Analysis of density profiles inside magnetic islands with Alkali Beam Emission Spectroscopy at Wendelstein 7-X

M. Vécsei[1], G. Anda[1], O. Asztalos[2], K.J. Brunner[3], D. Dunai[1], M. Hirsch[3], U. Höfel, J. Knauer[3], M. Otte[3], G. I. Pokol[2], S. Zoletnik[1] and the W7-X team[3]

[1]*Wigner Research Centre for Physics, Department of Plasma Physics, Hungary*

[2]*Budapest University of Technology and Economics, Institute of Nuclear Techniques, Hungary*

[3]*Max Planck Institute for Plasma Physics, Germany*

Introduction: The Alkali Beam Emission Spectroscopy (A-BES) system is a fast time-resolution diagnostic injecting a 60 keV Sodium atomic beam in the mid-plane of the W7-X stellarator [1] and observing the light emitted by it. It is capable of density reconstruction with a time resolution of ≈ 50 μs and for the analysis of turbulent processes. The diagnostic was operated during the OP1.2 campaign at W7-X.

For the standard iota configuration, the Sodium beam crosses the O point of one of the magnetic islands. The high sensitivity of the diagnostic in the island region suffices for an analysis of the transport processes in this region. A detailed analysis of the data nevertheless requires the implementation of a fast density reconstruction algorithm. For this purpose an approximative linearized density reconstruction method has been developed to obtain the solution to the rate equations. The obtained algorithm has been validated against the Bayesian method after which it has been utilized for a basic analysis the density profiles inside the magnetic island.

Data analysis: The density of the plasma is reconstructed by detecting the light profile along the beam. Through collisions with the plasma components, the injected Sodium atoms are excited and are subsequently deexcited either by further collisions or spontaneously. The rate equation for the occupation of the energy levels of the atoms in a reference frame comoving with the beam reads as:

$$\frac{d\boldsymbol{N}}{dz}=\left(n_e\boldsymbol{R}+\boldsymbol{A}\right)\cdot\boldsymbol{N} \quad .$$

The occupation of the energy levels is given by $\boldsymbol{N}$. The collisional excitation and deexcitation of the atoms is governed by the electron density n_e and the rate matrix $\boldsymbol{R}$. The Einstein coefficients are summarized in $\boldsymbol{A}$. The intensity of the detected light profile corresponds to the occupation of the first excited state in $\boldsymbol{N}$.

Assuming that one has found a solution to the rate equation $\boldsymbol{N_0}$ and n_{e0}, one can write the original variables as $\boldsymbol{N}=\boldsymbol{N_0}+\boldsymbol{\delta N}$ and $n_e=n_{e0}+\delta n_e$. If $\boldsymbol{\delta N}$ and δn_e, are sufficiently small then rate equation can be linearized in these variables to obtain:

$$\frac{d\boldsymbol{\delta N}}{dz} = \delta n_e \boldsymbol{R} \cdot \boldsymbol{N_0} + (n_{e0} \boldsymbol{R} + \boldsymbol{A}) \cdot \boldsymbol{\delta N} \quad .$$

By using a numerical method for expressing the derivative on the left hand side of the equation, obtaining $\boldsymbol{\delta N}$ and δn_e can be reduced to a linear equation system. Furthermore, by overdefining the equation system the measurement error and some properties of the density profile variations (such as a reasonably small second spatial derivative) can be incorporated to the equations as well. An example of a reconstructed density profile obtained this way and its comparison to the one obtained by Bayesian analysis [3] is shown in Figure 1. The results show a good agreement within the error limits.

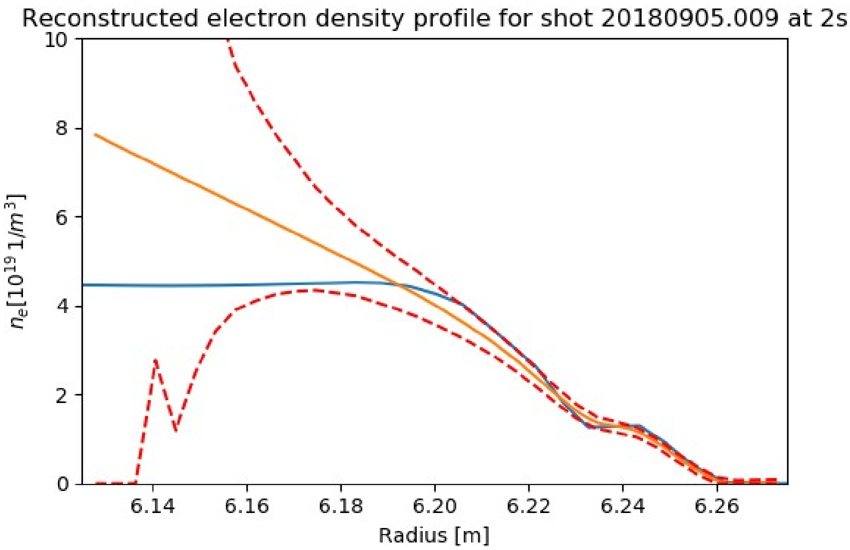

Figure 1: Comparison of the density profiles obtained by the Bayesian (orange) and the fast reconstruction (blue) method. The estimated error of the Bayesian reconstruction is shown on the dashed red curves.

In order to utilize the linear reconstruction, a database consisting of approximately 11000 corresponding light profile - density profile pairs has been created. When a density profile is reconstructed, the algorithm first searches this database for the light profile matching most closely the experimental data. Afterwards, the linear equation is solved according to the linearized rate equation. Currently, the code does not estimate the error of the reconstruction, which is necessary to utilize it for a detailed density profile analysis. Nevertheless, in order to characterize the reconstruction error, the full nonlinear rate equation can be solved afterwards for the obtained density profile. For the statistical analysis of this study, the light profiles calculated from the reconstructed density profiles matched the measurement data with a relative error below 10%.

Dependence of the island density on plasma parameters: The presence of the magnetic island can be clearly observed in a number of measurements performed with the A-BES diagnostic at W7-X, as it is shown by the section between 6.23m and 6.26m in Figure 1. Moreover, the results indicate that in a number of cases a clear local density maximum is also present near the O point of the magnetic island [2].

For the first part of the data analysis, the line integral of the density inside the divertor island has been obtained for plasma discharges from experimental data obtained on 5th and 6th September and 16th October, 2018. The range of integration was for [6.21m,6.26m] region of the large radius, as vacuum field calculations indicated the island to be located in this region. The density has been reconstructed with a 10-100Hz sampling rate. For each reconstructed density profile, the data from a number of diagnostics has been analyzed. However, the overarching relation between the diagnostic data has been found quite complex. As an example, the integrated island density is shown in Figure 2 for two discharge. The corresponding ECE temperature near the plasma center [4] and the full line integrated density obtained by the integral electron density dispersion interferometer (IEDDI) [5] are also plotted for reference.

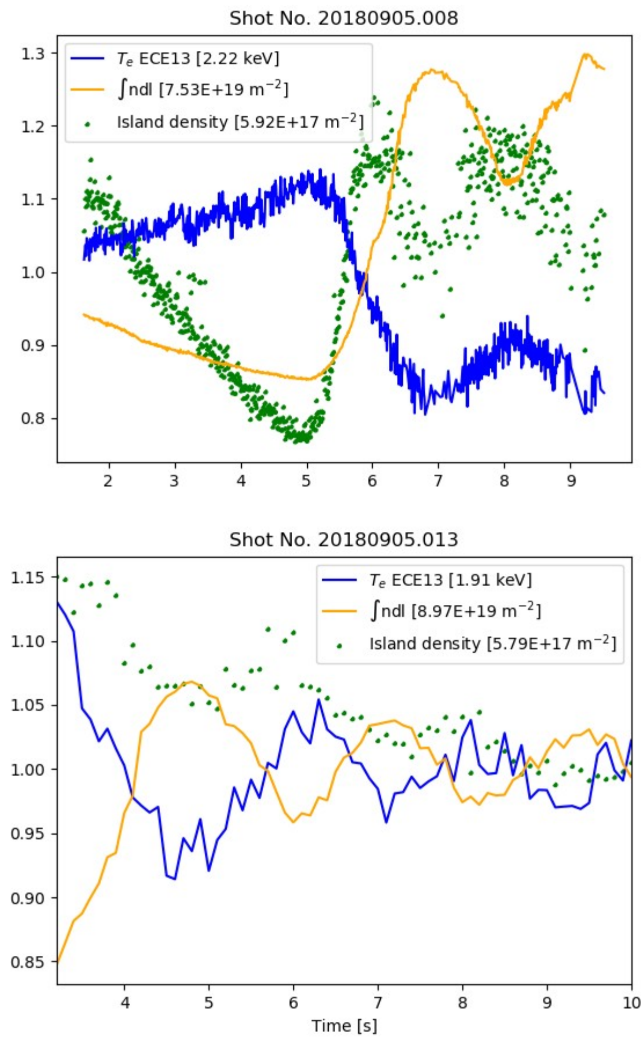

Figure 2: The time evolution of the density inside the magnetic island (green), the temperature near the plasma center (blue) and the line integrated density of the full plasma (orange). The data has been normalized according to the values given in the plot legends.

For shot No. 20180905.008, at higher core temperatures and lower integrated line densities, the island density is approximately in phase with the IEDDI data. However, during the second half of the shot, where the core temperature increases and the interferometer density data decreases, the phase changes. The A-BES data changes is seemingly in phase with the temperature variations in this region. The data from shot No. 20180905.013, with comparable plasma parameters as in the second half of shot No. 20180905.008, also show similar behavior. However, in order to obtain an understanding of these results, a more rigorous and detailed analysis of the data is necessary.

As a second example for the capabilities of the A-BES diagnostic, the spatial and temporal cross correlation function has been calculated for shot No. 20181017.022 for the time interval [0.4, 0.7s] with 50µs time resolution. The cross correlation was performed for a point inside the island, located at R= 6.249m. The results are plotted in Figure 3.

Figure 3 shows that the density fluctuations inside the island are closely correlated. Outside the island the correlation function becomes negative at 0s time shift. Moreover, the cross-correlation inside the island has been found higher at the edges of the island, than inside of it. This corresponds to earlier results obtained by the analysis of A-BES light profiles [2]. Interestingly, a jump in the sign of the cross-correlation function can be also observed at the inner edge of the magnetic island. The temporal axis of the plot indicates a slow (~330Hz) fluctuation at the plasma edge as well.

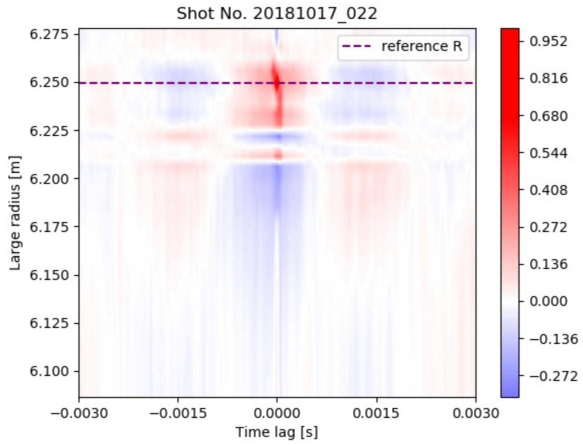

Figure 3: The spatiotemporal cross correlation of the density inside the divertor island.

Summary

A fast density reconstruction algorithm has been developed and implemented for the analysis of A-BES diagnostic results. The results of the new algorithm has been found to agree well with the results from the Bayesian method. The results obtained with this method has been used for two simple cases to analyze the time evolution and the cross correlation of the density profiles inside the magnetic island. Obtaining a deeper understanding of the observed features of the data nevertheless requires a more in-depth analysis of the data.

References:

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