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Probabilistic Lithium beam data analysis

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Electron density profiles at the edge region of magnetically confined fusion plasmas are of major interest for understanding the plasma-wall interaction as well as transport mechanisms. A routinely used method for measuring spatially and temporally resolved electron densities in the edge region of fusion plasmas is given by lithium beam impact excitation spectroscopy (Li-IXS) ([1] and references therein). The injected Li atoms become excited by collisions with plasma particles (electrons, hydrogen and impurity ions). The measured LiI(2s-2p) resonance line at 670.8 nm therefore depends on the electron density. The Li beam attenuation and LiI emission line is modeled by solving a balance equation of population and de-population mechanism by particle impact and spontaneous emission.

The established method to evaluate electron density profiles from line emission profiles is provided by the "IPP technique" [2] which is inherently capable of deriving absolute $n_e(z)$ profiles from the relative line emission profile without need for absolute calibration. The evaluation of density profiles employing the IPP technique is routinely used in ASDEX Upgrade. The method is based on a shooting method to invert the density profile from an implicit equation for n_e. It has been a workhorse for quite a long time and produces satisfactory results for most of the plasma scenarios. The drawback is that the method works only if a singularity condition (equation (4) in [2]) or a boundary condition of vanishing Li beam intensity for the innermost spatial channel (equation (6) in [2]) can be fulfilled. This is not the case for small density regimes where, therefore, no profiles can be provided. In addition, the method may suffer from numerical problems as well as from statistical fluctuations (noise) in the data. To extend the achievable spatial region for density evaluation and to improve numerical stability, the data were spatially smoothed and temporally binned to reduce the statistical noise in the data.

To overcome the intrinsic problems of the shooting method and to tackle the measurement errors in a consistent way a new probabilistic data analysis method was developed. It is based on a probabilistic description of the measured data and a forward model for the simulation of the data from a given density profile. Within the framework of Bayesian probability theory the measured data are compared with a model describing the line emission for a given density profile. Since only forward modeling is involved no direct inversion of the noisy data is necessary. An example of the Bayesian technique similarly applied to a Thomson scattering diagnostic can be found in [3] and references therein. Special attention was given to the description of the measurement errors of the line emission signal, the error of the background measurement of the chopped Li beam, and the uncertainty of the relative calibration of the spatial channels. An elaborate error assessment is crucial for recovering only the significant information in the measured data and for avoiding noise fitting. As a result, the uncertainty of the estimated density profile reflects all error sources encountered. A detailed description of the probabilistic method will be provided in a forthcoming paper.

A benefit of the new approach is that it allows to analyze low-density profiles since there is no need for fulfilling boundary or singularity conditions. It provides consistent profile error measures because there is no need to regularize the solution by smoothing measured data. The density profile is parameterized by cubic spline polynomials. To reduce unphysical density values or unreasonable profile oscillations *soft* monotonicity conditions are applied. A soft monotonicity condition penalizes profile segments increasing with ρ using a proper regularization parameter whereas monotonically decreasing profile segments are not affected. The method allows to recover density profiles from the Lithium beam for any plasma regime with a time resolution of up to 200 μs, a lower limit which is currently set by the data acquisition frequency. To

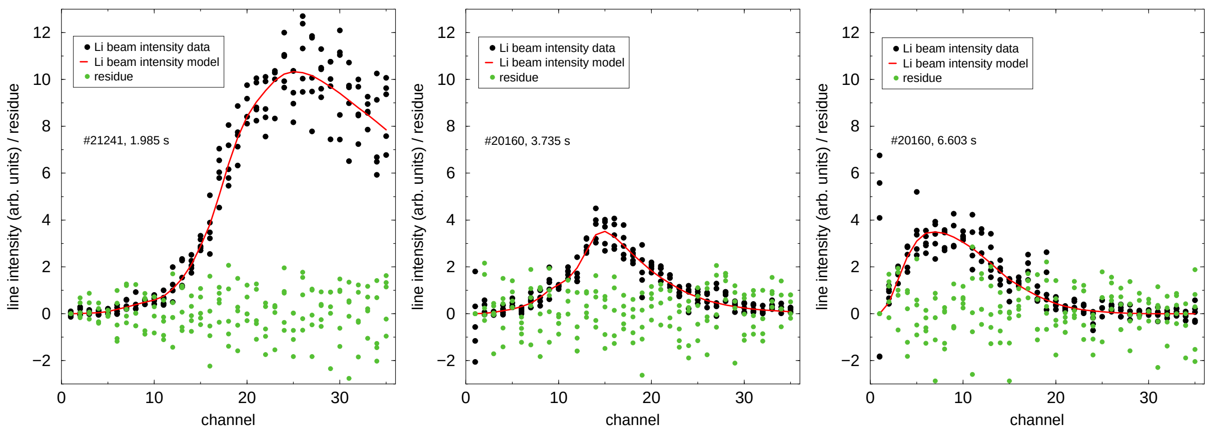

Figure 1: Data, fitted emission intensities and residues for 3 plasma scenarios

demonstrate the advanced data analysis method, an ohmic discharge with low (#21241, 2s), and an H-mode discharge with medium (#20160, 3.8s) and high (#20160, 6.6s) density regimes at ASDEX Upgrade were chosen. Figure 1 shows the line emission intensities, the fitted emission curves and the residues of the misfit of the data and the model weighted with the data uncertainties. Stationary plasma conditions were chosen to allow a simultaneous fit of a single density profile to 5 neighboring time frames. The residues show the thorough description of all measurement uncertainties. In addition, the residues would easily reveal non-stationary conditions where density profiles must be fitted for individual time frames.

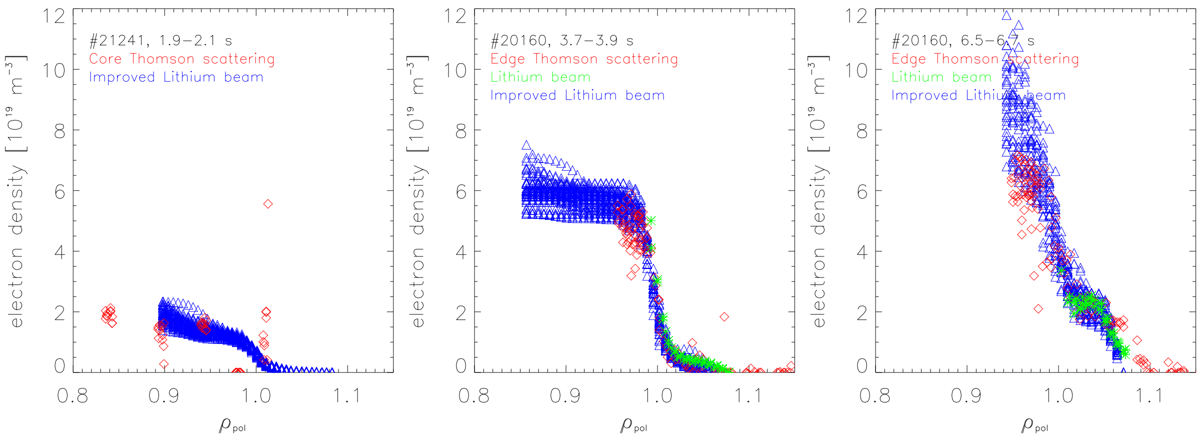

Figure 2: Comparison of the density profiles obtained with the new analysis tool (blue), the classical IPP algorithm (green) and the (core or edge) Thomson scattering diagnostics (red)

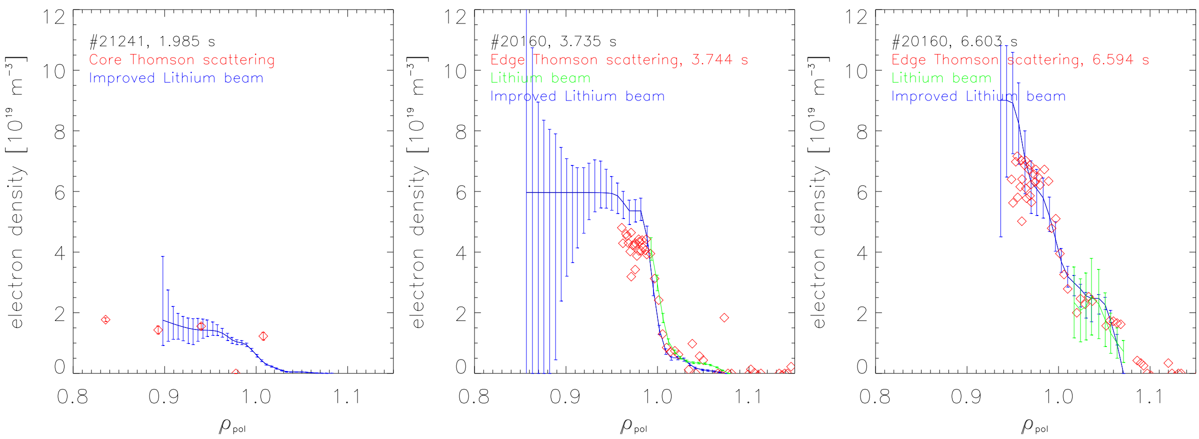

Figure 3: same as figure 2 but for a single time frame and estimation uncertainties

Figures 2 and 3 show a comparison of the density profiles obtained with the new improved analysis tool, the classical IPP algorithm and the (core or edge) Thomson scattering diagnostics (shifted with $\Delta\rho_{pol} = 0.01$). Figure 2 shows profiles within a time frame of 0.2 s and figure 3 depict single density profiles including estimation uncertainties.

The old analysis tool does not allow to obtain density profiles for small densities because the inner boundary condition cannot be fulfilled. The left panels show that the new probabilistic data analysis tool allows to obtain density profiles for any density regime independent of the existence of boundary or singularity conditions. From the error bars and the scatter of the profiles one can conclude that the reliability of the profile reconstruction for the small density regime is large up to $\rho_{pol} > 0.92$. This is not because the Li-beam becomes too faint for $\rho_{pol} < 0.92$ but due to the chosen positions of the spatial channels. Extending the spatial channels into the plasma would allow to recover the density profile for smaller ρ_{pol} values.

The middle panels depict an H-mode discharge with medium electron density. The pedestal is well resolved for the edge Thomson system and the new Li-beam analysis tool whereas the old tool does not provide the level of the pedestal top. With the old evaluation ELM resolved electron densities can be obtained, if several line emission profiles are binned relative to the onset time of the ELMs. Due to the consistent error treatment of the new probabilistic tool single emission profiles can be analyzed with the maximum sampling frequency of 5 kHz. Therefore, binning of the ELMs relative to their onset times is no longer necessary but single ELMs can be studied to recover differences in ELM behavior. A detailed study of the density evolution during ELMs measured with the Li-beam diagnostic with a time resolution of 0.2 ms is beyond the scope of this paper. Again, the reliability of the profile reconstruction for the medium density regime is large for $\rho_{\mathrm{pol}} > 0.93$. The error bars become large for $\rho_{\mathrm{pol}} < 0.93$ showing that the information content in the data about this part of the density profile diminishes.

A high-density regime within the same discharge (#20160, 6.5-6.7 s) is depicted in the right panels. The old density evaluation stops in the SOL whereas the new tool allows to reach the pedestal top although the level of the pedestal top is not clearly resolved. This is due to the diminishing Li-beam and can be resolved only with larger beam energy. The evaluated profile is reliable for $\rho_{\mathrm{pol}} > 0.96$. Both the position of the pedestal as well as the position of the limiter shadow can be resolved.

In conclusion, a new probabilistic data analysis tool for analyzing Li-beam emission profiles was developed. The probabilistic description of the data benefit from a thorough error analysis of all data involved. In comparison to the old algorithm it allows to analyze any density profile. For small densities the profiles are limited by the actual spatial distribution of the measurement channels in the plasma and not due to beam attenuation. The improved method allows to measure edge pedestal densities up to 7×10^{19} m^{-3}. For medium and large densities the reliable density region as well as the upper density limit can be extended by larger beam energies.

References

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