Combined density-temperature fluctuation measurement with beam emission spectroscopy

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The importance of anomalous transport, thought to be caused by turbulence, is well known in fusion plasmas. As the theory of plasma turbulence is not fully understood yet, the experimental verification of various theoretical predictions is an important task. Turbulence appears as fluctuation in the plasma parameters (density, temperature, potential etc.) and the correlation between the fluctuation of different quantities plays an important role. This paper describes numerical studies to explore the possibility of correlated density-temperature fluctuation measurement using Beam Emission Spectroscopy (BES).

BES has been used to measure electron density and, to some extent, temperature profiles of the plasma. Lithium beams are used for density measurement, while thermal helium beams exhibit a capability for temperature profile measurement [1]. BES proved to be a valuable tool for fluctuation measurement as well, but up to now it was used only for the measurement of density fluctuations [2-4]. The method presented in this paper was developed to calculate the correlation of density and temperature fluctuations from the correlation of fluctuations in the light emitted by the beam at different atomic transitions. Although the method is generally applicable to all BES experiments where at least one radiation line has adequate temperature dependence, this paper focuses on the simulation of accelerated helium beam experiment.

In a BES experiment a neutral beam penetrates the plasma and the atoms of the beam emit photons due to the excitations of collisions with the particles of the plasma. The measured radiation in a fixed line of sight is a nonlocal function of the plasma parameters. $S^0_\alpha(Z)$ is the time averaged light intensity distribution, where Z denotes the coordinate along the beam and α denotes the helium radiation line. Due to beam weakening and the finite depopulation time of excited states the light intensity at a given Z depends on the local and all $Z' < Z$ parameters of plasma:

$$S_\alpha(Z,t) \;=\; \mathcal{F}\{n_e(Z',t), T_e(Z',t)\}, \qquad Z' < Z. \tag{1}$$

The fast beam approximation is fulfilled for a (70 - 130 keV) accelerated helium beam: $\frac{Z_{max}-Z_{min}}{v} \ll \tau_{fluct}$, where v is the velocity of the beam. This means that the penetration time is shorter than the time resolution of the measurement and the lifetime of fluctuations. The electron density and temperature distribution can be generated as the sum of a time-independent (average) and a time-dependent perturbative part:

$$n_e(Z,t) = n^0_e(Z) + \tilde{n}_e(Z,t), \qquad T_e(Z,t) = T^0_e(Z) + \tilde{T}_e(Z,t). \tag{2}$$

The perturbations in plasma parameters will appear in the measured light which can be similarly divided into two parts:

$$S_\alpha = S^0_\alpha(Z) + \tilde{S}_\alpha(Z,t), \qquad \langle \tilde{S}_\alpha(Z,t)\rangle = 0. \tag{3}$$

Linear but non-local approximation is used to describe the connection between the emitted light and electron density and temperature fluctuations. This linearity was tested in the helium atomic beam model with low amplitude perturbations and found acceptable. In this case the luminosity distribution can expressed as a function of the density and temperature distribution with the following integral equation:

$$\tilde{S}_\alpha(Z,t) = \int_0^Z \tilde{n}_e(Z',t)h_\alpha(Z,Z')dZ' + \int_0^Z \tilde{T}_e(Z',t)g_\alpha(Z,Z')dZ' \tag{4}$$

Where h denotes the density transfer function and g denotes the temperature transfer function for radiation line α. The transfer function describes the change in the line radiation intensity at coordinate Z due to the perturbation of density or temperature at coordinate Z'.

In a real experiment the finite number of detected photons with microsecond sample time is a serious limit of observing the fluctuations. One possibility is to integrate the detected signal in time and examine the statistical behaviour of fluctuations. The correlation function is an appropriate tool for this task. The correlation function C^S (without normalization) between the light emission at Z_1 and Z_2 at time delay τ with T total measurement time is defined as

$$C^{S_{\alpha\alpha}}(Z_1,Z_2,\tau) = \frac{1}{T}\int_0^T \tilde{S}_\alpha(Z_1,t)\tilde{S}_\alpha(Z_2,t+\tau)dt. \tag{5}$$

The density (C^n), the temperature (C^T) and the density-temperature (C^{nT}) crosscorrelation function can be similarly defined:

$$C^{nT}(Z_1,Z_2,\tau) = \frac{1}{T}\int_0^T \tilde{n}_e(Z_1,t)\tilde{T}_e(Z_2,t+\tau)dt. \tag{6}$$

Using equations (4)-(6) the light intensity correlation function can be expressed the following way:

$$\begin{aligned} C^{S_{\alpha\alpha}}(Z_1,Z_2,\tau) \;=\; & \int_0^{Z_1}\int_0^{Z_2} h_\alpha(Z_1,Z')h_\alpha(Z_2,Z''')C^n(Z',Z''',\tau)dZ'dZ''' + \\ & \int_0^{Z_1}\int_0^{Z_2} g_\alpha(Z_1,Z'')g_\alpha(Z_2,Z'''')C^T(Z'',Z'''',\tau)dZ''dZ'''' + \\ & \int_0^{Z_1}\int_0^{Z_2} h_\alpha(Z_1,Z')g_\alpha(Z_2,Z'''')C^{nT}(Z',Z'''',\tau)dZ'dZ'''' + \\ & \int_0^{Z_1}\int_0^{Z_2} h_\alpha(Z_2,Z''')g_\alpha(Z_1,Z'')C^{Tn}(Z',Z''',\tau)dZ''dZ'''. \end{aligned} \tag{7}$$

If the two spectral lines (α and β) are measured at the same time an equation system of four equations (α, β=1,2) can be generated. In an actual measurement setup the light intensity can be detected in a finite number of channels and the equation system needs to be discretised:

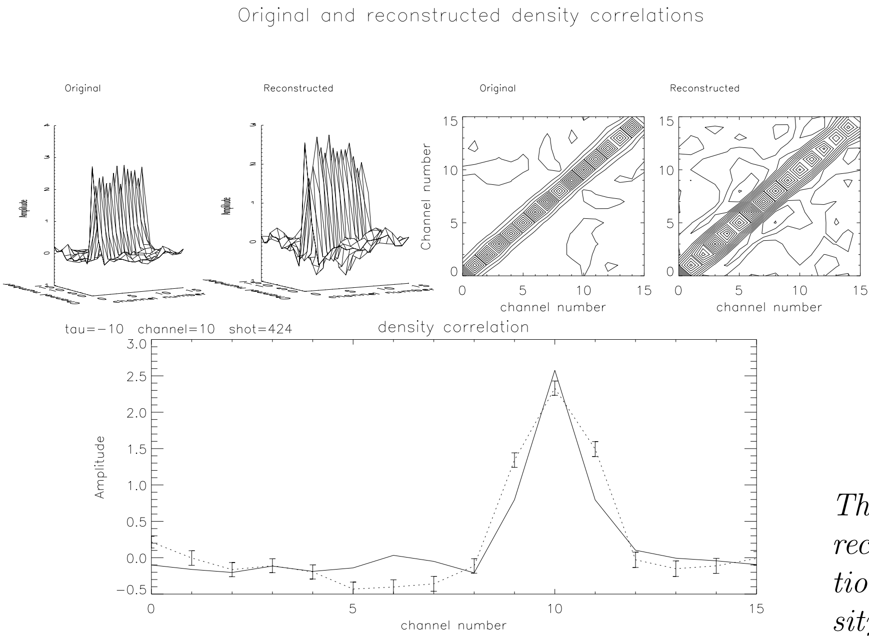
$$C_{kl}^{S_{\alpha\beta}}(\tau) = \sum_{i=1}^{N_N}\sum_{j=1}^{N_N} M_{ki}^{\alpha} M_{lj}^{\beta} C_{ij}^{n}(\tau) + \sum_{i=1}^{N_N}\sum_{j=1}^{N_N} N_{ki}^{\alpha} N_{lj}^{\beta} C_{ij}^{T}(\tau) + \sum_{i=1}^{N_N}\sum_{j=1}^{N_N} M_{ki}^{\alpha} N_{lj}^{\beta} C_{ij}^{nT}(\tau) + \sum_{i=1}^{N_N}\sum_{j=1}^{N_N} N_{ki}^{\alpha} M_{lj}^{\beta} C_{ij}^{Tn}(\tau). \quad (8)$$

Where matrices M and N are the discretised forms of the h and g transfer functions. The dimension of light correlation matrices and parameter matrices need not be the same. Four matrix equations are given with four unknown correlation matrices. This equation system can be solved using a tomography algorithm. The basic idea of the algorithm is that we find a solution using a regularization method, i.e. the smoothest solution within error bars.

A code was developed in IDL to realize the algorithm. At first the method was tested with simple artificial atomic physics exhibiting realistic tendencies, but not relying on any particular beam species. The general reconstruction ability was proven with different plasma density and temperature profiles. With the artificial atomic physics several key parameters of the reconstruction could be examined: different electron density and temperature profiles, relative fluctuation amplitudes, photon statistics.

After exploring the general reconstruction capabilities a more realistic accelerated helium atomic beam model was built into the simulation which uses atomic physics data from the ADAS database. The beam model was developed in the Vienna University of Technology and it was tested for reconstruction of n_e and T_e profiles on JET. [5]

In these simulations real, experiment-like density and temperature profiles were used. The parameters of the simulated helium beam were realistic as well: beam energy$\sim$70-130 keV, current$\sim$1 A, detection efficiency, metastable states. In the tests of reconstruction Gaussian shaped, temporally and spatially uniformly distributed density and temperature fluctuation pulses with 1% amplitude were assumed. The density and temperature fluctuation pulses were taken to be either the same, time delayed or statistically independent. The fluctuations added to the averaged density and temperature profiles give the temporal evolution of plasma profiles. With the atomic beam model the emitted light of different spectral lines can be obtained. The detected number of photons is calculated with $1MHz$ sample frequency taking into account a realistic detection efficiency. Artificial photon noise is added to the calculated light signals. At the end of this process realistic simulation of a BES experiment is obtained. The correlation and the crosscorrelation matrices of different spectral lines are calculated as the following step. The above described numerical method is used for reconstruction of correlation matrices of density and temperature fluctuation. As a last step the reconstructed correlation matrices are compared to the ones calculated from the simulated density and temperature profiles in order to determine the quality of reconstruction. The transfer matrices are calculated separately, but the averaged profiles are needed to calculate the appropriate transfer matrices.



The calculated and the reconstructed correlation matrices of density fluctuations.

Conclusions

The accelerated helium beam has certain advantages for BES experiment as deep penetration (compared to fast Li beam), temperature depending spectral lines. Additionally the depopulation time is rather small, that means local answers for perturbations (disregarding ionization). The approximations used in the calculation of reconstruction found to be acceptable (linearity, fast beam). **In a certain parametric region the reconstruction of correlation of density and temperature fluctuations is possible**. As it was mentioned helium has temperature depending spectral lines, but if these states are not populated sufficiently, then the reconstruction of the correlation of the temperature fluctuation is not possible. The initial fraction of metastable states mainly influence the population of the temperature depending lines, in this way in a real measurement it has to be measured precisely, which is not solved yet. If not enough light is collected to reconstruct the correlation of temperature fluctuations the reconstruction of the correlation of density fluctuation from other lines can be still possible. The ideal case would be if the initial fraction of metastable states could be set precisely. The reconstruction ability is very sensitive to the precision of the used atomic model as well, the error estimation of the atomic model is not built in the simulation yet. There are existing experiments having similar parameters, that we assumed, but multi channel BES measuring two lines at the same time has not been implemented yet.

Referenes

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