7ID Feb 2003 Resolution and linearity tests of the CoolSNAP microscope

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1 Introduction

This document reports the results obtained by Eric, Dohn and Nino in February 2003 on the resolution and linearity of the new Roper CoolSNAP camera coupled to a X2 microscope and looking at the visible fluorescence from a YAG:Ce crystal.

2 Experimental method

For this experiment, the monochromator was set to 10.0 keV and the second monochromator crystal was detuned to cut the intensity by 50 %. The detuning reduced the contamination from higher harmonics at 30 keV. An ion chamber recorded the intensity before the camera and a Roper CoolSNAP cf camera equipped with a microscope with X2, X5, or X10 objectives [2] imaged the visible fluorescence by a YAG:Ce single crystal. Fig. 1 shows the CCD camera, microscope, 90 degree mirror and YAG:Ce screen as well as its mechanical support. A computer controlled staged allowed to focus the microscope on the screen.

3 Results

Fig. 2 shows the detector response with the thick 0.5 mm YAG:Ce crystal. The incident flux was calculated from the ion chamber signal assuming N_2 filling the ion chamber. It was in air though so the absolute calibration is only approximate. Because the monochromator was detuned, little 3rd harmonic contamination was present. The foil transmission was consistent with values from tables. The three curves shown in the figure are consistent with each other. Small differences are caused by slight background drifts. Note that the zig-zag in the linear plot is caused by large background fluctuations of the CCD readout noise. This source of noise is not understood yet, but is more significant than the manufacturer's specification. The linearity of the CCD is fairly good although a trained eye would notice evidence of non-linear behavior. This is expected since the manufacturer specs less than 5% non-linearity.

Linear fits of these reponse curves were performed and the results are summarized in table 1. Here a thinly doped YAG:Ce screen (190 μm thick YAG, with 4μm thick Ce

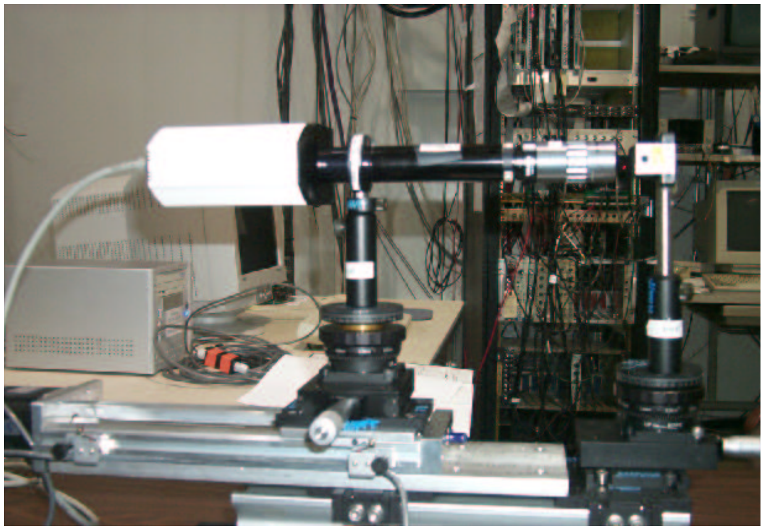

Figure 1: The camera system.

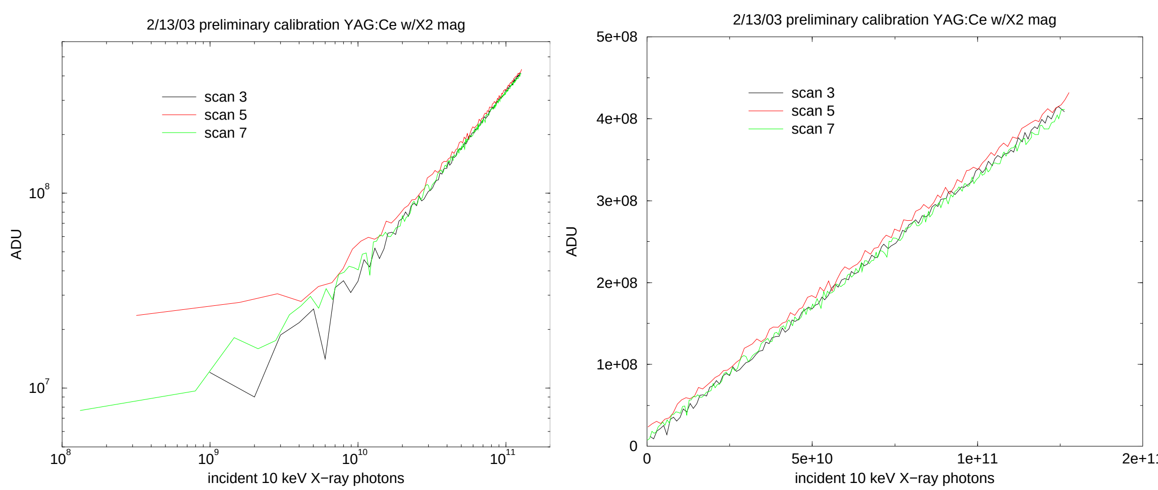

Figure 2: The detector system response versus the incident number of photons per exposure time for the thick Yag:Ce crystal. Scan 3 had no Al filter in. Scan 5 had about 0.18 mm of Al, and scan 7 0.36 mm.(left)Logarithmic plot. (Right)Linear plot.

Screen description	slope (ADC/10 keV ph)
Thick YAG	3.17e-3
Thin YAG X-ray incident on doping side	2.50e-4
Thin YAG X-ray incident on undoped side	1.98e-4

Table 1: Slope of the response curves for several experimental conditions.

doping) was measured as well as a single crystal YAG:Ce screen 0.5 mm thick. The thick YAG response is 12.7 times larger than the thin YAG's response. The thin YAG provides 1.26 times more light when the doping faces the incoming X-rays than when the undoped surface faces the X-rays.

A YAG:Ce single crystal emits visible light at 550 nm when an X-ray is absorbed. The CCD quantum efficiency at this wavelength is about 35%. Note that 1 ADC unit is 3e collected in the CCD well. When a 10 keV X-ray is absorbed in YAG:Ce, 311 visible photons are emmitted in 4π[1]. The microscope collection efficiency is about $CE = 0.25(NA/n)^2$, where NA=0.055 is the numerical aperture of the X2 objective and n = 1.95 is the index of refraction of the YAG screen[1]. Given that $CE = 1.99 \times 10^{-4}$ here, we expect about 0.062 visible photon (v-ph) per 10 keV X-rays absorbed, focussed on the CCD plane. 35 % of these photons are detected and collected as electrons in the CCD well. The scale factor for the thick YAG is expected to be (0.062 v-ph) * (0.35e/v-ph) * (1 ADC/3e) = 0.0072 ADC/10 keV photons. The calibration for the thick YAG is a factor 2 off, but given the approximate flux calibration, the agreement is reasonable. Furthermore, reflection losses at several interfaces have been ignored such as the YAG to air interface (10%), mirror interface($\approx$ 10%), in the objective, and in the tube lens.

Note that YAG has a composition of $Y_3Al_5O_{12}$ with a density of 4.55 g/cm^3. Thus the X-ray absorption length at 10 keV is 57.1μm. If only a thin layer of 4 μm is doped, this thin layer absorbs only $(1 - exp(-4/57.1)) \approx 0.07$. This absorption is quite consitent with the ratio we've measured between the response of the thick and thin YAG:Ce screens.

To test the resolution of the camera, an edge was placed in the beam in front of the YAG crystal, about 2 cm in front of it. A cleaved piece of a GaAs (100) wafer, 300 μm thick was used. It is well known that GaAs cleaves with atomically flat edges. Fig. 3 shows a typical slice of the CCD image where the GaAs edge blocks the beam. The data were fit to an atan() function with the intensity

$$I = A \times atan((x - x_0)/W) + B, \tag{1}$$

where A and B are constant, x_0, is the center of the edge, and W is the width.

Fig. 4 shows the best fit parameters, here the width, from the least square fit of a slice of the CCD data. The width is plotted versus the relative distance between the microscope and the YAG:Ce surface. The solid line is a least square fit with

$$W = W_{min} + C(X - X_c)^2, \tag{2}$$

where X_c is the CCD position at the best focus, C is a proportionality constant, and W_{min} the best focus resolution. In Fig. 4, the best resolution is $W_{min} = 0.61$ pixels or 1.4 μm. If one calls the depth of focus (DOF), the distance where $W = 2W_{min}$, then replacing in Eq. 1, one finds that

$$DOF = |X - X_c| = \sqrt{W_{min}/C} \tag{3}$$

In Fig. 4 the DOF is 0.18 mm. From the camera manufacturer, one would have expected 0.09mm?

Similar results were obtained for different YAG crystal screens and visible optics set up. For example, a thinly doped YAG:Ce screen (190 μm thick YAG, with 4μm thick Ce doping)

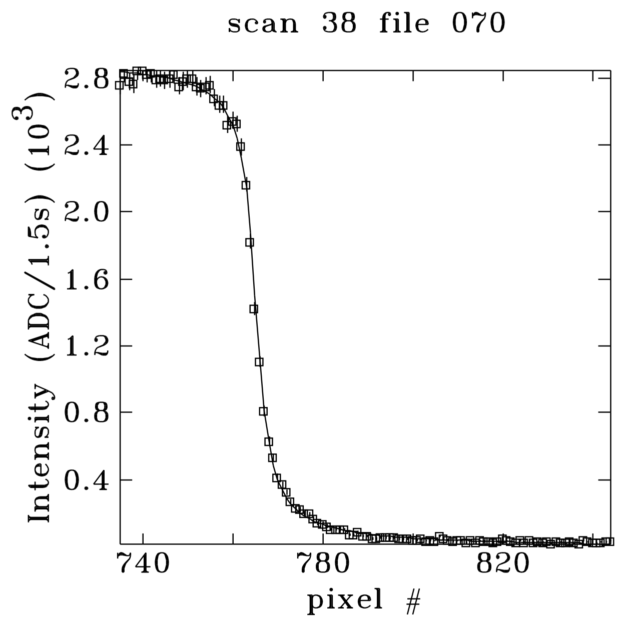

Figure 3: The edge profile measured with a thinly doped (4 μm) YAG:Ce single crystal with the doping facing towards the incoming X-rays

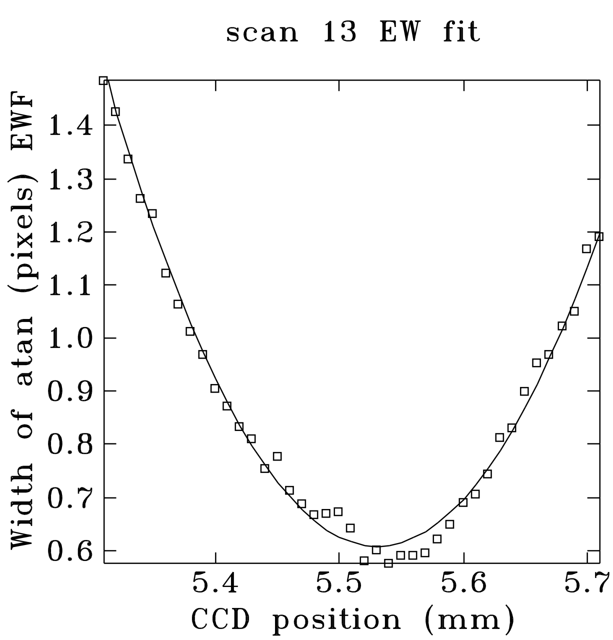

Figure 4: DOF of a thick YAG:Ce doped screen.

Screen description	E (keV)	tube length (mm)	Magnification	W_{min} (μm)	DOF (mm)
Thick YAG	10.00	142.5	2	1.41	0.18
Thick YAG	10.87	142.5	5	2.02-2.95	0.084
Thick YAG	10.00	141	2	1.91	0.22
Thin YAG doped side	10.00	141	2	5.32	0.61
Thin YAG undoped side	10.00	141	2	6.72	0.68
Thin YAG doped side	10.00	142.5	2	5.24	0.529
Thin YAG doped side	10.87	142.5	5	6.01	0.175
Thin YAG doped side	10.00	142.5	10	1.81	0.042

Table 2: Best resolution and DOF for several experimental conditions. The energy of the X-ray beam used was typically around 10 keV.

was measured as well as a single crystal YAG:Ce screen 0.5 mm thick. Two different distances between the tube lens and the CCD were used 142.5 and 141 mm. As expected the thin YAG works best when the X-rays are incident on the doped side. Surprisingly, the single crystal YAG:Ce performs much better than its thin counterpart. The thick YAG should be used from now on as its resolution is $2.29/0.82 = 2.8$ times better than the thin YAG. The focus is much sharper too, and the DOF is closer to the one specified by the objective's manufacturer. Taking the resolution as twice the fitted width, the best resolution achieved to date is $2.0 * W_{min} = 2.8$ μm. Note that the resolution is best with the tube length of 142.5 mm[2].

References

[1] A. Kohn, C. Raven, P. Spanne, A. Snigirev, J. Opt. Soc. Am. A, **15**, No. 7, p1940 (1998).

[2] The objectives were the Mitutoyo MPlan APO long working distance infinity corrected objectives. The X2, X5 objectives were used here with the MT-40 tube lens (X1) refocussing on a C-mount CCD. Edmunds Scientific recommends in their catalog a C-mount tube length of 142.5 mm.