EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(04)06-27

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**See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
Fusion Energy 2002 (Proc. 19th IAEA Fusion Energy Conference, Lyon (2002)).

Preprint of Paper to be submitted for publication in Proceedings of the
23rd SOFT Conference,
(Venice, Italy 20-24 September 2004)

ABSTRACT

At JET, the NE213 liquid scintillator is being validated as a diagnostic tool for spectral measurements of neutrons emitted from the plasma. Neutron spectra have to be unfolded from the measured pulse-height spectra, which is an ill-conditioned problem. Therefore, use of two independent unfolding methods allows for less ambiguity on the interpretation of the data. In parallel to the routine algorithm MAXED based on the Maximum Entropy method, the Minimum Fisher Regularisation (MFR) method has been introduced at JET. The MFR method, known from two-dimensional tomography applications, has proved to provide a new transparent tool to validate the JET neutron spectra measured with the NE213 liquid scintillators.

In this article, the MFR method applicable to spectra unfolding is briefly explained. After a mention of MFR tests on phantom spectra experimental neutron spectra are presented that were obtained by applying MFR to NE213 data in selected JET experiments. The results tend to confirm MAXED observations.

1. INTRODUCTION, THE MFR METHOD

The NE213 scintillation detectors are widely used for fast neutron measurements thanks to their relative simplicity, good neutron-gamma discrimination and high light output, see e.g. [1]. A NE213 detector comprising a ø50x20mm scintillator is installed in the JET roof laboratory in order to investigate its neutron and gamma spectral measurement capabilities. Its neutron energy spectrum $\Phi(E_n)$ is to be unfolded from the energies of light pulses $L(E_l)$ produced by the protons from neutron-proton recoil in the NE213 organic liquid scintillator and registered by a photomultiplier. A semi-empirical relation can be introduced

$$L_i = \sum_{j}^{N} R_{ij}\,\Phi_j + \tilde{\varepsilon}_i \qquad (1)$$

where the fixed response matrix R_{ij} is provided by theoretical predictions combined with accelerator calibrations [2], N is total number of neutron energy bins and the ideal corrections $\tilde{\varepsilon}_i$ are due to existing statistical and systematic errors. The set of eqs. (1) need to be inverted in order to obtain the neutron spectrum from the measured pulse-height spectrum. This operation presents an ill-conditioned problem, with high risk of producing large artefacts due to errors, even if $\tilde{\varepsilon}_i$ are low. Therefore, instead of direct inversion, either derivative unfolding codes like FLYSPEC [3] or Lagrange multipliers optimisation methods like MAXED [4] are usually applied in practice. The latter has been used at JET with satisfactory results, although occasional ambiguities called for an independent validation.

The set of eqs. (1) exhibits a striking parallel to the tomographic inversion problem [5]. This parallel motivated the application of the Minimum Fisher Regularisation (MFR) method, known from SXR and bolometric tomography [6], which indeed finds an inverted solution of (1) with a reconstruction matrix *Mji* :

$$\Phi_j = \sum_i^T M_{ji} L_i \tag{3}$$

where *T* is number of pulse-height energy bins.

In general terms, methods that lead to inverted set of eqs. (2) implement constraints namely on smoothness of the reconstructed object. In the case of MFR, a solution is searched thatsimultaneously minimises the Fisher information (thus effectively detailing regions with high neutron intensities)

$$I F = \int \frac{1}{d\Phi\,(E_n)} \left(\frac{d\Phi\,(E_n)}{dE_n} \right)^2 dE_n \tag{3}$$

and that keeps *expected* data errors σ_ι close to the *observed* corrections $\tilde{\varepsilon}_i$, which are obtained by substituting the solution into (1). To this end - similarly to other unfolding methods - an iterative process is run within MFR that performs a χ^2 -like test:

$$\chi^2 = \frac{1}{T} \sum_i^T \left(\frac{\varepsilon_i}{\sigma_i} \right)^2 \tag{4}$$

where the target value of χ^2 should be close to one. However, certain flexibility has to be allowed in this parameter to account for the loose link between ideal corrections $\tilde{\varepsilon}_i$ and the observed ones ε_i .

Unlike MAXED, MFR sets no assumptions on position and shape of the resulting spectra. For details concerning implementation of (3) and (4) into the MFR algorithm and the main advantages of this method see [7].

2. SETTING UP THE MFR UNFOLDING METHOD

On JET, the NE213 data acquisition system sorts light pulses into regular energy bins with their range and width depending on the initial set-up of the system. Therefore, a dedicated response matrix has to be interpolated in each experiment from the provided response matrix fixed to 1087x959 bins. The unfolding algorithm is to process raw pulse-height spectra so that any loss of information due to data manipulation is avoided. However, the data acquisition system cuts off very low pulse energies in order to avoid saturation, while high pulse energies suffer from low statistics.

When implementing an inversion algorithm, testing period is crucial to provide scrutiny of the behaviour and limits of the adopted inversion method, see e.g. [6]. To this end, several phantom neutron spectra were developed, including a simple step function and a Gaussian peak on slowly decreasing background. The performance of MFR was then tested on pulseheight spectra that had been generated from the phantom neutron spectra by application of (1) with realistic random errors ε_i. Thanks to these tests we could conclude, among others, the following statements:

- MFR proved to provide reliable results in the one-dimensional spectra unfolding.
- Both oversmoothing and overfitting can be avoided by refinements in the χ^2 target value, although it is hard to determine this value without a-priori knowledge of the phantom function.
- It is advisable to crop the neutron energy range according to the pulse-height spectrum limits so that the semi-triangular shape of the response matrix is preserved. The tests proved that cropping of the response matrix does not challenge the unfolding process, although it sets limits on neutron energy resolution.
- The reconstruction process is quite fast, in the order of seconds or tens of seconds depending on size of the response matrix.
- As expected, the energy resolution slightly decreases with increasing statistical errors. Judicious setting of the expected data errors σ_i is another task of prime importance. There is no explicit knowledge concerning expected errors in the experimental data. We adopted the assumption that probability of light pulse counts follow the Poisson distribution, hence

$$\sigma_i = \sqrt{N_i} \tag{5}$$

where N_i corresponds to number of counts in the i-th light energy bin. When implementing and testing (5) we noticed that noise in σ_i have a derogatory effect on the reconstructed neutron spectra. Therefore, in the final algorithm the expected errors are tracked down from a smooth polynomial fit on experimental data in (5). This solution has so far proven to be adequate, while setting e.g. a constant σ_i has resulted in a clear overfit in low neutron energies and oversmoothing in high energies.

3. FIRST EXPERIMENTAL RESULTS

An example of a NE213 light pulse-height spectrum is in Fig.1(a). The presented data were acquired within the recent JET Trace Tritium Experiment campaign in a discharge with tritium minority Ion Cyclotron Resonance Heating (ICRH) [8]. Counts of pulses with energies less than 0.7MeV were electronically suppressed, thus inhibiting data on neutrons from the D-D fusion reactions. The remaining pulses correspond to 14MeV neutrons from the D-T fusion reactions, as demonstrated by the result of the MFR unfolding, see Fig. 1b. Pulse-height data from 4 MeV - 10 MeV energy region were used (as delimited by dash-dot lines in Fig.1(a) and the χ^2 target had to be set slightly below one in order to prevent oversmoothing. The D-T peak has full-width at half maximum (FWHM) 2 MeV which agrees to MAXED analyses. A fit of a 14 MeV gaussian curve with this FWHM (dashed line in Fig.1(b) proves correct shape of the MFR reconstruction but approx. 0.1 MeV shift towards lower energies. Full line in Fig.1(a) corresponds to a retrofit, i.e. to substitution of the unfolded neutron spectra to set of eqs. (1).

Figure 2 shows MFR unfolded neutron spectrum from JET plasma discharge in pure deuterium with 18MW neutral beam and 6 MW ICRH power. This neutron spectrum was obtained from 0.24 MeV - 1.2MeV region of pulse height spectrum. The major peak corresponds to 2.45MeV neutrons from D-D fusion reactions, the minor peak at 1.5MeV is generally considered to be an artefact. The same artefact had been obtained also by MAXED and is therefore inherent either to the pulse - height spectrum or to the response matrix. The dashed line corresponds to gaussian curve at 2.45MeV (energy of neutrons from D-D fusion) with FWHM 0.53MeV.

In figure 3 a more complex neutron spectrum is presented, corresponding to JET plasma discharge in helium with high-energy alpha-tail produced by ICRH [9]. In the neutron spectrum, the 2.45MeV peak from D-D fusion reactions is well pronounced, demonstrating significant influx of deuterium from JET walls in the particular discharge. The higher neutron energy peaks have not be fully identified yet, but they are expected to originate in the Be(α,nγ)C nuclear reactions in plasma. While the γ-radiation peaks corresponding to this reaction had been already identified [10], analyses of the neutron energies are subtler due to their sensitivity to the energy distribution of the incident α particles.

To further investigate this challenge, a dedicated pulse-height database was acquired in a set of similar consecutive JET discharges, with pulse energy cut-off above the energies corresponding to the D-D fusion neutrons. The resulting neutron spectra as reconstructed by MFR and MAXED algorithms are presented in Figure 4(a). The two results qualitatively agree. The peaks observed in Fig. 3 now overlap, and there is another well-pronounced peak around 7.8MeV and a minor peak around 9.8 MeV, although the last one may be argued to be an artefact due to poor pulse statistics. Anyway, the indisputable presence of neutrons with energies above 5MeV provides an independent proof of efficiency of the α- particle acceleration by ICRH in the JET helium discharges.

Interestingly, the χ^2 target had to be set slightly higher here in order to prevent overfitting, which indicates that the superposed plasma discharges were not completely identical. The observed errors ε_i in this MFR unfolded spectrum (difference between the retrofit and the raw data) are printed in dots in Fig.4(b). Smoothing (averaging) the ε_i dependence on pulse height energy show some collective behaviour, which is most likely due to systematic errors either in the reconstruction matrix or in performance of the diagnostics hardware. In general, our preliminary expertise with the MFR spectra unfolding indicates that the error estimate (4) is rather conservative, i.e. in standard cases it leads to oversmoothing. It is desirable that an automated method is implemented to determine optimal χ^2 target similarly to L-curve method already used in MAXED [11]. Besides, the observed slightshift in MFR to lower neutron energies should be accounted for, thus requiring further tests on phantom functions.

First experimental spectra unfolded by the MFR qualitatively agree with previous results obtained by MAXED. Consequently, in future the main efforts should be focused on the quality of the response matrix. The MFR unfolding method, thanks to its transparency, could help in tracing systematic errors in individual elements of the matrix. The present, ITER-oriented fusion research calls for broader efforts in the field of neutron diagnostics [12]. To this end, a new algorithm based on Minimum Fisher Regularisation (MFR) proved to be a reliable and performing tool for unfolding the neutron spectra registered by the JET NE213 scintillator.

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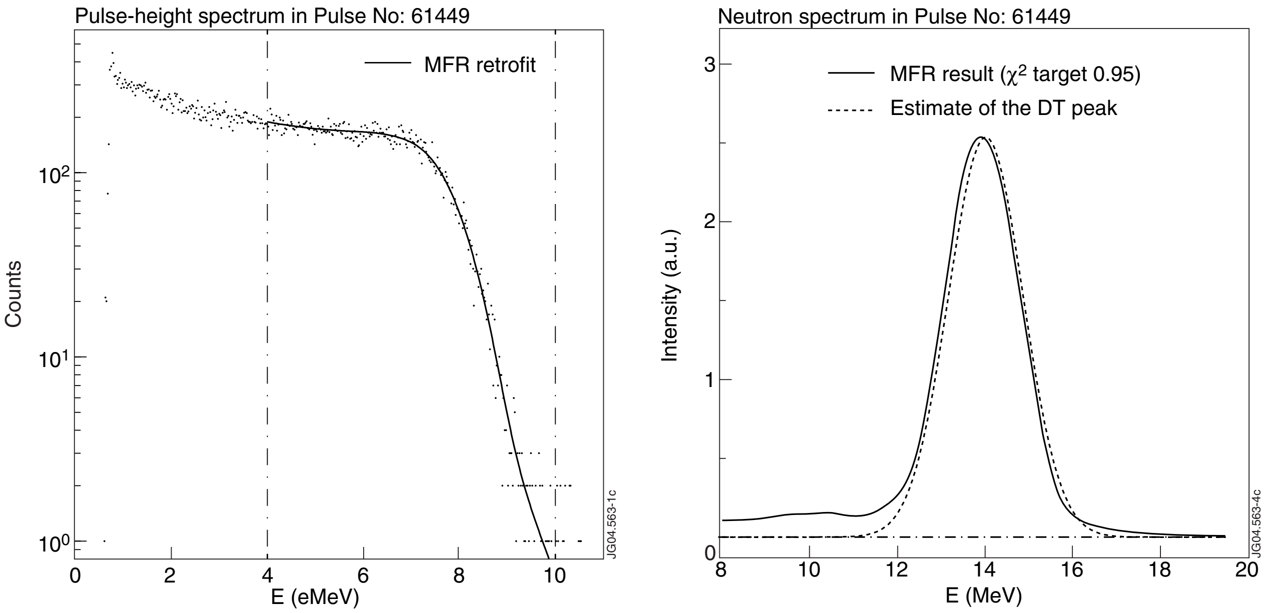
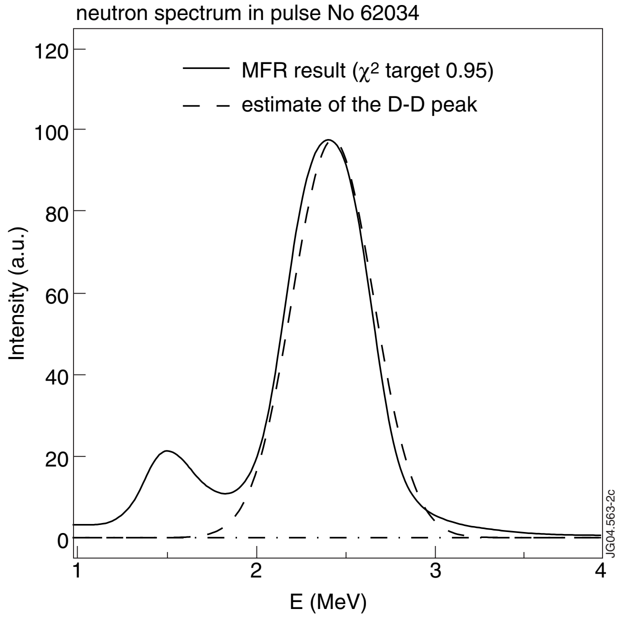


Figure 1: JET Trace Tritium Experiment a) time-integrated pulse-height spectrum from the NE213 detector b) neutron spectum as unfolded by MFR, compared to Gaussian function at 14 MeV D-Tfusion energy, 2 MeV FWHM (dashed line)



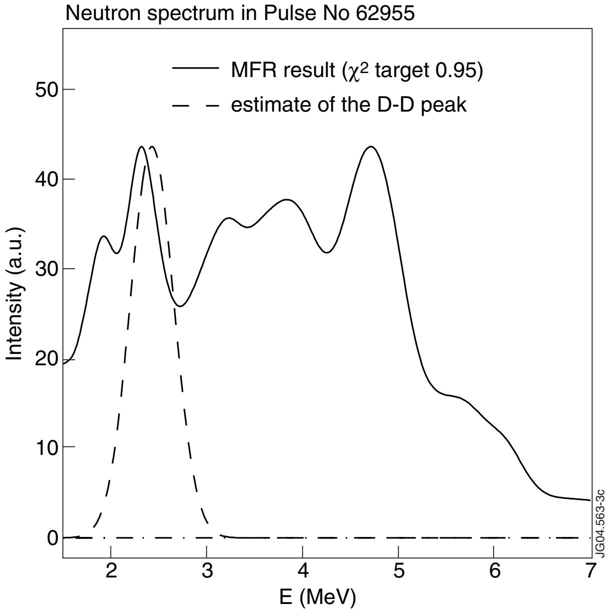


Figure 2: Neutron spectrum unfolded by MFR in a JET pure deuterium plasma, compared to Gaussian function at 2.45MeV D-D fusion neutron energy, 0.53MeV FWHM (dashed line)

Figure 3: Neutron spectrum unfolded by MFR in a JET helium plasma with ICRH accelerated highenergy alpha tail. 2.45MeV D-D peak in dashed line

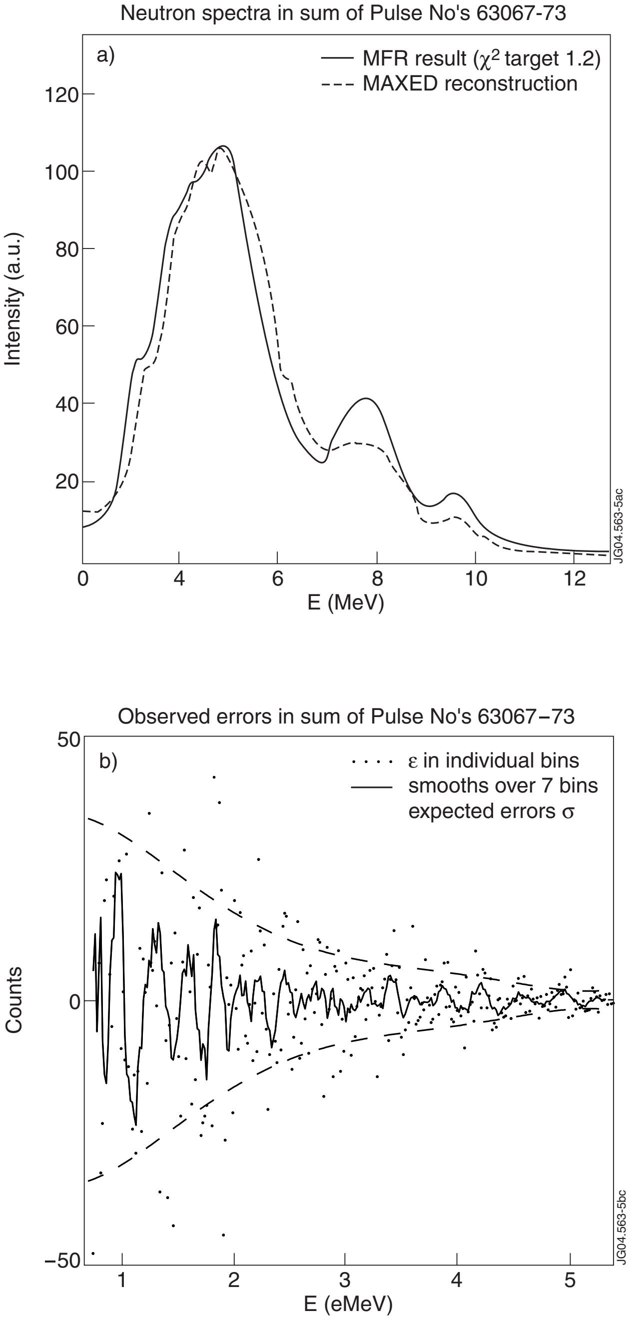


Figure 4: Cumulative data from a series of JET helium plasmas with ICRH produced high-energy alpha tail a) neutron spectrum unfolded by MFR (full line) and MAXED (dots) b) MFR observed corrections e_i (dots) and their averaged value over 7 bins (full line) compared to expected errors s_i (dashed line)