Solar-B **EIS** * EUV Imaging Spectrometer	The potential degradation of spectral resolution in Solar-B EIS CCDs

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1 Introduction

One of the main drivers for determining the operating temperature of the Solar-B EIS CCDs is the possibility that substantial Charge Transfer Inefficiency may occur towards the end of the mission lifetime. The magnitude of the CTI has been discussed in several technical notes (references 1-3) and this information has been used to judge the optimum and minimum operating temperature of the CCD (reference 4). Using spectral lines generated using CHIANTI, it will be shown that one of the main effects of CTI will be that the velocity resolution achievable for faint spectral lines could be reduced if the operating temperature of the CCD is too high.

2 Charge Transfer inefficiency

2.1 Theory

During integration of an image, charge will be collected under the imaging electrodes corresponding to each pixel. To read out the pixels, each charge packet must be transferred vertically down the column to the serial register, where it will then be transferred horizontally through the read out register, as shown in figure one. During the transfer process, the charge packets will encounter electron charge traps throughout the bulk silicon. When a charge packet passes over such a trap, a proportion of the charge in this packet will be captured by the traps. Each trap will have a definite lifetime, after which the charge will be released. This process is shown in figure two. Depending on the lifetime of the traps, the charge will either be released back into the original charge packet (figure 2a), into an adjoining charge packet (figure 2b), or released slowly over time (figure 2c).

If the charge is immediately released back into the original charge packet, as in figure 2a, no effect will be noticed. If the charge is released into an adjoining packet, as shown in 2b, then a loss of charge will occur for the original charge packet, and the adjoining charge packet will be increased. However, figure 2c shows the most likely outcome, with trapped charge being released slowly over time, leading to both a decrease in the original charge packet size and a complete loss of the trapped charge into ’empty’ pixels.

Electron traps in the bulk Silicon occur as a result of proton-induced displacement damage in the lattice. Therefore, immediately after launch, the CTI from the EIS CCDs will be very low. However, as the total non-ionising dose encountered by the CCDs increases throughout the mission, so will the displacement damage to the lattice. As discussed below, the total number of electron traps expected in each CCD by the end of the mission may be sufficient to lead to a significant loss in spectral resolution.

2.2 Calculation of CTI

A qualitative appreciation of the effect of operating temperature can be made by simply considering the charge trapping lifetimes, which have been measured by several authors (for example, see ref 5) who have calculated the trap lifetimes at different temperatures. At around -30°C a large number of traps have a lifetime of the order of 0.5ms whereas at -60° the lifetime is of the order of 10ms. For a clocking rate of about 3µs per pixel in the serial register (corresponding to a rate of about 350k pixels/s) then it would take about 3ms to transfer a charge packet from the centre of the CCD to an output amplifier. At -30°C, this packet could dynamically interact with a number of charge traps, whereas at -60°C, the trap lifetime would be much greater than the time taken to clock out the charge packet. As the calculations will show, there may still be charge trapping at -60°C, but the simple consideration of trapping lifetimes shows it will be greatly reduced.

An estimation of the effect of charge transfer inefficiency is usually made using Schockley-Read-Hall theory, described in appendix one. Briefly, it is assumed that the main factor determining the CTI will be the operating temperature, which determines the trap lifetime. However, for a given operating temperature, a number of other controllable factors will determine the extent to which CTI occurs:

I the nature of the image. For images containing a significant number of electrons (greater than a few thousand) the CTI diminishes rapidly. In addition, images in which most pixels have charge in them, such as when directly imaging the Sun, will also suffer much lower CTI as any empty traps will immediately be re-filled from the current pixel (e.g. see figure 2d). Thus, degradation of image quality is more likely for images containing substantial pixel-pixel variations in the charge packet profile, as are found in spectroscopic applications;

II the rate at which charge packets are clocked through the CCD. If the clocking rate is very slow then, for a given temperature any trapped charge will be re-emitted into the original charge packet. Conversely, if the clocking speed is fast enough, then all traps will be filled by the first charge packet (called the "sacrificial" charge packet) and all other charge packets will pass over the traps whilst they are still filled, and will thus be unaffected.

Figure 3 shows several examples of the CTI for different temperatures and clocking rates.

2.3 The effect of line density on CTI

CTI occurs when a charge packet encounters a pixel containing empty traps. Empty traps are most likely to occur when a number of "empty pixels" containing little or no charge have been clocked through them as no new charge is available to fill a trap once it is empty. Such a situation is most likely to occur when imaging spectral lines. For example, a simplified spectrum is shown in figure one. In the spatial direction, most pixels within a column will contain significant charge. As the charge packet in each pixel is clocked down the column towards the serial register, a situation similar to figure 2d will be found, where the traps are effectively permanently filled.

However, once a charge packet reaches the serial register, it will be clocked horizontally through the register. In this case a situation similar to figure 2c will be found. The first spectral line to be clocked through the CCD will encounter empty charge traps, leading to a loss of charge due to CTI. Depending on the spacing between spectral lines, the trapped charge may be re-released into a number of (mainly empty) pixels until all the traps are empty again. In such a case, the first few pixels of the next spectral line to be clocked through these traps will again experience a significant amount of charge loss.

Using the calculations outlined in appendix one, the CTI expected for the leading pixel in a spectral line is shown in table one for a range of operating temperatures. The CTI values calculated in table one assume that there is a gap of around 220 pixels between each spectral line on the CCD. This value is slightly higher than may actually occur, but is not outrageously so and should be accepted as a conservative figure. The number of traps has been estimated for the end of a five year mission, with 15mm Aluminium shielding surrounding the CCD.

2.4 Summary

Charge transfer inefficiency will increase over time due to the cumulative effect of proton-induced trap creation. **As a function of the trap lifetime, CTI will be directly related to the operating temperature of the CCD.** In addition, it will also be related to the image type, in particular, the signal strength, and the distance between charge packets. The spectral images which will occur with EIS is one of the worse cases for charge loss.

For a more detailed discussion on the potential effects of CTI in EIS, see references 1-4.

3 The Effect of charge trapping on spectral resolution

3.1 Charge loss within a spectral line

The principle of CTI is well understood, and a large amount of work has been undertaken in recent years to try and quantify the CTI which can be expected for given orbital proton dose (for example, recent work with Chandra and XMM-Newton). Detailed three-dimensional models are being developed which allow the production of charge trapping centres to be related to loss of charge from a three-dimensionally confined charge packet. The model described in appendix one, and used for the calculations here, is a simplified version of such models.

However, although there has been much work on understanding the solid state physics of CTI, there has been less work on applying the techniques to actual images. Most work (for Chandra, XMM and others) has concentrated on the X-ray region, and has been concerned with the effect of CTI on the pulse height distribution and the subsequent determination of X-ray energy.

Nevertheless, CTI is also a problem with a number of missions and as an example, experiences with the Hubble Space Telescope (HST) are summarised in section four. However, there is no established methodology for estimating the effect of CTI on a typical spectral image as the majority of work has concentrated on the loss of charge from discrete and faint stellar sources. Consequently, a number of slightly different techniques have been considered in this technical note. It is likely that none of the three methods used below will completely replicate the situation that will happen in a mission but they should highlight how changes in operational temperature may affect the spectral image.

Using CHIANTI a baseline profile has been generated for FeX and FeXII for a non-thermal velocity of 20km/s. The line width of each line corresponds to the charge levels which would be found in each pixel sampling the line profile. To obtain important diagnostic information, such as the non-thermal or Doppler velocity of the plasma, a gaussian line can be fitted to these profiles. Figures four and five show the basline profiles together with the profiles altered by CTI and the corresponding measured non-thermal velocity.

These "baseline" profiles have been altered in three different ways:

I by using the peak height value to calculate the charge loss and subtracting this value from the spectral line. That is, the amount of charge that would be lost is subtracted from pixel one, if the first pixel contains less charge than the total amount to be subtracted, charge is also subtracted from pixel two;

II the first three pixels are treated independently, with the charge loss expected for each one calculated and subtracted from that pixel;

III the first three pixels are treated as in II above but, it is assumed that any trapped charge is reemitted in a short timescale so that charge trapped in pixel one is reemitted into pixel four, pixel two into pixel five and charge trapped from pixel three is reemitted into pixel six (which is a new pixel for FeX).

Of the three possibilities considered, I and II are most probable as the trapping constants at the temperatures being considered are of the order of ms, much slower than the clocking speed.

Two different clocking speeds have been used. For FeX, a clocking speed of 350 kpixels/s has been used. This figure is slower than it is hoped will be achieved with Solar-B EIS (500 kpixels/s) but has been adopted as a conservative estimate (current CCD cameras designed at MSSL run at these rates). For FeXII a much slower speed of 100 kpixels/s has been adopted. This is slower than is expected on EIS, but the calculations have been included to show the problems that may encountered at such speeds. The degraded spectral profiles at t=238 K are also plotted in figures four and five. It can be seen that a number of line features have changed:

- for option I with FeX, the peak height has been increased, whereas for options II and III for both FeX and FeXII, the peak height has decreased;
- in all three options, the centre of the line has shifted towards higher wavelengths;
- in all three options, the linewidth has narrowed.

A summary of the changes in line width and line position obtained for different temperatures is shown in table two. As would be expected, at lower temperatures, the spectral profile tends towards the "baseline". For example, very little effect on the spectral lines can be seen for FeX below a temperature of about 228K (-45°C). In contrast, for FeXII, the line profile is severely degraded at all temperatures if option three is used, and is strongly degraded for the other two options, even as low as 208K (-65 C°). No figures are included for option three in table two as the line profile has been so severely degraded at all temperatures that no suitable fit could be obtained. As an example, the line profile found for option III is shown at 238K in figure five. As discussed above, option III is much less likely to occur than options I and II.

3.2 The Impact of the loss of spectral information on the science requirements

The major science goals of EIS include investigating the physical mechanisms responsible for coronal heating; the study of the initiation of transient phenomena such as flares, CMEs, jets and network brightenings; and understanding the causal relationship between events in the photosphere and corona.

In order to achieve these goals accurate spectroscopic measurements of velocity, temperature and density are crucial. For example, we require accurate non-thermal and Doppler velocity measurements to compare the predictions of wave heating and reconnection models to better understand coronal heating. The main effects of CTI on the parameters derived from fitting the affected line profiles include a narrowing of the line profile, a shifting of the line centre and general distortion of the line shape. These affect the derived non-thermal and Doppler velocities. There could be serious effects in the flare impulsive phase when large blue shifts and wings are often observed. The determination of the spatial location of the highest V_nt in order to determine the role of turbulence in the flare energy release and particle acceleration processes is another important goal which would be affected by CTI problems. The total line intensity is also affected, which in turn affects temperature and density determination from line ratios.

4 Findings from other Missions

It can be seen from the above discussion that CTI is a particular problem for spectroscopic measurements, and becomes less important, even at the same operating temperature, for missions in which imaging is involved. For example, if the CCD is used to image the entire Solar disk, then the majority of the pixels will contain a substantial number of electrons. Consequently, these electrons will provide a "fat zero" effect, effectively ensuring that any empty trap will be almost immediately filled, minimising the CTI.

Nevertheless, CTI has been found to be a problem for missions in which a small number of relatively faint discrete objects are imaged against a more-or-less dark background. The Hubble Space Telescope Wide Field and Planetary Camera II has a well-known charge transfer problem, and has degraded from an initial CTI loss of 3% of charge to up to 40% of the non-corrected charge being lost in pixels which are a long way from the amplifier [ref 6]. This can lead to a loss of sensitivity of over two magnitudes.

The problem also occurs with the Space Telescope Imaging Spectrograph (STIS) on board Hubble. This spectrograph (which operates at -88°C) can display significant (over 10%) CTI when imaging faint spectra [ref 7].

5 Conclusions

CTI is an extremely complex issue, and no current models can completely predict the extent to which it may occur for a particular CCD.

Nevertheless, even the simplified model discussed in appendix one is sufficient to enable the potential CTI to estimated (for example, see reference one). Using the CTI figures from that model, the potential effect on the spectral resolution available from EIS can be calculated.

Noticeable CTI has been observed at temperatures from about -25°C to -45°C. This CTI in turn leads to significant affects on the line profile, the line centre and causes a general distortion of the line profile. All of the major science goals of EIS rely on our ability to accurately determine non-thermal and Doppler velocities, temperatures and densities. The effects of CTI on the observed line profiles appear to severely compromise this ability, particularly in the case of weak lines.

6 References

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[5] Prediction of CCD Performance in Space, Marshall, P., Dale, C., and Petersen, E. Goddard Working Group Meeting, 6/5/91.

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[9] Hardy, T. Murowinski, R. and Deen, D. J. Charge Transfer Efficiency in Proton Damaged CCDs. IEEE transactions on nuclear science. Vol 45 No 2, 1998

[10] Gendreau, K.C. "X-ray CCDs for Space Applications: Calibration, Radiation Hardness, and Use for Measuring the Spectrum of the Cosmic Ray Background". PhD thesis, MIT, 1995

Appendix 1

Estimation of potential CTI values

Some simplistic simulations have been done, estimating the effect on CTI of clocking rate, electron charge cloud size, and initial radiation dose. The calculations are based on Dale et al. (ref 8) and also make use of the theory outlined in Hardy (ref 9) and Gendreau (ref 10).

The emission time constants for an electron trap is given by

$$Q_{trap} = \frac{g}{\sigma x V_t x N_c} \text{ x } \exp\left(\frac{E_t}{kT}\right)$$

where g = the level degeneracy (0.5)

σ_n = the electron trapping cross-section

Vt = the electron thermal velocity

Nc = the conduction band density of states ($v_t N_c = 1.6 \text{ x} 10^{21} \text{ x } T^2 \text{ s}^{-1}\text{cm}^{-2}$)

E_t = the trapping state energy band below the conduction band

If we consider a charge being transferred into a pixel into which no charge has previously been transferred (i.e all traps are empty) then the percentage of the charge packet that will be trapped within this pixel is given by CTI_{trap}:

$$CTI_{trap} = \frac{V_s * N_t}{N_s}$$

where V_s = volume of the signal charge packets

N_s = the number of electrons in the charge packet

N_t = the trap density

Due to the finite emission lifetime of the traps, some of this trapped charge will be re-emitted whilst the charge packet is still within the pixel. However, a proportion Q_{remain} of the charge will be retained and will be lost from the charge packet as it transfers out of the pixel, thus, the higher the value of Q_{remain} (for example, at low temperature) the higher will be the CTI (as more charge is retained):

$$Q_{remain} = \exp\left(\frac{-T_t}{T_s}\right)$$

where T_t = the time the charge remains in the pixel (approximated by the clocking time)

T_e = the emission time constant

Finally, if it is assumed that the charge packet is n pixels behind another charge packet, then as the charge packet is clocked towards the readout register, it will encounter charge that is emitted from traps containing charge from the previous charge packet. This will tend to reduce the CTI (as the charge packet size increases). For example, at very low temperatures, none of the previous trapped charge will be re-emitted, and consequently the CTI will not be reduced

$$Qemit = 1\text{-}\exp\left(-\frac{Ts}{Te}\right)$$

Thus, the effective CTI per pixel is:

$$CTI = CTI_{trap} \times Q_{remain} \times Q_{emit}$$

Assumptions

There are simplifications with the above derivation which mean that the calculation of CTI per pixel should be seen only as providing a "ball park" estimation of potential CTI. It is particularly useful however in seeing how the effects of charge packet size and clocking speed can have dramatic effects on the CTI.

The main simplifications and assumptions made are:

- The probability of encountering an electron trap (CTI_{trap}). The actual charge distribution within a pixel will vary greatly, depending particularly on the amount of charge present, and the pixel structure (for example, whether a "notch" is present to help confine the charge). Effectively, the electron trapping cross section will vary depending on the charge distribution, with proportionally more charge being trapped from smaller packets (for example, see Hardy for a plot of simulated charge concentrations).
- The values assumed for trap energies, trapping cross-sections, etc. - in particular the values that we should use to estimate the CTI near the end of the mission.

Thus for an approximate estimation of the CTI that could be expected at the end of the mission we can use the figures presented in discussion note three. The values determined for the trap concentrations depends on the total proton flux (and the overall dose). As can be seen, there is a linear relationship between the total proton flux (converted to the equivalent flux @ 10 MeV) and the displacement damage in Silicon.

Trap concentration	Total proton flux (@10 MeV equivalent)	Total dose
5.2×10^{10} displacements/cm^2	6×10^{9} protons/cm^2	-
1.3×10^{10} displacements/cm^2	1.5×10^{9} protons/cm^2	-
	1.79×10^{9} protons/cm^2	1 krad
	1×10^{10} protons/cm^2	7 krad

Table three: the approximate relationship between proton flux, trap concentration and dose

Thus, the values assumed are:

Vs = 3×10^{-11} cm^3 (13.5µm x 4.5µm x 0.5 µm). - It is assumed that the charge will be found across the pixel dimension, and all accross one gate of the pixel in the vertical dimension. The approximate depth into the CCD is taken from calculations in Hardy et al. (ref 9). (Thus, the CTI is quite sensitive to the depth assumed for the pixel -it is also assumed that all the charge is collected under one phase)

Nt = 6×10^{10} cm^2 for 4 krad dose (approximate end of mission dose with 15mm Al shielding)

= 1.5×10^{10} cm^2 for 1 krad dose

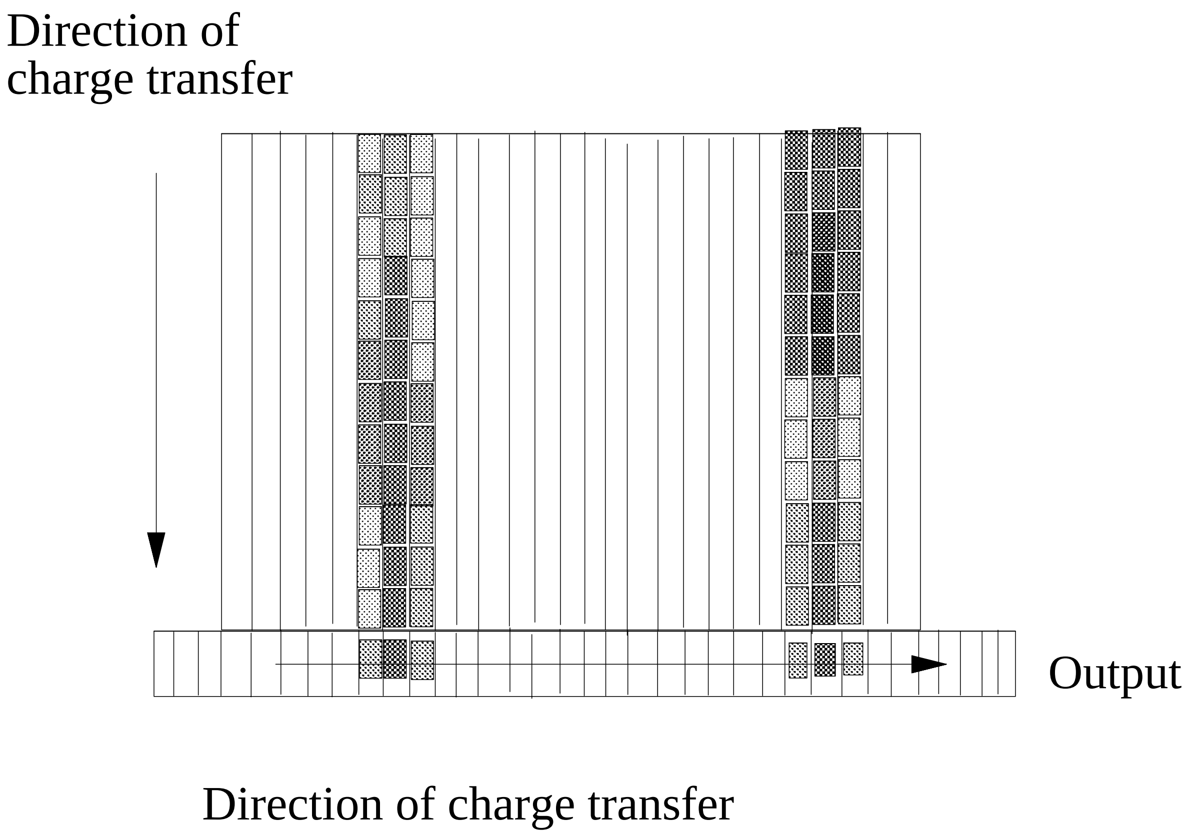


Figure one: Clocking out a CCD

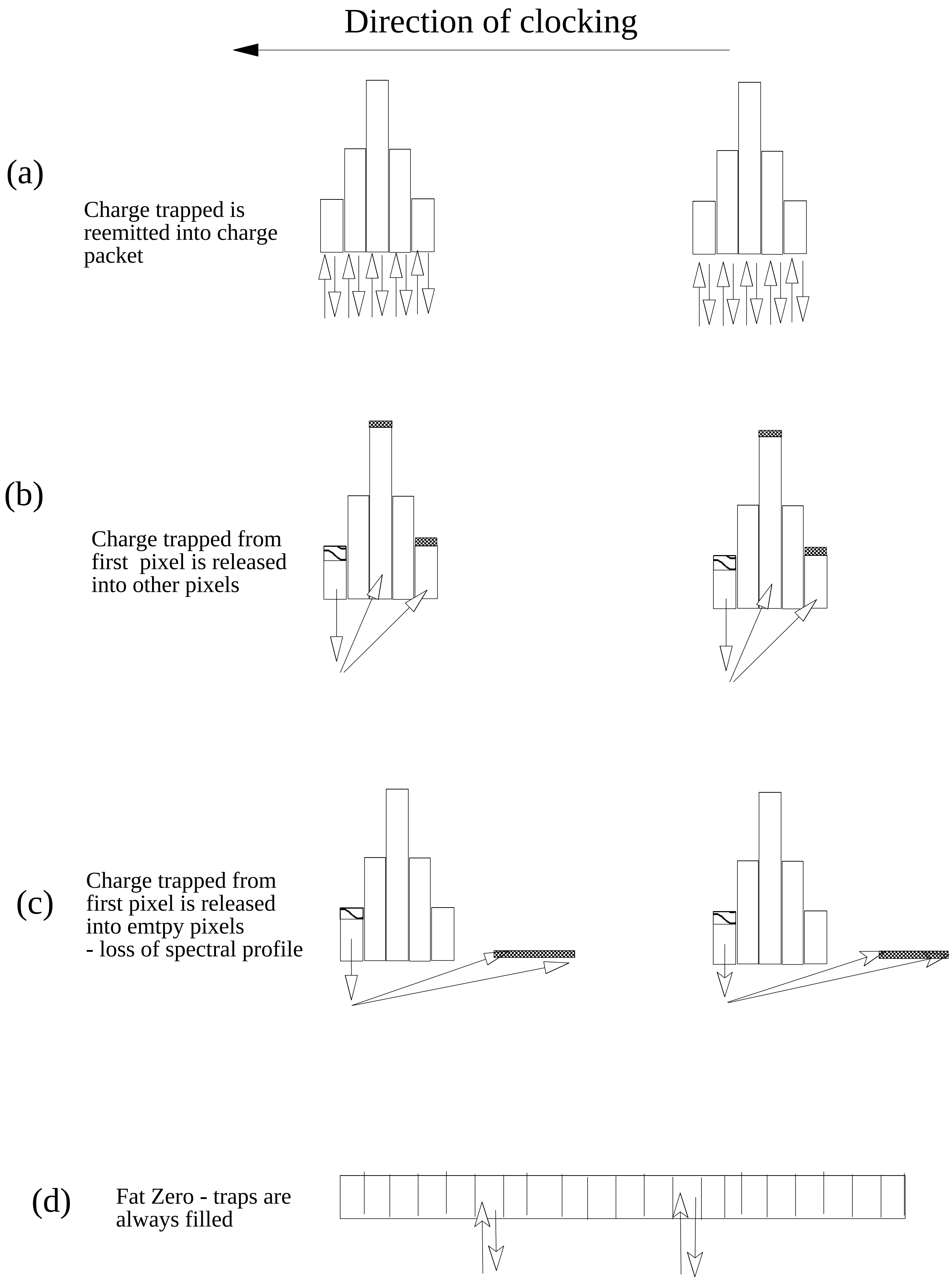
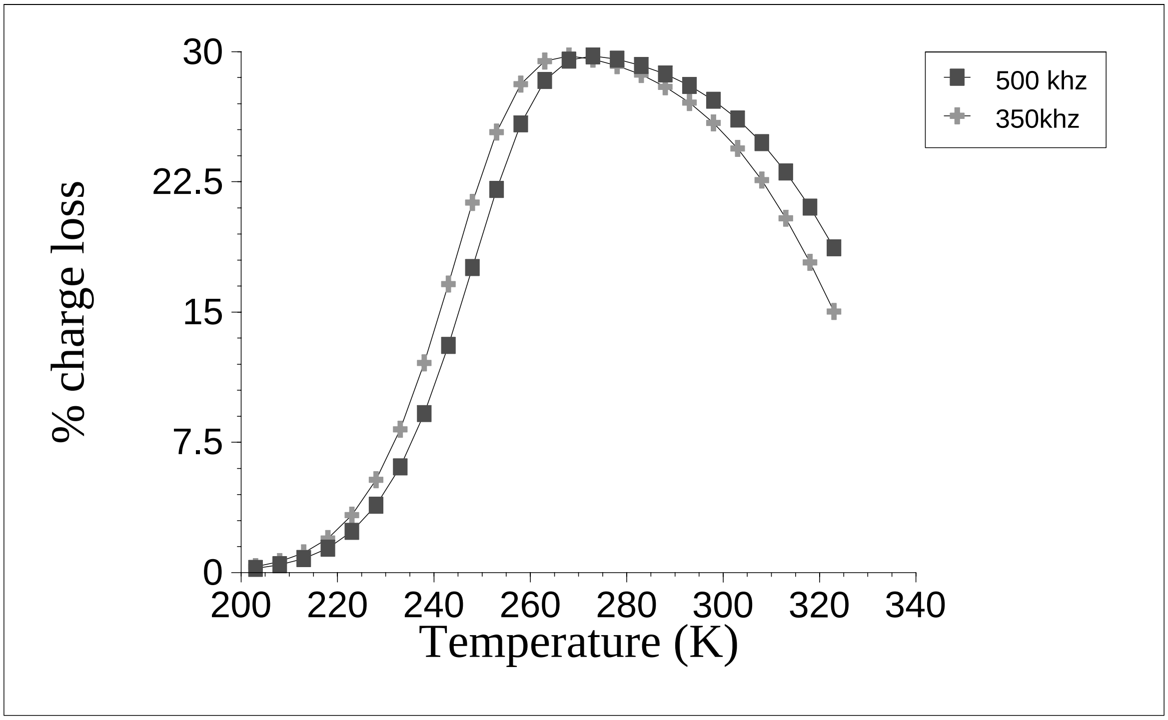
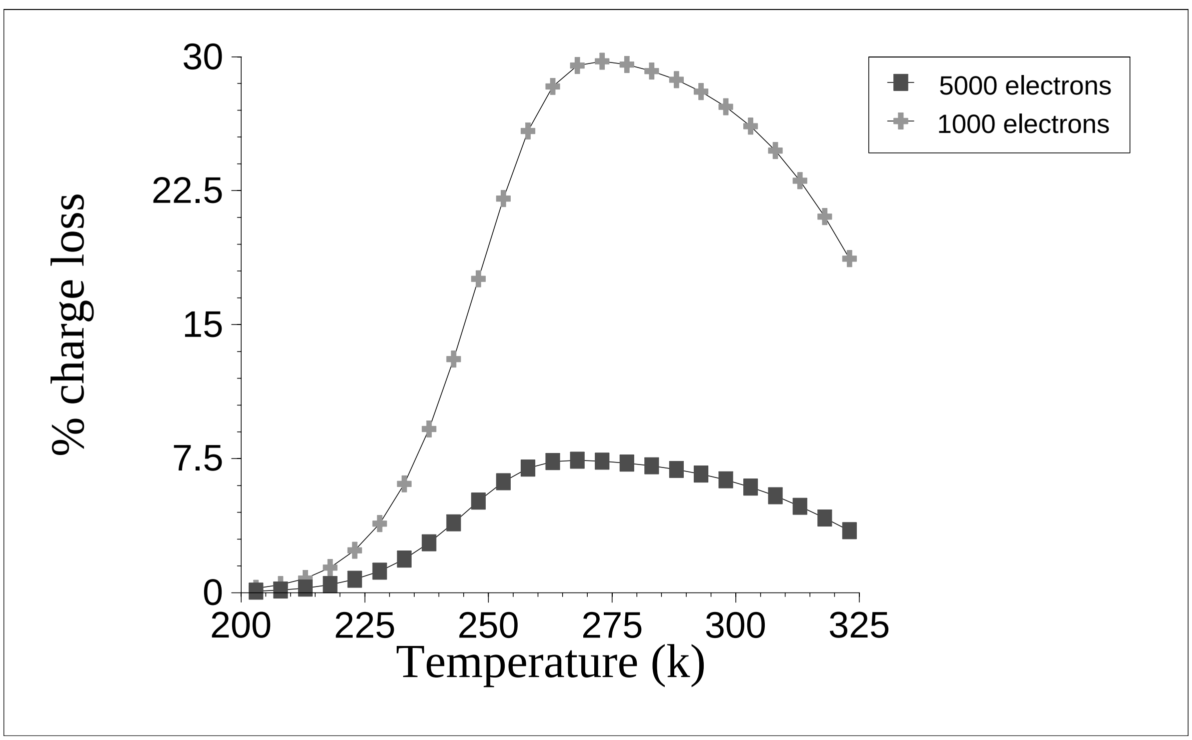


Figure Two: Possible effects of CTI



CTI loss for 1000 electrons, for 2 clocking rates
Assuming 220 pixel spacing between transfers



%charge loss for 1000 and 5000 electrons, for 500khz clocking
Assuming 220 pixel spacing between transfers

Figure three

The CTI observed for FeX at 350kpixels/s and 238K

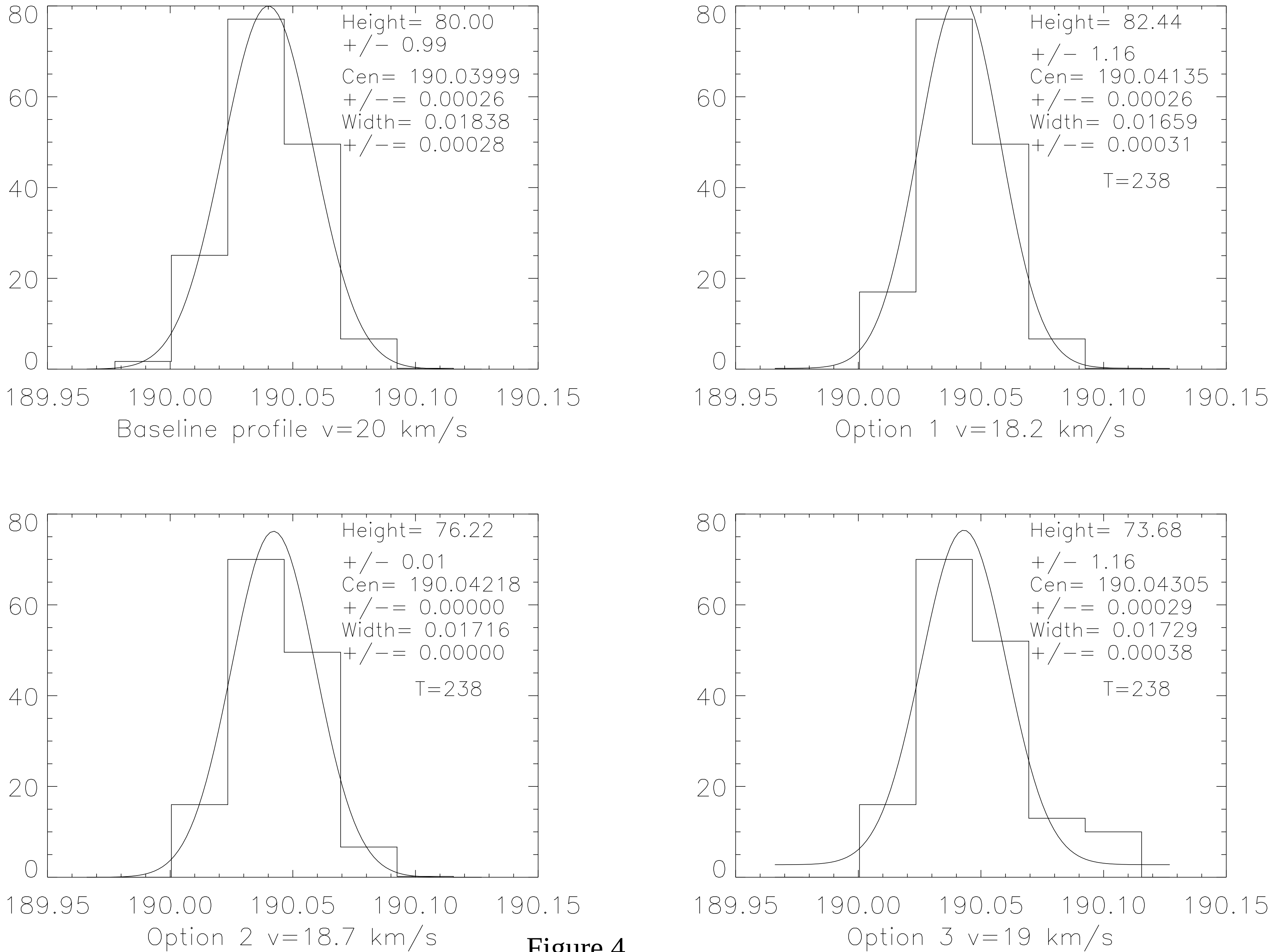


Figure 4

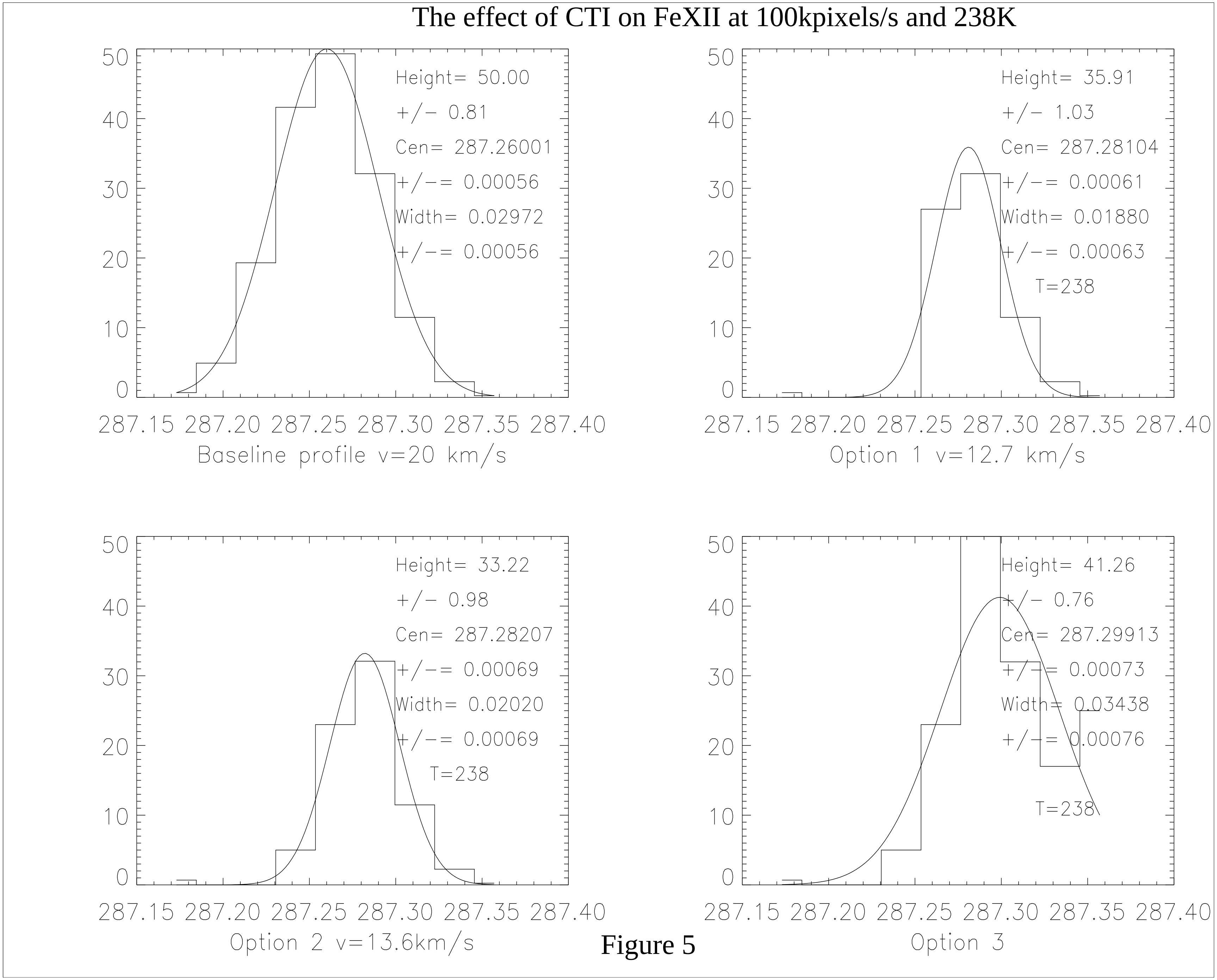

The effect of CTI on FeXII at 100kpixels/s and 238K
Height= 50.00
+/- 0.81
Cen= 287.26001
+/-= 0.00056
Width= 0.02972
+/-= 0.00056
Baseline profile v=20 km/s
Height= 35.91
+/- 1.03
Cen= 287.28104
+/-= 0.00061
Width= 0.01880
+/-= 0.00063
T=238
Option 1 v=12.7 km/s
Height= 33.22
+/- 0.98
Cen= 287.28207
+/-= 0.00069
Width= 0.02020
+/-= 0.00069
T=238
Option 2 v=13.6km/s
Height= 41.26
+/- 0.76
Cen= 287.29913
+/-= 0.00073
Width= 0.03438
+/-= 0.00076
T=238
Option 3
0
10
20
30
40
50
287.15
287.20
287.25
287.30
287.35
287.40

Figure 5

Temp (K)	500 khz	350khz	100khz
323	20	19	2
318	23	21	4
313	25	23	7
308	27	25	11
303	28	26	15
298	29	27	18
293	30	28	21
288	31	29	24
283	31	29	26
278	32	30	28
273	32	30	29
268	32	29	30
263	30	28	31
258	28	26	32
253	24	22	32
248	19	18	32
243	14	13	30
238	10	9	27
233	7	6	21
228	4	4	16
223	3	2	11
218	2	1	7
213	1	1	4
208	0	0	2
203	0	0	1
198	0	0	1
193	0	0	0

Table one: the % charge loss for a 1000 electron charge packet with different clocking rates

The variation in velocity and line centre for different operating temperatures

clocking rate = 350 kpixels/s
baseline" velocity = 20 km/s

	velocity (km/s)				increase in position of line centre (Å)		
Temperature (k)	option 1	option 2	option 3		option 1	option 2	option 3
248	16.5	18	19.4		0.0022	0.0037	0.0052
243	17.4	18.3	19		0.0018	0.0029	0.0041
238	18.2	18.7	19		0.0013	0.0021	0.0031
233	19	19	19.1		0.0008	0.0015	0.0023
228	19.7	19.1	19.1		0.0003	0.0009	0.0014

clocking rate = 100 kpixel/s
baseline" velocity = 20km/s

	veloctity (km/s)				increase in position of line centre (Å)		
Temperature (k)	option 1	option 2	option 3		option 1	option 2	option 3
248	12.3	13	n/a		0.024	0.024	n/a
243	12.5	13.2	n/a		0.0233	0.0232	n/a
238	12.7	13.6	n/a		0.021	0.0221	n/a
233	12.2	14.3	n/a		0.018	0.02	n/a
228	10.6	14.7	n/a		0.015	0.018	n/a
223	13	15.3	n/a		0.014	0.016	n/a
218	14.4	21.2	n/a		0.013	0.01	n/a
213	15.2	15.6	n/a		0.012	0.0131	n/a
208	15.4	15.8	n/a		0.0117	0.0125	n/a

Table 2