PLASMA EDGE TURBULENCE:
COMPARISON BETWEEN THEORY AND EXPERIMENT

J. Bleuel, B. Scott, M. Endler, H. Niedermeyer, U. Pfeiffer,
G. Theimer and the W7-AS Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association,
Garching, Germany

1. Introduction

The physics of plasma edge turbulence is very complex and all efforts towards a theoretical description rely on major simplifications. This implies the necessity to compare theoretical predictions and experimental observations in order to identify the most appropriate models.

While earlier investigations [1] focused mainly on the scaling behaviour of different fluctuation features like amplitudes and transport coefficients, the aim of this work is a detailed comparison of the structure, the statistical properties and the scales of these fluctuations in space and time. It is related to the investigation of electrostatic fluctuations by means of Langmuir-probe measurements in the SOL and the outer confinement zone of the Wendelstein 7-AS stellarator, which allowed a fully three-dimensional characterization of these fluctuations [2]. Within the last years, nonlinear simulation methods have been developed which can treat the saturated turbulent state represented by these fluctuations.

As no global simulation of a plasma discharge is feasible as yet, input parameters for these simulations must be taken from the experiments. These parameters are the local temperature and density, the temperature and density gradients and the radial fluxes of particles and energy.

By using spatially resolving Langmuir probe arrays for the simultaneous measurement of the fluctuating floating potential and ion saturation current in combination with a slowly swept Langmuir probe, all these input parameters could be directly measured or fairly well approximated.

2. The Model

The underlying model is a nonlinear electrostatic drift wave model, which describes the SOL plasma by taking the sheath dynamics at the target plates into account as parallel boundary conditions. By neglecting ion temperature effects and viscosity and assuming electrostatic fluctuations, a set of nonlinear equations can be derived, which describes the time evolution of the fluctuating quantities density, temperature and electrostatic potential on a twodimensional area perpendicular to the magnetic field. The model assumes zero parallel wavenumber. Two different numerical schemes have been applied to this set of equations: The first one assumes the background gradients of density and temperature to be fixed in time (local model), while the second one allows for a self-consistent evolution of the plasma profiles together with the fluctuations (nonlocal model). The geometry of the machine is approximated by assuming the magnetic curvature to be constant along the magnetic field and that the connection length to the limiters is the same everywhere.

The experimental determination of the code's input parameters was realised by using a Langmuir probe array measuring both the fluctuating floating potential and ion saturation current simultaneously with high resolution in time and poloidal direction, and the average values of density and temperature by a slowly swept probe tip. The whole array was moved radially inwards during a stationary discharge phase in order to allow for a measurement of the plasma profiles. In case of the local model the determination of the local density and temperature and the gradients of density and temperature is sufficient, while for the nonlocal model the radial fluxes of particles and energy are needed instead of the gradients. The forementioned probe array allows the calculation of the radial particle flux from the simultaneous measurement of density and potential fluctuations if $E \times B$ drift is assumed as transport mechanism. For a direct calculation of the radial energy flux, temperature flucutation data would be necessary, which were not available for our investigations. However, it is known that temperature fluctuations are nearly in phase with the density fluctuations and that their relative amplitudes are also comparable [3]. Assuming temperature and density fluctuations to be in phase and of the same relative amplitude, one gets:

$$\mathbf{Q}_{rad} = 3kT\ \mathbf{\Gamma}_{rad} \quad , \tag{1}$$

if $\mathbf{\Gamma}_{rad}$ is the radial particle flux.

3. Results

At first glance, different fluctuation amplitudes in experiment and simulation results attract attention. In the local model, the amplitudes are by a factor of 3-5 larger than in the experiment. This occurs due to the assumption of fixed gradients of density and temperature made in this model. The nonlocal model gives much smaller amplitudes, by a factor of 2 smaller than in the experiment. This may be due to the assumption of a constant connection length to the target plates. In the experiment, the connection length varies with the radial position, resulting in steeper gradients of density and temperature than observed in the nonlocal simulations. Since the gradients are the major driving term, the lower fluctuation level is due to the simplification made by assuming a constant connection length.

The structure of the fluctuations can be characterized by their correlation functions. Both the local and the nonlocal model can reproduce the poloidal structure of the fluctuations quite well (see Fig. 1). The poloidal velocity is made up of two parts: The fluctuations' poloidal velocity, which is in the electron drift direction, and the plasma rotation velocity due to radial electric fields, which is in the ion drift direction and typically overcompensates the fluctuations' propagation velocity. The local model neglects radial electric fields for numerical reasons and therefore its results can not be compared to the experimental results as far as poloidal velocities are concerned. The nonlocal model generates smaller radial electric fields than observed in the experiments because the temperature gradients generated in the simulations are smaller. Due to the sheath boundary condition at the target plates the radial electron temperature gradient largely determines the radial electric field in the SOL. If the different temperature gradients are taken into account, the poloidal velocity in experiment and nonlocal simulation is the same within the errors. Lifetime and poloidal size of the fluctuations show an agreement better than 30 %.

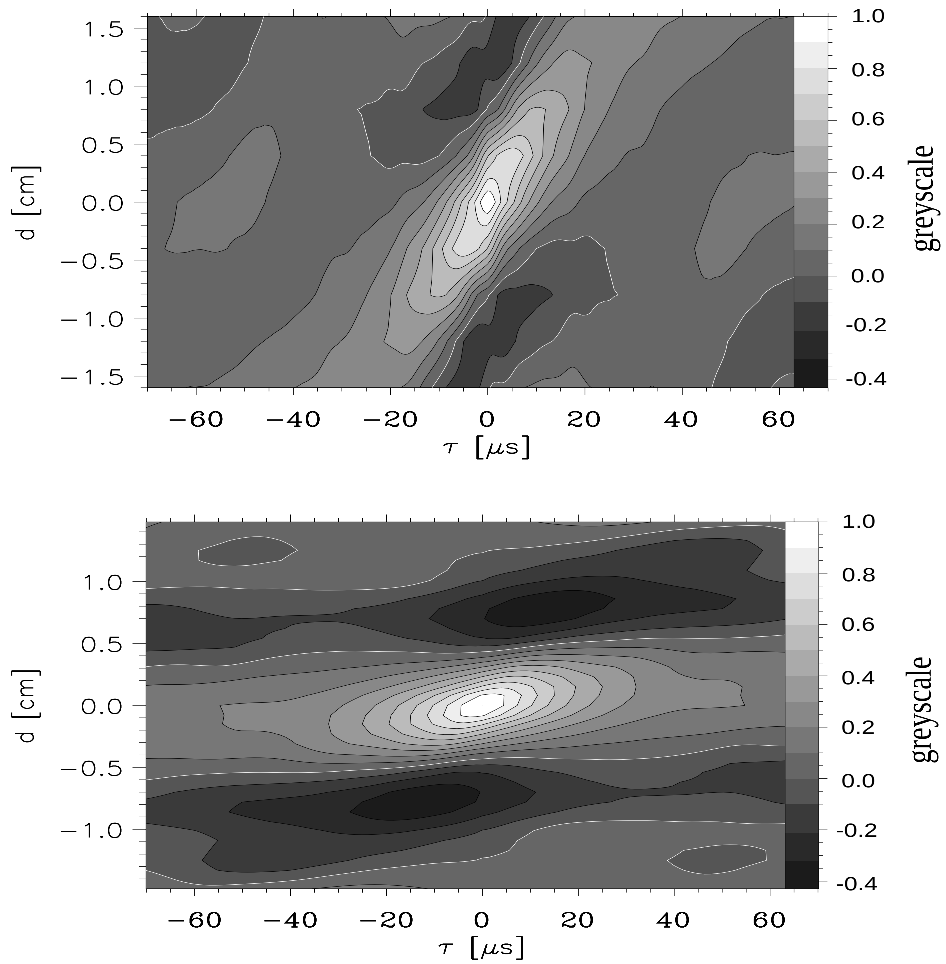

Figure 1. Poloidal-temporal correlation function of floating potential fluctuations in the SOL of the Wendelstein 7-AS stellarator (top) and of simulated fluctuation data (nonlocal model, bottom).

The two-dimensional structure of the fluctuations is qualitatively reproduced both by local and nonlocal models. In the radial direction, the neglect of magnetic shear is a critical issue. It may be the reason for the overestimation of the radial correlation length by a factor of two both in the local and the nonlocal model.

The floating potential fluctuations have a gaussian amplitude distribution function in all the experiments and numerical simulations. Despite of this, the ion saturation current distribution funtion observed depends on the radial density profile assumed. The assumption of constant gradients in the local model automatically leads to a gaussian distribution of the ion saturation current amplitudes. In the experiment and the nonlocal model the profiles are nearly exponential resulting in a non-gaussian distribution of ion saturation current amplitudes.

The simulated fluctuation spectra extend over a smaller frequency range than in the experiment. Investigations including ion temperature effects [4] showed much broader spectra, so that the neglect of them may be the reason for the difference observed here.

4. Conclusions

The results of nonlinear electrostatic drift wave simulations were compared to the observations of Langmuir probe arrays in the SOL of the Wendelstein 7-AS stellarator. While the basic structure of the fluctuations could be reproduced both by local and nonlocal models, only the nonlocal version of the code could reproduce the fluctuation amplitudes, the spectra (qualitatively) and the amplitude distribution functions correctly.

There are still differences between theory and experiment due to the simplifcations of these models: The radial scales are not described correctly since magnetic shear is not considered. There is also no radial propagation of fluctuations in the simulations while there is one in the experiments [2]. The width of the fluctuation spectrum is somewhat smaller in the simulations than in the experiments. This may be due to the neglect of ion temperature effects [4].

References

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