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Reconstruction Of The Edge Z_{eff} Profile From Bremsstrahlung Data Via Extensions Of Independent Component Analysis On TEXTOR

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1. Introduction

The understanding of the behaviour of impurities is a critical issue in tokamak physics. Firstly, these impurities increase the fuel dilution and, at reactor parameters, they are responsible for a considerable power loss from the plasma core by bremsstrahlung. Secondly, they largely determine the edge radiation profile and finally, they can affect the growth rate of plasma instabilities.

At the tokamak TEXTOR (Forschungszentrum Jülich, Germany), we run a diagnostic for determining the effective ion charge Z_{eff} from bremsstrahlung measurements in the visible [1]. To obtain a radial profile for Z_{eff} from our line-integrated data, an Abel-inversion is used.

2. Edge radiation, T_e and n_e uncertainties

In our measuring wavelength region, 99 percent of the collected light coming from the central plasma consists of bremsstrahlung, but there is an incertitude at the plasma edge on the different contributions (e.g. recombination and black-body radiation and molecular bands) to the measured continuum signal. Also, at the edge only estimated values are routinely used for the electron temperature T_e and the electron density n_e, which are moreover determined at different toroidal locations. These various uncertainties render the interpretation of a Z_{eff} profile problematic outside the centre. In fact, so far none of the available methods for the determination of Z_{eff} has provided a full profile, which is at present a real challenge.

Therefore, in addition to the efforts already being done to obtain a knowledge of the different radiation processes (and, consequently, of Z_{eff}) in the plasma edge from the physical point of view, we are also trying to extract quantitative information on the edge Z_{eff} directly from the measured signals using methods from statistical data analysis.

3. Independent Component Analysis and extraction of Z_{eff} information

Recent advances in statistical data analysis have made it possible to decompose mixtures of signals into their individual components (*sources*), solely based on the statistics of the

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mixtures. One of the methods is called Independent Component Analysis [2] (ICA), which can be implemented in neural networks, and is a form of unsupervised learning. For ICA to be possible, two conditions have to be fulfilled: the individual sources have to be statistically independent (not exactly in practice) and nongaussian.

Suppose we measure only bremsstrahlung and recombination radiation, then the total emissivity signal H can in fact be regarded as a nonlinear mix of the signal of the electron density n_e, the electron temperature T_e and the various ion densities n_i and charges Z_i. In order to extract information about Z_{eff} from the measurements of H one could think of two approaches:

1. Separate the contribution by bremsstrahlung from the total emissivity.
2. Separate the information of the various impurity densities from H and construct Z_{eff} from these densities (*without the need for* $n_e(t)$ *and* $T_e(t)$?).

4. Multi-channel linear ICA – preliminary tests

In the following preliminary experiment, we have tested the applicability and performance of basic multi-channel linear ICA on line-integrated emissivity time signals. Although from the foregoing it is clear that an algorithm suited for linear mixtures will never be able to do a full separation of the information on the various impurity densities, we will nevertheless show that a linear algorithm can already extract some striking information.

4.1. Temporal dependence scale

The use of several line-integrated emissivity time signals as mixtures involves in fact already a simplification. Indeed, the situation here is quite different from standard ICA, since different channels are oriented along different lines-of-sight through the plasma cross-section. This means that we only consider the time evolution of the signals on a sufficiently large scale T, and that any time behaviour on a shorter scale is considered as due to noise (we will call this *pseudo-noise*). If the temporal dependence of the signals from different channels is different on the scale T, than the ICA algorithm will most likely separate or emphasize this difference in the output independent components.

4.2. Five-channel linear ICA on line-integrated emissivities

In this experiment (Figure 1), we used line-integrated emissivity time signals (TEXTOR discharge number 68803) from five channels, covering all of the plasma cross-section, except for the very edge. The data were sampled at 100 Hz and averaged to reduce both pseudo- and physical noise levels. For these first tests we chose the widely used FastICA algorithm [3]. The signals from a central and a more peripheral looking channel are shown in Figure 1. There are two "bumps" in the time signals (also present in the density signal), but they are more apparent in the central than in the peripheral channel. Precisely this difference allowed the ICA algorithm to emphasize this behaviour in one of the extracted independent components, shown in Figure 2. It is interesting to see that this component shows a remarkable correspondence with the time signal of the central Z_{eff}, especially in the more explicit presence of the two bumps (or peaks).

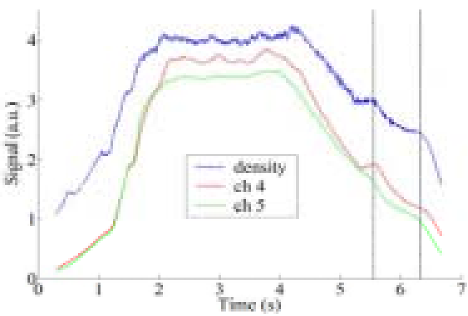

Figure 1: The time signal of the line-integrated emissivity from a central channel (ch 4) and a more peripheral channel (ch 5). The signal (rescaled) of the central line-integrated density is also shown. The two bumps are marked by dashed lines.

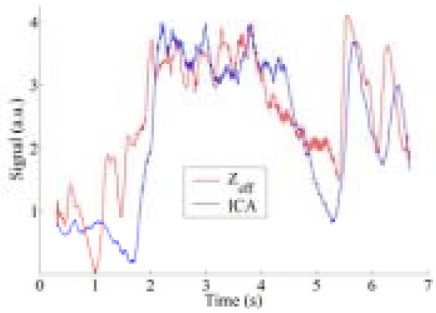

Figure 2: The time signal (ICA) of one of the extracted independent components and the signal (rescaled) of the central Z_{eff}. Note the good correspondence, especially at the time of the bumps in the emissivity signal.

5. Future developments

Here we present some possible future developments of this work. These include:

- **Single-channel ICA:** an ICA algorithm that uses data from a single channel could use much more information on the time structure of the signals, and would thus be likely to generate a better separation than a multi-channel method. However, one would need prior information on the time structure of the independent sources [4]. This information could be extracted from time signals of central quantities, obtained through Abel-inversion, or from other diagnostics, e.g. the study of impurity lines.
- **Nonlinear ICA:** to be able to separate also nonlinear mixtures (see section 3).

- **Study of signal independence:** the signals of the bremsstrahlung and recombination radiation emissivity are not mutually statistically independent, as are many of the signals that contribute to a given emissivity signal (e.g. Z_{eff} and n_e). We will examine to what extent various pairs of signals are dependent. Moreover, there exist methods to relax the independence assumption even more than in standard ICA [5,6,7].

6. Neural networks for profile reconstruction

As a second, and possibly complementary, approach to the problem of profile reconstruction, we are considering the direct use of neural networks. Indeed, an Abel-inversion is computationally fairly intensive and quite sensitive to noise on the input signal (introduction of artefacts). The measured line-integrated bremsstrahlung data for a number of discharges and the corresponding profiles obtained through the Abel-inversion, could be used as a set of training data for the network, which would then be able to quickly reconstruct a profile wherein any artefacts introduced by the Abel-inversion are trained out.

7. Conclusions

We have pointed out that the routine use of estimated values of T_e and n_e and the incertitude on the various contributions to continuum radiation at the edge of a tokamak plasma, prevent the reconstruction of a full Z_{eff} profile. We have proposed the use of Independent Component Analysis to extract information on Z_{eff} from continuum measurements. We have conducted a preliminary experiment with multi-channel linear ICA, and have suggested the use of several extensions of ICA to improve the separation. Finally, we have mentioned an alternative to the Abel-inversion for Z_{eff} profile reconstruction, namely the direct use of neural networks.

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