

Effective ion charge Z_{eff} from integrated analysis of multiple diagnostics at ASDEX Upgrade

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A major challenge in nuclear fusion research is the coherent combination of measurements from heterogeneous diagnostics. Different measurement techniques for measuring the same subset of physical parameters provide complementary and redundant data for, e.g., improving the reliability of physical parameters, considering all dependencies within and between diagnostics, and resolving data inconsistencies. The concept of Integrated Data Analysis (IDA) within the framework of Bayesian probability theory was applied to the combined analysis of CXRS- and bremsstrahlung diagnostics to reconstruct profiles of the effective ion charge Z_{eff} . There is a long-standing issue of inconsistencies between the Z_{eff} profiles determined with different measurement techniques or different diagnostic set-ups due to systematic uncertainties [1]. Redundancies provided by the joint analysis of heterogeneous diagnostics allow one to resolve data inconsistencies. At this, a thorough assessment of statistical and systematic uncertainties is vital for a quantitative comparison and validation of measured data and results.

Typical causes for distorting the reconstruction of Z_{eff} profiles are given by wall reflections, gas fuelling close to lines of sight (LOS), passive or active line contributions to the bremsstrahlung background, incomplete knowledge about impurity concentrations, and systematic uncertainties in electron density n_e and temperature T_e profiles. Some of them, e.g. wall reflections, can be identified within a set of data by systematic deviations between the measured and modelled data. Others need sophisticated analysis methods allowing for outlier robust estimation techniques, e.g. tolerant fits of the bremsstrahlung amplitude with respect to additional (line) contributions. Additionally, plasma scenarios with well-known properties provide important references for validation beyond the consistent description of diagnostics data. Reference plasma scenarios are important to rule out systematic effects which cannot be resolved from diagnostics redundancies alone, e.g. systematic uncertainties in n_e and T_e .

At ASDEX Upgrade three CXRS diagnostics and one dedicated bremsstrahlung diagnostic were jointly analysed. The three CXRS diagnostics provide temporally and spatially resolved impurity densities as well as line-integrated bremsstrahlung information from the background intensity. Two diagnostics are dedicated to the plasma edge. On the basis of quantified uncertainties of the raw data, the combined analysis of the different diagnostics, and different plasma

scenarios clear indicators for contaminated signals are developed. Distortions from gas fuelling close to LOS and from wall reflections are easily detected from the residues of the measured and modelled data. Whereas significant wall reflections in ASDEX Upgrade occur only in a minor number of LOS identified with distinguished wall structures, two of the diagnostics are routinely suffering from gas fuelling due to valves close to the LOS. Since in present fusion devices with their heterogeneous first wall modelling of bremsstrahlung reflections is challenging, wall reflections can only be mitigated by LOS arrangements which end in shielded areas. To reduce the spurious effects from gas fuelling and thereby to increase the number of reliable diagnostics for routine analysis the gas valves in ASDEX Upgrade are presently rearranged from the midplane to the divertor dome.

The estimation of Z_{eff} profiles relies on the knowledge of the kinetic profiles n_e and T_e which are obtained from an integrated analysis of the Lithium beam, interferometry, and ECE diagnostics [2]. Systematic errors in the kinetic profiles or other unknown effects could be ruled out employing two reference scenarios: A freshly boronized H-mode discharge ($Z_{\text{eff}} \approx 1.0$) as well as helium discharges with known helium concentration ($Z_{\text{eff}} \approx 2.0$) show the expected Z_{eff} profiles. Additionally, the reconstructed Z_{eff} profiles are validated with results from simulations of the loop voltage and the neutron rate which both depend on Z_{eff} . A detailed description of the combined analysis of CXRS- and bremsstrahlung data at ASDEX Upgrade can be found in [3].

As a result of the thorough validation process a small set of reliable data was chosen for routine estimation of Z_{eff} profiles. Ongoing diagnostic improvements together with the new gas fuelling setup will shortly allow to extend the set of diagnostics for routine analysis. Nevertheless, due to the many candidates for systematic error, outlier robust estimation techniques are mandatory to address transient systematic effects automatically. There are different approaches to deal with systematic effects or outliers depending on the knowledge about the systematic effect. Two approaches will be summarised here due to their general applicability: First, a physical quantity will be estimated in the presence of nuisance signals (line contribution). Second, an easy-to-implement method will be shown to cope with outliers. Both methods are applied routinely in various applications (signal-background separation, outlier handling in ECE or Thomson scattering data, fringe jump mitigation for interferometry measurements, etc).

The estimation of a physical quantity (here the bremsstrahlung amplitude) from spectra "polluted" with additional contributions (here active or passive lines) is an omnipresent problem in data fitting. The traditional approach is to select spectral regions which show only the interesting physical effect and estimate the parameters by maximising a Gaussian likelihood (least squares minimisation). Frequently it is difficult to find such "clean" regions or a large number

of data sets has to be analysed routinely where the pollution is unknown and transient. An alternative method is to allow the data to have additional contributions. The method is based on mixture modelling with a likelihood consisting of two parts: A Gaussian and a marginalised Gaussian likelihood which allows for additional but unspecified signals. The key ingredient is the measurement uncertainty which provides the criterion for clean or contaminated data. With this outlier robust method the bremsstrahlung emission can be estimated in the presence of line intensity and a probability can be calculated if the measured intensity at a given wavelength is only due to bremsstrahlung or contaminated with additional signals. No data censoring prior to the analysis is necessary. The contaminated signals are mitigated automatically. Details about the method can be found in [4]. The upper left panel of figure 1 shows the estimated

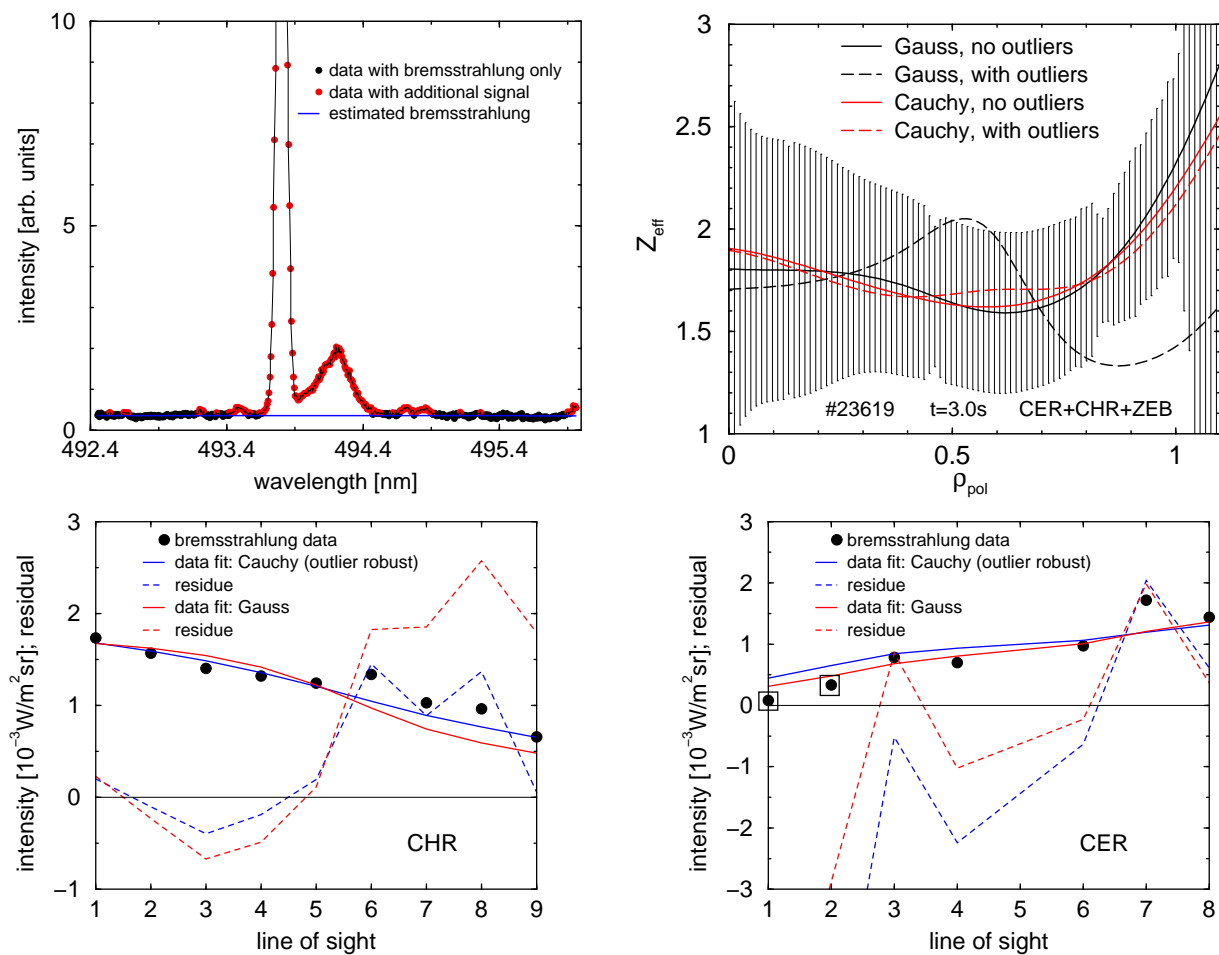


Figure 1: Upper left: Estimated bremsstrahlung background (blue line) from a CXRS spectrum. Contaminated intensities are marked in red. Upper right: Z_{eff} profiles for a Helium discharge from the combined analysis of three diagnostics without (solid lines) and with (dashed lines) outliers due to reflections using either a conventional Gaussian likelihood (black) or an outlier robust Cauchy likelihood distribution (red). Lower panels: Data, data fits, and residues with outlier data (see profiles upper right panel).

bremsstrahlung background (blue line) from a spectrum with nuisance line contributions. Data points with a probability $> 50\%$ of having additional signal contribution are marked in red.

Another easy-to-implement method to handle outliers routinely is based on the assumption that the given data uncertainties might be mis-specified [5]. The upper right panel of figure 1 shows Z_{eff} profiles estimated with two different data sets and two different likelihoods. The lower two panels of figure 1 show the corresponding data, data fits, and residues. A first data set without outliers is augmented in the second set with outlying data suffering from wall reflections (LOS 6-8 of CHR) and partly blocked lines of sight (LOS 1-2 of CER). The results from a Gaussian likelihood probability distribution function (pdf) corresponding to the familiar least squares (χ^2) method are compared to the results from an outlier tolerant Cauchy likelihood pdf,

$$p(\vec{d}|\vec{D}, \vec{\sigma}, a) \propto \prod_i \left\{ a + \frac{(d_i - D_i)^2}{2\sigma_i^2} \right\}^{-(a+1/2)} \quad (1)$$

where \vec{D} and \vec{d} are the modelled and measured data, respectively, and $\vec{\sigma}$ the data uncertainties. For the special case $a = 1/2$ eqn. (1) reduces to the product of Lorentzians (Cauchy pdfs). Due to the heavy tails of the Cauchy pdf outlying data are orders of magnitude less penalised compared to a Gaussian pdf which diminishes after a couple of standard deviations. The Z_{eff} profiles obtained with the outlier robust method both without and with outlying data are close to the profile using the Gaussian likelihood without outlying data. In contrast, the Z_{eff} profile (black dashed) deviates significantly from the others when the Gaussian likelihood is used for the analysis of the data set with outliers. Summarising, if a small fraction of all data are outliers which do not fit the main trend of most data, an outlier robust technique is capable of mitigating their effects. This technique is especially useful if a large number of data sets has to be analysed routinely where a detailed inspection of each data set is not feasible.

References

- [1] G. Verdoolaege, R. Fischer, and G. Van Oost. *IEEE Trans. Plasma Sci.*, 2010. to be published.
- [2] R. Fischer, C.J. Fuchs, B. Kurzan, W. Suttrop, E. Wolfrum, and ASDEX Upgrade Team. *Fusion Sci. Technol.*, 2010. accepted for publication.
- [3] S.K. Rathgeber, R. Fischer, S. Fietz, J. Hobirk, A. Kallenbach, H. Meister, T. Pütterich, F. Ryter, G. Tardini, E. Wolfrum, and the ASDEX Upgrade Team. *Plasma Phys. Control. Fusion*, 2010. to be published.
- [4] R. Fischer, K. M. Hanson, V. Dose, and W. von der Linden. *Phys. Rev. E*, 61:1152, 2000.
- [5] V. Dose and W. von der Linden. In W. von der Linden, V. Dose, R. Fischer, and R. Preuss, editors, *Maximum Entropy and Bayesian Methods*. Kluwer Academic Publishers, Dordrecht, 1999.