magnetic configuration with the plasma column shifted towards the high field side of the torus. As a consequence, a fraction of the poloidal ring (on the low field side) appears to be located inside the SOL. More specificaly, the experimental data from 32 probes, located on a poloidal quarter of the ring corresponding to the bottom low field side of the plasma, are analyzed. The biased electrode is inserted slightly deeper than the radius of the poloidal ring, but being still outside the last closed flux surface.

The most important effect of biasing is the creation of a strongly sheared radial electric field in the SOL as documented in Fig. 3, where the shearing rate is plotted as a function of the radius. The radial electric field is deduced from the radial profile of the floating potential measured by the rake probe, assuming that the gradient of the electron temperature can be neglected. The figure demonstrates that the shearing rate at biasing (~$3\times10^{6}$ $s^{-1}$) is much higher than the growth rate of the fluctuations, which can be roughly estimated as the inverse autocorrelation time of the fluctuations (of about $7\times10^{4}$ $s^{-1}$). Therefore, a strong effect of biasing on the fluctuation levels and associated transport is expected. This is confirmed by experimental results shown in Figure 4, which displays the poloidal distribution of the mean turbulent particle flux along one quarter of the poloidal ring (low field side, bottom).



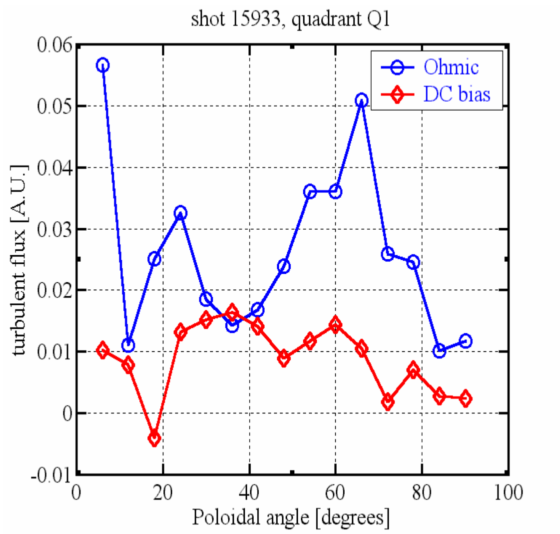
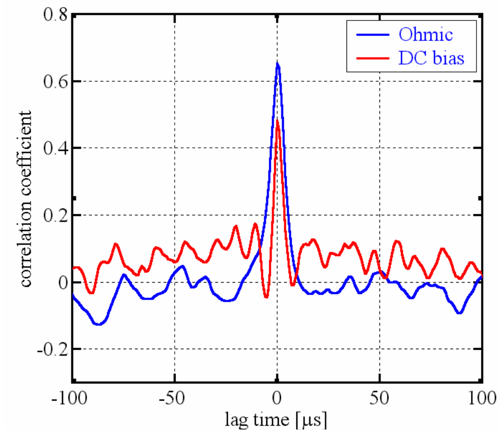




***Figure 3 :** Shearing rate of the radial electric field measured by the rake probe as a function of radius. The vertical line indicates the position of the poloidal ring. The biasing electrode is located inside the SOL.*

***Figure 4:** Mean turbulent particle flux measured on a quadrant of the poloidal ring, located at the low field side bottom of the plasma, 0 degree is the equatorial plane, 90 degrees is the bottom of the chamber.*

Figure 4 shows that some poloidal asymmetries of the turbulent flux are observed during the ohmic phase of the discharge, but the turbulent particle flux is reduced to approximately the same level everywhere at biasing. We found that the turbulent flux is reduced because of two reasons. At first, the level of density fluctuations is strongly reduced. Secondly, a de-correlation between the density, $\delta n$, and radial velocity, $\delta v_r$, fluctuations is observed as documented in Fig. 5. There, the correlation function $f(\tau)=<\delta v_r(t)\ \delta n(t+\tau)>$ is plotted as a function of the poloidal angle. It is seen from the figure that the maximum correlation is indeed reduced at biasing from 0.65 to 0.5. However, the maximum of the correlation function occurs at zero time lag in both the regimes, which indicates that the phase remains adjusted to maximize the transport. Thus the turbulent flux is reduced due a decrease of the cross-correlation between density and radial velocity fluctuations and their levels, but not due to an additional phase shift between them.



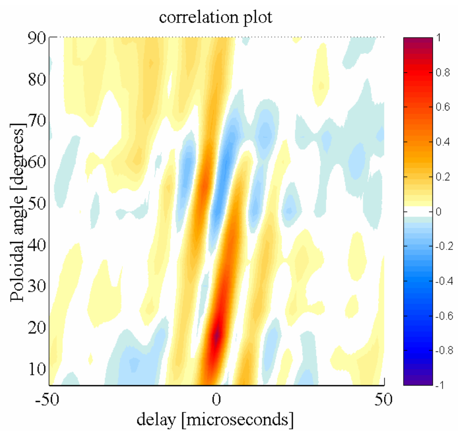




**Figure 5 :** *Cross correlation function between density and radial velocity fluctuations measured at 60° below the equatorial plane, low field side. The biasing electrode is localized in the SOL.*

**Figure 6:** *Spatial-temporal correlation plot of the ion saturation current fluctuations on a quadrant of the poloidal ring of probes during biasing. The reference probe is located at 20°.*

Another interesting feature, which should be noted in Fig. 5, is the presence of a few periodic oscillations on the correlation function around zero lag time during biasing. Such oscillations are more evident on the spatial-temporal correlation plot of density fluctuations shown in Fig 6. There, the signals of a reference probe and all remaining probes of the selected quadrant are correlated and the correlation amplitude is plotted as a function of the poloidal angle. There, along the time axis, three pronounced maxima are evident at a broad range of poloidal angles before the correlation amplitude drops to the noise level. The corresponding frequency is estimated to be around 100 kHz. The poloidal phase velocity can be deduced from the slope of the correlation patterns, being about 4.4 km/s, which is roughly four times more than in the ohmic case.

Information on the poloidal structure of the density fluctuations can be drawn from the correlation plot shown in Fig. 6. The two maxima of the correlation amplitude can be easily counted along the vertical axis of the plot (one quarter of the poloidal circumference) at the time lag $\tau$=0. This implies the poloidal mode number m=8, which again roughly equal to the edge safety factor $q$. This value is confirmed by the 2D Fourier analysis of the probe data.

Finaly, it must be noted that any significant inpact of the SOL biasing on the global particle confinement time is not observed.

*4b) Electrode is located in the confinement region*

When the bias is applied to the electrode located in the confinement region ($r_{bias}$=45 mm), the whole plasma column is biased and the mean floating potential increases everywhere including in the SOL. An increase of the mean density is observed during biasing, which indicates formation of a transport barrier in front of the last closed flux surface [8]. In the SOL, the turbulent transport is reduced (see Fig. 7), most probably due to modification of the radial profile of the local $E_r \times B$ shearing rate.

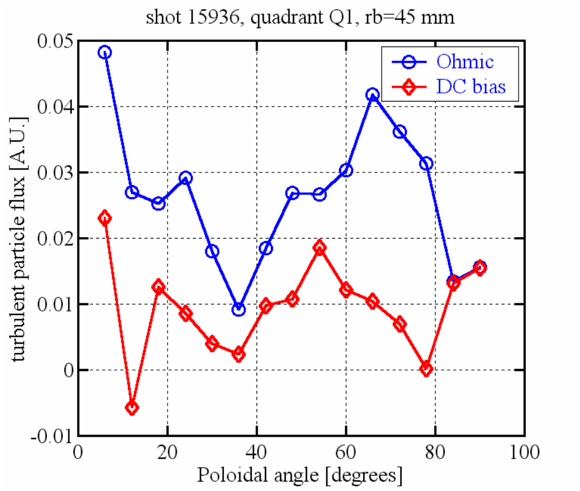



**Figure 7:** *Mean turbulent particle flux measured on a quadrant of the poloidal ring, located on the low field side bottom of the plasma, 0 degree is the equatorial plane, 90 degrees is the bottom of the chamber.*

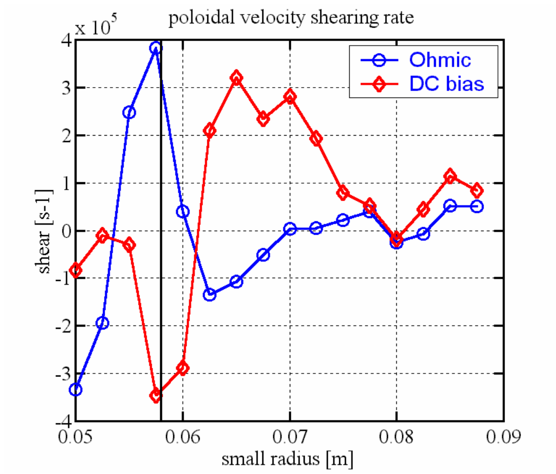



**Figure 8**: *Shearing rate of the radial electric field measured on the rake probe as a function of radius. The vertical line indicates the position of the poloidal ring. The biasing electrode is in the confinement region.*

Figure 8 shows that during the ohmic phase, the maximum of the $E_r \times B$ shearing rate is about $4 \times 10^5$ $s^{-1}$, but only in a narrow region in the proximity of the shear layer, being negligible in the rest of the SOL. The shearing rate does not increase during biasing, but the sheared region extends deeper inside the SOL. The average shearing rate, of about $3 \times 10^5$ $s^{-1}$, is still higher than the ohmic one (~$7 \times 10^4$ $s^{-1}$). Both the density and radial velocity fluctuations are reduced and de-correlated during biasing as illustrated in Fig. 9 where their cross correlation function is plotted. But, the correlation maximum remains again at zero time delay, therefore, there is any additional phase shift does not appear with biasing. In contrast to the SOL biasing (compare with Fig. 5), the oscillations in the correlation function are more apparent and detected for more than 100 μs.

Figure 10 shows the spatial-temporal correlation plot of the density fluctuations, equivalent to that shown in Fig. 2. The temporal periodicity is evident. The corresponding frequency (of about 80 kHz) is concomitant with an increase of the poloidal velocity from ohmic value ~1.3 km/s to 3.8 km/s during biasing. Again, the temporal periodicity is associated with the poloidal periodicity m=8.

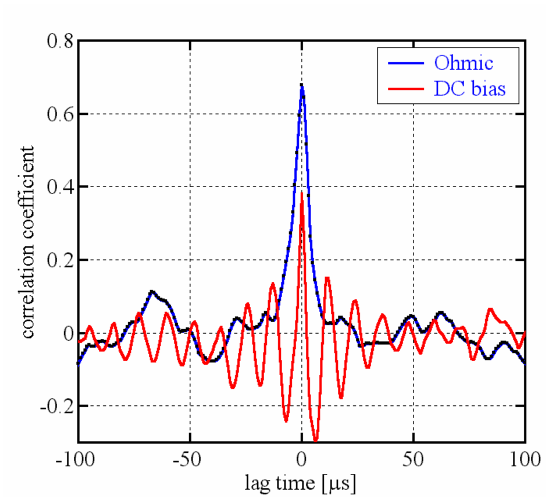



**Figure 9 :** *Cross correlation function between density and radial velocity fluctuations measured at 60° below the equatorial plane, low field side. The biasing electrode is localized in the confinement region.*

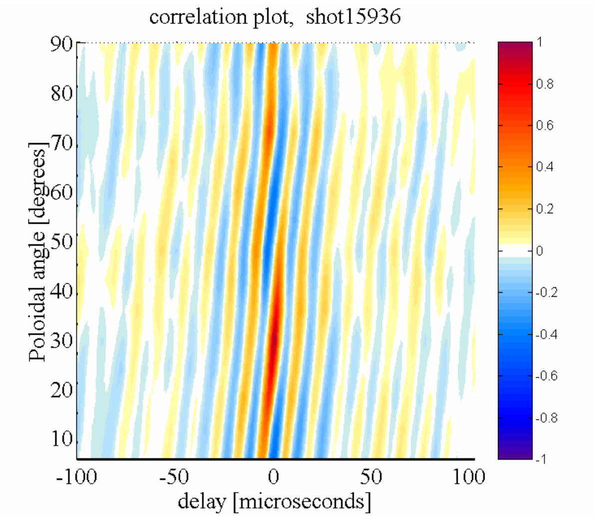



**Figure 10 :** *Temporal correlation plot of the potential fluctuations on a quadrant of the poloidal ring of probes during ohmic phase. The reference probe is at 30°. The biasing electrode is localized in the confinement region.*

The oscillations in the correlation function can be explained by the poloidal rotation of the m=q mode. First of all, because of the parallel continuity of the turbulence, the same turbulent structure reappears *q* times (giving *q* "nodes") around the poloidal section. The distance separating two consecutive nodes is $L=2\times\pi\times a/q(a)$ where *a* is the small radius and *q(a)* is the edge safety factor. As the turbulence rotates poloidally, a node at position N will be reached by the node at position N-1 in the time $L/v_\theta$ and will give rise to one oscillation in the correlation function, the node at N-2 will reach position N at the time $2L/v_\theta$ and will give an additional oscillation on the correlation function, etc. The number of oscillations M observed in the correlation function depends on the correlation time of the turbulence $\tau_l$ in the frame moving with the plasma and can be expressed approximately as

$$M\sim\tau_l/(L/v_\theta)=\tau_l\times v_\theta\times q/(2\times\pi\times a) \qquad (1)$$

This expression is valid in all cases including the ohmic phase and oscillations can always be observed provided that $\tau\times v_\theta\times q > 2\times\pi\times a$.

The different oscillatory behavior in the SOL and confinement region biasing schemes (Fig. 6 and Fig. 10) occurs most probably because of different correlation times, since all other parameters of expression (1) (i.e. q, $v_\theta$, a) are of a similar value. More oscillations is observed in the case of confinement region biasing, because the shearing rate is by one order of magnitude lower than with the SOL biasing, which seem to be not sufficient to reduce the lifetime of the turbulence in the SOL.

However, it must be noted that the temporal correlation function in the case of Fig. 10 oscillates much beyond the ohmic correlation time of the SOL turbulence. This implies that the rotating m=8 mode has a longer lifetime at biasing than that in the ohmic phase. This feature is not understood at the moment.

## 5. Conclusions:

The behavior of the turbulent SOL transport turns out to be very similar whichever the bias is applied inside the SOL or deeper in the confinement region. The shearing rate measured within the SOL is found to be sufficient to de-correlate the density and radial velocity fluctuations and reduce their levels in both the biasing schemes. This leads to a reduction of the turbulent particle flux at biasing. However, no phase shift between density and radial velocity fluctuations is found.

In addition, regular oscillations in the temporal correlation function are observed. A simple geometrical interpretation, based on the poloidal rotation of the m=q structure, is suggested and the condition for appearance of the oscillations is proposed.

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