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Forward modeling of pile-up events in liquid scintillator detectors for neutron emission spectroscopy

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ABSTRACT

When using liquid scintillator detectors to measure the neutron emission spectrum from fusion plasmas, the problem of pile-up distortion can be significant. Because of the large neutron rates encountered in many fusion experiments, some pile-up distortion can remain even after applying traditional pile-up elimination methods, which alters the shape of the measured light-yield spectrum and influences the spectroscopic analysis. Particularly, pile-up events appear as a high-energy tail in the measured light-yield spectrum, which obfuscates the contribution that supra-thermal ions make to the energy spectrum. It is important to understand the behavior of such "fast ions" in fusion plasmas, and it is hence desirable to be able to measure their contribution to the neutron spectrum as accurately as possible. This paper presents a technique for incorporating distortion from undetected pile-up events into the analysis of the light-yield spectrum, hence compensating for pile-up distortion. The spectral contribution from undetected pile-up events is determined using Monte Carlo methods and is included in the spectroscopic study as a pile-up component. The method is applied to data from an NE213 scintillator detector at JET and validated by comparing with results from the time-of-flight spectrometer TOFOR, which is not susceptible to pile-up distortion. Based on the results, we conclude that the suggested analysis method helps counteract the problem of pile-up effects and improves the possibilities for extracting accurate fast-ion information from the light-yield spectrum.

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I. INTRODUCTION

Liquid scintillator detectors have often been used in fusion neutron plasma diagnostics, both as neutron flux monitors and for neutron spectroscopy. While the spectroscopic capabilities of liquid scintillator detectors are somewhat limited in comparison to dedicated spectrometers, they have been shown to be useful, for example, for determining the fraction of thermonuclear fusion reactions[1] and estimating fast-ion energies (i.e., energies of supra-thermal ions).[2]

When a particle deposits energy in a scintillator detector, it causes a light-pulse, which is typically converted to an easily measured voltage pulse via a photomultiplier (PM)-tube, a preamplifier, and shaping filters. The shapes of the pulses differ slightly between particle types (e.g., can be used to separate neutrons and gammas), and the magnitudes are related to the deposited energy. For this reason, modern data acquisition systems generally store the waveforms of the pulses digitally, where they can be processed and analyzed in retrospect. In neutron spectroscopy, we usually apply pulse shape discrimination (PSD)[3] to exclude gamma

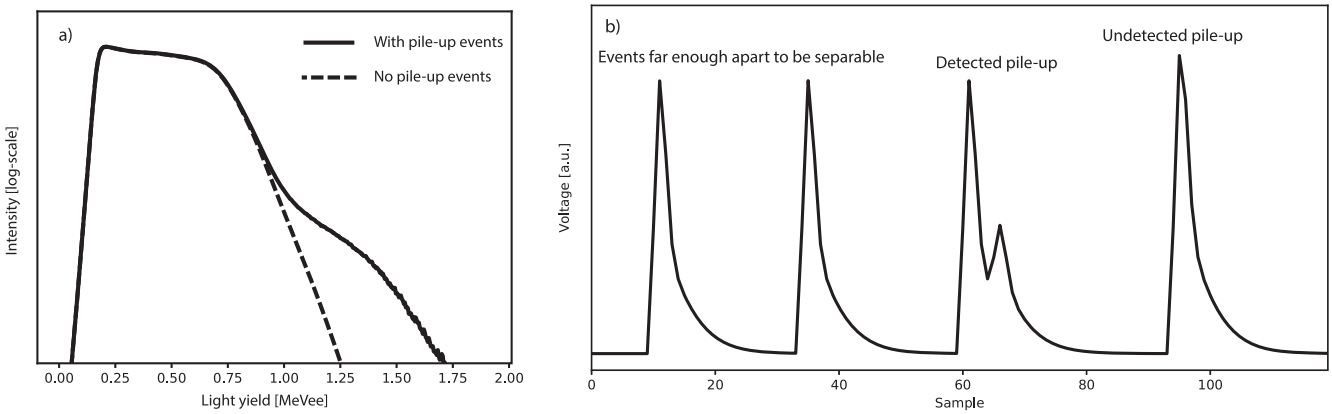

FIG. 1. (a) Example of simulated light-yield spectra, with and without distortion from pile-up effects. The simulated light-yield spectrum corresponds to the neutron emission from an NBI-heated deuterium plasma, with equal contributions from thermonuclear and beam-thermal fusion reactions. (b) Simulation of events in the data acquisition system of a liquid scintillator.

pulses and generate a spectrum from integrating the remaining ones.

The analysis of a neutron emission spectrum requires a precise measurement of the shape of the neutron spectrum. However, the spectrum measured by a scintillator detector can be distorted by the so-called pile-up effects, i.e., when an event occurs in the detector before the preceding one has died away, and hence, a greater light-yield is recorded. Such effects can be highly present in cases of a large count rate, such as with high-performing fusion reactors. While pile-ups can have a slight distorting effect on the spectrum overall, the most prominent sign is that of a high-energy tail,[4,5] as can be seen in Fig. 1(a). This extra high-energy tail is problematic in fusion neutron spectroscopy since it overlaps with the spectral signatures from reactions involving supra-thermal ions, which also appear as a high-energy tail in the spectrum.[6,7] Hence, when using a liquid scintillator detector for spectroscopy on high-performing fusion plasmas, pile-up effects need to be removed or otherwise dealt with.

Usually, the pile-up distortion is handled by removing the pile-up events from the spectrum. Most pile-up events can be sorted out by PSD[3,8] or processed and reconstructed by more advanced techniques.[9] While pile-up rejection is a useful and well-tried method, no pile-up rejection routine is perfect, and if the neutron rate is high enough, significant distortions can remain, influencing the spectroscopic analysis. We have observed this in spectroscopic data from the tokamak JET, for high-performing discharges, even after a pile-up rejection routine has been used.

In this paper, we treat detected pile-up events and undetected pile-up events separately. We propose that detected pile-up events are dealt with in conventional ways, i.e., discard them or reconstruct both pulses if possible. The undetected pile-up events, however, also need to be handled. The aim of this paper is to model the contribution of undetected pile-up pulses in the light-yield spectrum. By knowing the event rate in the detector, the time interval between pulses during which a pile-up can go undetected, and with an estimate of the ideal spectrum, we can calculate the spectroscopic contributions from undetected pile-up events in the detector. The approach proposed is to first handle detected pile-up events as best one can, then model the effects of undetected pile-up events (as described in Sec. II), and incorporate them in the analysis. Figure 1(b) shows an example of simulated pulses from a liquid scintillator detector, where two pulses can be integrated separately, one detected and one undetected pile-up event.

The pile-up model is validated by including it in an analysis of data from a liquid scintillator detector at JET and comparing the results with corresponding results from a time-of-flight spectrometer not sensitive to pile-up distortion. The analysis procedure is described in Sec. III, and the results are presented and discussed in Sec. IV.

II. NEUTRON SPECTROSCOPY WITH PILE-UP DISTORTION

In order to do any spectroscopic analysis with liquid scintillators, we need a way of determining how the energy spectrum of incident neutrons translates to the light-yield spectrum measured by the detector. Such a mapping is typically found in the form of a detector response function (DRF), often simulated with Monte Carlo calculations (e.g., as described in the work of Binda *et al.*[10]). The response function does, however, not account for the effects of pile-up events. In a light-yield spectrum, pile-up events show up as a high-energy tail, obfuscating a region in the spectrum of high interest in fusion plasma diagnostics due to its importance for estimating fast-ion energies.[7] Figure 2(a) illustrates how fast ions in a fusion plasma, accelerated with RF heating,[11] also cause a high-energy tail similarly to pile-up distortion. Here, the energy distribution of the fast ions is characterized by an RF temperature, using the Maxwellian approximation further described in the work of Sahlberg *et al.*[2]

This section describes a method for modeling the contribution to the light-yield spectrum from the undetected pile-up events.

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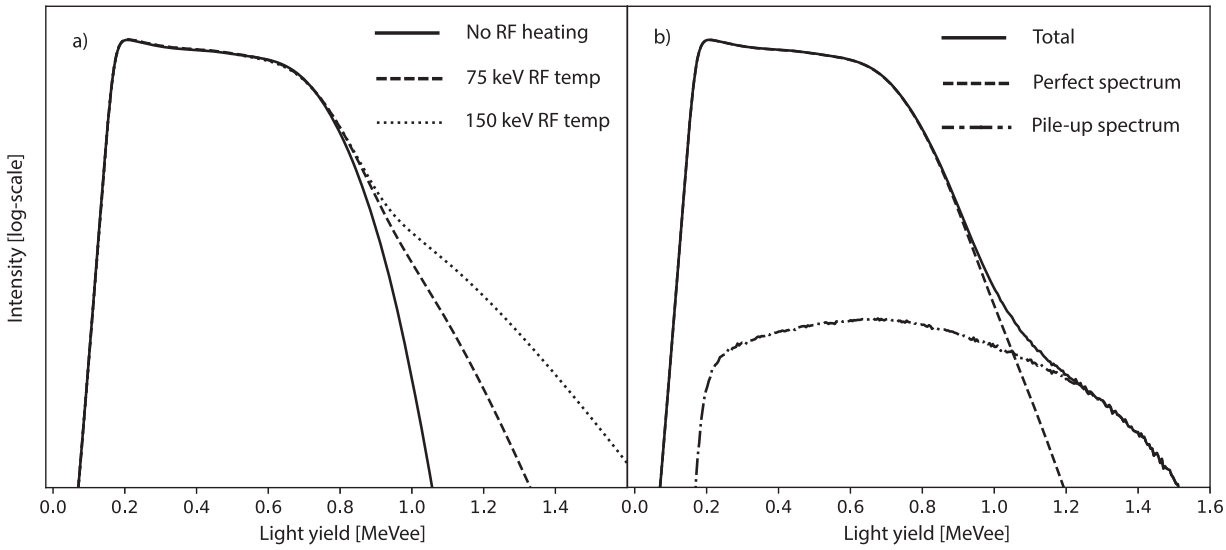

FIG. 2. (a) Examples of calculated light-yield spectra without RF heating, with an RF temperature of 75 keV, and with 150 keV. (b) Example of a modeled ideal (i.e., pile-up free) light-yield spectrum and a calculated pile-up spectrum, using an event rate of 3×10^5 s^{-1} and a pile-up resolution of 50 ns. We can note how both the RF tail and pile-up contribution occupy a similar region in the spectrum.

A. Calculating the pile-up contribution to the light-yield spectrum

Assume we know the energy distribution of neutrons interacting with a liquid scintillator detector. From the known detector response function (DRF), we can calculate the shape of the measured light-yield spectrum that we would see if these particles interact with our detector. However, the response function does not take undetected pile-up events into account. If the neutron rate is high enough, this causes a difference between the ideal light-yield spectrum and the measured one. The energy spectrum of these pile-up events originates from more than one particle depositing their energy in the detector close enough in time to be registered as a single event, i.e., by the sum of several events from the ideal energy spectrum.

To determine the spectrum of pile-up events, we need to know (i) the rate at which particles interact in the detector and (ii) how close in time events can take place while still being detected by the pile-up rejection routine. This minimum time difference between events is here called the "time resolution" of the pile-up rejection routine and is denoted by τ.

Assuming an event-rate (r), the time (t) until a new event arrives in the detector is sampled from an exponential distribution $f(t) = re^{-rt}$. If the time resolution of the pile-up rejection routine is τ, we can note that the probability of an undetected pile-up event is

$$P(\text{undetected pile} - \text{up}|\tau) = \int_0^\tau re^{-rt}\mathrm{d}t = 1 - e^{-r\tau}. \quad (1)$$

The ideal light-yield spectrum (Ψ) works as a distribution for the light-yields recorded by the detector, and by sampling it several times, we can determine the spectral contribution of undetected pile-up events using the procedure described in Algorithm 1. An example of the result of the method (for an event rate of 3×10^5 s^{-1} and a pile-up time resolution of 50 ns) is presented in Fig. 2(b) together with the ideal light-yield spectrum without pile-up distortion.

Algorithm 1: A description of how the pile-up component is calculated.

Input: Perfect light-yield spectrum Ψ, event rate r, time-resolution of pile-up the rejection routine τ, detector threshold T, number of samples to use N
Result: Spectrum of pile-up events P

```
Initialize list S
for N times do
    s ← Sample from Ψ with the condition that s > T
    s ← s + Sample from Ψ
    p ← Sample from U(0,1) (uniform distribution between 0 and 1)
    while p < 1 − e^{−rτ} do
        s ← s + Sample from Ψ
        p ← Sample from U(0,1)
    end
    Add s to list S
end
P ← Histogram of all samples in S
Normalize P to be 1 − e^{−rτ} of the total events in the spectrum.
```


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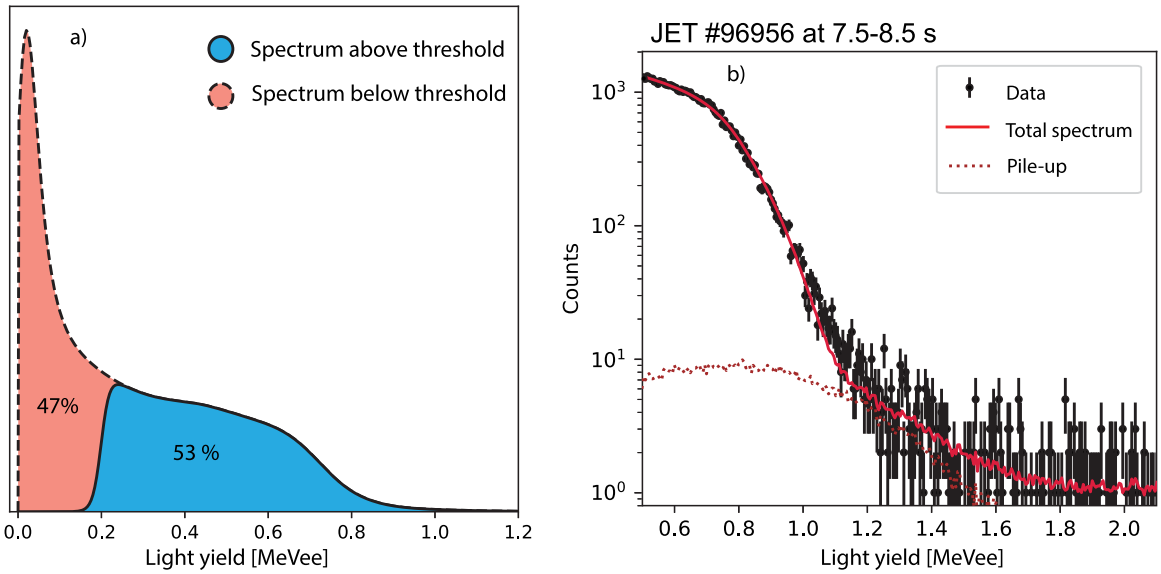

FIG. 3. (a) MCNP simulation of the deposited energy in an NE213 liquid scintillator detector from the neutron emission of a typical JET pulse with deuterium fuel, using NBI heating and second harmonic RF heating of deuterons. (b) Light-yield spectrum of JET pulse 96956, which does not use RF heating, to which the τ parameter has been calibrated to give a matching pile-up intensity.

1. Input parameter estimation

The results of the application of the algorithm depend on how well the input parameters are determined, and the process is not necessarily straightforward. In this paper, we use a detector response function measured at the Ion Accelerator Facility of the Physikalisch-Technische Bundesanstalt,[12] with which we calculate an estimation of the pile-up free light-yield spectrum, Ψ.

The event rate, r, may appear straightforward enough to determine from the number of counts in the detector but is more involved than one may think at first. The estimation used here starts with the number of pulses registered in the detector. However, the actual event rate is higher than the measured number of pulses since some recorded events will be pile-ups and hence actually be two or more events. If the true event rate is r_{true} and the time during which a pile-up can occur undetected is τ, the measured event rate is related to the true one as

$$r_{\text{measured}} = r_{\text{true}}\ \exp(-r_{\text{true}}\tau). \tag{2}$$

By solving the said equation, we can estimate r_{true}, but this value still is not satisfactory. The reason is that a considerable number of events in the detector occur below the threshold level of the data acquisition software. While such pulses, by themselves, should not be included in the light-yield spectrum, they can still deposit energy and contribute to the pile-up distortion if they occur in close proximity to a larger pulse. Figure 3(a) shows a simulation of deposited energy from a fusion reactor's neutron emission in the scintillator detector used in this paper, calculated using the Monte Carlo N-Particle transport code (MCNP).[13] In this simulation, we note that ~47% of the events in the detector occur below the threshold. The estimations of r used in this paper have been adjusted up to take the events below the threshold into account. The fraction of 47% is estimated for typical high-performance deuterium-plasma scenarios used in the benchmarking in this paper. This number should suffice for most high-performing deuterium plasmas but needs to be recalculated if the method were to be applied, e.g., for a scenario with a deuterium–tritium fuel.

The value of τ will depend on a variety of parameters, e.g., the characteristics of the pile-up rejection routine employed and the sampling frequency of the data acquisition system used by the detector. In the benchmarking performed for his paper (described in Sec. III), we estimate the value of τ by calibrating it to match the high-energy tail in the light-yield data of a JET pulse without RF heating since, in the absence of RF, pile-up events should be the only source of events in the tail. In Fig. 3(b), we see the light-yield spectrum recorded by the spectrometer VNS[14] for JET pulse 96956, where no RF heating is applied. The calibration shows that a τ value of 60 ns makes the pile-up component match the otherwise unexplained high-energy tail in the data. This assessment is further discussed in Sec. IV.

III. BENCHMARKING

The method for calculating the pile-up component of a light-yield spectrum has been applied to data from the VNS spectrometer at JET,[14] which is a liquid scintillator with a collimated view of the central part of the plasma. In the test, we estimate the RF tail temperature from the spectroscopic data, a property describing the energy distribution of fast RF-accelerated ions, which is of importance in tokamak physics.[7,15,16] The analysis here includes an estimation of the spectral contributions from undetected pile-up events. For comparison, the same spectroscopic analysis is also made without accounting for pile-up distortion.

The results of the analysis are compared to a similar study performed using the spectrometer TOFOR,[17] which has the same sightline as VNS but is not sensitive to distortion from pile-up

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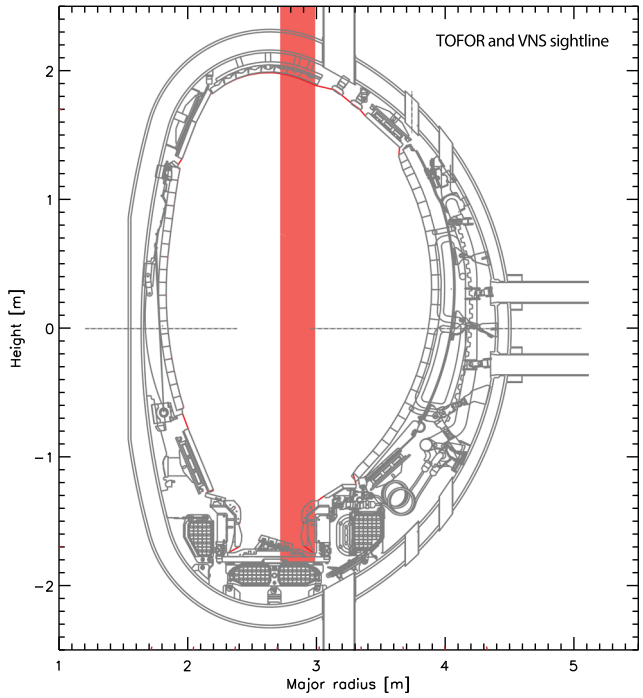

FIG. 4. Poloidal cross section of the JET tokamak. The red shaded region indicates the common sightline of the two spectrometers used in this comparison, TOFOR and VNS.

events. The common sightline of TOFOR and VNS is shown in Fig. 4.

The spectroscopic analysis is similar to the one described in Sahlberg *et al.*,[2] where the neutron emission spectrum is divided into separate components, originating from different sub-populations of fuel ions reacting with each other. The different fuel ion populations are produced by the auxiliary plasma-heating schemes used in the fusion reactor, including neutral beam injection[18] and radio-frequency heating.[11] These components are parameterized in terms of relative reaction intensities, ion temperature, and RF temperature. To these components, we add the estimated spectrum of neutrons that enter the detector via back-scattering in the reactor wall (for VNS calculated as in the work of Binda *et al.*[19] and for TOFOR as in the work of Gatu Johnson *et al.*[17]) and in the VNS also add a background spectrum originating from triton burn-up. We then fold the total spectrum with a detector response function and fit this model to the measurement. This procedure is used to estimate the fitting parameters. In this paper, we add an additional component representing the undetected pile-up events. Note that neither the shape nor the intensity of the pile-up component is considered a free parameter in the fitting routine but is determined by the algorithm described in Sec. II A.

The benchmarking performs such a component analysis on the measured light-yield spectra, specifically to estimate the tail temperature of ions accelerated by RF heating, the signatures of which overlap with pile-up distortion, as shown in Fig. 2.

In the benchmarking, we assume that the value obtained from the TOFOR result is correct since it has been shown to reliably estimate fast-ion energy distributions,[7,20] and it is not susceptible to pile-up events. The resulting RF temperatures are compared, between TOFOR and the liquid scintillator, both with and without the pile-up component included. The six JET discharges that have been analyzed in this paper are listed in Table I.

In the tests, we include one discharge (97235) with no RF heating applied during the analyzed time-window. For this discharge, we still include an RF component and determine an RF temperature as if such a component existed. In the ideal case, the analysis should determine a small RF temperature (lower than 50 keV) for this pulse, but due to pile-up distortion, the data can appear to have a high-energy tail similar to the signatures from energetic ions. Including such a pulse serves to demonstrate that the proposed method models the undetected pile-up contributions with sufficient accuracy and counteracts the overestimation of the RF temperature.

On benchmarking this method, it is important not to allow effects from short-term gain-drift[21] to influence the data, i.e., variations in gain in the photomultiplier tube (PMT), which can occur because of large fluctuations in the event rate of the detector. Such effects could produce signatures in the light-yield spectrum similar to those from pile-up events. In the spectrometer used in this benchmarking, gain variations are compensated for using an LED pulser, which deposits a continuous stream of events in the PMT with a constant and known energy. If the signal from the LED changes in light-yield during the discharge, it is clear that the PMT gain has drifted. The gain drift is then corrected by rescaling the light-yield from neutron and gamma events by the same amount. A more detailed description of the methods used for gain-drift compensation can be found in, e.g., the work of Belli *et al.*[22] or Marocco *et al.*[23]

IV. RESULTS AND DISCUSSION

In this section, we present the results from the method for the spectroscopic analysis of light-yield spectra with a component

TABLE I. List of the analyzed time interval, neutron rate, electron temperature and density, plasma current, on-axis magnetic field, and auxiliary heating power of the studied JET discharges.

Shot	Time (s)	Rnt (s^{-1})	T_e (keV)	n_e (m^{-3})	I_p (MA)	B_t (T)	$P_{NBI/RF}$ (MW)
96 673	7.8–8.6	3.6×10^{16}	9.3	5.6×10^{19}	2.2	3.3	30/3.1
97 235	13–15	1.1×10^{16}	5	9×10^{19}	2.2	2.7	24/0
97 779	7.5–8.5	4.5×10^{16}	9	7×10^{19}	2.3	3.4	29/1.5
97 781	7.7–8.5	3.6×10^{16}	7.7	6.6×10^{19}	2.3	3.4	31/3.3
97 797	8.2–8.9	3.5×10^{16}	7	7×10^{19}	2.2	3.4	30/4
97 851	8.8–9.8	3.5×10^{16}	6	7.8×10^{19}	2.3	3.4	29/5.7

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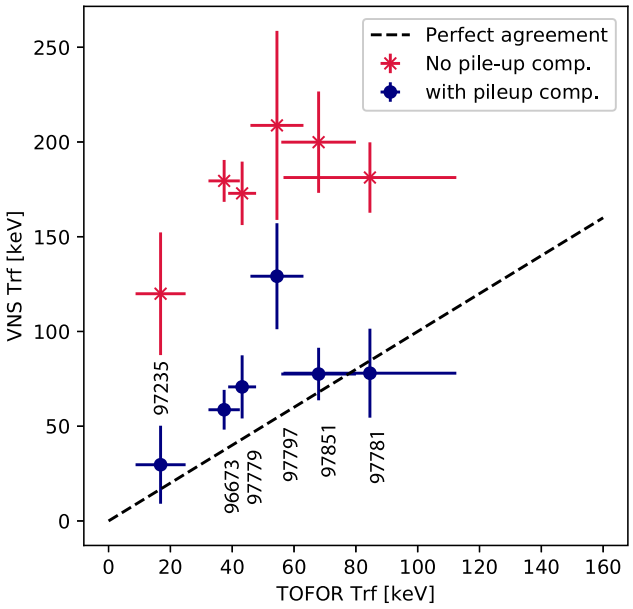

FIG. 5. Comparison between the RF temperatures determined using TOFOR and the liquid scintillator detector VNS. The comparison is made both with (blue) and without (red) a pile-up component included in the analysis of the VNS data.

describing undetected pile-up events. The result of the comparison of all the pulses analyzed is presented in Fig. 5, which shows the RF temperature from VNS vs the corresponding value obtained with TOFOR both with and without a pile-up component included in the analysis. In general, the RF temperature determined by the scintillator scales the same way as the one determined with TOFOR but disagrees on the absolute scale. We can, however, note that agreement with the TOFOR analysis is significantly improved when we account for undetected pile-ups.

An example of a comparison between the analysis with and without a pile-up component is presented in Fig. 6, with data from JET pulse 97851. We see that even though the light-yield data have undergone pile-up removal, the analysis of the liquid scintillator overestimates the RF temperature to 200 keV, compared to the 68 keV determined by TOFOR. If we, however, include the pile-up component, describing the undetected pile-up events, in the analysis, we find an RF temperature of 74 keV, in significantly better agreement with the TOFOR value.

For the pulse that does not use RF heating, 97235, we expect the fitted RF temperature to be small since, in reality, there are no RF accelerated ions in the plasma. However, if we do not account for undetected pile-ups, our analysis routine still detects a significant RF temperature of 123 keV, as shown in Fig. 5. However, with the pile-up component included, we fit a much more reasonable temperature of 30 keV. This result serves to demonstrate the need for a pile-up component for pulses with high count rates.

It should be emphasized that, after adjusting the pile-up parameter τ to match the calibration data [shown in Fig. 3(b)], the fit results for all other discharges follow without any additional adjustments of the model parameters. This means that the distortion of the light-yield spectra that is observed for these discharges both scales like we would expect pile-up distortion to scale and has the spectral shape that we would expect pile-up distortion to have.

From Fig. 5, we see that including undetected pile-up events in the analysis serves to compensate for the pile-up distortion that can be present in light-yield spectra. Even if the agreement with TOFOR is better when we include a pile-up component there is occasionally still a notable discrepancy between TOFOR and VNS, especially in pulse 97797. The reason for the discrepancy is not known but could be an effect of uncertainties in the input parameters to the pile-up model.

The main source of inaccuracies in the analysis is the uncertainty in the parameters used to calculate the spectrum of undetected pile-up events, r and τ. The time-window during which a pile-up

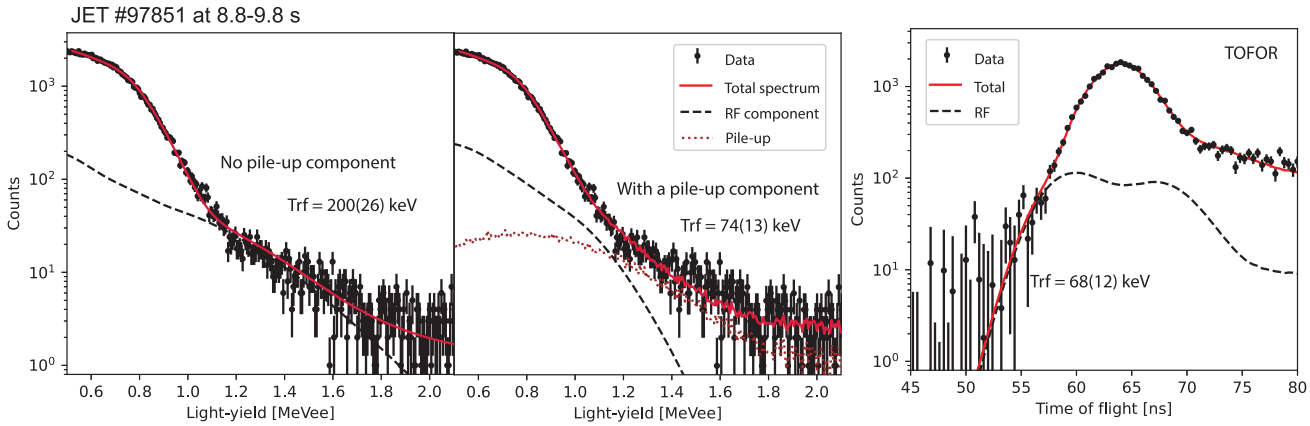

FIG. 6. Comparison between the RF temperature determined using the spectrometers VNS and TOFOR for pulse 97 851. For the liquid scintillator VNS, we show the RF temperature obtained both with and without pile-up events included in the analysis.

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event can occur and not be recognized by the pile-up rejection routine, τ, is not always easy to know and will probably differ based on the particle type, detector type, data acquisition system, and pile-up rejection method. In this paper, we have, as described in Sec. II A 1, determined τ by calibrating it to data from a pulse with no RF heating. From this calibration, we have obtained a value of 60 ns, which may seem high considering that the FWHM of the typical waveform of an event in VNS is around 25 ns. There are presumably significant sources of uncertainty in the event-rate r also since events that occur below the threshold be pile-up events and distort the spectrum, but the rate of these is hard to identify. As described in Sec. II A 1, the spectrum and fraction of events that occur below the threshold are, in this paper, estimated from an MCNP simulation, but assessing the accuracy of this simulation is difficult. However, the unexpectedly large τ value gained from the calibration might absorb some of the uncertainties in r. Because of this, one may view τ as a calibration parameter rather than a direct property of the pile-up rejection routine.

V. CONCLUSIONS

From the results obtained in this paper, we conclude that including undetected pile-up events in the analysis of spectroscopic data from scintillator detectors helps compensate for the problem of pile-up distortion and that this may be needed even if the data have undergone traditional pile-up rejection. A comparison with a similar analysis using data from the spectrometer TOFOR, and by performing the analysis on a pulse with no RF-heating, meaning that the contribution from undetected pile-up events is easier to identify, demonstrates the effectiveness of the method.

By knowing the event rate and time interval during which an undetected pile-up can occur, along with the detector response function, we can calculate the distortion from undetected pile-up events expected to occur in a measured light-yield spectrum. The presented method can be used in, for example, neutron spectroscopy to separate the true fast-ion high-energy tail from the tail caused by pile-up distortion The tests in this paper have focused on determining the RF temperature, but any spectroscopic analysis in situations where pile-up distortion occurs could benefit from incorporating this procedure in the analysis.

While the presented method is developed and validated in the field of fusion plasma diagnostics, the approach is general enough to be applicable in other spectroscopic scenarios where pile-up distortion is a problem.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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