

## Identifying turbulence phenomena in the Wendelstein 7-AS stellarator

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### Introduction.

Numerical simulations of turbulence in a fusion plasma often show the appearance of various large scale structures like streamers and zonal flows. Although some of these structures are believed to have a decisive role in anomalous transport processes[1] their experimental observation is still missing. To detect these phenomena one would need spatially and temporally highly resolved measurement of the fluctuation of various plasma parameters ( $\tilde{n}_e$ ,  $\tilde{T}_e$ , ...) especially in the core plasma where these structures are expected. This is an extremely difficult task given the small amplitude ( $\approx 1\%$ ) and limited access.

Most of the relevant fluctuation diagnostics (e.g. collective laser scattering;  $\tilde{n}_e$ , Electron Cyclotron Emission (ECE);  $\tilde{T}_e$ , Beam Emission Spectroscopy (BES);  $\tilde{n}_e$ , reflectometry;  $\tilde{n}_e$ ) are either limited in resolution or even can deliver only spatially integrated measurements. Even if these diagnostics are available on the same machine, the interpretation of data from various measurements would require some preliminary information on the shape of the spatial structures. In stellarator configuration the situation is further complicated by the three-dimensional geometry. Combining data from several diagnostics requires detailed numerical simulation of turbulence in real 3D geometry and a realistic calculation of measurement signals. To compare theory to experiment a large number of calculations would be necessary which is currently not possible due to the huge computing power requirements.

The work presented in this paper is the first step in an attempt to bridge the gap between theory and experiment by starting from the experimental side; diagnostic signals are simulated from a random ensemble of fluctuation phenomena with prescribed spatial and temporal behavior. We believe that such a procedure will give more insight into the shape and movement of the perturbations and finally will allow fitting of free parameters of the structures (e.g.  $B_{\parallel}$  length, flow velocity, etc.) from correlation measurement with various diagnostics.

### The simulated perturbations.

As fluctuation measurements on various machines show  $k_{\parallel} \approx 0$ , the structures are simulated in *magnetic flux coordinates* (straight field-line coordinates), following the magnetic field lines. Gaussian shapes are considered with different widths in radial, poloidal and  $B_{\parallel}$  direction.

The three coordinates of the flux coordinate system are defined as follows. The  $\psi$  coordinate is taken equal to the toroidal angle. The  $R_{eff}$  radial coordinate labels the magnetic surfaces. The  $\varphi$  poloidal angle labels the magnetic field lines on a magnetic surface (*field line label*), therefore  $\varphi = const$ ,  $R_{eff} = const$  marks a single field line.  $\varphi$  is set to 0 along a horizontal line starting from the magnetic axis to the outer edge of the plasma in a fixed  $\psi = \psi_0$  section, as shown in Fig. 1. The scale of  $\varphi$  is defined in a way that the flux in a  $d\varphi \times dR_{eff}$  box is constant on a flux contour.

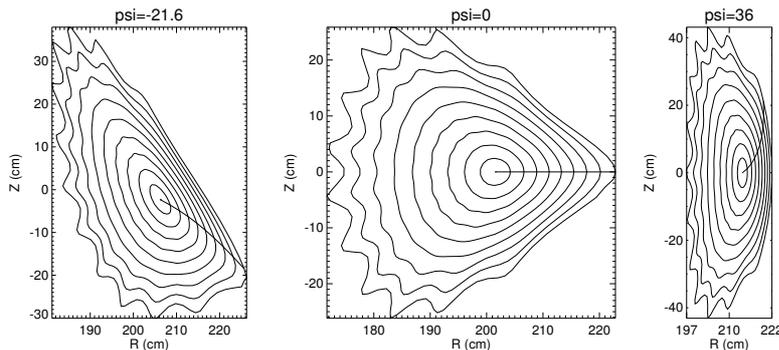


Fig. 1.  $\varphi = 0$  lines in various sections of the Wendelstein 7-AS stellarator.

As we need to calculate the effect of these perturbations in an  $(R, Z, \psi)$  cylindrical coordinate system, a mapping between these two systems constitutes the essence of the simulation. For a given  $(R, Z, \psi)$  point  $R_{eff}$  is calculated from the local flux contours at  $\psi$ , while  $\varphi$  is determined by following the magnetic field line around the torus to  $\psi_0$ .

Mapping along the field lines is not done explicitly but it is based on interpolation in a table of precalculated field line mapping data. This method ensures short calculation times and flexibility to use magnetic geometry from different machines and discharges. The results shown in this paper were calculated using mapping data from the TRANS code, which represents a finite beta equilibrium reconstruction of a W7-AS discharge.

The above described  $(R, Z, \psi) \rightarrow (R_{eff}, \varphi, \psi)$  transformation provides multiple  $\varphi$  values for one point as field line tracing can be done in either positive or negative  $\psi$  direction and it can be continued over many toroidal turns. This is indeed necessary if the structures have a length comparable to the major circumference of the torus, as observed experimentally[2]. This problem of multivalued coordinates is handled by keeping a finite number of these mappings with appropriate  $\psi = \psi \pm n \cdot 2\pi$ , ( $n = 0, 1, \dots$ ) coordinates as shown by  $P_0, P_1^\pm, \dots, P_i^\pm$  in Fig. 2.

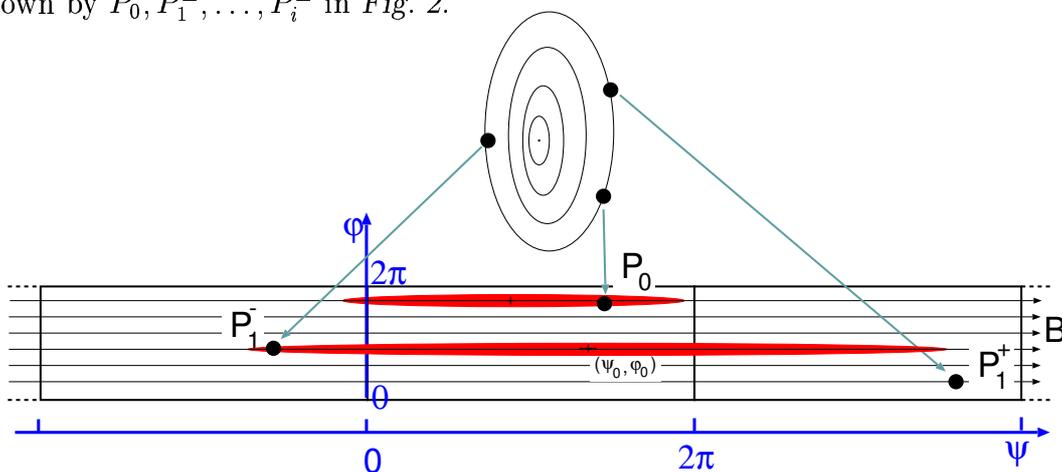


Fig.2. Measurement points and Gaussian structures in an  $R_{eff} = const$  surface in the  $(\psi, \varphi)$  coordinate system. Explanation in the text.

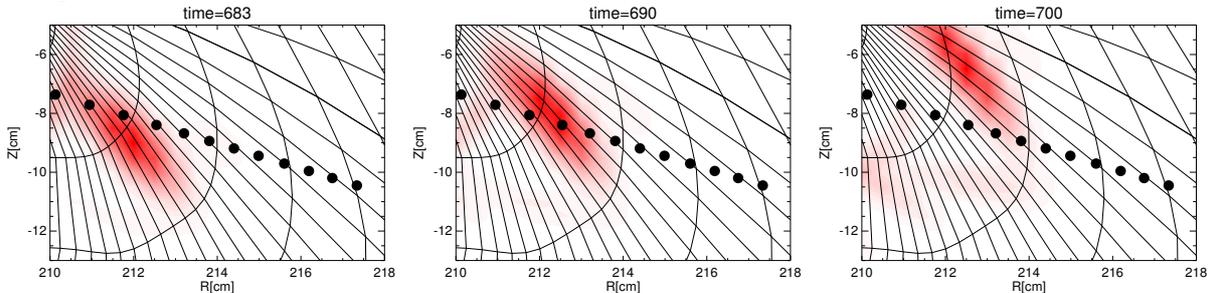
The structures are generated with  $\varphi_0, \psi_0$  center points in the  $\psi_0, \varphi_0 \in [0, 2\pi]$  range but observation points are enabled outside of this  $\psi$  range as well. This corresponds to the fact that the "tail" of a structure might be seen by the measurement after several toroidal turns. In the actual simulation the value of the perturbation is calculated at every mapped measurement point and the largest value is kept as the actual measurement signal. If the perturbation is sufficiently localised poloidally only one of these "virtual

measurement values” will be different from zero. This approach fails if the rotational transform is close to a low-order rational so as the structures map on themselves along a field line. This case is excluded from the current version of the simulation.

The shape of the perturbations is described by a Gaussian with fixed (but different) widths along  $R_{eff}$ ,  $\varphi$  and  $\psi$ . Their temporal behavior is also taken to be Gaussian with a certain lifetime and they are moved along  $\varphi$  with a given  $v_\varphi$  velocity:

$$A(R_{eff}, \varphi, \psi, t) = A_0 \exp \left\{ -\frac{(R_{eff} - R_{eff}^0)^2}{2w_R^2} - \frac{(\varphi + v_\varphi(R_{eff})t - \varphi_0)^2}{2w_\varphi^2} - \frac{(\psi - \psi_0)^2}{2w_\psi^2} - \frac{(t - t_0)^2}{2w_t^2} \right\}$$

(Toroidal flow is not considered because in the non-axisymmetric W7-AS machine the dominant flow velocity is expected to be poloidal.) To be able to base the simulation on experimental data the flow velocity is not given by  $v_\varphi$  but by the  $v_p$  poloidal velocity in the physical  $R, Z$  coordinate system at  $\psi_0, \varphi_0 = 0$ , where the poloidal velocity is vertical. The flow velocity in the transformed coordinates is calculated as  $v_\varphi = (\partial\varphi/\partial Z) v_p$ . Taking a  $v_p(R)$  velocity profile we arrive at  $v_\varphi(R_{eff})$ . Although  $v_\varphi$  is independent of  $\phi$  the flow velocity in real physical space is strongly dependent on the poloidal location due to flux compression.



*Fig. 3. Movement of a simulated structure in the  $R - Z$  space in case of constant  $v_p(R)$  velocity profile. The solid lines mark constant  $R_{eff}$  and  $\varphi$  contours. The  $\psi = const$  section is the same where the Li-beam diagnostic is located, the dots mark the measurement points.*

### Simulations and measurements

As a first attempt signals of the quasi-twodimensional Lithium-beam Beam Emission Spectroscopy (BES) fluctuation diagnostics[3] are simulated. This diagnostic is capable — although with a limited range and spatial resolution — of analyzing the correlation function of electron density fluctuations in both the radial and poloidal direction. In the standard onedimensional operation density fluctuations at multiple points along a straight line in the plasma are measured; the measurement points are shown in *Fig. 3*.

Experimental signals were simulated by generating several thousand structures with fixed  $A_0$  amplitude and  $w_t, w_\psi, w_\varphi, w_R$  widths and various  $v_p(R)$  poloidal flow velocity profiles. The  $B_{||}$  size of the structures was short, so as each structure was seen only by one mapped measurement point during their lifetime. The numerically generated signals were analysed statistically using the same programs as for the analysis of real experimental data. Crosscorrelation functions  $C(Z_i^b, Z_j^b, \tau)$  are calculated, where  $Z_i^b$  is the coordinate of a measuring channel along the Lithium beam, and  $\tau$  is the time lag.

The calculation were done with two different flow velocity profiles: constant  $v_p(R)$  and sheared flow with  $v_p$  changing a factor of three in 3 cm. The resulting correlation functions are shown in *Fig. 4*. The plot with constant flow shows a clear virtual radial propagation velocity which is caused by the angle between the Li-beam and the structures. In the sheared flow case the correlation function is more complex, it looks like

superposition of structures with different inclination. This happens due to the fact that structures originating at different poloidal distances upstream from the observing beam suffer different amount of shearing while reaching the beam.

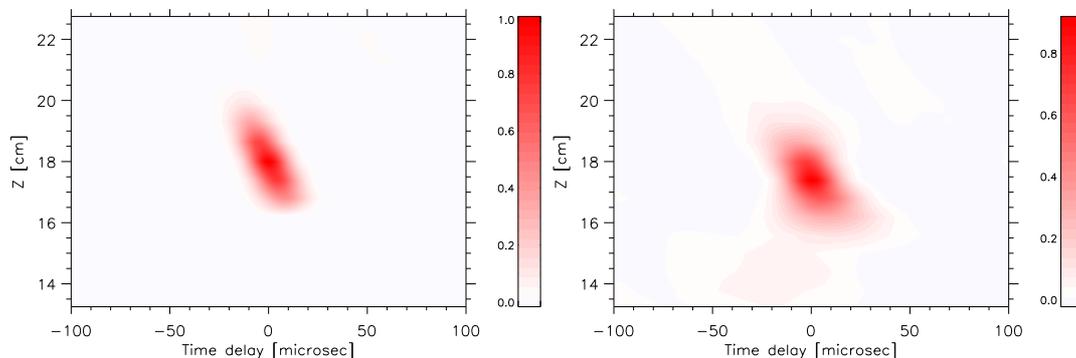


Fig. 4. Simulated spatiotemporal correlation functions in the SOL. Constant poloidal flow velocity (left), and sheared flow (right).

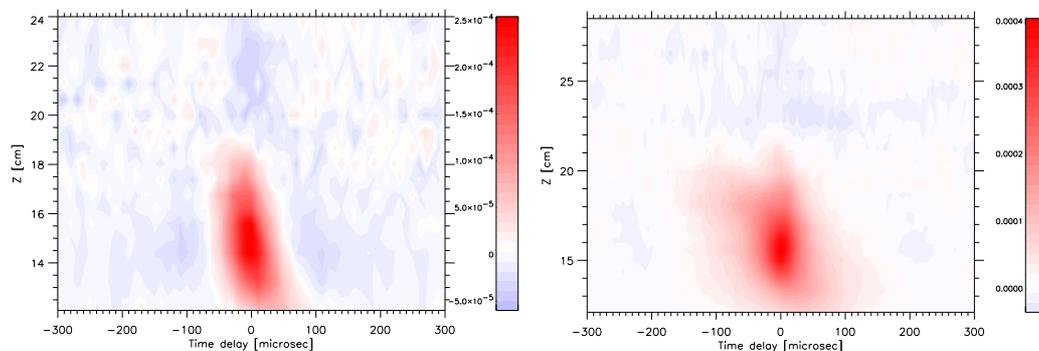


Fig. 5. Measured spatiotemporal correlation functions in the SOL of Wendelstein 7-AS. (left: #52127, right: #43990)

### Conclusions and outlook.

A three-dimensional simulation of experimental signals from prescribed shape turbulent structures in a non-axisymmetric toroidal plasma is presented which aims at a detailed understanding of fluctuation measurements. First comparisons with experimental results in the SOL and edge of Wendelstein 7-AS plasmas show characteristic differences for sheared and non-sheared flows.

Future work will aim at finding differences between simulations of circular (eddy) and radially elongated (streamer) structures. Besides Beam Emission Spectroscopy  $\text{CO}_2$  laser scattering measurements and other diagnostics will also be simulated. Effects of zonal flows will be investigated by adding random zonal flows to the poloidal flow velocity profile while simulating eddies.

### References

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