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Polarimetric Thomson scattering measurements in JET high Temperature Plasmas

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ABSTRACT: Thomson scattered light is polarised in the same orientation as the incident laser beam at low electron temperatures (T_e). At high T_e part of the spectrum begins to become randomly polarised due to relativistic reasons. First measurements of the depolarised Thomson scattering spectrum during were obtained from JET pulses in 2016. This paper builds upon these initial measurements with new measurements obtained during 2021. These new measurements improve upon first results, in particular by obtaining spectral measurements of the depolarised spectrum. The recent JET campaign was well suited to these measurements with long and hot plasmas. The resulting data are averaged over many plasmas and laser pulses to obtain a measurement of the amount of ‘p‘ and ‘s‘ scattered light as a function of T_e. This experimentally obtained ‘p/s‘ ratio versus T_e is then fitted and found to show reasonable agreement with the theoretically predicted depolarised fraction. Error estimates on the measured ‘p/s‘ have been obtained and show that the measurements are meaningful. This is good news for ITER for which the intention is to use this measurement as a check on the T_e determined by the core plasma Thomson scattering diagnostic by conventional spectral measurement techniques.

KEYWORDS: Polarimetic, Thomson scattering, laser diagnostics

Contents

1. Introduction

The ITER Core Plasma Thomson Scattering (CPTS) diagnostic is required to measure up to 40keV. This implies measuring down to wavelengths of ~400nm using conventional or 'spectral' Thomson scattering (Scannell R. et al 2017) from a 1064nm laser. This low wavelength requirement arises due to the broad spectral width at T_e=40keV at the large CPTS scattering angles of ~160degrees in the core. Measuring at low wavelengths is challenging as many of the expected losses due to neutron or radiation damage of optics or fibres will be largest in lower wavelength region (400-700nm). Similarly, line emission will be largest in this same wavelength region.

Polarimetric Thomson scattering is an alternative Thomson scattering technique, not currently deployed on existing machines. It takes advantage of the fact that a small fraction of the Thomson scattering spectrum becomes depolarised at high electron temperature (T_e). The depolarisation increases with T_e for a given scattering angle and is uniform across the spectrum. These properties mean that an increase in the lower wavelength limit, due to losses or line emission, would not impact the ability to infer T_e from polarimetric measurements. In fact, polarimetric measurements would be immune to any potential unquantified systematics in spectral transmission, provided the spectral transmission is not polarisation dependent.

The technique of polarimetric Thomson scattering was first proposed in (Orsitto F et al 1999). Since then, there have been significant advances in the theoretical basis (Segre S.E. et al 2000)(Parke E. et al 2014)(Mirnov V.V. et al 2016) The amount of depolarisation may now be readily determined for a given T_e and scattering angle. In a spectral Thomson scattering system, the injected light is typically orthogonal or 's' polarised (senkrecht – perpendicular) with respect to the scattering plane formed by incident and scattering vectors. Depolarised light is randomly polarised and therefore equal in both 's' and 'p' (parallel) polarisations. In a spectral Thomson scattering system, 'p' polarised light is often removed by polarisers as it is considered to contain no scattered light. For a polarimetric Thomson scattering system, the 's' and 'p' components of the scattered light are separately measured and quantified and the ratio of the two ('p/s') used to infer T_e.

At a 90 degree scattering angle, the fraction of light in the non-standard ‘p’ polarisation increases approximately linearly at 0.191%/keV as calculated from theoretical predictions in the range 1-10keV. The JET data that are considered in this paper are taken at a scattering angle 91.4 degrees and up to temperatures of ~9keV from the HRTS (high resolution Thomson scattering) diagnostic. Hence for these scattering events a p/s ratio of up to ~1.53% is expected at T_e=8keV. The ITER CPTS diagnostic operates from ~131 degrees at the low field side edge, r/a~0.85, to ~160 degrees at the plasma center. The depolarisation is significantly less at a 160 degree scattering angle such that the JET results at 6keV are approximately equivalent to ITER results at 20keV. This is illustrated in figure 1 which shows the relative sensitivity at these two scattering angles. The CPTS system will allow for more averaging than JET as it is based on a 100Hz rather than a 20Hz laser and with longer plasma pulse durations. Additionally, the ITER system can provide polarimetric measurements over all spatial points observed compared to at just one point for JET.

2. Installation on JET

The first polarimetric Thomson scattering measurement on a fusion machine were obtained on JET during the DD campaign in 2016, from pulses 92038-92504 (Giudicotti et al, 2018). We will refer to these measurements as DD in contrast to our recent measurements during DT. This campaign was the second Deuterium Tritium campaign on JET (DTE2), since the initial DT campaign in 1997, and as such had a goal to maximise fusion energy produced. This led to long high temperature plasmas which were particularly suitable for the polarimetric measurements. From the initial results during DD the ratio of ‘p’ to ‘s’ light was obtained as function of T_e by taking each pulse and averaging the scattered signals from that JET pulse during the heating phase. These results indicated that polarimetric Thomson scattering works as a technique and is in line with theoretical predictions.

The motivation for new measurements during the DT campaign are as follows:

- Significant variation in the p/s ratio was observed in the DD measurements. This is inherent from the fact that the number of ‘p’ scattered photons is very low and motivates further measurements to confirm the initial result. Estimating the uncertainty on the determined $d(p/s)/dT_e$ in these new measurements was another key goal.
- After the initial measurements during DD a Raman calibration was performed. The result of this calibration implied a significant difference in the sensitivity of the fibre with the ‘p’ polarizer versus that of the fibre with the standard ‘s’ polarizer. This arose from the fact that the ‘s’ fibre was misaligned to the laser beam making it ~6.7 times less sensitive to scattered light. This has now been corrected and in the DT campaign the two fibres should be equally sensitive.
- The $d(p/s)/dT_e$ value was obtained by a linear fit to the p/s ratio versus T_e for a given pulse number. In the DD measurements a significant offset was observed at the origin. This offset implied a phenomenon such as stray laser light was causing some measurement in the ‘p’ channel even at very low T_e. There is a concern that the unknown source of this offset could in some way lead to a systematic error in the measurement of the ‘p’ signal. New polychromators have been used for the DT

measurements that are significantly more resilient to stray laser light, both because the filters have stronger optical blocking of the laser line but also because a special transmissive filter was installed as the first cascade in the polychromator. This transmissive filter should transmit (and therefore remove) at least 95% of 1064nm light, so if the offset in the linear fit to the p/s ratio is produced by stray laser light it should be significantly reduced.

- The measurements during DD were taken from a single channel polychromator with a laser line notch filter in front of it. The rationale for this was that in order to improve the signal to noise ratio the full scattered spectrum could be measured on a single detector, thereby reducing detector noise. For the measurements during DT we elected to use a more conventional polychromator design with multiple spectral channels, so the $d(p/s)/dT_e$ could be independently calculated for each spectral channel. The rationale for this is that while it would add some extra random noise to the measurements, in the form of additional detector noise for each APD utilized, it would reduce potential systematic error by providing independent measurements.

The spectral responsivity of the installed polychromator on JET is shown in Figure 2 with an overlaid modelled 6keV spectrum at $\theta=\pi/2$. A 3-channel polychromator was installed which should be responsive to temperatures in the $1keV < T_e < 10keV$ range.

3. Overview of Dataset

JET pulses during the DT campaign as indicated in Table 1 form the dataset used to analyse $d(p/s)/dT_e$. These pulses were filtered to remove low temperature pulses as obtaining good signal to noise ratio for the higher JET pulses with high T_e is the limiting factor. The condition for inclusion was at least one second at T_e>4keV was observed, this corresponds to 20 data points as the HRTS laser operates at 20Hz. Applying this filtering 323 JET pulses were selected for the dataset. In all cases the T_e is determined from the HRTS measurement point adjacent to the polarimetric measurements.

Figure 3a shows the median T_e observed during the phase of selected shots where the T_e is >4keV effectively corresponding to the temperature during the 'hot' phase of the pulse. Figure 3b shows the duration of time where these pulses were above 4keV.

Once a JET pulse was selected for the dataset, the full duration of that pulse is used including the low temperature part of the pulse before the heating phase. Since these low temperature parts of the pulse are significantly longer than the heating phase there are a lot of low temperature points in the dataset. Sixteen sequential 0.5keV temperature 'bins' are defined from 1keV to 9keV. Each HRTS measurement timeslice is assigned a temperature bin, based on the measured HRTS temperature at the most high field side point which is adjacent to the image of fibres with the dedicated 'p', 's' and 45 degree polarisers. The number of HRTS timeslices in each bin is shown in figure 4, as can be seen there are >10,000 timeslices in the 1-1.5keV bin, ~500 timeslices in the 8.5-9keV bin. The number of timeslices in these bins is one of the fundamental limits on our ability to accurately measure the 'p/s ratio' and hence $d(p/s)/dT_e$.

4. Polarimetric Measurements

Once each timeslice is assigned an appropriate T_e bin, as described previously, the signal time traces are then accumulated for that bin and then divided by the number of observations in that bin. The time traces for six of the bins are shown in figure 5 to illustrate the data obtained. There are three scattered signals timings corresponding to three delay lines for each time trace as summarised in table 2. The set-up used is such that there are 6 optical fibres combined into a single polychromator, each pulse corresponds to two fibres which have identical delay lines and are adjacent in the plasma. The first pulse, at approximately 80ns has scattered light from a single 's' fibre as well as scattered light from a polariser oriented at 45 degrees so $0.5\times(s + p)$. The second pulse, at approximately 210ns, is connected to two fibres measuring 'p' polarised light. The third pulse, at approximately 380ns is similar to the first pulse measuring the addition of an 's' and 45 degree fibre. The time integral of the three pulses are calculated and the determined ratio of 'p/s' used is pulse 2 / (pulse 1 + pulse 3) which corresponds to $2\times p/(3\times s+p)$ which approximates to $2/3\times p/s$. Details on the design of the HRTS system and fibre delay lines are given in (Pasqualotto 2004 et al).

Figure 5 also illustrates the magnitude of the scattered signals obtained in comparison to the noise fluctuations seen outside of the time windows of interest. At low T_e, where averaging is performed over many timeslices, the fluctuations are much lower compared to fluctuations observed at high T_e. These time traces indicate an increasing 'p' scattered signal with increasing T_e. There is a tendency for low T_e to be correlated with low n_e as the low T_e data are not obtained during the heating phases of JET pulses, hence a comparison of the 'p' and 1% × 's' pulses also shown in the figure is required.

For each JET pulse, HRTS diagnostic data acquisition operates for 259 segments, approximately 13 seconds, before the plasma when the laser is firing into the vessel. Measurements taken during this time period are used for straylight subtraction. One of the motivations for measurement during the DT campaign was to remove straylight using a high laser line rejection polychromator, as it was assumed the offset observed in DD originated from transmission by the optical filters of light at 1064nm. The measurements during these 259 segments have subsequently shown that there is very low measureable straylight signal in spectral channel 2, but there is a measurable straylight signal in spectral channel 1 which is approximately 3.4% of the average 's' light observed. For this data set, the averaged time trace obtained during this 259 segment straylight period has in all cases been subtracted from subsequent measurements obtained during plasma. This subtraction was performed on a JET pulse to pulse basis. Initially, no subtraction of straylight was performed and the 'p/s' ratio obtained from channel 1 was found not to be linear with increasing T_e as the measurement was polluted by this straylight which was much larger than the level of 'p' signal expected. It was found that the subtraction of the straylight had to be performed on a JET pulse to pulse basis in order to obtain a meaningful measurement. This indicates that the straylight level is in fact varying over the plasma pulses observed. It is not clear if the straylight observed in spectral channel 1 is due to transmission at the laser wavelength, or some other in-band source of light related to the laser pulse. In any case, there is much lower straylight observed in spectral channel 2 ~0.46% so the data obtained in this channel is not compromised by this.

A comparison of the signal integrals from the ‘p’ and ‘s’ polarisations are shown in figure 6a for spectral channel 1 (the 1017/45nm filter). Up to 2keV the ‘p’ signal approximately equals the 1% of the ‘s’ signal integral. At higher T_e, the ‘s’ signal is relatively flat with T_e, probably a combination of increasing signal due to higher electron density and decreasing signal due to T_e shifting the scattered spectrum out of this wavelength band. At these higher T_e, the ‘p’ signal increases faster than the ‘s’ signal. A linear fit to the ‘p/s’ ratio is shown in figure 6b. The slope of the linear fit corresponds well with theoretical predictions of 0.191%/keV. Uncertainties were derived for the p/s values, these uncertainties are based on the scatter in the signal traces where there are no scattered pulses and the expected contribution of this to a signal integral.

A similar comparison is shown in figure 6c for spectral channel 2. The measurements in this channel show increasing ‘p’ signal levels above and beyond the ‘s’ signals with increasing T_e. The linear fit to the ratio shown in figure 6d again shows good agreement on the slope with theoretical predictions and some offset at T_e=0. The quality of data for channel 2 appears better than that in channel 1, this might be the case because a) at the temperatures of interest there is more signal in spectral channel 2 improving data quality and b) there is much lower straylight in spectral channel 2 (~0.46% of ‘s’ signal) compared with spectral channel 1 (~3.4% of ‘s’ signal) which may impact on measurements. Results from channel 3 are also shown in figure 6e and 6f for completeness but are not considered as the scattered signal levels are much lower than in channels 1 and 2 and not high enough to provide good ‘p’ signal measurements.

The theoretical estimate of a linear variation of 0.191% $d(p/s)/dT_e$ is a very good approximation. If we numerically determine the derivative, values of ~0.187/keV% and ~0.194/keV% are obtained at 1keV and 8keV respectively. To represent this non-linearity an error bar has been assigned to the theoretical prediction in table 3.

In order to estimate the uncertainty on the determined d(p/s)/dTe, a Monte Carlo approach was taken varying which JET pulses were accumulated and examining the resulting d(p/s)/dTe parameter and offsets. Monte Carlo runs were constructed by randomly including individual JET pulses with a 50% probability from the full 323 pulses in the dataset. Hence each individual Monte Carlo run had ~160 pulses. The results of 100 such Monte Carlo runs are shown in figure 7 where the resulting $d(p/s)/dT_e$ are shown for spectral channels 1 and 2. To illustrate the variation in results, the value of $d(p/s)/dT_e$ are plotted in ascending order for each channel. This shows that the $d(p/s)/dT_e$ values determined in spectral channel 1 and spectral 2 are both under the theoretical estimate. For the spectral channel 1 the mean value determined is within 1-sigma of the theoretical range. For the spectral channel 2 dataset the mean value determined is close to 2-sigma away from the theoretical estimate.

5. Conclusions

The aim of this work was to verify the technique of polarimetric Thomson scattering for use on ITER. Thomson scattering is inherently a difficult measurement to make as you need to obtain a rejection of stray laser light of approximately $n_e \times \sigma_{Te} \sim 10^{-10}$ using optical rejection of filters and geometry which is challenging. Polarimetric Thomson scattering is even more challenging as it is typically a factor 10^2 below ‘s’ Thomson scattered light and it is required to distinguish the ‘p’ light from the ‘s’ light. The key measurements obtained in this work are summarised in table 3. The main conclusion of this work is then that the $d(p/s)/dT_e$ obtained is close to theoretical predictions as measured independently by two spectral bands of a polychromator. This gives support to application of this technique on ITER. The discrepancy between the theoretical predictions and experimental measurements are larger than the error bars obtained by including random pulses. This we cannot fully explain, but attribute to the very small signal levels we are measuring and sensitivities to systematic effects.

That similar results are obtained in spectral channels 1 and 2 despite some ~3.37% straylight being observed in spectral channel 1 indicates that pollution due to straylight observed in previous experiments did not significantly influence those results.

Both spectral channel 1 and 2 see a non-negligible offset signal in the 'p' channel that we interpret as 'bleed through'. At this low level, a number of origins for this offset are possible, it could be due to physical accuracy of polariser installation, laser beam polarisation or extinction ratio of the polariser. Alternatively it could be some combination of these phenomena.

The measurements taken on JET show the variation of p/s with T_e over a few hundred JET pulses and with ~19,000 samples over 4keV. The goal of this technique as applied to ITER is to do the opposite and infer T_e from p/s. JET has one advantage over ITER in measurement of polarimetric Thomson scattering, it is at a favourable scattering angle. This favourable scattering provides 3× as many photons. ITER has two significant advantages over JET, the core plasma Thomson scattering system will operate at 100Hz and it can install measurement samples of polarimetric light across the full laser chord giving it up to ~70 spatial samples compared to a single spatial sample on JET. Hypothetically then for a 20keV peaking profile on ITER, a polarimetric measurement with equivalent quality to the full ~19,000 samples from this JET dataset could be obtained in tens of seconds of an ITER discharge by averaging over a number of spatial points from the Core Plasma Thomson scattering diagnostic.

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Condition for Inclusion	1s > 4keV
First JET Pulse	99147
Last JET Pulse	99982
No. of JET Pulses used	323
No. of HRTS segments >4keV	19051

Table 1 - Key parameters of the JET DT campaign database used for analysis.

Scattered Signal/ Delay line	**Fibre 1 polariser**	**Fibre 2 polariser**
#1: ~80ns	S	45 degree
#2: ~220ns	P	P
#3: ~380ns	S	45 degree

Table 2 - Fibres used in polarimetric spectrometer with corresponding polarizer orientations and scattered signal timings.

	Straylight *light before plasma*	**Bleed through** *offset of linear fit*	**$d(p/s)/dT_e$** (%/keV)
Theoretical Prediction	-	-	0.187-0.194
Channel 1	3.37%	0.796±0.122%	0.178±0.037%
Channel 2	0.46%	0.638±0.067%	0.158±0.017%

Table 3 – Comparison of theoretical and experimentally observed increase in p/s ratio with electron temperature for various spectral channels. Uncertainty estimates are obtained from Monte Carlo analysis. Spectral Channel 3 is excluded due to large uncertainty.

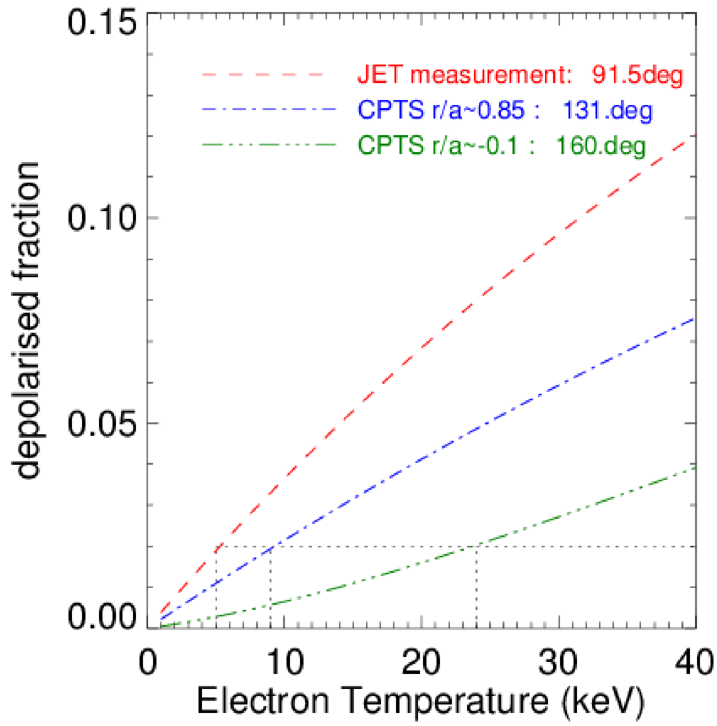

Figure 1. Fraction of light depolarized as a function of electron temperature, for the JET measurements and for the two extreme scattering angles of the ITER CPTS diagnostic.

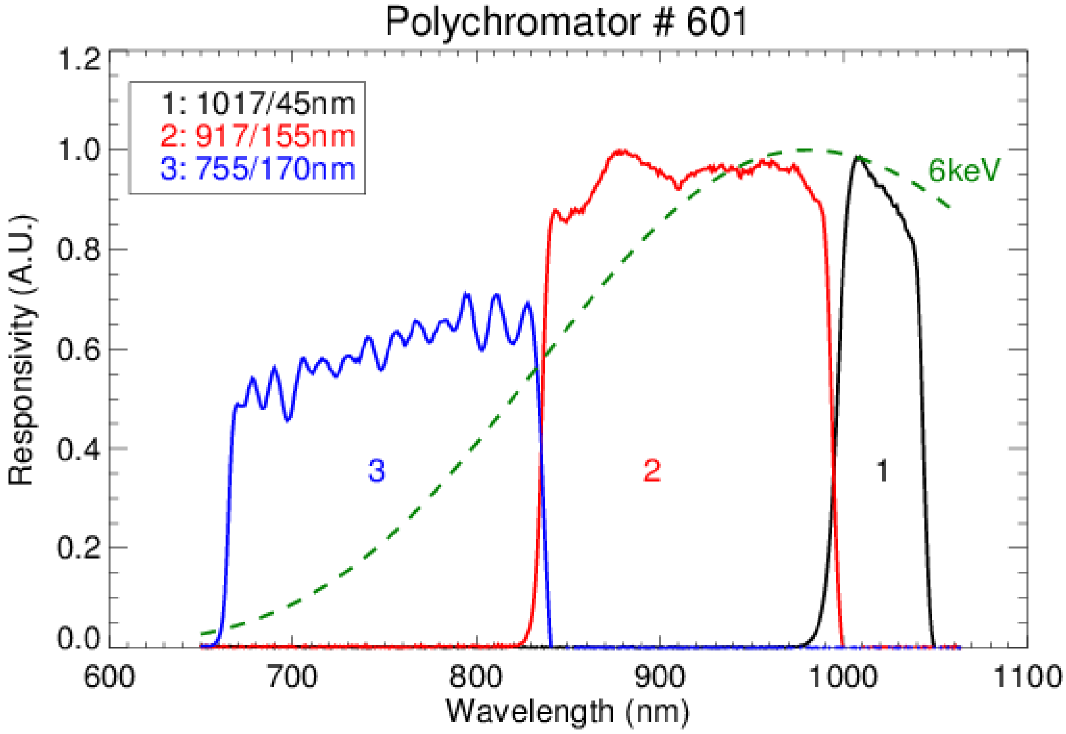

Figure 2. Spectral responsivity of the polychromator installed to detect ‘p’ polarized light. Also shown is the spectral intensity of the expected light at 6keV.

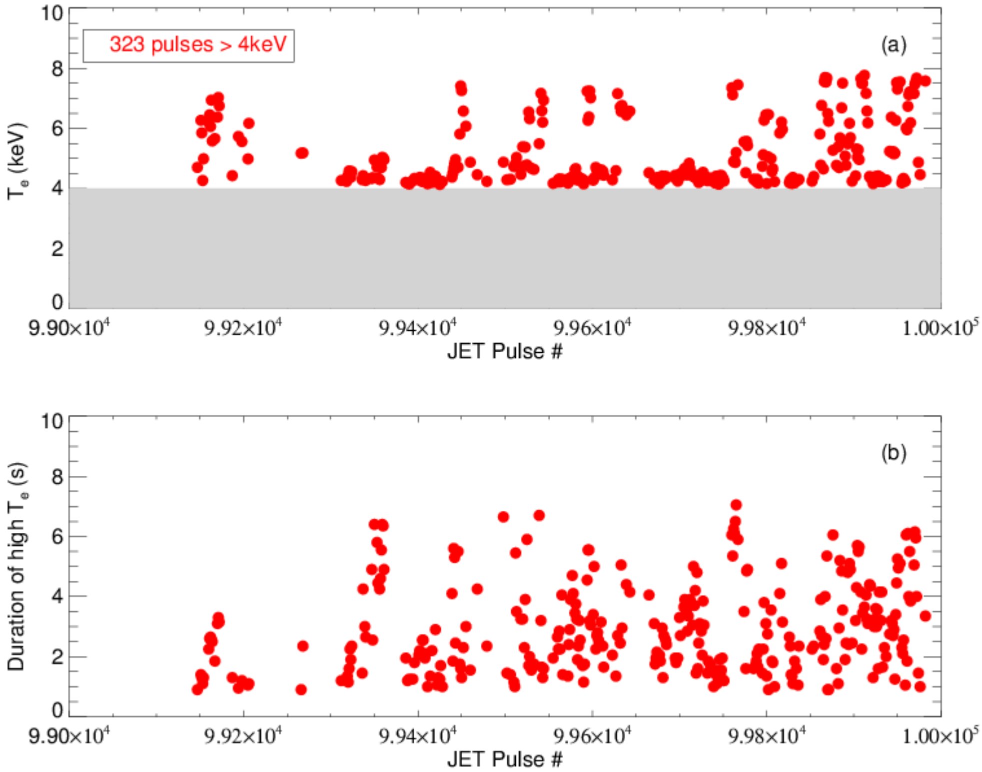

Figure 3. (a) Median T_e observed during the hot (>4keV) phase of JET pulses and (b) duration of the >4keV period of these pulses.

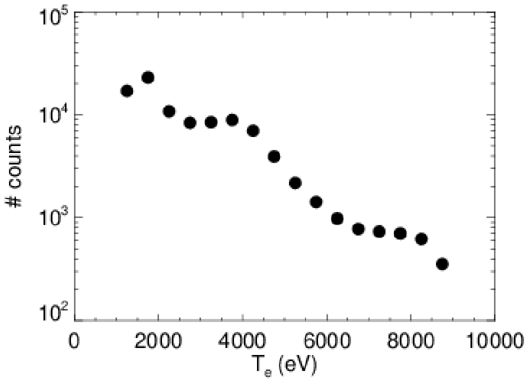

Figure 4. Number of counts observed in 500eV temperature bins used to construct the dataset.

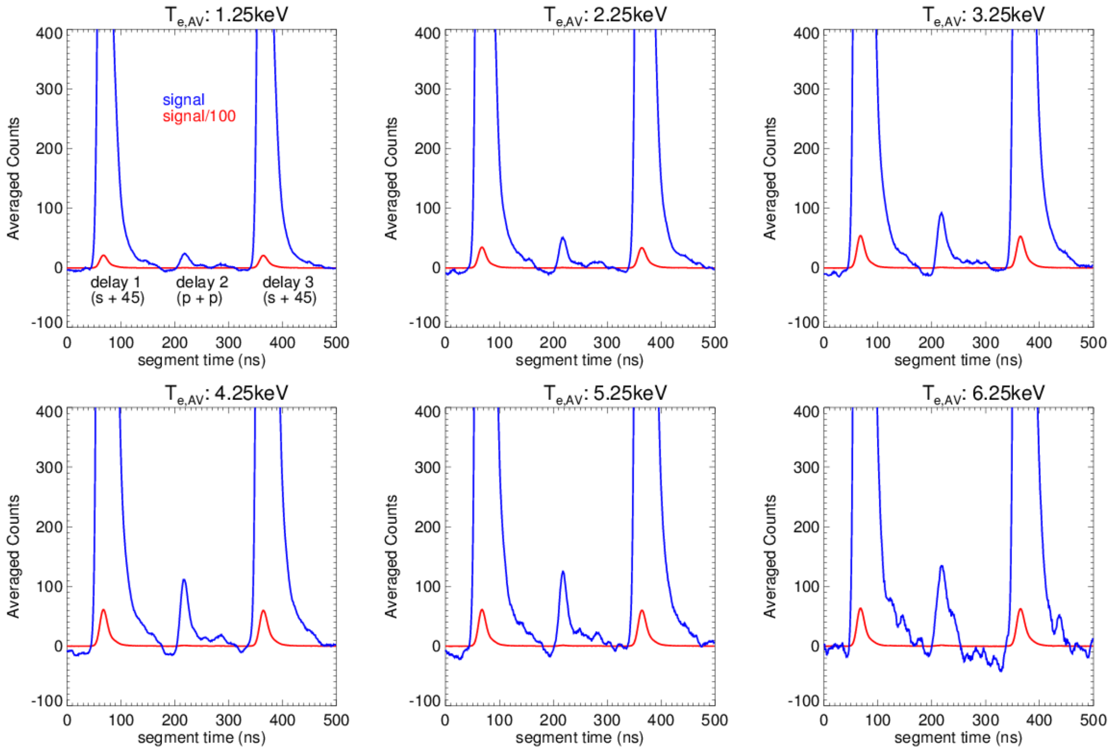

Figure 5 – Time traces of scattered signals observed in spectral channel 2 for six temperature bins accumulated over the full dataset. Each time trace has three pulses with different optical delays. Each pulse comes from two fibres with the same optical delay line. The first and third pulses, at ~80ns and ~380ns respectively, each come from one fibre with an ‘s’ polarizer and one fibre with a 45 degree polarizer. The second pulse at ~210ns comes from two fibres with ‘p’ polarisers. The fibres are located in adjacent spatial channels in the plasma. As well as the averaged scattered signal trace a second trace illustrating 1% of the scattered signal trace is overlaid.

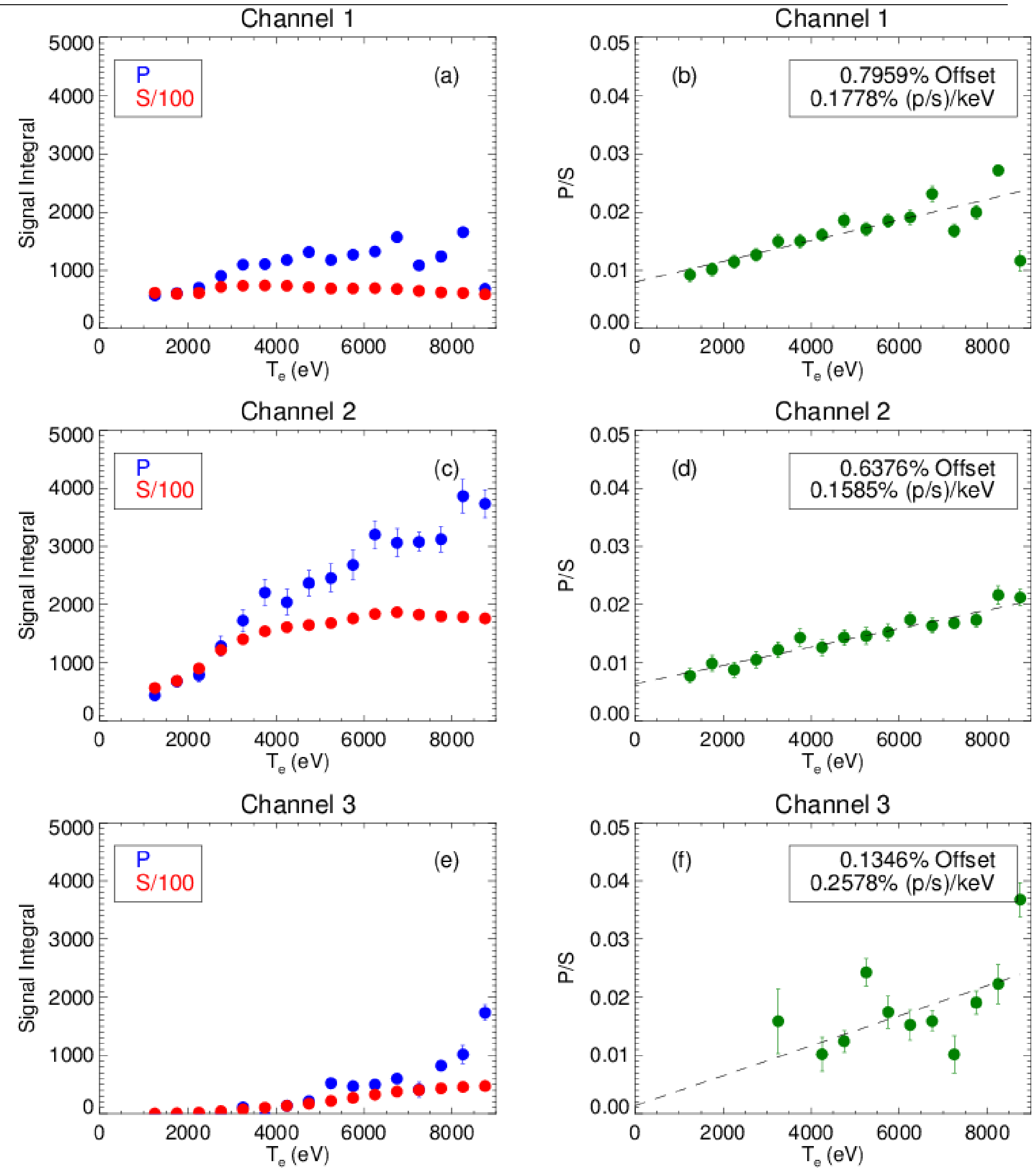

Figure 6 – For spectral channels 1, 2 and 3, the change in 'p' and 's' signal integrals with T_e are shown as well as the increase in the 'p/s' ratio with T_e. For the plots showing the ratio, a linear fit and best fit parameters of that linear fit are provided in the legend. These data here is determined by accumulating the full dataset in contrast with the values in figure 7 obtained from subsets of this full dataset.

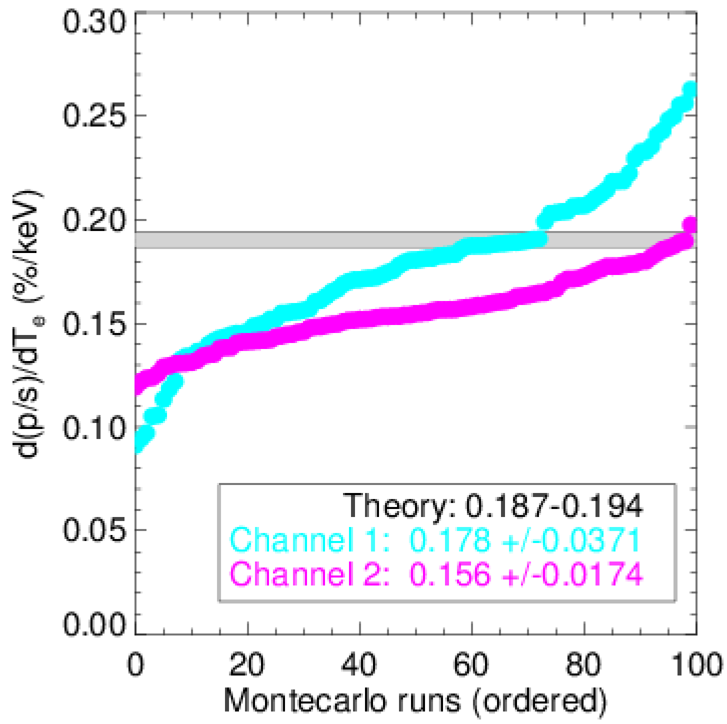

Figure 7 – Results of slope d(p/s)/dT_e from Monte Carlo runs, where each JET discharge is randomly included or excluded from the dataset in each run. The determined slopes for each run have been arranged in ascending order for each spectral bin for illustrative purposes and comparison with the theoretical values.