Direct reconstruction of density fluctuations observed by Alkali Beam Emission Spectroscopy

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The Alkali Beam Emission Spectroscopy (A-BES) of W7-X measures the radial electron density profiles in the SOL at the low-field side of the bean-shaped cross section of the plasma [2]. The injection axis of the sodium atoms lies on the mid-plane of the stellarator, and as such it crosses the O point of one of the divertor islands for the standard configuration.

Based on a recent density reconstruction method [3], an iterative approach has been implemented, aiming at resolving density fluctuations directly. The study presents the limitations of the method. For this purpose, experimental data from OP2.2 and OP2.3 has been utilized to create synthetic diagnostic data. The reconstruction accuracy of the method is characterized as a function of the properties of the simulated fluctuations.

An application of the algorithm to both significant and small density fluctuations is presented for an experiment at W7-X.

Introduction:

The high modulation frequency of the A-BES diagnostics allows it to be used for the analysis of turbulent processes. This is usually performed with the direct analysis of light profiles. This approach is especially useful for sufficiently low electron densities (below 3e19m^{-3} at W7-X), as the light fluctuations can be assumed to be local functions of the light profiles. This method is capable of analyzing turbulent transport with a spatial resolution of approximately 0.5-1cm [5]. A different approach is the reconstruction of small density fluctuations that can be obtained from the light profiles with a linear response matrix [6].

For the current study, an improved version of the SPADE algorithm [3], utilizing a database of known solutions to linearize the equations to solve, has been implemented, improved upon and validated against synthetic experimental data for the usage of electron density profiles. The aim of the new method is to obtain a straightforward and reliable method for the direct analysis of electron density fluctuations.

Improved algorithm for the analysis of density fluctuations:

The improvement on [3] is twofold: In order to increase the accuracy of the reconstruction and to decrease the dependency on the profiles stored in the initial database of known solutions, the reconstruction is performed in an iterative way: After the first reconstruction is performed, the light profile is calculated corresponding to the obtained density profile and is compared to

the original measured data. The differential equations that one needs to solve to obtain the profiles is once again linearized by the difference between the newly obtained light profile and the measured one. Depending on the exact shape of the experimental data, it has been found that repeating this step 3-5 times is sufficient. This is discussed in further details in [7].
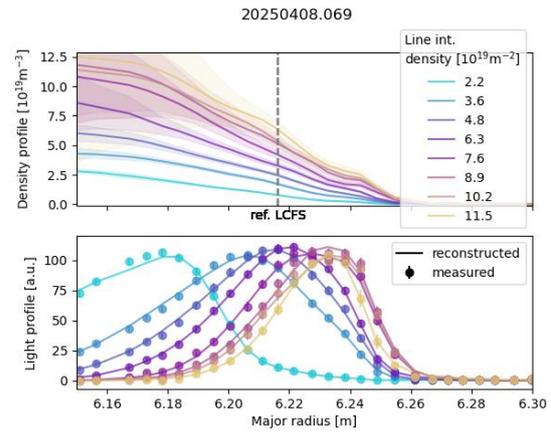

Figure 1 An example for the measured and reconstructed light profiles (lower plot) and the corresponding density profiles during a density ramp up experiment.

The second improvement is in the choice of the prior values for the Tikhonov regularization. Due to the numerical errors and the not always reliable noise statistics during the 100kHz of the A-BES diagnostic, choosing proper prior weights is not straightforward. It has been found, that setting the prior values so that the difference between the measured and the reconstructed light profiles is minimal is an effective metric for this purpose. Once the prior weights are determined, they are effective as long as the observed light profiles or the beam modulation frequency does not change significantly.
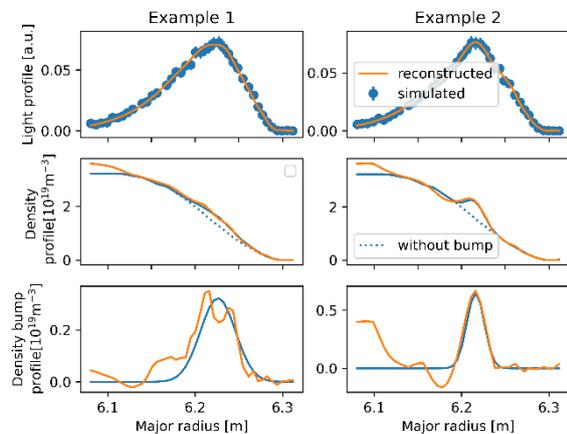

Figure 2 Two examples for the reconstruction of synthetic density profiles with added fluctuations. The blue curves correspond to the synthetic light data and the orange on to the reconstructed results. The dotted plots of the density profiles correspond to the plots without the added fluctuation.

Practically, this implies that the optimization of the priors only has to be repeated a few times for an experiment as the plasma evolves. As an example, Figure 1 shows the results of the algorithm for experimental data.

Applicability for density fluctuation analysis:

In order to validate the reconstruction method, we used synthetic data based on experimental results from OP2.2 and 2.3. 17 different magnetic configurations with high-quality A-BES diagnostic data were taken. From the corresponding experiments, 211 different density profiles with the most different shapes and magnitudes were utilized. The error of the reconstructed light profiles normalized by the measurement error were below 0.3 for all experimental profiles. Afterwards, a Gaussian shaped positive fluctuation was added to all density profiles. The locations, magnitudes and widths of the added fluctuation were varied, resulting in approximately 30500 different density profiles. Finally, the corresponding light profiles were calculated and a noise with realistic SNR values was added to them. An example for the reconstructions is shown in Figure 2.

It has been found that 5495 (about 20%) of the fluctuations has been reconstructed with a relative error less than 1 and is believed to be suitably accurate for fluctuation analysis. With the utilized SNR values, this corresponds to a mean reconstruction error of approximately 0.2 of the synthetic light data (normalized by the simulated measurement uncertainties). For these reconstructions, the dependence of the bump location, width and height are shown in Figure 3. Although full characterization of the accuracy of the reconstructions is complex, the
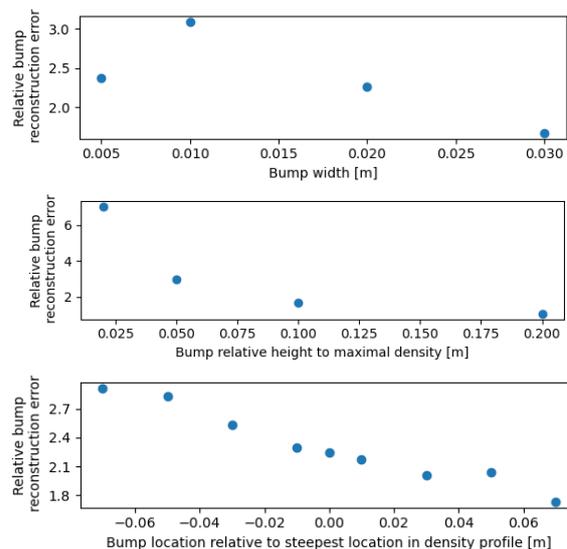

Figure 3 The dependence of the reconstruction accuracy on the parameters of the added fluctuations.

general findings are the following: The method is applicable for the reconstructions of fluctuations of minimum 2cm width, and located at the plasma edge. The reconstruction accuracy increases with the increasing magnitude of the fluctuations: the result indicate that a fluctuation with a magnitude of about 10% of the plasma core density can be reconstructed with sufficient accuracy. It is nevertheless noted, that aside from the required fluctuation width, that is believed to be a consequence of the lifetime of the excited state of the sodium and the spatial resolution of the diagnostic, the findings for the fluctuation magnitude and location can be improved upon with higher SNR values. Thus, sufficient statistics of the fluctuations can improve the accuracy of the analysis significantly.

Application:

During the improved confinement mode at W7-X, occasional significant losses in Wdia and density have been observed. As an example, the density evolution during one such event for experiment 20250312.099 is shown in Figure 4. From the 10kHz density reconstruction, one observes that the density loss occurs approximately 0.5ms later than the fluctuations in Wdia and the Soft X-ray results appear. The density profiles indicate a swift outwards propagation of the fluctuation. This is even more apparent from the light at the bottom of Figure 4.

As another example, Figure 5 shows the reconstruction of the low-frequency (~150Hz) quasi-continuous density oscillation, present for the whole experiment, 20250312.099. Due to the small magnitude of the oscillations, the results have been obtained by conditional averaging of multiple events.
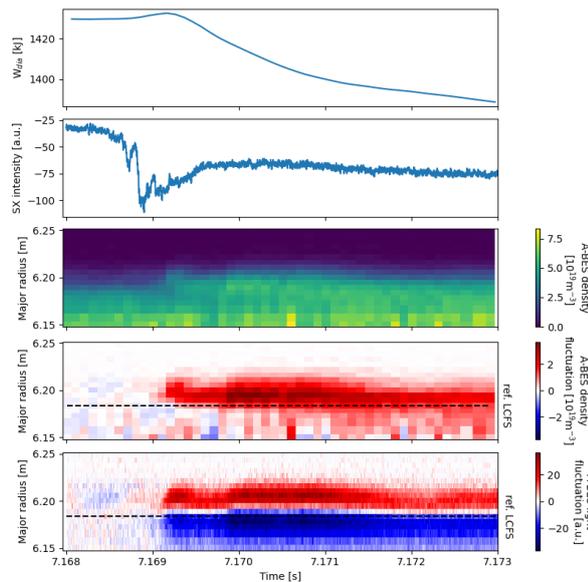
Figure 4 The time evolution of Wdia, an XMCTS channel and the A-BES density profiles during an event corresponding to significant loss of Wdia in the improved confinement mode. [8]
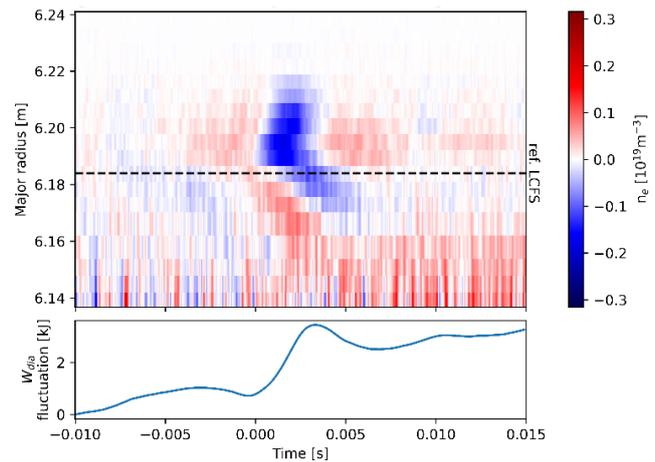

Figure 5 Reconstruction of a low-magnitude, low-frequency, quasi-continuous density fluctuation [9]. The data is based on conditional averaging using seven sample events and calculating their rolling correlation. The average Wdia signal also shows a small (0.1%) magnitude oscillation.

Summary:

The improved density reconstruction method based on the SPADE algorithm [3] has been found to be sufficiently robust to be utilized for density fluctuation reconstructions. The applicability of the algorithm has been verified with synthetic experimental data, based on real measurement data and using realistic SNR values.

It has been found that the direct reconstruction of fluctuations of sufficiently large width (~2cm) was possible in the plasma edge. While the algorithm accuracy has been found to be dependent on the magnitude of the fluctuations, this is believed to be the result of the limited SNR values and not inherent to the algorithm. This is demonstrated by the statistical analysis of experimental data of a density fluctuation of smaller magnitude.

Acknowledgement:

References

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