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Development of Nuclear Radiation Based Tomography Methods for Runaway Electrons in Fusion Plasmas: First Results and Prospects

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INTRODUCTION

The study of Runaway Electron (RE) physics and their response to mitigation strategies is crucial to safeguard ITER structural integrity. During their motion REs collide with background ions before hitting the inner vessel of the machine and thus they emit Bremsstrahlung photons in the gamma range of the spectrum. It is possible to detect such radiation using a $LaBr_3$(Ce) spectrometer with counting rate capability in the MHz range and high energy resolution [1][5]. The measured spectra contain information about the RE energy distribution, which can be reconstructed using specific inversion (or deconvolution) algorithms. The deconvolution operation is computationally faster than first principles simulations and its use in RE studies might be many fold: it can be used to improve synthetic diagnostic calculations or as a preliminary method for RE spectra analysis.

THE INVERSION PROBLEM

The RE energy distribution F is related to the measured gamma-ray spectrum S through a matrix W, which describes the probability for an electron of energy E to produce a signal of energy E^{II} in the diagnostics system, as follows:

$$S = W * F \quad .$$

The operation of reconstructing F, known W and S, is called inversion and it has been solved here using three different methods for comparison. ML-EM [2], an iterative algorithm which, starting from a first guess of the type $F^0 = \frac{S}{\|W^T S\|}$, makes the estimate evolve according to

$F_i^{n+1} = \frac{F_i^n}{\sum_j W_{ji}} \sum_j W_{ji} \frac{S_j}{\sum_k W_{jk} F_k^n}$ and applies a first close bins average every n_{smooth}

iterations to smooth the solution. Tikhonov [7], which evaluates the non negative least squares minimum of $min_{nnls}\|WF-S+\alpha F\|$, where the minimization is performed over a χ^2 statistics which includes a smoothing operator. Singular Value Decomposition (SVD) [3], which employs a generalization of the matrix spectral decomposition for rectangular matrices $W=U\Sigma V^T$ to calculate a truncated pseudo inverse $W^{-1}=V\Sigma^{-1}U^T$, where Σ is a diagonal matrix. Varying degrees of smoothing is possible by varying the number of singular values taken into account to evaluate Σ.

THE TRANSFER MATRIX W

The transfer matrix (figure 1) has been estimated for the two $LaBr_3(Ce)$ gamma-ray spectrometers installed at ASDEX Upgrade (AUG) and described in [1] and [5]. It can be factorized into $W(E_d,E_{RE})=W_d(E_d,E_\gamma)*W_b(E_\gamma,E_{RE})$, where W_b describes the Bremsstrahlung generation of gamma rays inside the tokamak, W_d describes both the transport of photons to the detector and the Detector Response Function (DRF) and E_{RE},E_γ,E_d are respectively the energy scale of REs, emitted gamma-ray and the detector.

In this work W_b includes only the emission on the line of sight due to REs scattering on plasma ions and impurities, in particular Argon40 which is typically used for Massive Gas Injection (MGI). In the hypothesis of a radially collimated diagnostic and relativistic REs, it can be approximated at 0th order as:

$$W_b(E_\gamma,E_{RE})\propto\frac{d\sigma_B}{dE_\gamma d\Omega}\left(E_\gamma,E_{RE},\frac{\pi}{2}\right)\approx\frac{d\sigma_B}{dE_\gamma}(E_\gamma,E_{RE},Z)\frac{1}{2\pi}p\left(E_{RE},\frac{\pi}{2}\right)$$

where Z is the atomic number of the ion under consideration, $\frac{\pi}{2}$ is the angle of emission and the Bremsstrahlung cross section σ_B has been factorized according to [4].

The contribution of Bremsstrahlung photons that experience Compton scattering on plasma ions before being detected has been neglected, since it gives a second order correction. Also

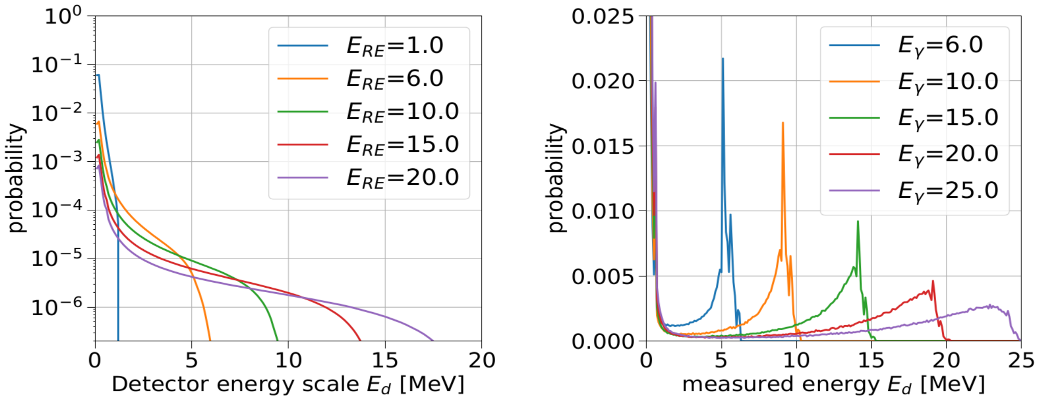

Figure 1: Left: $W(E_d, E_{RE})$ at different RE energies E_{RE} (given in MeV). Right: $LaBr_3(Ce)$ detector response function at different gamma-ray energies E_γ (given in MeV) for [5]

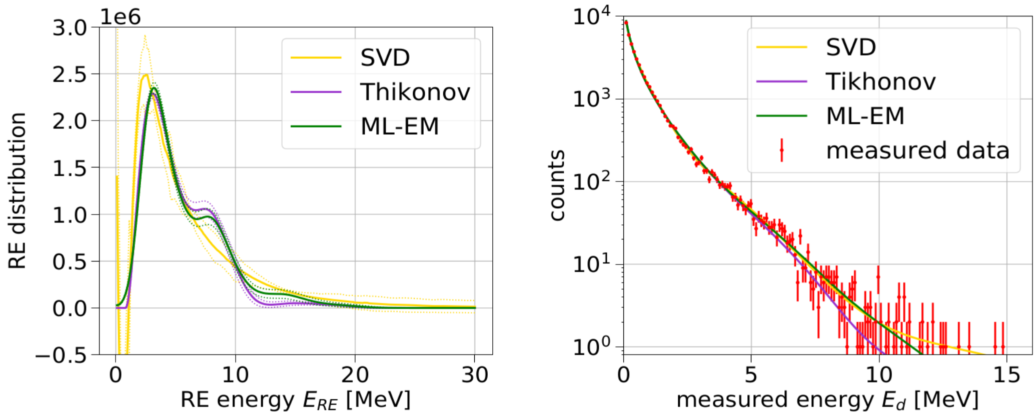

Figure 2: AUG shot #34084 Left: RE energy distribution reconstruction performed with three algorithms: SVD, Tikhonov and ML-EM. Right: agreement between the convolution of the reconstructed spectra with the transport matrix W and the experimental data.

Bremsstrahlung emission due to the impact of RE beam on the vessel is not included in W calculation, since it can be easily identified from sharp peaks in the measured counting rate graph and excluded from the analysis.

AN EXAMPLE OF DECONVOLUTION

AUG shot #34084 has been previously analysed using ML-EM only [5]. The same data have been analysed using the three deconvolution methods described above. The three solutions reasonably fit the experimental data, as shown in figure 2 (left picture) where the convolution $W * F$ evaluated for the three methods is shown over S. ML-EM and Tikhonov reconstructions (figure 2 right picture) agree within statistical errors all over the whole dynamic range. Among the two, Tikhonov allows a stronger smoothing of the reconstructed distribution while keeping the residual low and so it might give better results when dealing with noisy data. On the other hand SVD roughly reproduce the same spectrum as the other two methods, but it also suffers severe artefacts in parts of the reconstruction while others are apparently reconstructed well. SVD is not constrained to be non-negative, so that a typical artefact is the negative count rate for low energies.

RECONSTRUCTION PARAMETERS

It is convenient to evaluate some parameters of the reconstructed spectrum both for data analysis and to compare reconstructions with first principle simulations. For example, the first few moments of the RE distribution are useful and the precision of their reconstruction has been studied using synthetic tests. I.e. RE spectra, generated with a known distribution (e.g. Gaussian or exponential), were convolved with the matrix W to create synthetic measured spectra, which were then deconvolved to find an estimate of the original RE spectrum. In all the tests conducted so far, the mean of the original distribution is correctly reconstructed with an error lower than 5%, while higher order moments appear to be less reliable. The cut-off

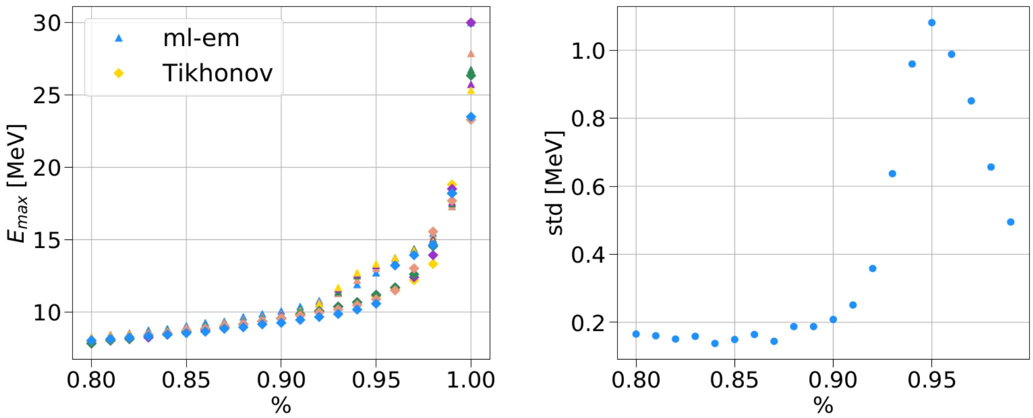

Figure 3: AUG shot #34084. Left: relations between the max RE energy (E_{max}) and the fraction of REs that have an energy less than E_{max}. Triangles and squares represent respectively ML-EM and Tikhonov reconstructions, different colors refer to different smoothing levels. Right: standard deviations of the graph on the left.

energy of the spectrum is expected to be influenced by some plasma parameters (e.g. the current drop experienced during the disruption). It is evaluated as the energy at which the RE cumulative pdf is equal to X%. For AUG shot #34084 X was set to 90% (see figure 3): this value was chosen performing many reconstructions of the measured gamma-ray spectrum using different deconvolution parameters. The highest point in the cumulative pdf with low standard deviation was chosen as the ending energy and it is: $E_{0.9}=9.8$ MeV.

CONCLUSIONS

Three deconvolution methods have been implemented and tested on the reconstruction of runaway electron energy distribution using measurements of gamma ray spectra performed with a single detector. Their combined use allows the identification both of artefacts and reliable parameters of the deconvolved spectrum. W will be computed for other diagnostics, in particular the new gamma camera installed at JET [6] (figure 2), which will allow to perform 2D tomography (energy + spatial distribution) both of runaway electron and of fast ions. Reconstructed spectra will be compared with first principle simulations in order to improve the understanding of RE physics.

Acknowledgemnt

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