DEAR Technical Note IR-14

Measurement of the temperature dependence of the CCD-22 chip performance

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1) Experimental setup:

Using the new cryogenic setup placed in the DEAR laboratory and two CCD-22 chips we have performed measurements to investigate the temperature behaviour of these new CCD chips and to check the cooling temperature necessary for a good performance. Stage two of DEAR will use in total 16 CCD-22 chips, to be cooled below 180 K in order to increase the performance. Two refrigerators (APD Cryo Tiger) are foreseen for the cooling process.

We have used a ^{55}Fe source which was placed behind a 200 μm thick Hostaphan foil in the center of the top of the vacuum jacket. The exposure time of the measurements was 3 minutes. The CCDs were allowed to warm up from ~173 K to ~200 K which took about 70 minutes. The temperature gradient within the 3 minutes of exposure time ($\leq$ 1 K) was assumed to be small enough to avoid possible additional effects due to a fast temperature change.

2) Temperature dependence of the energy resolution

The observed energy spectra were analyzed. The K_α peak of manganese following the ^{55}Fe decay at 5.9 keV was fitted with a Gaussian function using the program Origin 5.0. Figures 1 and 2 show the results for the temperature dependence of the energy resolution ΔE at FWHM for both CCDs, A and B. We can clearly see an exponential dependence of the energy resolution which starts at a pedestal level depending on the chip used. For the present setup, with the electronics at the presently given conditions and the chips used, this pedestal was reached at ~180 eV for CCD-A and ~200 eV for CCD-B.

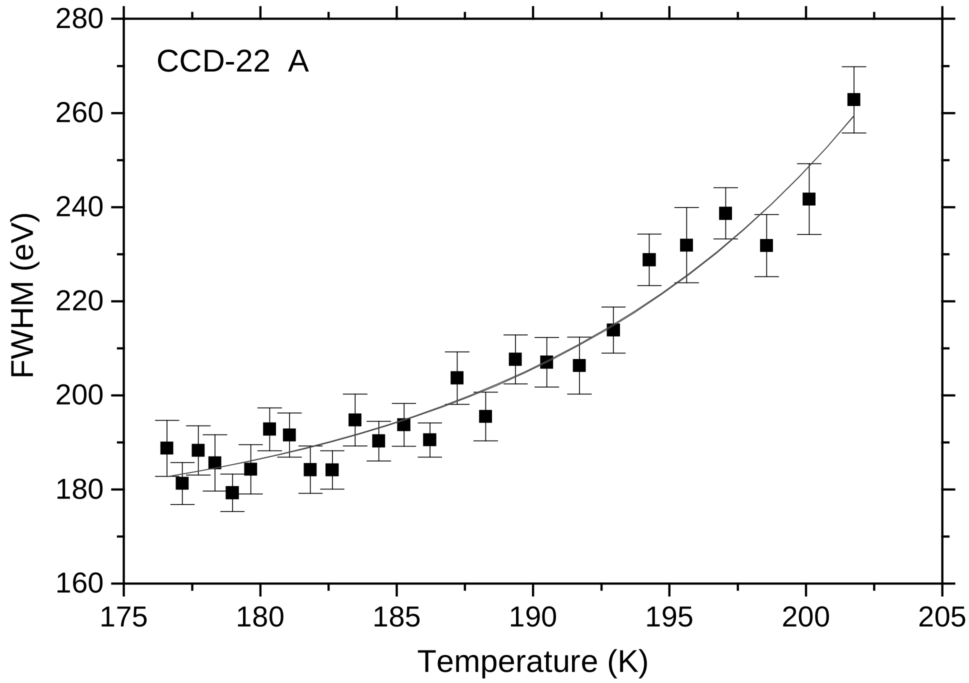

Fig.1: Temperature dependence of the FWHM of the 5.9 keV peak of CCD22-A together with an exponential fit function.

The exponential temperature dependence can be explained with the exponential temperature dependence of charge excitation into the conduction band of silicon semi-conductors. This dependence is given by the "Aarhenius curve" as [1]:

$$n = N \times e^{-\left(\frac{W_0}{2kT}\right)} \qquad (1)$$

n ... number of charge carriers in the conduction band
N ... number of available states in the conduction band
W_0 ... gap energy of the semi-conductor material
k ... Boltzmann's constant
T ... Temperature [K]

This exponential temperature dependence is reflected in our measurements.

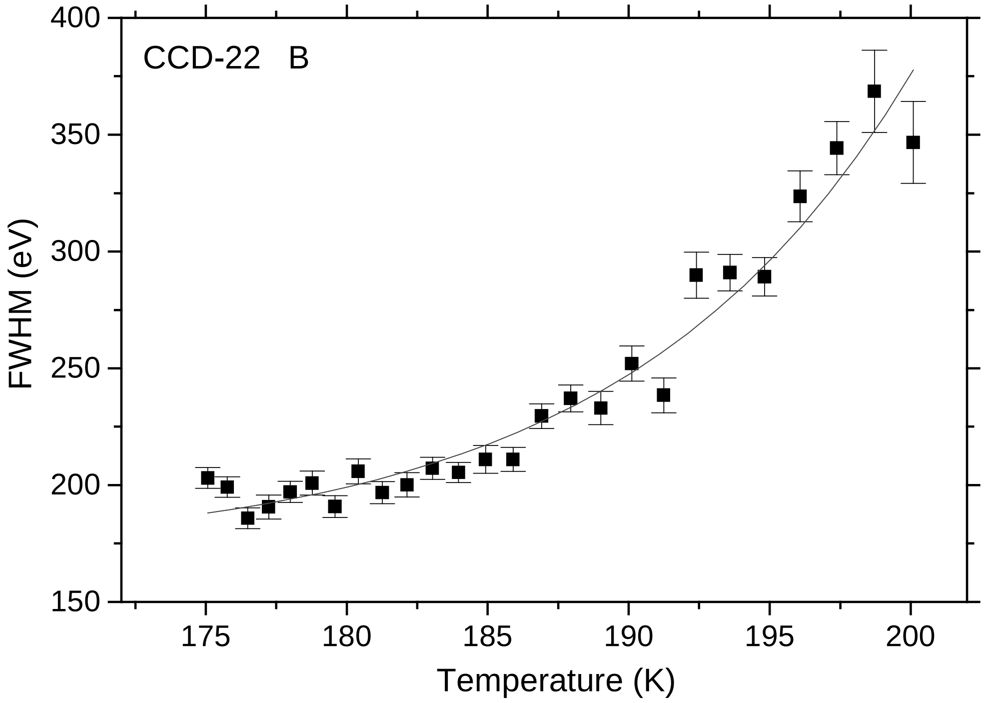

Fig.2: Temperature dependence of the FWHM of the 5.9 keV peak of CCD22-B together with an exponential fit function.

Comparing Fig.1 and Fig.2 one can determine a clear exponential dependence which starts from a plateau reached below approximately 180 K. The plateau reflects the fact that, at such a temperature, too little energy is available to allow the charge carriers to "jump" to the conduction band of the semi-conductor. Therefore no temperature dependence is displayed below that temperature.

CCD-A and CCD-B display two main differences:

- The minimum resolution at FWHM which is ~ 180 eV for CCD-A and ~ 190 eV for CCD-B, and
- the increase of the resolution at FWHM with temperature, which is for CCD-A only a factor of 1.4 at 200 K, while for CCD-B a factor of 2.0 was measured.

The energy dependence of the resolution ΔE(FWHM) of a silicon CCD can be described by the well known formula [2]:

$$\Delta E \text{ (FWHM)} = 2.355\,\omega \cdot \left(N^2 + \frac{FE}{\omega} \right)^{\frac{1}{2}} \text{ (eV)} \qquad (2)$$

2.355 ... r.m.s. (root mean square)
N ... r.m.s. transfer and readout noise
E ... x-ray energy
F ... Fano factor for silicon ~ 0.12
ω ... production energy for an electron-hole pair in silicon ≈ 3.68 eV

Using this equation the theoretical limit of the CCD energy resolution is calculated to be ~ 120 eV at 5900 eV. The additional 60-70 eV to reach the observed energy resolution at 5.9 keV are dominantly due to electronics noise during the read out process.

Studies and R&D work to improve the read-out electronics and therefore the energy resolution of the CCD-22 chips are presently carried out in the DEAR laboratory at Frascati.

3) Temperature dependence of the noise peak positions

Regarding the position of the noise peak one, of course, expects an increase in correlation with temperature because its position directly reflects the amount of charges present as zero-level in an unexposed CCD chip. The exponential dependence on temperature of charge carriers release is reflected by the exponential temperature dependence of the noise peak position above a temperature of 180 K, as expected from equation 1.

Figures 3 and 4 show the respective measurements for CCD-A and CCD-B together with a constant level and an exponential fit. Clearly the constant behaviour below 180 K is visible. Again, a much faster increase up to 200 K is shown by CCD-B (factor 5.7) than by CCD-A (factor 2.8).

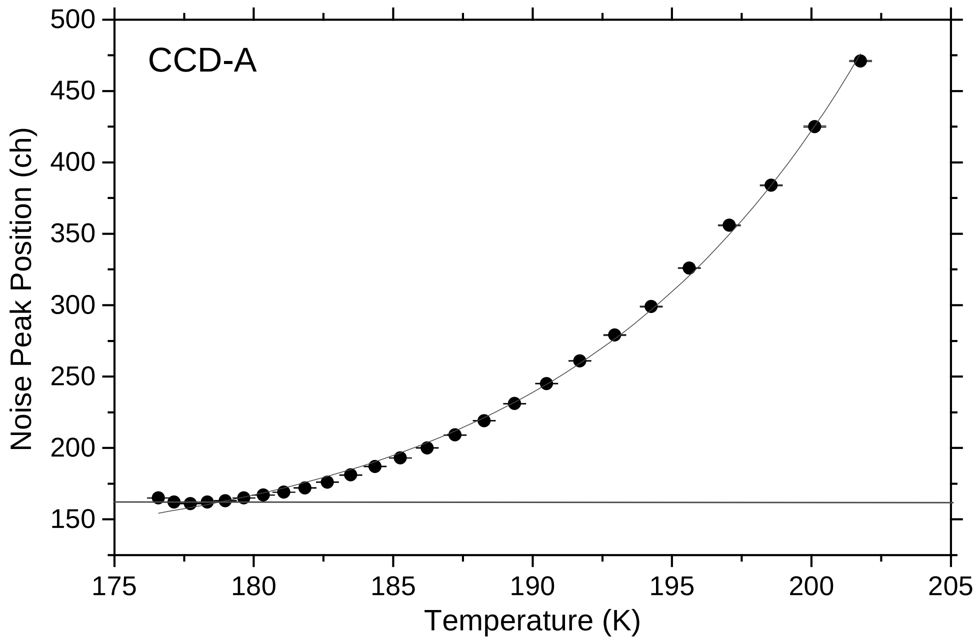

Fig.3: Temperature dependence of the noise peak position of CCD-A together with an exponential fit and a constant line visualizing the plateau below 180 K.

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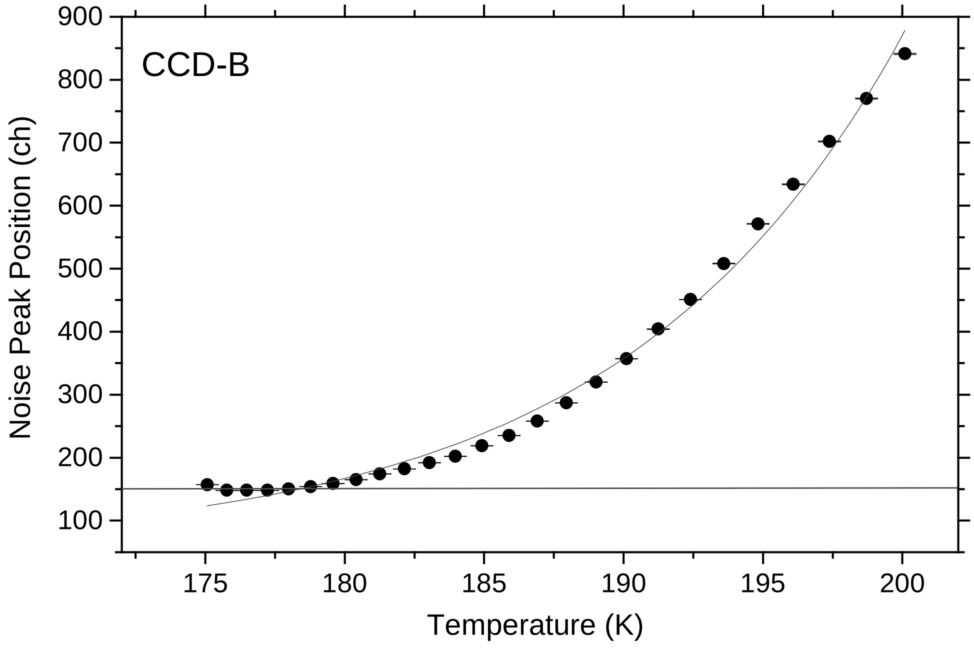

Fig.4: Temperature dependence of the noise peak position of CCD-B together with an exponential fit and a constant line visualizing the plateau below 180 K. For CCD-B, the single-exponential does not so well reproduce the temperature dependence of the noise peak.

4) Temperature dependence of the peak positions

Additionally to the changing of the energy resolution and position of the noise peak we have noticed a temperature dependence of the line position of the Mn(K_α) line.
In the CCD analysis programs (Pion, Hydrogen) the determination of the zero-level of the energy spectrum depends on the noise peak position. In a first approximation one would expect a similar increase for any peak as for the noise peak, as the pedestal-value of charges should add up identically in all pixels, not depending on the available amount of charges. This is approximately true, otherwise a stronger change for the Mn(K_α) peak position would have been observed.
But the decrease of the peak position reflects a slightly slower increase with temperature of the ADC channel number for the Mn(K_α) peak than for the noise peak. This can be explained by an additional small dependence on x-ray energy; i.e. for smaller energies (less available charges in one pixel) the temperature increase is slightly stronger. It is a small effect, but visible due to the rather strong change in the noise peak position during the conducted measurements: for CCD-A the noise peak position changed for ~ 300 channels, while the peak position changed 3 channels; for CCD-B the respective changes were ~ 700 channels for the noise peak and ~ 3.5 channels for the peak position. Although big statistical uncertainties and "other unknown" effects might cover the "pure" temperature dependence, an approximately linear temperature dependence of the peak position can be deduced from figure 5 and figure 6.

As consequence for the DEAR experiment it follows that it is important to stabilize and monitor the CCD temperature during the measurements to avoid a systematical error in the peak position due to temperature drifts.

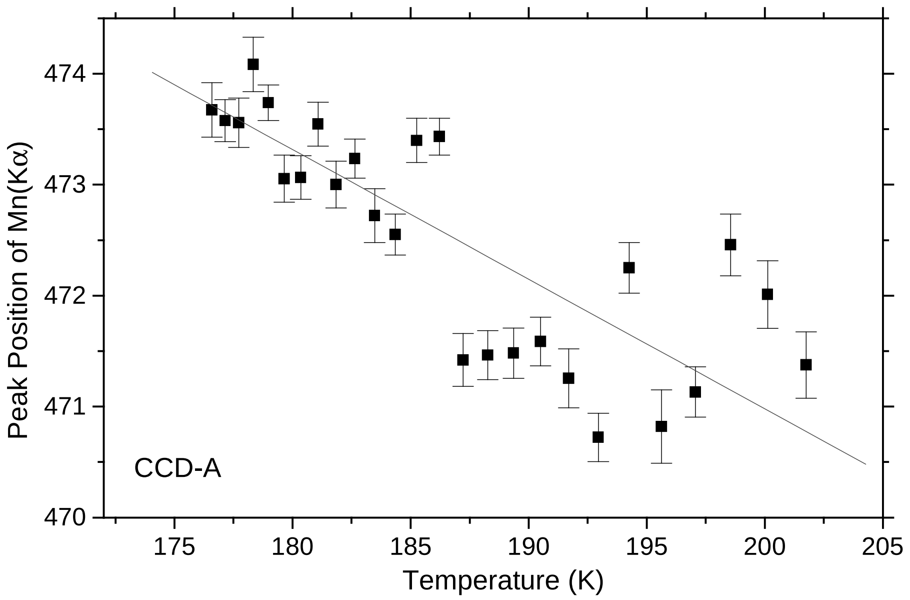

Fig.5: Temperature dependence of the position of the Mn(K_α) peak for CCD-A together with a linear fit.

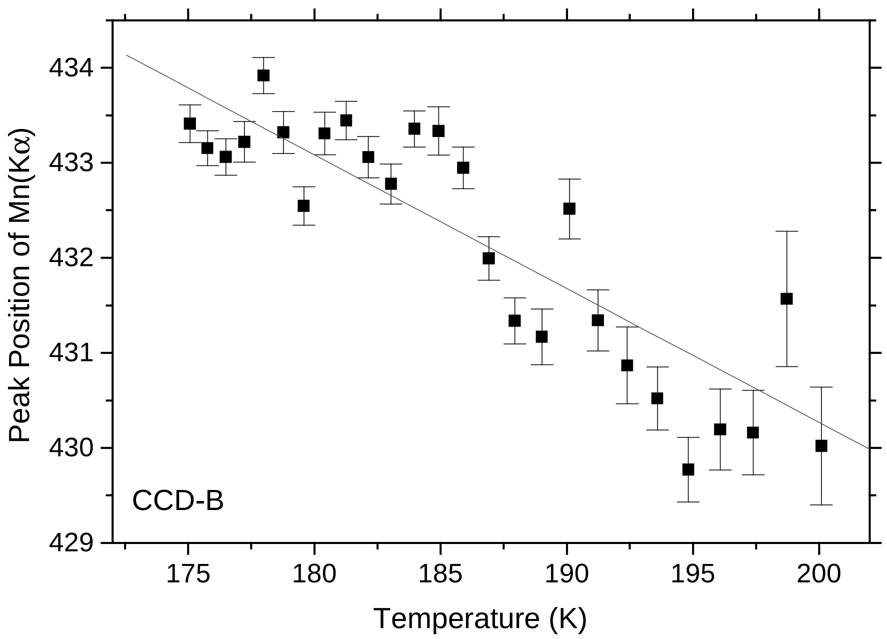

Fig.6: Temperature dependence of the position of the Mn(K_α) peak for CCD-B together with a linear fit.

5) Summary

For the DEAR experiment we can deduce from our measurements that:

1. the CCD-22 chips must be cooled below 180 K in order to obtain the best performance with respect to the energy resolution;
2. the CCD temperature must be stabilized in order to avoid an additional systematical error in the energy calibration due to a line shift depending on the CCD temperature.

Acknowledgements:

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References:

[1] Gerthsen-Kneser-Vogel, Physik, Springer Verlag, Berlin-Heidelberg-New York,14. Auflage, 1982), p.711.

[2] J.P. Egger, D. Chattelard, E. Jeannet, Part. World 3 (1993) 139.