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ABSTRACT

In this paper we present the results obtained from the data analysis of neutron spectra measured with a NE213 liquid scintillator at JET. We calculated the neutron response matrix of the instrument combining MCNPX simulations, a standard proton light output function and the fit of data from ohmic pulses. For the analysis we selected a set of pulses with neutral beam injection heating (NBI) only and we applied a forward fitting procedure of modeled spectral components to extract the fraction of thermal neutron emission. The results showed the same trend of the ones obtained with the dedicated spectrometer TOFOR, even though the values from the NE213 analysis were systematically higher. The uncertainties on the thermal fraction estimates were from 4 to 7 times higher than the ones from the TOFOR analysis.

1. INTRODUCTION

Neutron emission spectroscopy is a valuable tool for plasma diagnostics. The complex spectrometer systems built in the past have very good resolution and their data analysis procedures are relatively simple [1, 2]. On the other hand, their handling is cumbersome, they require constant maintenance, and their big dimensions could constitute a problem in future reactor-grade tokamaks, where the space allotted for diagnostics needs to be drastically reduced. For these reasons it is of interest to investigate the potential of small, compact detectors for fusion neutron spectroscopy, such as NE213 liquid scintillators and diamonds [3, 4, 5]. The application of such detectors has so far mainly been focused on neutron flux measurements, the reason being their rather complex response function that makes the analysis of the measured spectrum a challenging task. Spectra from compact neutron detectors have been measured and analyzed in the past, but their interpretation in terms of plasma parameters has been rather limited [6].

In this work we investigated the possibility of using NE213 scintillators to evaluate the fraction of thermal neutron emission from the plasma applying a forward fitting algorithm to the measured pulse height spectrum (PHS). As a means of validation, we have compared our results with the values obtained with the TOFOR neutron spectrometer [1].

The detector used is located in the back of the Magnetic Proton Recoil upgraded spectrometer (MPRu)2 at JET. This detector utilizes the same field-of-view and radiation shield as the MPRu instrument. The data analyzed were collected during the JET experimental campaigns C31 and C32 in 2013.

In section 2 we briefly describe the detector installation; in section 3 we present the calibration method for the spectrometer; in section 4 we introduce the method for data analysis and error estimate; in section 5 we discuss the results and we finally draw conclusions in section 6.

2. DETECTOR INSTALLATION

The detector assembly consists of an active cylindrical cell of about $1cm^3$ (12.3mm diameter, 8.4mm height). The cell is connected to a Photomultiplier Tube (PMT), which is covered with a layer of

mu-metal for magnetic shielding. The assembly is embedded in an aluminum case. An additional soft iron magnetic shielding surrounds the detector and is used as a holder to keep it in place. The detector and holder are placed inside a pre-prepared cavity in the back of the MPRu. A ^{22}Na gamma source is mounted in front of the scintillator and is used for calibration and monitoring of the PMT gain. The detector is also equipped with a LED pulser directly connected to the PMT for the monitoring of the gain variations due to high count rates.

The data is collected using a digitizer ADQ214 from SP Devices (400MSPS, 14bit). The full signals are recorded and the analysis is performed digitally.

3. CALIBRATION

3.1.GAMMA ENERGY AND RESOLUTION

The ^{22}Na spectrum contains two lines of gamma emission, namely, at 0.511 and 1.275MeV. Each of these produces a Compton edge, whose position and slope are related respectively to the energy calibration and resolution.

The electron (gamma) light output of the scintillator is linearly proportional to the deposited energy. Therefore the energy calibration is described by:

$$E\,[MeVee] = ch \times k + m \tag{1}$$

where *ch* is the channel corresponding to the total integrated charge, *k* and *m* are calibration parameters.

The resolution of the detector is usually described by the three parameters function:

$$\frac{FWHM\,(E)}{E} = \alpha^2 + \frac{\beta^2}{E} + \frac{\gamma^2}{E}. \tag{2}$$

The term α represents the spread due to the non-homogeneity of the light collection efficiency in the scintillator volume. Since our scintillator has a small volume we can neglect this term.

We evaluated the response of the detector to the two gamma energies using a MCNPX model [7].

The calibration and resolution parameters (k, m, β, γ) are then obtained fitting the measured PHS with the MCNPX response convoluted with the resolution.

A fitted gamma spectrum is shown in Figure 1.

3.2. NEUTRON RESPONSE MATRIX

The response of the detector to neutrons is more complex than that of electrons, since the relation between proton (neutron) light output and deposited energy is not linear as in the case of electron (gamma) interactions. The best way of dealing with this problem is to measure the response of the detector to a source of monoenergetic neutrons. Since we did not have access to such a neutron facility, we obtained the response matrix by combining MCNPX simulations, the proton light output function measured for another NE213 scintillator of similar dimensions [8], and the spectrum

from ohmic plasmas measured at JET. The latter gives us a reference point for the light output of 2.45MeV neutrons. The procedure is the following: first we use the MCNPX and Adams results to obtain a starting estimate of the response matrix, then we fit the ohmic spectrum (assuming T_i = 2keV) introducing a parameter k_n, a scaling factor that compensates for the discrepancy between the actual light output function of the detector and the one of Adams. If the actual light output of 2.45MeV neutrons is higher (lower) than the starting guess, the value of k_n is higher (lower) than 1. In the final response matrix we include the energy scaling given by the fitted value of k_n.

4. DATA ANALYSIS

4.1. DATA ANALYSIS

The neutron spectrum consists of components that correspond to neutrons generated by different ion populations of the plasma. For the analysis presented here we selected pulses where the only additional heating was the neutral beam injection (NBI), in which case the spectral components are three: neutrons emitted due to thermal, beam-thermal and beam-beam fuel ion interactions. To reduce the degrees of freedom of the fitting procedure, we selected pulses with high electron density ($n_e \sim 10^{20}$), so that we could neglect the neutron emission due to beam-beam interaction, leaving only two spectral components. With high density we could also assume $T_i \approx T_e$ and we use the electron cyclotron emission measurement of T_e as a Bayesian prior for T_i in the fit.

4.2 ANALYSIS METHOD

To analyze the data we applied a forward fitting procedure. This allowed us to separate the different spectral components, hence to obtain information about the plasma state.

First we evaluated the expected fuel ion distribution in the plasma by modeling the selected pulses with the TRANSP code [9]. From these ion distributions we then obtain the neutron spectral components by means of Monte Carlo calculations.

Finally we used these components folded with the neutron response matrix and the resolution function to fit the experimental data, applying the following procedure:

1. Fit the intensity of the thermal and beam-thermal components to the measured PHS;
2. Use the obtained neutron spectrum to evaluate the backscatter component, i.e. the component due to the neutrons that reach the detector after scattering against the far tokamak wall;
3. Fit again including the intensity of the backscatter component.

Figure 2 shows an example of fitted PHS and the corresponding neutron spectrum.

Finally we calculate the thermal fraction from the intensity of the fitted components:

$$TF = I_{th} / (I_{th} + I_{nbi}), \tag{3}$$

where I_{th} is the intensity of the thermal component and I_{nbi} is the intensity of the beam-thermal component.

The procedure for the analysis of the TOFOR spectra is very similar to the procedure described above. A detailed description of it is presented by C. Hellesen et. al. [10].

4.3 ERROR ESTIMATE

The statistical uncertainties can be obtained directly from the fit by sampling the probability space independently for each parameter. To estimate the systematic uncertainties introduced by the calibration we ran the fit changing separately each of the calibration parameters (β, γ, k, m, k_n) by $\pm\sigma$. The error introduced by the uncertainty on the considered parameter is the difference between the thermal fraction value obtained this way and the one obtained with parameters unchanged. The total upper and lower uncertainties are given by:

$$\sigma_{(\pm)} = \sqrt{\sigma_{stat}^2 + \sigma_{sys\,(\pm)}^2} = \sqrt{\sigma_{stat}^2 + \sigma_{i\,(\pm)}^2} \tag{4}$$

where $i = \beta, \gamma, k, m, k_n$ and $\pm$ means upper or lower uncertainty.

5. RESULTS AND DISCUSSION

The comparison between the thermal fraction obtained with the NE213 and with TOFOR is shown in Figure 3.

First of all we can notice that the error on the NE213 estimate is significantly larger than the one from TOFOR. That is expected and it is mainly due to the worse energy resolution and the uncertainties introduced by the detector responseFor TOFOR, only statistical uncertainties are used, since the systematic component for this well-characterized instrument is expected to be small. We can notice that there is a correlation between the two measurements. However the values resulting from the NE213 analysis are systematically higher than the TOFOR reference. This might be explained considering the very different lines of sight of the two instruments: the plasma regions that fall into the field of view of the two detectors are different, so it can be for instance that in one of these regions the beam-thermal interaction is more or less important than in the other. It has to be noted also that the spectral components can be affected by the plasma rotation induced by the beams, an effect which affects the two instruments differently but has not been taken into account in the analysis presented here. Further investigation to understand this observation is needed.

CONCLUSIONS

We have presented a method to obtain the neutron response matrix of an NE213 detector using a combination of MCNPX modeling and ohmic data employing a generic scintillator light output function from the literature.

We have described a robust analysis method to obtain the thermal fraction from a pulse height spectrum measured with a NE213 and to estimate both the statistical and systematic uncertainties on the thermal fraction.

We have presented the results obtained applying the analysis method to data collected with a NE213 installed at JET during the experimental campaigns C31-32. Finally we have compared the results with the ones from the TOFOR spectrometer and found that there is a clear correlation between the estimates given by the two instruments, although we observe that the NE213 estimate is systematically higher than the TOFOR estimate.

We can therefore conclude that it is possible to estimate important plasma parameters, such as the thermal fraction in suitable fusion plasmas, with NE213 detectors, but that the analysis procedure is not trivial and some details still need to be understood. Moreover the errors introduced by the NE213's poor resolution and its non-optimal instrumental response are significantly higher than the uncertainties on the values estimated with a well-established, optimized spectrometer such as TOFOR.

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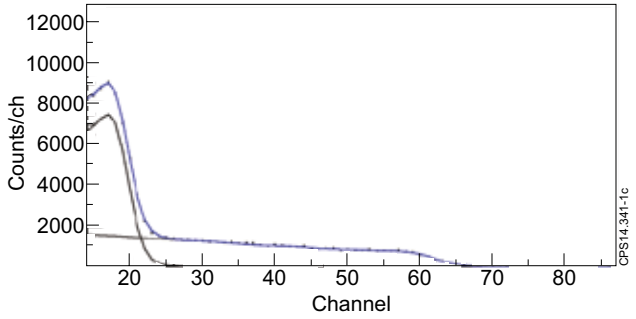

Figure 1: Measured gamma spectrum from the 22Na source (points) with fitted spectrum (blue line).

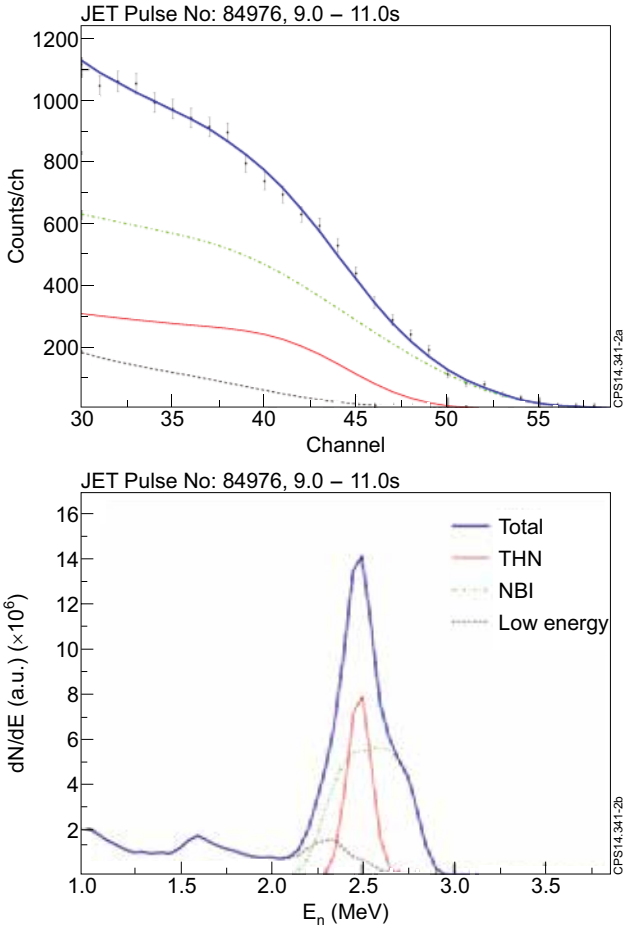

Figure 2: Fitted PHS from JET Pulse No: 84976 between 9 and 11 seconds (a) and corresponding neutron spectrum (b). The components are the thermal component (red solid), the beam-thermal component (dashed-dotted green), the backscatter component (dashed black). The sum of the components is the blue bold line.

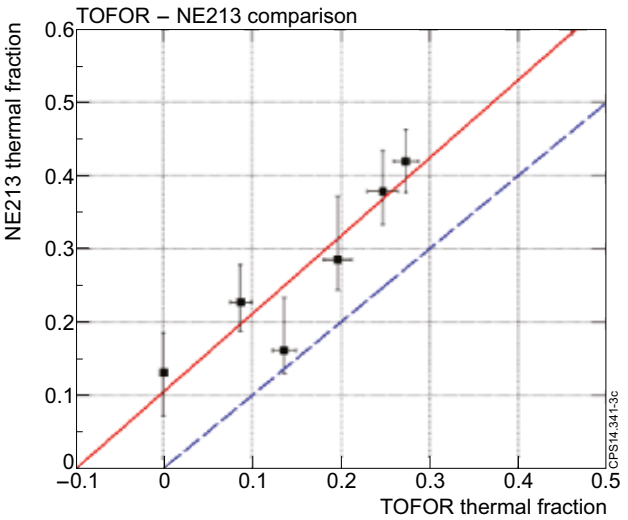

Figure 3: Comparison between the thermal fractions obtained from the TOFOR analysis and the NE213 analysis. The red solid line is the best linear fit, the blue dashed line is the ideal 1 to 1 relationship.