Choice of X-ray filters used in the alignment procedure of the MHATT-CAT Double Mirror Filter.

Eric Dufresne and Steve Dierker, February 27, 1998

The double mirror filter alignment procedure is based on the observation of the direct and singly or doubly reflected beam by a YAG scintillation crystal. This crystal emits about 8-9 visible photons (λ=550 nm) per keV of hard X-rays. In this report, we will find the required thicknesses of various X-ray filters which will ensure the integrity of the YAG crystal and generate sufficient light to observe the visible fluorescence using a 1:1 imaging system. The alignment procedure has three steps. The observation of the direct beam and the careful calibration of the upstream slits is the first step. The slits have to be closed to an opening of about 0.1mm by 0.1 mm in order to reduce the thermal load on the downstream optics. Because of the low thermal conductivity of the YAG and the large power densities at the APS, we require to reduce the absorbed power in theYAG by the use of appropriate X-ray filters. The second step involves bisecting the filtered direct beam with the first mirror and observing both the direct and singly reflected beam on the YAG. By tilting the first mirror until the images of the direct beam and of the reflected beam nearly overlap, we will be able to zero the mirror angles of incidence. Once the first mirror is calibrated, we can set its angle to 8.75 mrad. After this step, some filter can be taken out because the first mirror will kill a large fraction of the power above its critical energy. Given that the beam is also small, the thermal load on the YAG and optics will be quite small. The final step involves zeroing the second mirror using the same alignment procedure as the first mirror. Once the angle is calibrated, it will be set also to 8.75 mrad. We describe next the issue relevant to the three alignments steps.

1) Filter requirements to observe the direct beam.

In order to observe the direct beam with a YAG scintillation screen, we plan to use a combination of Cu and graphite filters to reduce the peak absorbed power density in the YAG to below the power density which would cause thermal gradients large enough to break the crystal. For the filter to work effectively, each individual filter should sustain the heat load of the full beam without melting. This problem is not as trivial as one would think given the large power density delivered by APS undulators. Let us first focus on the choice of a graphite filter and its appropriate thickness. We will then choose a graphite filter thickness and determine a set of Cu foil which would adequately work to both sustain the heat load and reduce the X-ray power absorbed in the YAG.

The simulation shown next will use two programs, URGENT or US, to calculate the spectral power through a fixed aperture placed at 27 m from the source which is the location of our L5 white beam slits. To determine the required aperture size for the simulation, we first simulate the off-axis power density integrated over all energies produced by the undulator.

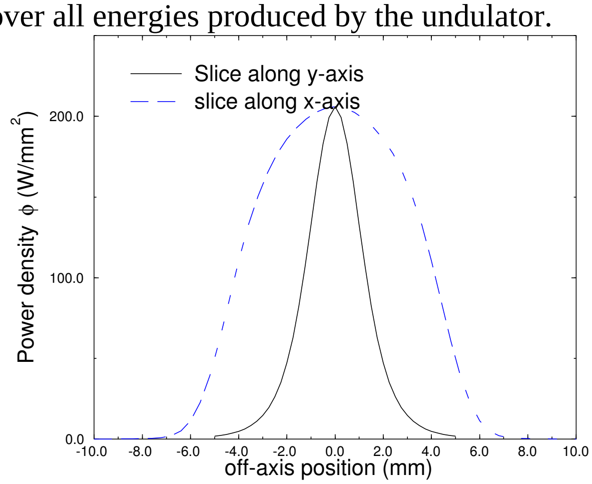

Figure 1. Two slices of the power density versus the off-axis distance for a 3.3 keV fundamental.

Figure 1 shows the power density ϕ versus the horizontal (x-axis) or the vertical (y-axis) off-axis position. This simulation was done with the program US (R. Dejus, part of XOP) using the APS electron beam parameters of 7 GeV and 100 mA. The undulator has 72 magnetic periods each 3.3 cm long for a total length of 2.4 m. The electron beam phase space parameters are σ_x= 0.30 mm , σ_y = 0.06 mm, $\sigma_{x'}$ = 0.025 mrad and $\sigma_{y'}$ = 0.0053 mrad, yielding a horizontal emittance of 7.5 nm-rad and a 4.2 % vertical coupling. These parameters are believed to be close to the current operation parameters of the APS. The deflection parameter for the simulation is k = 2.57, which is achieved at the smallest gap of 10.5 mm. The power density is plotted in a plane 27 m from the source. The power density has a FWHM of 2.6 mm in the vertical and 8.2 mm in the horizontal direction. The fundamental RMS beam sizes at 27 m can be calculated from the electron beam parameters and the inherent X-ray photon divergence $\sigma_{r'} = (\lambda/2L)^{1/2}$ where L=2.4m is the undulator length, The contribution from radiation divergence is small in the horizontal, but significant in the vertical at low fundamental energies. Using the APS parameters and λ=3.78 Å, one finds $\sigma_x = (0.3^2 + (27x0.0265)^2)^{1/2}$ mm = 0.78 mm and similarly $\sigma_y = (0.06^2 + (27x0.0103)^2)^{1/2}$ = 0.29 mm. The rms beam size at 27 m are dominated by the beam divergences. Given that the FWHM for a Gaussian is 2.355σ, the ratio of the FWHM of the power density over the FWHM of the fundamental are 4.5 and 3.8 in the horizontal and the vertical respectively. This discrepancy is most likely due to the fact that higher harmonics exhibit extended tails with sufficient power to broaden the power density profile. More details on the power densities predicted at the APS are shown in Table 1.

E1 (keV)	Deflection parameter k	FWHMx (mm)	FWHMy (mm)	Total power (W)	Peak power density (W/mm2)
2.93	2.76	8.76	2.57	5910	228
3.28	2.57	8.25	2.57	5124	212
6.14	1.61	5.17	2.49	2011	131
6.89	1.45	4.73	2.47	1596	117
8.25	1.19	3.89	2.41	1099	95.2
9.55	0.977	3.38	2.37	740.5	77.0

Table 1. The FWHM in the horizontal and vertical directions, the total power emitted and the peak power density for several undulator gap settings.

Table 1 shows that the horizontal beam size depends strongly on the fundamental energy. For the range of gap settings shown, it is proportional to the deflection parameter k. Because the electron orbit is only affected in the horizontal plane, the vertical FWHM only weakly varies with k. At a closed gap of 10.5 mm (k=2.57), over 5 kW of power will be emitted by the undulator! The peak power densities will range from 77 to 228 W/mm^2 , but in the pink beam operation mode it will typically not be above 131 W/mm^2. To compare the power density present in the first phase of operation of the APS with power densities we typically experience, the power density produced by a typical 1500 W hairdryer with a 4 cm diameter is $\phi = 1500W/(\pi 400mm^2) = 1.2$ W/mm^2, thus at closed gap the peak power density at the APS would be equivalent to a hairdryer with a similar diameter but an output power of nearly 0.3 MW! To properly simulate the spectral power absorbed by filters, we will use a large rectangular aperture of 20 mm horizontally by 10 mm vertically. This aperture passes about 98 % of the total power. To perform thermal calculation, we will also use the beam size parameters found in Table 1. Note that the total power shown in Table 1 are worst case scenarios, and would be reduced if a fixed mask was present before any optical elements A differential pump for example may reduce the transmitted power due to its small aperture.

Note that the size of the **vertical** footprint of the power density is also important for the operation of the double mirror filter. When the mirrors will be out of the beam, we should make sure that the first mirror is far enough away not to intercept a significant amount of power. This is particularly important during any **white beam mode operation** of the beamline. During monochromatic operation, the first mirror could also absorb large power densities because it is placed upstream of the monochromator tank. From Fig. 1 for example, 2 mm away from the central axis of the undulator in the vertical, the power density could still be as high as about 50 W/mm^2, a factor four smaller than the peak power density. Given the large horizontal footprint, several hundred watts could be absorbed if any material is hit by the full white beam.

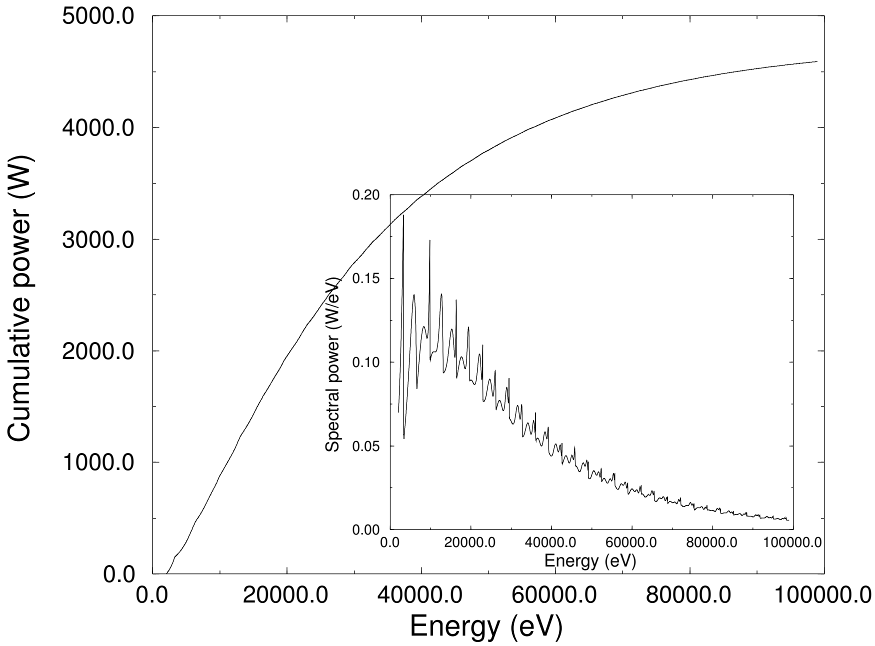

Figure 2. Cumulative power versus energy for a 3.3 keV undulator fundamental . (Inset) Spectral power. Both are calculated in a 20 mm by 10 mm aperture placed 27 m from the source.

Fig.2 shows the cumulative power and the spectral power for the worst case scenario one can encounter at the APS i.e. a closed gap. The spectral power shows the usual harmonics, the fundamental being set at 3.3 keV corresponding to a deflection parameter of 2.57. The integral of the spectral power with respect to energy is the cumulative power. The simulation here is performed using the program URGENT up to 99 keV, and the power generated by the undulator is relatively well distributed over this range starting to show signs of saturation toward the end of this range. Note that the first three harmonics in Fig. 2 subtend about 17 % of the total power emitted by the undulator. For larger gap settings, this fraction is typically larger.

After generating the raw spectrum, the beam is then filtered with the software package XOP and the absorbed and transmitted power are calculated. Looking at materials available in the GoodFellow catalog, thick graphite foils (> 1mm) are typically made of ***rigid graphite***, a form of graphite which can sustain high temperatures and is often used in heat exchanger. Given its high purity (99.95%), low density (ρ=1.8g/cm^3) and good thermal conductivity (κ = 150 WK^{-1}m^{-1}), we have decided to use rigid graphite from GoodFellow in the simulations below. Let us first get a ball park figure of the power absorbed in graphite filters for different gap settings

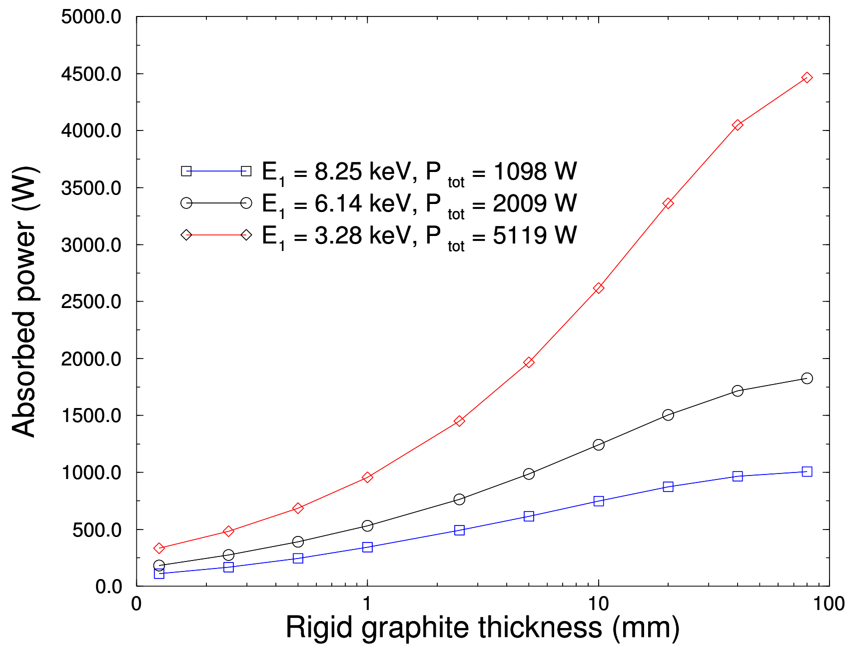

Figure 3. The absorbed power in various rigid graphite filter thicknesses for three undulator fundamental settings E_1. The total power emitted by the undulator is labelled P_{tot}.

Figure 3 shows the dependence of the absorbed power on the graphite filter thickness. The results for three deflection parameters k = 1.19 ,1.61 and 2.57 are shown, corresponding respectively to fundamentals at 8.25, 6.14 and 3.28 keV. The energy chosen represent the range of usable coherent flux for the double mirror operation (6.14-8.25 keV), and the closed gap position (3.28 keV). To compute the **worst case scenario** in term of power absorbed, no commissioning window is in the beamline before the filters. The total power absorbed is labelled in the plot legend as P_{tot}. For the 3.28 keV fundamental, 40 mm of graphite is required to absorb 4050/5119 = 79% of the source power. For the larger gap settings, 85 and 88 % of the power are absorbed with 40 mm of graphite for the 6.14 and 8.25 keV fundamentals respectively.

The maximum temperature reached by these filter can be estimated using rough approximations. For a Gaussian, the total power absorbed $P = 2\pi\phi\sigma_x\sigma_y$ where ϕ is the on-axis power density and σ_x is the horizontal rms beam size at a given distance. Using the results shown in Table 1 assuming that the power density profile is Gaussian, we can use σ=FWHM/2.355 to determine the rms beam size. For simplicity, if we assume that all this power is spread uniformly on a disc of area $A=2\pi\sigma_x\sigma_y$ then the radius of this disc is just $a = (2\sigma_x\sigma_y)^{1/2}$. For k = 2.57 in Table 1 $a = (2x8.2x2.6)^{1/2}/2.355$ mm = 2.8 mm. If we assume that our filters will also be discs of 1" diameter, cooled on their edges and kept at constant temperature on their outside rim, we can get a rough estimate of the maximum temperature reached at the center of the disc using the following simple relation $T = T_1 + P/(2\pi\kappa\Delta z)\{\ln(r_1/a) + 0.5\}$, where T_1 and r_1 are the temperature at the edge of the filter disc of radius r_1, and the power is absorbed uniformly within the foil thickness Δz. This assumption can be verified for different cases by estimating the X-ray absorption length at a given energy.

Figure 4 shows the absorption length for Cu, rigid graphite and the YAG crystal up to 99 keV. For rigid graphite, the assumption of uniform absorption in the foil thickness will be good for nearly all energies simulated here given that its absorption length is larger than 2 mm above 10 keV. For the YAG and Cu foils, X-rays below 10 keV will be absorbed close to the surface since the penetration depth is below 55 μm. Given that the YAG is 0.5 mm thick, the energy absorbed will become more uniform above the Yttrium K edge near 20 keV, and above 42 keV, the penetration depth is larger than the YAG thickness. Similar arguments can be used with Cu foils.

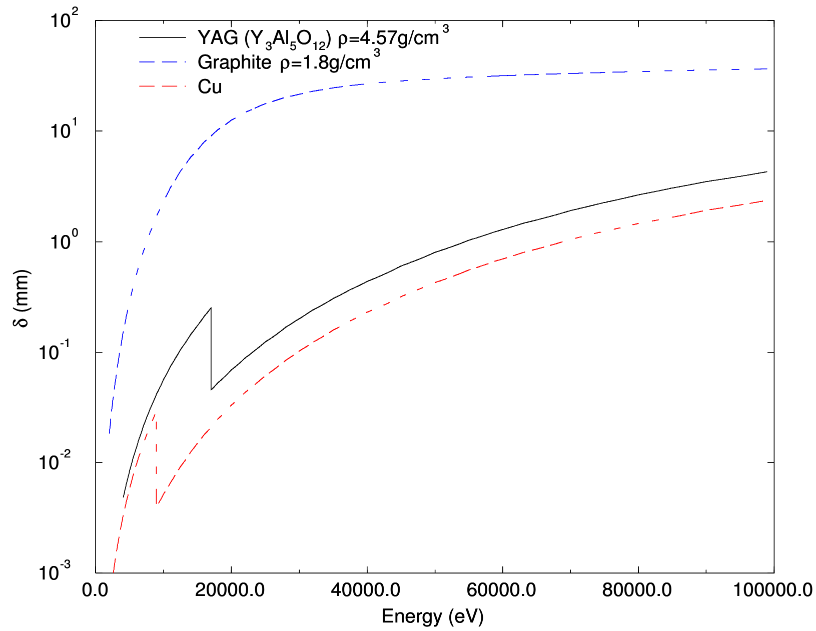

Figure 4. Absorption length of a YAG single crystal, rigid graphite and Cu versus energy.

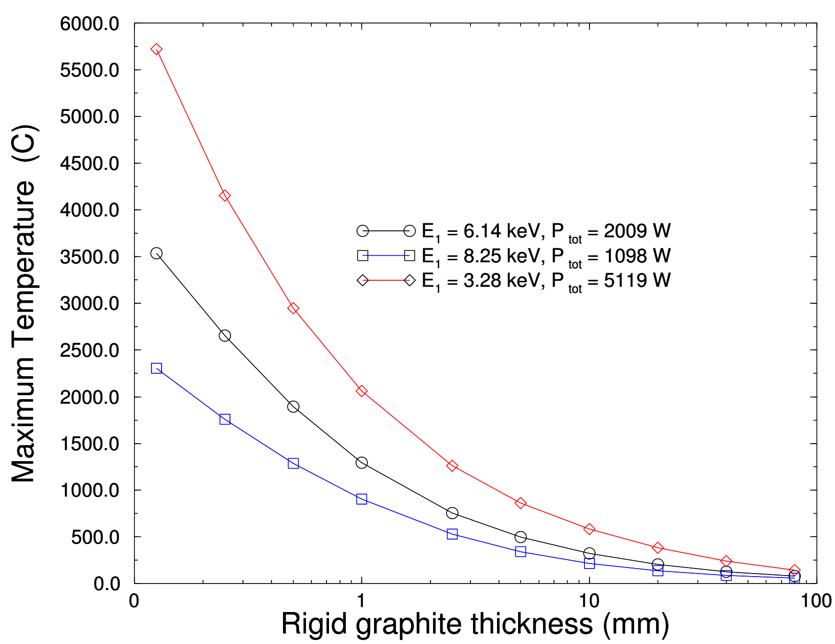

Figure 5. Calculated maximum temperature for carbon filters of various thicknesses.

Figure 5 shows the calculated maximum temperature from the data generated previously in Fig. 3, using the room temperature thermal conductivity of graphite $\kappa = 0.15$ W/mm/K. Note that we ought to be very careful in selecting filters to place in the beam. For rigid carbon available at GoodFellow, the temperature rise can be substantial for thin specimen because of the $1/\Delta z$ dependence of the maximum temperature and the fact that thin specimens can absorb still tens of Watts, especially at closed undulator gap settings. The results for thin foils of graphite are overestimates of the actual temperature rise because we have neglected any radiative cooling which is increasingly important for large temperature since it scales like T^4. As the foil thickness is reduced, one can show that the absorbed power P becomes proportional to $\Delta z/\delta$, the ratio of the foil thickness over the X-ray absorption length. For very thin foils, the thermal rise predicted by thermal conduction will saturate and radiation becomes an effective heat loss mechanism.

Wang and Kuzay recently introduced the idea of the critical thickness of a thin filter for which the temperature reaches a maximum (Proceedings of the SRI 96, RSI 67 (9) 1996). For thicknesses above the critical thickness, conduction dominates, while for thicknesses below it, radiation is the dominant heat transfer mechanism. In their more detailed simulations including conduction and radiation heat transfer, they found that a temperature of about 2500 K can be reached for a thickness of **pyrolytic graphite** of about 100 μm when the deflection parameter is 2.78. In a vacuum, it is recommended to keep graphite below 2000 C to prevent sublimation. In an earlier MHATT-CAT internal report (Gene Ice, "White Beam Filters", December 96) Gene Ice suggested a range of thickness from 10 μm to 4 mm of *diamond* for a MHATT-CAT *general purpose filter*, but from purely thermal reasons, one should be very careful to avoid filter thicknesses near the critical thickness of diamond which would have to be calculated carefully. Another important point made by Wang and Kuzay is that thin foils sustaining large thermal gradients may buckle under the thermal stress. This can yield to a failure of the filter as well.

Fortunately, we want to use a *thick* graphite filter to take most of the power from to beam, so that a higher Z filter can sustain the power density afterwards. A graphite filter of 10 mm has a maximum temperature of about 583 C when the fundamental is tuned at 3.28 keV. Given that it is the thickest graphite foil available from GoodFellow, this represents the highest temperature a single foil will reach for the current APS parameters. This temperature could be reduced if a fixed mask is present in the beamline.

We probably will need 40 mm of graphite to really reduce the power density on the YAG and the temperature rise on the Cu foil. If we follow four 10 mm graphite foil with a Cu filter, what is the minimum thickness of the Cu foil required to prevent its melting if say (100-79)%x5119W $\approx$ 1075 W are absorbed in it? Given that the melting point of Cu is at 1083 C, and using its thermal conductivity of 0.4 $Wmm^{-1}K^{-1}$ and a ratio $r_1/a = 12.5/2.8$, we find a minimum thickness of $P/(2\pi\kappa\Delta T)\{\ln(r_1/a) + 0.5\} \approx 0.8$ mm. To prevent melting of the Cu foil, its minimum thickness should be set much higher than 0.8 mm in case one needs to observe the white beam for a fundamental at 3.28 keV. The minimum thicknesses of Cu foils for 6.14 and 8.25 keV fundamental are respectively 0.25 mm and 0.12 mm, thus if the gap was never fully closed, thinner foils could be used.

Cu thickness Δz (mm)	Absorbed power in Cu (W)	ΔTmax of Cu foil (C)	Absorbed peak power density in YAG (mW/100μm2)	Visible light intensity on CCD (Lux)	Total absorbed power in YAG (W)	ΔT max of the YAG (C)	Average absorbed Energy (keV)
0.5	112.1	201	12.3	5.4e4	9.75	500	55.8
1.0	126.6	114	5.0	2.4e4	3.53	181	63.5
2.0	134.9	60.5	1.5	7.2e3	0.954	49.0	72.2
4.0	138.4	31.1	2.83e-1	1.4e3	0.164	8.40	80.9
8.0	139.3	15.6	2.3e-2	1.1e2	1.23e-2	0.629	87.4
16.0	139.4	7.82	3.6e-4	1.7	1.78e-4	9.14e-3	92.7

Table 2. A 40 mm graphite foil is placed before a Cu foil for $E_1 = 6.14$ keV.

Table 2 shows the results for a 6.14 keV fundamental, filtered by a 40 mm graphite foil and some Cu foil. This energy is chosen because it corresponds to the lower limit of operability of the double mirror filter, but also it is the worst case scenario in terms of power levels during pink beam operation. The maximum temperature of the Cu foil decreases as expected with the increasing foil thickness.   Although the Cu temperature rise is modest for this gap setting, the temperature rise is larger at closed gap. A question we should address by the way is where will all the power absorbed in the Cu and graphite filters go by the way? If by mistake, one was to close the gap down to 10.5 mm, the filter assembly would certainly get quite hot given it would have to absorb about a 5 kW of power. Are the filter holder water cooled? If the filter holder are not water cooled, than the thermal gradients will be much larger than calculated because the equations assume cooling at constant temperature on the edges. Also, an excellent thermal coupling between the filter and the mount is essential to keep the temperature rises to levels predicted in Table 2.

The peak power density absorbed in the YAG was calculated using a simulation with a square aperture of $(100\mu m)^2$. The 0.5 mm thick YAG ($Y_3Al_5O_{12}$) crystal has a density of 4.57 g/cm^3. To keep the absorbed power density on the YAG below its critical value, we should use at least 4 mm of Cu if we were to choose a 40 mm graphite filter. Note that the total power absorbed in the YAG is on the order of the product $P_c = 2\pi\phi\sigma_x\sigma_y$. For example, for Δz = 4mm, $2\pi\{0.283 mW/(0.1mm)^2\}$x5.17-mmx2.49mm/$2.355^2 \approx 0.412$ W. The total power in Table 2 is 0.164 W, which is a factor 2.5 smaller than P_c. The discrepancy probably reflects the fact that the power density profile is not quite Gaussian and that the transmitted power density profile may be modified due to the energy dependence of the absorption in the filter material and the complex spectral energy distribution.

Fig. 6 shows the effect of the various filters on the spectral power of the source using a 5 mm by 2 mm aperture at 27 m. No X-rays at the fundamental energy remains after transmission through 40 mm of graphite and 4 mm of Cu. The absorbed X-rays in the YAG are very hard X-rays. For a 4 mm Cu foil, the average energy of the X-ray absorbed by the YAG will be greater than 80 keV. The quantitative values of the average energy in Table 2 are most likely biased to lower energies for $\Delta z \geq$ 8 mm because the URGENT calculation is done up to 99 keV.

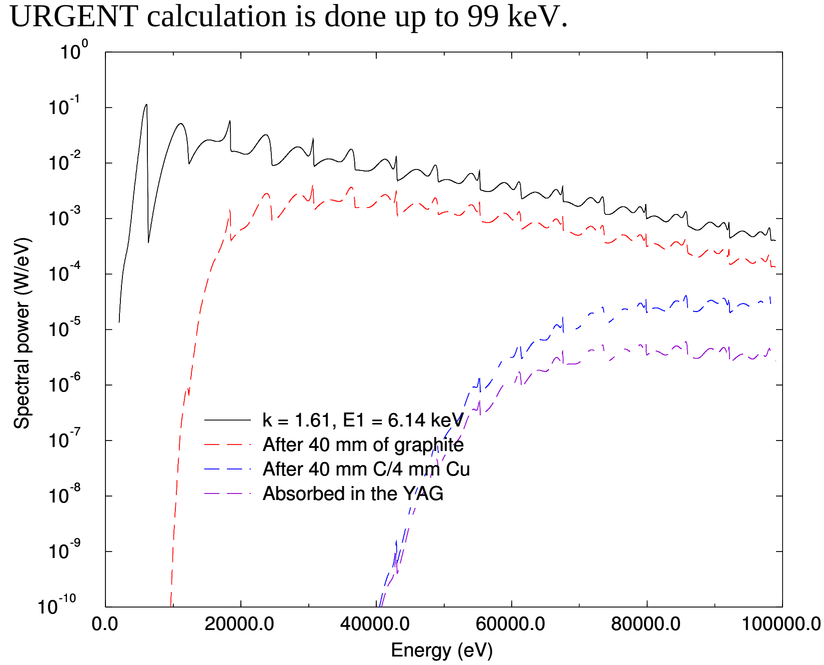

Figure 6. Spectral power versus energy for E1 = 6.14 keV. The spectrum is shown after transmission through 40 mm graphite, then an additional 4 mm of Cu. The absorbed power in the YAG is also shown.

Table 2 also shows the expected light intensity observed in the detector plane of our imaging optics. The YAG crystal emits about 8 visible photons each at 2.25 eV per 1000 eV of X-ray photon, thus the visible power emitted is 8x2.25/1000 = 0.018 time the X-ray power absorbed, i.e. about 2%. We plan to use a light collection system with a numerical aperture of f/# = 4, thus for a lens of diameter 2R, if R >> f then the collection efficiency will be about $\pi R^2/4\pi f^2 = 1/[16(f/\#)^2] = 3.9\times10^{-3}$. Given that 1 lux is 1/683 W/m^2, we find that $I_{visible} = 3.9\times10^{-3} \times 0.018 \times (1m/0.1mm)^2 \times 683$ Lux/(W/m^2) $P_{xray} = 4.8\times10^6\ P_{xray}$, where P_{xray} is the power absorbed per (0.1mm)^2.

If we assume that the power density profile transmitted by the filters is also Gaussian with FWHM identical to those found in Table 1, we can use the peak power densities absorbed in the YAG in Table 2 to estimate the thermal gradient that the crystal will sustain when hit by the full beam or an apertured beam. The absorbed power will be $P = 2\pi\phi\sigma_x\sigma_y$. Given that the power will be absorbed uniformly within the YAG because the average absorbed energy is above 50 keV, we can use the equation derived earlier for other filters. Table 2 shows the peak temperature reached by the YAG using its known thermal conductivity κ = 0.014W/(mmK). A 4 mm thick Cu foil would be sufficient to prevent any large thermal gradients in both the Cu foils and the YAG screen, resulting in a thermal rise of the YAG screen of only 8.4 K. Given the known thermal expansion coefficient of the YAG (8×10^{-5}/K), the lattice would only expand by 0.07 %. An intensity of over a thousand lux is predicted for a 4 mm Cu foil, thus even a CCD with a relatively poor sensitivity would be sufficient.

2) Alignment of the first mirror: .

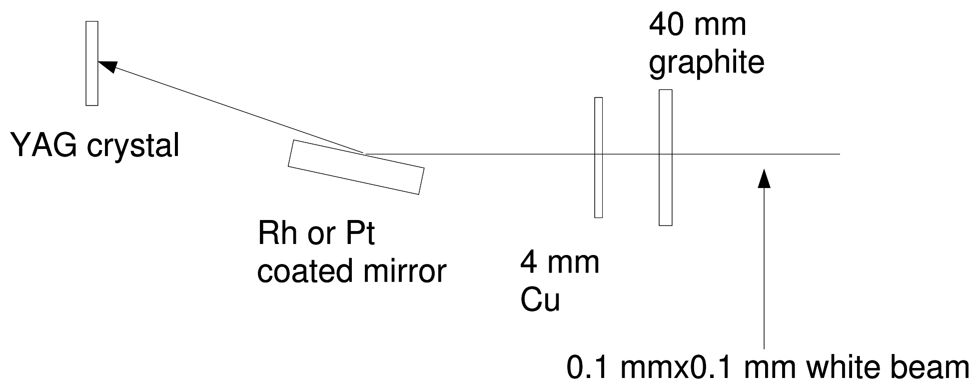

Fig 7. Alignment of the first mirror.

Once we have set our slits to say 0.1 mm x 0.1 mm, we will bring in the first mirror to bisect the beam and observe the reflected beam on the YAG screen. Fig. 7 shows the set up for the alignment of the first mirror. Once the beam size has been reduced by the slits, the thermal gradient on the YAG will be negligible since the one given in Table 2 is for the full beam.

Figure 8 shows the visible light intensity on the CCD predicted when a 6.14 keV white beam is filtered by 40 mm of rigid graphite, 4 mm of Cu, and a Rh coated mirror set at various angles of incidence. With 4 mm of Cu, we would observe 1360 lux for the direct beam, 850 lux at 0.8 mrad, 15 lux at 1.6 mrad. The angle of incidence where the intensity drops by a factor two from the direct beam is 0.83 mrad for the 4 mm thick Cu foil and Rh mirror. For a 8.25 keV fundamental, filtered by 40 mm of graphite and 3 mm of Cu, the angle where the CCD drops by a factor two is 1.1 mrad. The incident beam will be fully reflected at angles above 0.1mm/50mm = 2 mrad, but the intensities given in Fig.8 are unaffected by this sliting effect provided that the beam remains wider that one pixel element of the CCD.

For a 0.2 m (8 ") spacing between the YAG and the mirror, the spacing between the direct beam and the singly reflected beam would be 400 μm/mrad. An inexpensive CCD with a sensitivity of 0.5 lux would be able to observe the singly reflected beam up to 3.2 mrad with for the Rh mirror alignment, and up to 3.9 mrad mrad for the Pt mirror case. A CCD with a viewing area of 5 mm would be plenty for the first screen. Our angular resolution is limited by the CCD and imaging optics resolution. Neglecting the imaging optics resolution, a 0.1 mrad angle of reflection will cause a 40 μm offset between the direct and singly reflected beam on the CCD but the reflected beam would be only a 0.1mm wide by 5 μm high. Given the large reflected signal near grazing incidence, there should be sufficient signal to see this 1 pixel high reflection. Given the size of the incident beam though, this reflection would overlap near the edge of the direct beam if we assume that the mirror bisect the direct beam. Therefore the best resolution we can hope for will be slightly above 0.1 mrad. At X13, we typically aligned the zero of the mirrors to within 0.1 mrad.

Once the mirror angle is properly zeroed, we will be able to steer the singly reflected beam onto the mirror in the second tank by setting the mirror angle to 8.75 mrad using the angular feedback from the Applied Geomechanics tilt sensors, with a vertical spatial resolution in the second tank of 2x0.1mradx2m = 0.4 mm. This vertical resolution is slightly smaller that the vertical acceptance of the 50 mm long mirror at 8.75 mrad, so we will have to try to zero the first mirror angle of incidence to better than 0.1 mrad to ensure that the full beam is accepted on the second mirror. If we have problems with accepting the full beam, we can always zero the first mirror using the second YAG crystal screen. Then the long distance of 2 m will ensure more than adequate resolution. The proposed set up should have sufficient resolution and sensitivity to line up the mirror as we did in the past at the NSLS, but care will be needed to zero the angle of incidence of the first mirror.

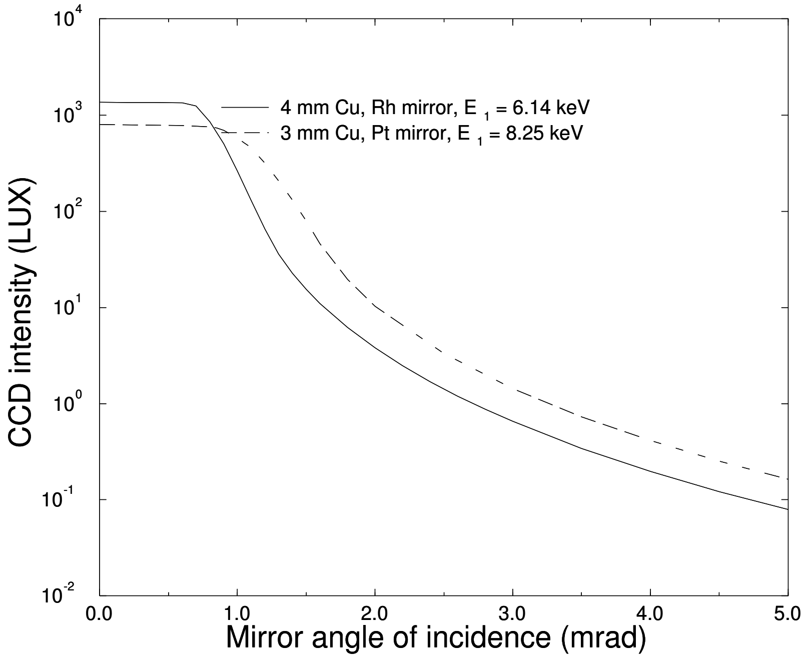

Fig. 8. The detected visible light intensity versus the Rh or Pt mirror angle of incidence. A 6.14 keV fundamental is filtered here by 40 mm of graphite and a Cu foil(solid), **or** a 8.25 keV fundamental is filtered by graphite and Cu and reflected by the Pt mirror (dashed). The YAG emits visible light that is imaged by an optical system with a numerical aperture f/#=4.

3) Alignment of the second mirror.

Finally, let us investigate which filter thicknesses one should use to align the second mirror, once the first mirror has been set to 8.75 mrad. In the April report on the double mirror filter, we were suggesting to use either thin Cu foils or graphite. In case the upstream slits were inadvertently opened it is probably better to use graphite because it would not absorb nearly as much heat and has a much higher melting point. So the discussion below will focus on selecting the appropriate rigid graphite thickness required to filter a white beam beam singly reflected by a Pt or Rh mirror.

Foil thickness (mm)	Absorbed power in the mirror (W)	Absorbed power in the YAG (mW)	Intensity on CCD (lux)	ΔT (YAG) (K)	<E> (eV)
0	1.04	149	7.2e5	47.1	6141
0.25	0.994	91.6	4.4e5	28.9	6252
0.5	0.960	56.8	2.7e5	17.9	6401
1.0	0.908	22.9	1.1e5	7.2	6909
2.0	0.833	5.17	2.5e4	1.6	9191
4.0	0.722	1.46	7.0e3	0.46	13440

Table 3. The power absorbed in the Rh mirror and the YAG, the visible light collected by the CCD, the largest temperature difference in the YAG, and the average energy absorbed in the YAG for several thicknesses of rigid graphite.

Table 3 shows the absorbed power in the first mirror as a function of the thickness of a rigid graphite filter for a 6.14 keV fundamental and an angle of incidence of 8.75 mrad on the Rh mirror. The absorbed power in the Rh coated mirror decreases with increasing graphite thickness. As discussed earlier in the April 97 report on the mirror filters, the absorbed power density in the first mirror is small and would not cause any large thermal gradients because the beam is spread over the mirror surface due to the grazing angle of incidence. For the simulation here, the white beam is 0.1mm high by 0.1 mm wide, thus the beam footprint will be 0.1mm/8.75mrad = 11.4 mm. This asymmetric footprint reduces the absorbed power density on the mirror to about 0.9 W/mm^2.

Foil thickness (mm)	Absorbed power in mirror (W)	Absorbed power in YAG (mW)	Intensity on CCD (lux)	ΔT (YAG) (K)	<E> (eV)
0	0.645	203	9.7e5	64	7989
1	0.561	88.4	4.2e5	27.9	8253
2	0.505	39.6	1.9e5	12.5	8524
3	0.463	18.4	8.8e4	5.8	8985
4	0.429	9.02	4.3e4	2.8	9741

Table 4. Same data as in Table 3 for a Pt mirror set at 8.75 mrad reflecting a 8.25 keV fundamental.

The average energy of the X-ray absorbed by the YAG increases with the increasing foil thickness. The average energy lies mostly between the fundamental at 6.14 keV and the second harmonic. As the foil thickness increases the spectrum becomes dominated by the second and third harmonics. From the data in Fig. 4, most of the X-rays will be absorbed on the surface of the YAG thus we can estimate the thermal rise on the center of the YAG by $\Delta T = P \ln(4a/b)/(\pi a \kappa)$, where P is the power absorbed in the YAG which scales as the beam cross section ($P \propto ab$), and a > b. This relation assumes that a semi-infinite solid kept at a constant temperature absorbs heat on its surface only. Here we use, a = b = 0.1mm and κ=0.014 W/(mmK). The thermal rise of the YAG in Table 4 is slightly higher for a constant thickness of graphite than the rise found in Table 3. This is caused by the increase penetration power of the 8.25 keV fundamental over the 6.14 keV one. We plan to use a range of foils between 2-4 mm for the low and high energy settings of the double mirror filter, thus the thermal rise on the YAG should be on the order of a few K and the thermal expansion on the order of 0.01%. The intensity on the CCD would also be large for this foil thickness.

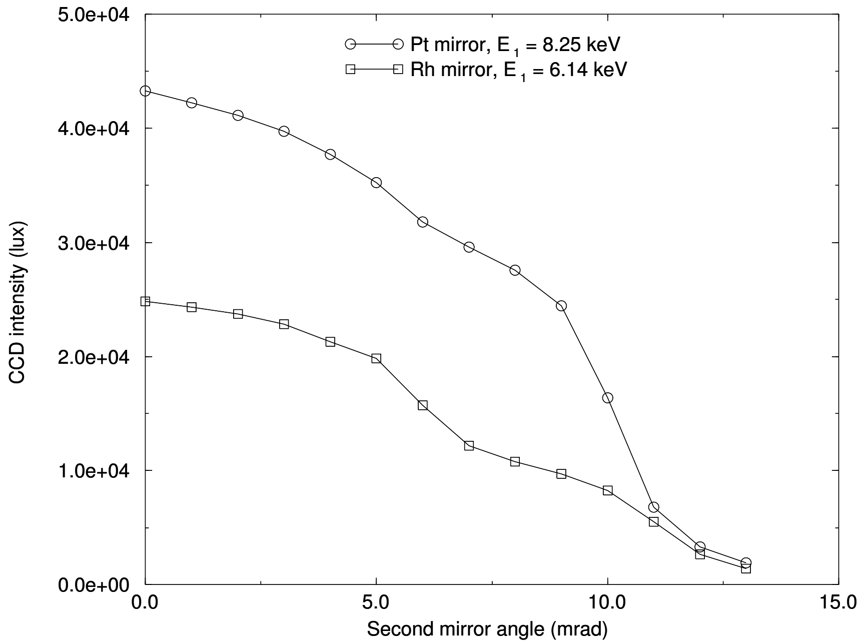

Figure 9. The predicted light intensity on the CCD versus second mirror angle. 4 mm and 2 mm of rigid graphite are used to filter the white beam for the Pt (circles) and Rh (squares) coatings respectively.

Fig. 9 shows the calculated intensity on the CCD versus the second mirror angle when the first mirror is set at 8.75 mrad. The predicted intensity is several orders of magnitude above the detection limit of an inexpensive camera for the Pt and Rh settings shown over an angular range of 13 mrad. The second mirror should be easier to zero than the first mirror because of this extended range of sensitivity.

4) Conclusion:

To align the upstream slits and observe the unapertured white beam using a YAG scintillation screen, we will filter down the power density incoming on the YAG with 40 mm of graphite and 4 mm of Cu. The graphite we intend to purchase is in stock at Goodfellow and is sold in a maximum thickness of 10 mm (Stock C 000360, 216$/10 pieces of 25mmx25mm), thus if we buy 10 foils, we can place a filter combination of 10, 20, 30, 40 mm in one of the filter holder part of the P4 filter assembly. One filter mount may not be able to handle a 40 mm thick foil. If this is the case, the foils will be distributed on several filter paddles to reach the 40 mm thickness. The 10 mm foil would not melt and could sustain the full white beam at the smallest gap available. Before purchasing the filters though, we plan to correctly model the thermal load on a 10 mm rigid graphite with a commercial finite element analysis program (ANSYS) taking into consideration the change of density of graphite and the change of the thermal conductivity with temperature and we plan to include the exact three dimensional absorbed power density profile. It is entirely possible that the above recommendation will change if we find that any of the ANSYS calculations are substantially different from the values derived in section 1.

We plan to purchase Cu foils and place a 2, 3, 4, 5 mm Cu foils in the second filter holder, **placed downstream** of the graphite filters. They are placed downstream because they cannot sustain the full unfiltered white undulator beam at closed gap without melting. They should **never** be used without the graphite filters before them. We plan to buy 10 pieces of 1 mm thick Cu foils from Goodfellow (CU000749, 20/259$, 99.99+% purity, as rolled, 25mmx25mm). The 1 mm thick foil should be able to handle the graphite-filtered beam without melting even at closed gap. We plan to perform a finite element analysis for the Cu foil as well.

Finally, to align the second mirror once the first mirror is aligned and set at its correct angle of incidence, we propose to install rigid graphite filters with 1, 2, 3, 4 mm thick foils. The Cu foils and most of the rigid graphite thicknesses can be reduced in this case because the slits have then been well calibrated and are closed to about 0.1 mm by 0.1 mm, reducing the maximum total transmitted power to about 2 W. Again, we propose to purchase 10 pieces of rigid graphite from Goodfellow, each 1mm thick (C 000430, 178$/10, 25 mmx25 mm). The 1 mm foil could sustain the full white beam at closed gap without melting as seen from Fig. 5, but without a careful calculation with ANSYS, these foils should only be used when the upstream slits are set to their design opening.

Appendix

The calculation we have performed above can also be extended to a related problem. Recently members from other CATs have suggested that a standard Be window may be able to withstand the power of the unapertured white beam provided that the window is placed far enough from the undulator. How far should this distance be is not clear at this point. To get an estimate of the appropriate distance where the window can survive the power densities with a closed undulator gap, we have performed a simple thermal analysis.

d (m)	FWHM x	FWHMy	Peak power density (W/mm2)	Ptot (W)	Absorbed power in window (W)	Tmax (C)
15	4.52	1.4	686.6	4679	312	4999
20	6.07	1.91	386.2	4674	308	4156
25	7.59	2.37	240.4	4690	319	3716
33	10.04	3.11	137.9	4586	253	2368
41	12.46	3.86	91.9	4602	263	1987
49	14.79	4.62	64.3	4293	228	1391

Table 5. Thermal analysis of a 10 mils Be window at closed gap.

Table 5 shows the results of this analysis as a function of the distance d from the undulator. The fundamental here is set at 3.28 keV. As expected, the FWHM of the power density profile increase linearly with the distance d. Similarly the peak power density scales as $1/d^2$. P_{tot} is the total power accepted in a 20 mm by 10 mm or in a 30 mm by 12.5 mm aperture. Given that the Be window does not aperture the beam horizontally, we extended the horizontal size for the simulation at 41 and 49 m because the beam is so wide there as seen from its horizontal beam size. The absorbed power in a 254 μm thick Be window is also shown. It varies weakly with d, although the peak absorbed power density will be greatly reduced with distance. The maximum temperature Tmax is calculated assuming the power is uniformly distributed in a circle of radius $a = (2\ \mathrm{FWHMx}\ \mathrm{FWHMy})^{1/2}/2.355$ and the cooling radius is chosen as $r_1 = 6.25$ mm, half of the Be window vertical opening. The melting point of Be is 1278 C. To make a conservative estimate, we use the thermal conductivity of Be at its melting point, $\kappa = 0.0751$ W/(mmK), which is a factor 2.7 less than at room temperature.

The smallest peak power density absorbed in Be are approximately 64.3 W/mm^2*(228/4293) = 3.4 W/mm^2. The radiative power density loss at the melting point of Be is $\phi = 5.67 \times 10^{-14}$ W/(mm^{2}K^4) (1278+273K)^4 = 0.33 W/mm^2, thus the smallest absorbed power density present at 49 m would still be much larger than the radiative losses at the melting temperature. For simplicity, we have assumed that the emissivity of Be is unity, but it actually varies from 0.4-0.9 in the temperature range between room temperature and the melting point. The Be window would melt at all distances shown here because the peak absorbed power densities in the Be are much larger than the radiated peak power densities. It is possible that the results at 41 and 49 m are overestimated because we have underestimated the average thermal conductivity of the foil.

The calculation above makes some simplistic assumption, i.e. a uniform thermal conductivity a uniform circular beam and neglects the three dimensional thermal loads in the foil. If one were to aperture the beam by the commissioning window or by a differential pump, these calculation would have to be redone, and the above conclusion would likely change. We plan to perform these calculations again with a finite element analysis program including the proper cooling geometry, beam asymmetry, temperature dependent density, thermal conductivity and emissivity.