Study of Synchrotron Radiation for the Electron Beam Polarimeter for the MEIC

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Introduction

This is a look at the synchrotron radiation coming from the chicane in the electron beam line for the MEIC design. The power density on the beam pipe as well as transmission through the beam pipe is studied. The optics design is version 12.

Layout

The chicane section of the electron beam is located 13-34 m downstream of the Interaction Point (IP). The chicane consists of 8 dipole magnets and displaces the beam 290 cm in x at the center. The dipole magnets are 1.5 m long. Fig. 1 shows the magnet layout and beam line trajectory. The four central magnets are shown. The window for the polarimeter would be located downstream of the 6th magnet in the chicane (the last of the 4 magnets in the middle of the chicane (see fig. 1). The photons that Compton scatter off of the electrons would be boosted forward and exit the beam pipe tangent to the peak of the chicane orbit. In addition, the electrons from the Compton scatter would be over bent by the 5th and 6th dipoles and be detected on the left side of the beam before the beam enters the last two bend magnets of the chicane.

Figure 1. Drawing of the chicane geometry. There are two synchrotron radiation fan segments of interest (#1 and #2). The last segment from the bend magnet before the laser interaction point and the first segment after the laser interaction point. Each fan segment is $\frac{1}{4}$ of the total magnet length.

The beam is traced through the chicane magnets with a program called MAGBENDS. This program traces only the ideal orbit of the beam (pencil beam) and calculates the bend synchrotron radiation for each bend magnet segment. The magnets are segmented into 64 slices inside the program and the slice information is summed and printed out into 4 segments for each 1.5 m magnet. For the 2 magnet segments of interest (the one just before the Compton IP and the one just after the Compton IP) we have the following table of information. As we can see in the table, the numbers for these two magnet segments are essentially equal.

Table 1. SR numbers for the two magnet segments closest to the Compton IP.

Beam parameters			E (GeV)	5.0			
			I (A)	3.0			
Magnet segment	SR pwr (W)	Bend angle (mrad)	Crit. energy (k_c) keV	Beam pipe W/mm perp.	Beam pipe W/mm sloped	Surface of perp. pipe hit (mm)	Surface of sloped pipe hit (mm)
Before (#1)	1761	5.007	3.7	176	4.4	10	400
After (#2)	1761	5.007	3.7	176	4.4	10	400
Det. SA	4396	12.5	3.7				
Beam parameters			E (GeV)	11.0			
			I (A)	0.18			
Before (#1)	2475	5.007	39.4	248	6.2	10	400
After (#2)	2475	5.007	39.4	248	6.2	10	400
Det. SA	6179	12.5	39.4				

Looking at the table, we find that the perpendicular SR power density is too high for a perpendicular beam pipe window unless more than 90% of the SR power goes through the window. The sloped surfaced beam pipe does have acceptable power densities (<10 W/mm) for essentially all beam pipe materials with good thermal conductivity. Some exceptions would be Stainless Steel or perhaps Tantalum. The sloped surface is obviously unfavorable since the Compton photons will travel through more beam pipe material before being detected. We next consider various possibilities of beam pipe materials and thicknesses.

Beam pipe modeling

We use a program called MASKING which is an EGS4 interface program that utilizes a simple slab geometry. A beam pipe can be modeled as a series of slabs of different materials with an arbitrary angle of incidence for the incoming photons. The program has the option of tallying the number of incident photons that either reflect from the surface, pass through the slabs or are absorbed by the materials in the slabs. The slabs can be several metals and gases as well as water. Several slabs can be defined for the

same run allowing for multi-layered surfaces. In EGS4, the photon direction is defined by 3 direction cosines (U, V, W). The U, V and W axes form a right-handed system with the U direction cosine along the X axis, the V direction cosine along the Y axis and the W direction cosine along the Z axis. The W direction is defined as perpendicular to and into the slab geometry. The U and V directions are then parallel to the slab surface and define a plane (the UV plane, on surface of the initial face of the slab geometry).

Aluminum Beam pipe

The first and simplest beam pipe to consider is one that has a sloped water-cooled Al wall. We will use a wall with a 3 mm ($\sim 1/8''$) thickness. The wall is sloped making the angle of incidence for the SR photons 25 mrad. This angle of incidence is modeled by assigning the U direction cosine the value of $\cos(25 \text{ mrad}) = 0.99968752$, the V direction cosine equal to 0.0 and the W direction cosine to be $\sin(25 \text{ mrad}) = 0.0249974$. This small grazing angle makes an effective wall thickness of 120 mm ($3 \text{ mm} / 0.025$) which is 1.35 of a Radiation Length (R.L.). This may be too much material for the Compton photons. The wall slope can be steepened a bit but I consider 20 W/mm an upper limit and at this power density the only material that can take this high power level is dispersion strengthened copper (GlidCop). The high density of Cu makes this material undesirable as a photon window. So, leaving the slope of the beam pipe at 25 mrad we can consider Be as another possible window material. If the Be is 1 mm thick and assuming the wall is water cooled with 2 mm of water followed by another sheet of 1 mm Be to enclose the water then we have (Be which has a R.L. = 35.28 cm and H₂O with a R.L. = 36.08 cm) and with an effective thickness of 160 mm of material because of the 25 mrad angle of incidence we get a total R. L. of about 45%. This looks more reasonable but now there is the question of how many SR photons (X-rays) get through this window. The following is the result of simulation runs using the photon spectrum from the bend magnets as input to the MASKING program which then gives us the photon spectrum of the X-rays that pass through the beam pipe.

A beam pipe with 2 mm of Be and 2 mm of Water

For the first case shown below in Figs 2 and 3, we have a 1 mm Be beam pipe window cooled with a 2 mm layer of water and followed by another 1 mm of Be to contain the water. The photon beam strikes the Be surface at a 25 mrad grazing angle. The photon generator has a minimum energy of 1 keV. For a 3.697 keV critical energy (see Table 1) photon spectrum this corresponds to 30% of the total number of photons in the entire spectrum and 87% of the total energy. We see in Fig. 3 that the lowest energy photon to pass through the beam pipe is greater than 5 keV therefore we conclude that the low-energy photons not included in the generator are all absorbed in the beam pipe. Dividing the number of photons in Figure 3 by the number in Figure 2 we find that 0.37% of the generated photons go through the beam pipe. Tallying up the total energy of the photons in Fig 3 and dividing by the total energy of the photons in Figure 2 and accounting for the fraction of the total energy the generator produces we find that 98.57% of the incident photon energy is absorbed by the beam pipe. The rest, (1.43%) goes through the pipe and some fraction of this power is incident on the Compton photon detector.

Figures 2 and 3. Figure 2 (left) is a plot of the incident photon energy spectrum for the 5 GeV electron beam energy case. The critical energy for this spectrum is 3.697 keV and the photon generation starts at 1 keV. Figure 3 (right) is a plot of the energy spectrum of the photons that pass through the water-cooled Be window.

In order to determine approximately how many of the X-rays passing through the beam pipe are incident on the Compton detector we need to estimate the solid angle of the detector from the beam pipe location. The beam pipe actually is located from a range of 2 m away from the detector to only 1 m away at the close end (see Fig 1). We will assume the solid angle acceptance for all photons that pass through the beam pipe to be the same as the ones that pass through at the closest end, namely 1 m away. Assuming the size of the photon detector is 5 cm, then the angle of acceptance from the beam pipe is 50 mm divided by 1 m or 50 mrad. This means that the maximum value for the V direction cosine should be no more than ± 0.025 which is $\sim \sin(0.025)$ and the W direction cosine should be no smaller than 0.0 and no larger than +0.050 (also $\sim \sin(0.050)$). Then the U direction cosine will be close to 1.0 (Remember that $U^2 + V^2 + W^2 = 1$). Figs. 4-6 are plots of the direction cosine distributions for the photons that pass through the beam pipe with no angular cuts. We immediately see that these distributions are quite large and span essentially all of the available space. This means that if we select on the detector solid angle as described above we will end up with a small fraction of the total number of photons that pass through the beam pipe. Figs 7-9 show the U, V and W direction cosine distributions with the above solid angle cuts for the detector applied.

Figures 4-6. Plots of the direction cosine distributions for the X-rays that pass through the beam pipe.

Figures 7-9. Direction cosine plots after the angular selection described in the text is applied for photons that are in the solid angle acceptance of the Compton photon detector.

The reduction factor due to solid angle acceptance is 3.46×10^{-4} for the 5 GeV case. In order to try to further reduce the number of X-ray photons that pass through the beam pipe and yet maintain as low a radiation length as possible we introduce a thin Au layer on the inside of the beam pipe window. Fig. 10 shows the resultant spectrum of photons that pass through the same beam pipe as in the first case but with an additional layer of 10 μm of Au on the inside. A 10 μm layer of Au at a 25 mrad angle introduces an additional 12% of a R.L. to the beam pipe ($10/0.025=400 \mu\text{m}$ of Au).

Again, dividing the number of photons in Fig. 4 by the number of photons in Fig 2, we get 1.20×10^{-5} (0.0012%) of the incident photons passing through the beam pipe. The total energy of the photons passing through the beam pipe is now 5.82×10^{-5} (0.0058%) of the incident energy. The photon energy spectrum is harder (higher average) for the photons that pass through the beam pipe. Table 2 summarizes these results as well as results from a similar study for the 11 GeV beam. As one can see from the table, the attenuation of the 11 GeV synchrotron photons is much less. This is an important issue and we will return to this below.

Table 2. Summary of penetration factors for various beam pipe designs and for the 5 GeV and 11 GeV electron beam energies.

Beam pipe options	1 mm Be, 2 mm H ₂ O, 1 mm Be		10 μm Au, 1 mm Be, 2 mm H ₂ O, 1 mm Be		25 μm Au, 1 mm Be, 2 mm H ₂ O, 1 mm Be	
5 GeV e- beam 25 mrad inc. angle 4.830×10^{13} γ s/bun. inc. 5.498×10^{13} keV/bun. inc.		Fraction with solid ang. cut applied (3.46×10^{-4})		Fraction with solid ang. cut applied (3.46×10^{-4})		
Frac. of inc. γ s through bp	0.003715	1.285×10^{-6}	1.184×10^{-5}	4.097×10^{-9}		
Frac. of inc. enr. through bp	0.01626	5.626×10^{-6}	5.764×10^{-5}	1.994×10^{-8}		
11 GeV e- beam 25 mrad inc. angle 6.371×10^{12} γ s/bun. inc. 7.729×10^{13} keV/bun. inc.				Fraction with solid ang. cut applied (2.103×10^{-2})		Fraction with solid ang. cut applied (2.254×10^{-3})
Frac. of inc. γ s through bp			0.0103	2.166×10^{-4}	4.467×10^{-3}	1.007×10^{-5}
Frac. of inc. enr. through bp			0.0267	5.615×10^{-4}	0.0116	2.615×10^{-5}

Figure 10. Plot of the transmitted photons for a beam pipe consisting of 10 μm Au, 2 mm of Be and 2 mm of water. We get a reduction factor of over 300 compared to the beam pipe without the Au layer.

SR photons at the Compton photon detector

The next question is how many X-ray photons are there that would strike a photon detector for the Compton photons? We need to know where and how large the detector might be. Continuing with the assumption above concerning detector size (5 cm in diameter) and putting the detector 4 meters away from the source point then the detector intercepts 12.5 mrad of angle. The two fans in Table 1 are each 5 mrad. So the angle of acceptance for the photon calorimeter corresponds to 4.396 kW of X-ray power for the 5 GeV beam. The total photon energy per electron bunch incident on the beam pipe can be calculated from this power by the following conversion:

$$E_{tot}(keV) = P(W) \times 6.24151 \times 10^{15}(keV/J)/(bunch\ freq.)$$

$$N_\gamma = \frac{E_{tot}}{0.3079 k_c}$$

For the MEIC the bunch frequency is 499 kHz which gives us 5.498×10^{13} keV per electron bunch. This energy corresponds to 4.830×10^{13} photons incident on the beam pipe for our 3.697 keV critical energy case from the 5 GeV electron beam. Looking at the 10 μm Au case above, we get 5.76×10^{-5} of the incident energy going through the Au coated beam pipe which is 3.17×10^9 keV per bunch or 0.25 W. Using the average photon energy exiting the beam pipe of 16.6 keV we have 1.91×10^8 photons per bunch that pass through the beam pipe.

If we now include the solid angle reduction for the Compton photon detector we get 1.097×10^6 keV (1.097 GeV) incident on the Compton detector per electron bunch. Without the Au coating, the energy incident on the detector increases to 3.094×10^8 keV (309 GeV). The number of photons incident on the detector is 6.608×10^4 .

We want to further reduce the X-ray energy incident on the detector. One possibility is to place, just in front of the detector, an absorber that stops most of the rest of the X-rays while letting the Compton photons (gammas) get through without too much energy degradation. The X-ray power hitting such an absorber is negligible so there is no cooling issue. One suggestion is a layer of Cu of some thickness to further attenuate the X-rays. Below is the result of a series of runs using the through photon energy spectrum (Fig. 10) as the incident photon energy spectrum onto a sheet of material. The angle of incidence is chosen to be perpendicular. The events in Fig.10 were saved and rerun through the program as input photon events. The 23,683 events in Fig. 10 are run through the program as many times as needed to generate 1,000,000 events. We looked at 4 thicknesses of Cu: 1 mm, 500 μ m, 200 μ m and 100 μ m and two sheets of Ta (50 and 100 μ m). Preliminary conclusions are that a 1 mm Cu sheet is probably too thick and a 100 μ m Cu sheet is probably too thin. Figs 11-14 are plots of the X-ray energy spectrum of the photons that pass through the Cu sheet and are incident on the Compton photon detector. Figs 15 and 16 are energy plots of the photons that penetrate the Ta sheets. Table 3 summarizes the results of these runs.

Figures 11 and 12. The left plot is a histogram of the energy of the X-rays that penetrate a Cu sheet 100 μ m thick in front of the Compton photon detector. The right plot is a histogram of the energy for the X-rays that penetrate a 200 μ m Cu sheet. For these and the following four plots we generated 1×10^6 events using the energy distribution in Fig. 10.

Figures 13 and 14. The left plot is a histogram of the energy of the X-rays that penetrate a Cu sheet 500 μm thick in front of the Compton photon detector. The right plot is a histogram of the energy for the X-rays that penetrate a 1 mm Cu sheet.

Figures 15 and 16. The left plot is a histogram of the energy of the X-rays that penetrate a Ta sheet 50 μm thick in front of the Compton photon detector. The right plot is a histogram of the energy for the X-rays that penetrate a 100 μm Ta sheet.

Table 3. Summary of the data for various thicknesses of Cu sheets used as a shield for X-rays just in front of the Compton photon detector for the 5 GeV beam. We also include two Ta sheets.

5 GeV beam				
Beam pipe: 10 μm Au, 1 mm Be, 2 mm H ₂ O and 1 mm Be				
6.61×10^4 γ /bunch 1.10×10^6 keV/bunch	Frac. inc. γ s thru	γ s thru to det.	Fraction of the inc. energy thru sheet	Energy/bunch on the detector (GeV)
1 mm Cu sheet	3.57×10^{-4}	23.6	9.13×10^{-4}	0.001
500 μm Cu sheet	3.97×10^{-3}	262	9.06×10^{-3}	0.010
200 μm Cu sheet	2.97×10^{-2}	1964	0.0590	0.065
100 μm Cu sheet	8.24×10^{-2}	5445	0.1477	0.162
100 μm Ta sheet	8.32×10^{-3}	550	1.80×10^{-2}	0.0198
50 μm Ta sheet	3.47×10^{-2}	2295	6.74×10^{-2}	0.0741

11 GeV electron beam

The above study concentrated on the 5 GeV electron beam case. Looking at Table 1, we see that the 11 GeV beam produces more SR power per mrad than the 5 GeV beam even though the beam current is 6% of the 5 GeV beam current (180 mA vs 3 A). Moreover, the X-ray critical energy is over ten times higher (3.697 keV vs 39.4 keV). The higher photon energy spectrum means that many more photons will penetrate the beam pipe that has been designed above for the 5 GeV beam. This is seen in Table 2, where we show the fraction of SR photons that pass through the beam pipe for two cases, one with a layer of 10 μm of Au and another with a layer of 25 μm of Au on the inside of the pipe for the 11 GeV beam. Figures 17 and 18 below show the energy spectrum of the photons that pass through the beam pipe for the case with a 10 μm Au layer.

Figures 17 and 18. Figure 17 (left) is a plot of the photon energy spectrum for all photons that pass through the beam pipe with a 10 μm Au layer for the 11 GeV case. Figure 18 (right) is a plot of the energy spectrum of the photons that are inside the solid angle cuts that define the acceptance of the Compton photon detector. The sharp edge in the plot is due to the k-edge of the Au layer in the beam pipe (81 keV). The photons with energies that are below the k-edge are the ones that tend to minimally scatter and hence many remain in the acceptance of the detector. About 20% of the photons that pass through the beam pipe are inside the Compton photon detector acceptance.

Figures 19-21 below show the direction cosine distributions of all of the photons that pass through the beam pipe for the case with a 10 μm Au layer. As we see in the figures, there is a significant fraction of incident photons that pass directly through the beam pipe with little or no scattering. This is the spike in the direction cosine distributions which match the grazing incident angle of 25 mrad in the UW plane. Because of the large number of incident photons that do not or have very little angular scatter we do not get as much of a solid angle acceptance reduction as we did in the 5 GeV case. In this case, we have an acceptance reduction factor of 2.1×10^{-2} .

Figures 19-21. The U, V and W direction cosine distributions for the photons that pass through the beam pipe for the 11 GeV case. The spikes in the plots match the incident direction cosine values (0.99968752, 0.0, 0.249974).

The direction cosine distributions for the case of a 25 μm Au layer all have significantly reduced spikes which means more of the photons that pass through the pipe are scattered. For this case, we have an acceptance reduction factor of 2.25×10^{-3} . 25 μm of Au is about 30% of a RL, with the 25 mrad angle of incidence we are using, and this will have some effect on the energy resolution of the Compton photons. Using the values in Table 2 for the 10 μm and 25 μm Au beam pipe options for the 11 GeV electron beam as the initial energy and number of X-rays, we have the following table for various thicknesses of materials in front of the detector for the 11 GeV beam energy case.

Table 4. Summary of runs that list the attenuation factors for Cu sheets in front of the Compton photon detector for the 11 GeV beam energy case.

11 GeV beam (critical energy = 39.4 keV)				
γ s and energy that are inc. on detector	Frac. of inc. γ s thru sheet	γ s thru to the detector/bunch	Fraction of inc. energy thru sheet	Energy/bunch on the detector (GeV)
1.38×10 ⁹ γ /bunch 4.34×10 ¹⁰ keV/bun.	Beam pipe: 10 μ m Au, 1 mm Be, 2 mm H ₂ O and 1 mm Be			
2 mm Cu sheet	0.399	5.50×10 ⁸	0.472	2.05×10 ⁴
1 mm Cu sheet	0.656	9.06×10 ⁸	0.711	3.09×10 ⁴
6.42×10 ⁷ γ /bunch 2.02×10 ⁹ keV/bun.	Beam pipe: 25 μ m Au, 1 mm Be, 2 mm H ₂ O and 1 mm Be			
2 mm Cu sheet	0.459	2.95×10 ⁷	0.531	1.07×10 ³
1 mm Cu sheet	0.656	4.21×10 ⁷	0.711	1.44×10 ³

Adding soft bend magnets

As we can see in Table 4, the SR from the 11 GeV beam deposits far too much energy on the Compton detector. Increasing the thickness of the Au layer on the beam pipe helped as much as a factor of 10 but

we would need to thicken the Au layer too much to make a significant reduction in the SR energy incident on the detector. Increasing the thickness of the Cu sheet in front of the detector would also help but as we can see a factor of 2 increase in thickness reduces the SR energy by less than a factor of 2 and we need at least a factor of 1000. Higher Z materials in front of the detector help (see below).

The high critical energy of the SR photons is the biggest problem so the best solution is to lower this critical energy by introducing soft bend magnets in the chicane. Estimating the Compton photon detector to subtend about 12.5 mrad of SR fan radiation means that each soft bend magnet needs to bend the 11 GeV beam by about 6 mrad. We place two soft bend magnets in between the 4th and 5th chicane bend magnets. We would like to keep the critical energy below 20 keV so, using the following formula:

$$k_c(keV) = 6.6502638 \left(\frac{E(GeV)}{10} \right)^2 B(kG)$$

we find that the magnetic field strength of the soft bend can be no more than 2.49 kG. This gives us a bend radius of 148 m. In order to get 6 mrad of bending we therefore need a magnet that is at least 0.9 m long. We will model 1 m soft bend magnets to see if we can develop a reasonable X-ray absorbing system for the Compton photon detector at 11 GeV. This estimate is based on the assumption that we need about 12.5 mrad of angular acceptance for the Compton photon detector. If this can be made smaller then we can further shorten the soft bend magnets. For a 1 m magnet with a 6.25 mrad bend angle we have a magnetic field of 2.3 kG and 160 m for the bend radius (ρ). Using the below formulas we have:

$$P(W)/mrad = 14.085 \times I(A) \times E^4(GeV)/\rho(m)$$

$$P(W)/mrad = 232 (W)/mrad$$

$$k_c(keV) = 2.2183 \times E^3(GeV)/\rho(m) = 18.45 keV$$

For a 12.5 mrad of acceptance for the Compton polarimeter we have 2900 W incident on the beam pipe.

Note: If soft bend magnets are added to the beam line, then the Compton photon detector would most likely have to move farther away from the source point and this would probably decrease the solid angle acceptance of the detector. For now, we will disregard possible reduction in the X-ray rate on the detector as it is also possible that the detector size would need to increase in order to efficiently capture the Compton photons in which case the acceptance would be constant.

The number of photons/bunch incident on the beam pipe is 6.385×10^{12} and the incident energy/bunch is 3.627×10^{13} keV. Using the critical energy value above (18.45 keV) we find that 2.46×10^{-3} of the incident photons penetrate the beam pipe with the 10 μ m Au layer. This corresponds to 1.03×10^{-2} of the incident power or 29.8 W. If we account for the solid angle acceptance of the detector we find another reduction factor of 1.09×10^{-2} . Using these values then for the beam pipe with the 10 μ m of Au we have that 4.07×10^9 keV of X-ray energy per bunch and that 1.71×10^8 photons per bunch pass through the pipe and are incident on the Compton photon detector. These X-rays have an average photon energy of 77 keV. These values are still significantly higher than the 5 GeV case studied above (compare with the numbers in the upper left corner of Table 3). We will try to improve these values by using a 25 μ m Au layer to replace the 10 μ m layer used thus far. The results are summarized in Table 5.

Table 5. Summary of photon and energy transmission per electron beam bunch for two thicknesses of Au on the inside of the beam pipe for the 11 GeV beam.

11 GeV e- with 2.3 kG soft bends		γ s transmitted inside SA		Energy transmitted	
γ s incident = 6.385×10^{12} Enr. incident = 3.627×10^{13} keV	SA accept fraction	Frac. of Inc. $\times$ SA fraction	Number	Frac. of Inc. $\times$ SA fraction	Energy (GeV)
10 μ m Au, 2 mm Be, 2 mm H ₂ O	1.09×10^{-2}	2.68×10^{-5}	1.71×10^8	1.12×10^{-4}	4.06×10^3
25 μ m Au, 2 mm Be, 2 mm H ₂ O	9.35×10^{-4}	9.96×10^{-7}	6.36×10^6	4.41×10^{-6}	1.60×10^2

As one can see from Table 5, the gain in attenuation by increasing the thickness of the Au layer is very helpful due to the fact that more of the incident photons scatter through the pipe. This can be seen by the smaller number of photons that pass through the beam pipe that are in the solid angle acceptance of the Compton photon detector. Of course, the increased thickness of the Au layer increases the radiation length of the beam pipe. A 10 μ m layer of Au is 12% of a R.L. and a 25 μ m layer is 30% of a R.L. We now need to redo Table 4 for this case of soft bend magnets in order to see how much attenuation is achieved by placing various thickness sheets in front of the detector. The results are shown below in Table 6.

Table 6. Summary of X-ray attenuation for various thicknesses of material in front of the Compton photon detector for the case of 11 GeV electron beam with soft bend magnets in the chicane.

11 GeV beam with soft bend magnets (critical energy = 18.45 keV)				
	Frac. of inc. γ s thru sheet	γ s thru to the detector/bunch	Fraction of inc. energy thru sheet	Energy/bunch on the detector (GeV)
1.71×10^8 γ /bunch 4.06×10^9 keV/bun.	Beam pipe: 10 μ m Au, 1 mm Be, 2 mm H ₂ O and 1 mm Be			
2 mm Cu sheet	0.245	4.19×10^7	0.287	1.16×10^3
1 mm Cu sheet	0.470	5.50×10^7	0.509	2.06×10^3
6.36×10^6 γ /bunch 1.60×10^8 keV/bun.	Beam pipe: 25 μ m Au, 1 mm Be, 2 mm H ₂ O and 1 mm Be			
2 mm Cu sheet	0.291	1.85×10^6	0.327	52.2
1 mm Cu sheet	0.527	3.35×10^6	0.556	88.9
2 mm Ag sheet	3.00×10^{-2}	1.91×10^5	4.92×10^{-2}	7.87
2 mm Pb sheet	4.22×10^{-3}	2.68×10^4	4.48×10^{-3}	0.716
3 mm Pb sheet	3.25×10^{-4}	2.07×10^3	3.49×10^{-4}	0.0558

Summary and thoughts

As we can see from Table 6, up to 2 mm of Cu is insufficient to absorb enough of the X-ray energy even with the soft bend magnets for the 11 GeV beam energy. The 25 μ m Au layer on the beam pipe helps considerably but there is still not enough energy absorption in front of the detector. 2 mm of Ag is a significant improvement and 2 mm of Pb is even better but it takes nearly 3 mm of Pb to absorb enough of the X-ray energy to put the value into an acceptable range. The R.L. of Pb is 5.6 mm so 3 mm is 53% of a R.L. This may be too much material in front of the detector. A next step is to look at further soften the bend magnets which will additionally lower the X-ray critical energy. This should make it possible to get enough X-ray absorption by using thinner and lower Z materials in front of the detector which will lower

the total R.L. for the Compton gammas. However, softening the bend magnets even more will necessitate longer bend magnets and this may eventually cause space problems in the lattice design. If the acceptance of the detector can be reduced from 12.5 mrad then we can gain in reduced solid angle acceptance for the detector. We should also be able to shorten the soft bend magnets if the solid angle acceptance can be reduced.

Another important note is that the Au layer on the inside surface of the beam pipe absorbs at least 93% of the incident X-ray energy in all cases (and up to 97% for the 25 μ m thick layer). This is a lot of power (see Table 1) in a small volume and this means the Au layer must be very well attached to the water-cooled Be wall. Either plating or sputtering of the Au layer should work but a careful ANSYS calculation should be made to make sure this design can work and not cause the Au layer to separate due to thermal differences.