Dose rate calculation using Geant4

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An electromagnetic(EM) calorimeter for the DVCS experiments in Hall C at Jefferson Lab needs to withstand a high radiation environment due to the high luminosity($\sim 10^{38} cm^{-2} sec^{-1}$) and its small distance from the beam-line. For these reasons, a precise expected dose rate calculation is needed. There has been a particle flux calculation and its corresponding dose equivalent by RadCon. In this document, comparisons between results using Geant4 and RadCon's will be presented. To further study the radiation damage to the calorimeter by the background and the effect of the sweeping magnet, more realistic dose rate calculation has been done. This method contains essential geometries of Hall C including sweeping magnet.

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1 Dose rate calculation

There are two ways to calculate estimated dose using Geant4; one is to calculate it from the flux(fluence) of particles at a certain distance from a target, the other is to calculate it from the energy deposition in crystals. In this document, both of the methods and results will be shown.

1.1 From flux to dose rate

For a flux calculation, a target(LH2) and a 4π sphere to detect particles made of vacuum material are the only geometries in the simulation as depicted in Figure 1.

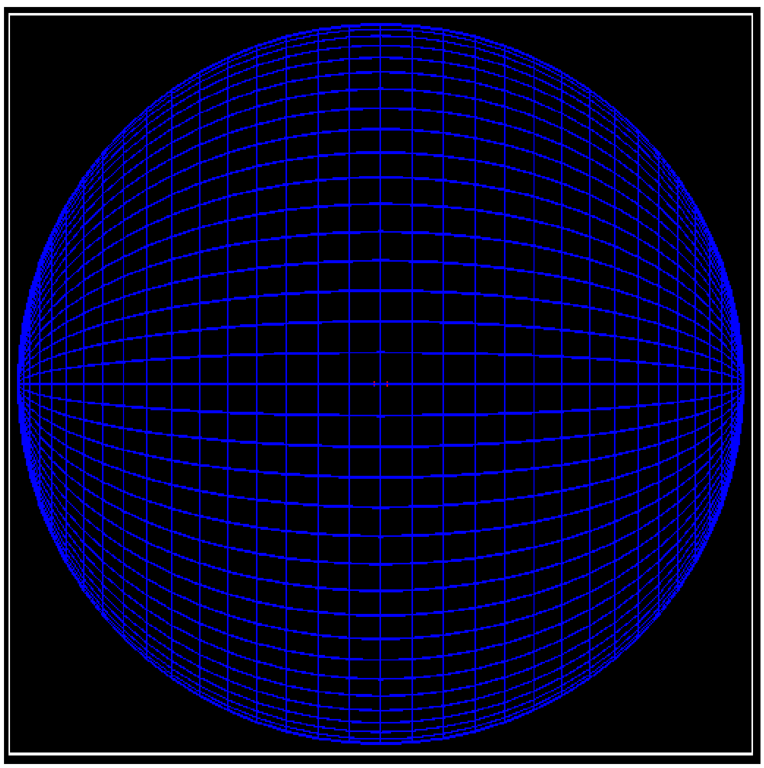
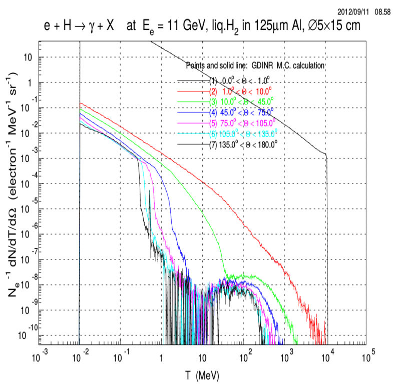


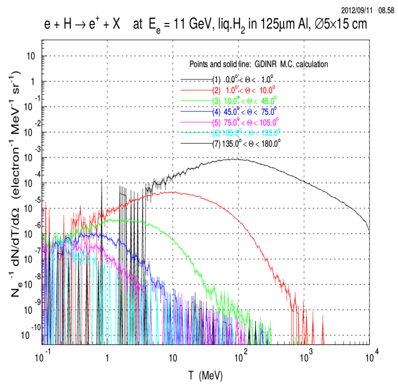
Figure 1: Simulation geometry for the flux calculation.
15cm cylindrical target in the middle(red). 4π sphere with 4m in radius to detect particles(blue).Vacuum environment.

1.1.1 Comparisons with RadCon's results

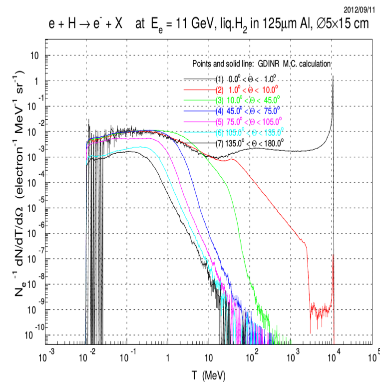
The 4π sphere detects and saves the energies and momenta of the particles going through it. Figure 2 and 3 show comparisons of energy and angular distributions of the particles between RadCon's and Geant4's.



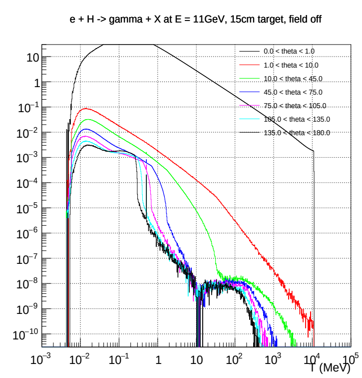
(a) RadCon gamma



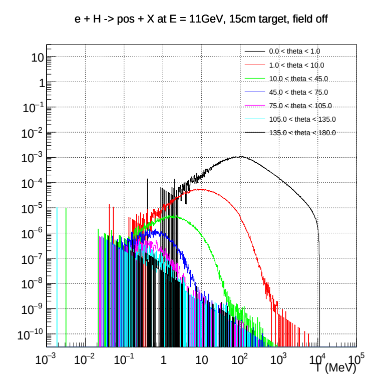
(b) RadCon positron



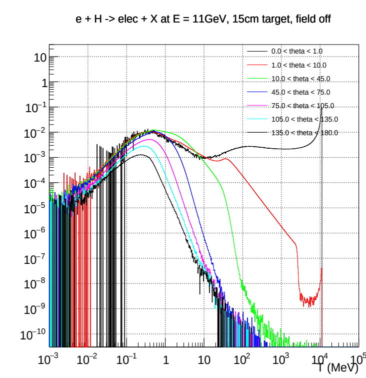
(c) RadCon electron



(d) Geant4 gamma

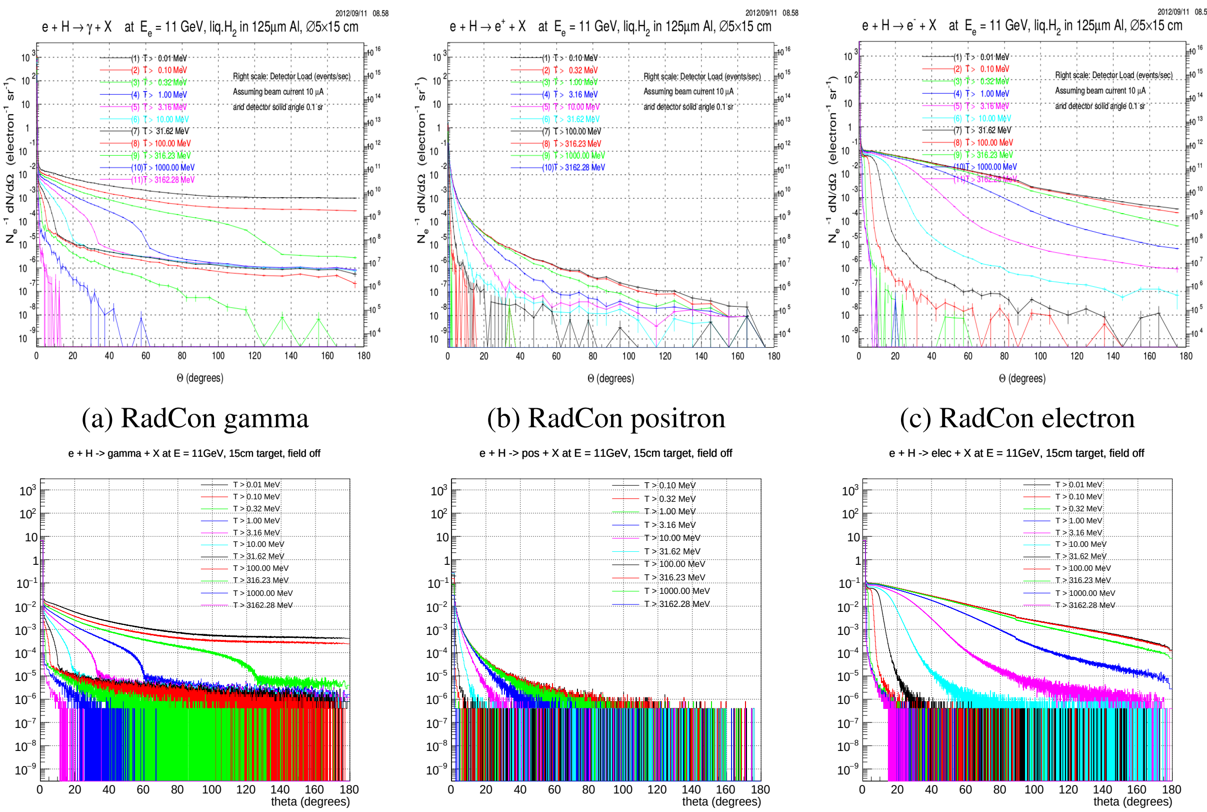


(e) Geant4 positron



(f) Geant4 electron

Figure 2: Background particles' kinetic energy distribution comparison between P. Degtiarenko's and Geant4's .



(a) RadCon gamma (b) RadCon positron (c) RadCon electron

(d) Geant4 gamma (e) Geant4 positron (f) Geant4 electron

Figure 3: Background particles' polar-angle distribution comparison between P. Degtiarenko's and Geant4 .

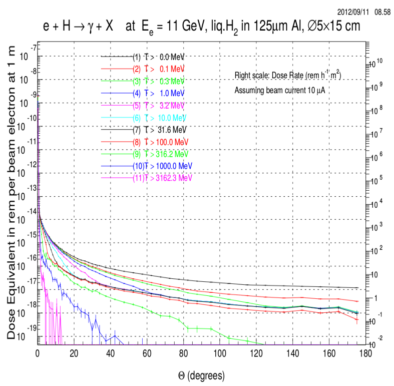
1.1.2 Dose-equivalent calculation

Dose equivalent is a physical quantity of absorbed dose which takes into account the biological effect of radiation. The definition is given by

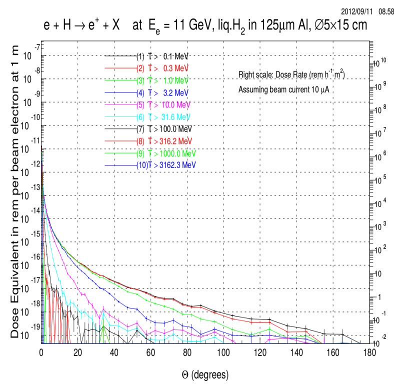
$$H_T = \sum_R w_R D_{T,R}, \tag{1}$$

where w_R is the radiation weighting factor for radiation R and $D_{T,R}$ is the absorbed dose for tissue or organ, T, due to radiation R [1]. With Equation (1), it can be cumbersome to convert from flux(or fluence) to dose equivalent. There are however, conversion factors which converts flux (number of particles in unit area) to dose equivalent (rem per unit time), with corresponding energy of the particles. The conversion factors, for example, can be found in [2].

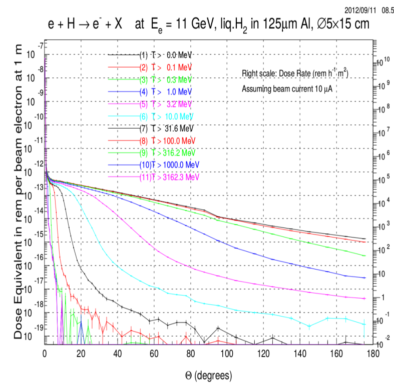
Using a conversion factor to the (polar-)angular distributions of the particles (unit : number of particles per steradian per beam electron), it is straight forward to obtain dose equivalent. The results and comparisons with RadCon's are shown in Figure 4. Linear interpolation were used to calculate dose equivalent from the conversion factor tables. To be noted, the particles were detected 4m away from the target however, the dose equivalent was calculated as if the particles were detected 1m away from the target.



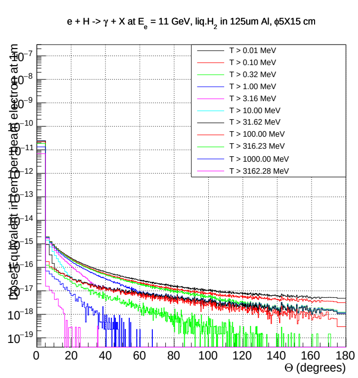
(a) RadCon gamma



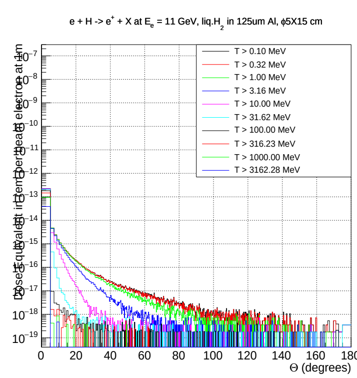
(b) RadCon positron



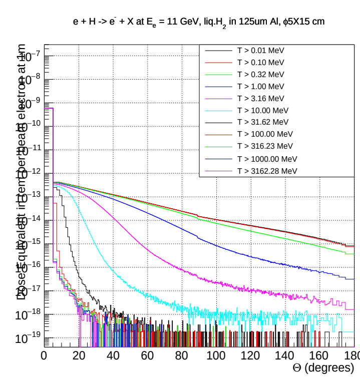
(c) RadCon electron



(d) Geant4 gamma



(e) Geant4 positron



(f) Geant4 electron

Figure 4: Dose equivalent comparison between P. Degtiarenko's and Geant4 .
★ The same conversion factors and linear interpolation methods were used for both RadCon and Geant4.

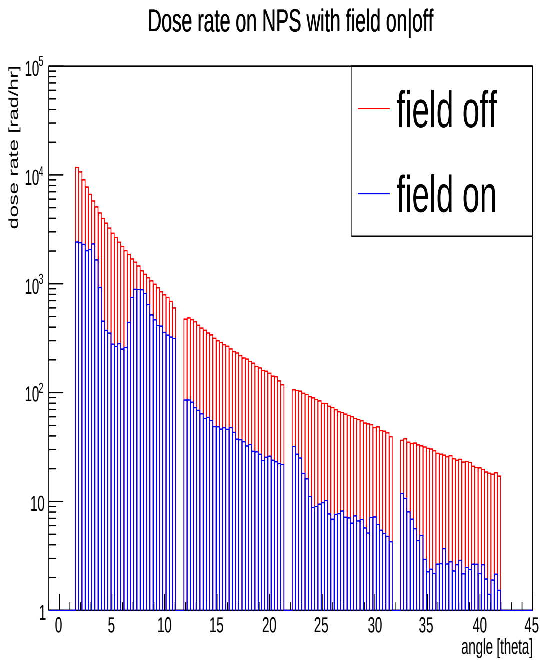
1.1.3 Dose rate calculation

Dose is a quantity of the energy deposited in a matter by ionizing radiation per unit mass. By using the same (polar-)angular distributions of the particles (unit : number of particles per steradian per beam electron), one can also calculate dose rates on the crystals.

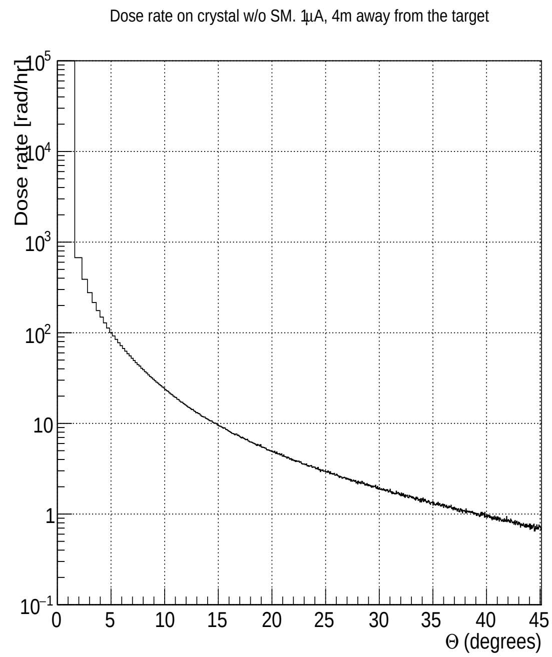
$$\frac{dN}{d\Omega}\,N_e^{-1} \;\rightarrow\; \frac{dN}{dA}\,N_e^{-1} \tag{2}$$

$$\times \text{ detected particle's energy } \;\rightarrow\; \frac{dE}{dA}\,N_e^{-1}, \tag{3}$$

where N is number of particles, Ω is steradian, N_e is number of beam electrons, A is area of crystal's front face, and E is particle's energy. The final equation in (3) means the amount of energy going through (the front face of the) crystal per beam electron. By dividing a mass of the crystal, one can obtain dose per beam electron; $\frac{E}{M}\,N_e^{-1}$, where M is a mass of one crystal. Further, by converting number of beam electrons to beam current, one can finally get dose rate. The dose rate calculated by this method assumes that the crystal absorbs all the energy going through its front face. One of the results of the dose rate from this method is shown in Figure 5(b). The setting of the geometry was the same as Figure 1 which was used to compare the results with RadCon's.



(a) Geometry : target and EM calorimeter (previous result, 1μA, 4m away from the target)



(b) Geometry : target

Figure 5: Dose rate calculation comparison with previous results.
SM : sweeping magnet.
Please, look at only the red plot in (a) for the comparison with (b); without the SM.

Figure 5(a), which is a previous dose rate calculation, was calculated using EM calorimeter with a method described in section 1.2.2. Each angle in x-axis in Figure 5(a) represents one column of the calorimeter, made of 36 crystals. To plot the angle dependence of the dose rate on the calorimeter, the calorimeter's (front face's) center was placed 4m away from the target in 4 different angles; 6.3°, 16.6°, 26.9°, and 37.2°. In order to calculate dose from the energy deposition of the particles on the matter, one needs to divide the mass of that matter. However instead of dividing the mass of one column of crystals, that of one crystal was used. That is one of the reasons there are around one order of magnitude difference between the plots in Figure 5.

To bare in mind, the angle in Figure 5(a)(please, look at only the red plot; without sweeping magnet) is the angular position of the crystal at the center row of the calorimeter, on the other hand, the angle in Figure 5(b) is the actual angle from the beam-line. Since the background is isotropic around the beam-line, the discrepancy of the dose rate between the two results by the factor of 36 is more easily explained when they are compared in larger angles than smaller angles. The dose rate in each crystal which was used to plot Figure 5(a) can be found in Appendix A. Figure A.1 explains the discrepancy of the dose rate by the factor smaller than 36 when the angle is small.

1.2 Dose rate calculation with EM calorimeter

In section 1.1, all the calculations were done with only the target as a geometry. To estimate a realistic dose rate, all the geometries including a sweeping magnet and its magnetic field are needed. In this section, dose rate calculation for two of the kinematics (one low-x_B and the other high-Q^2 from Table 1) for the DVCS at Hall C will be shown.

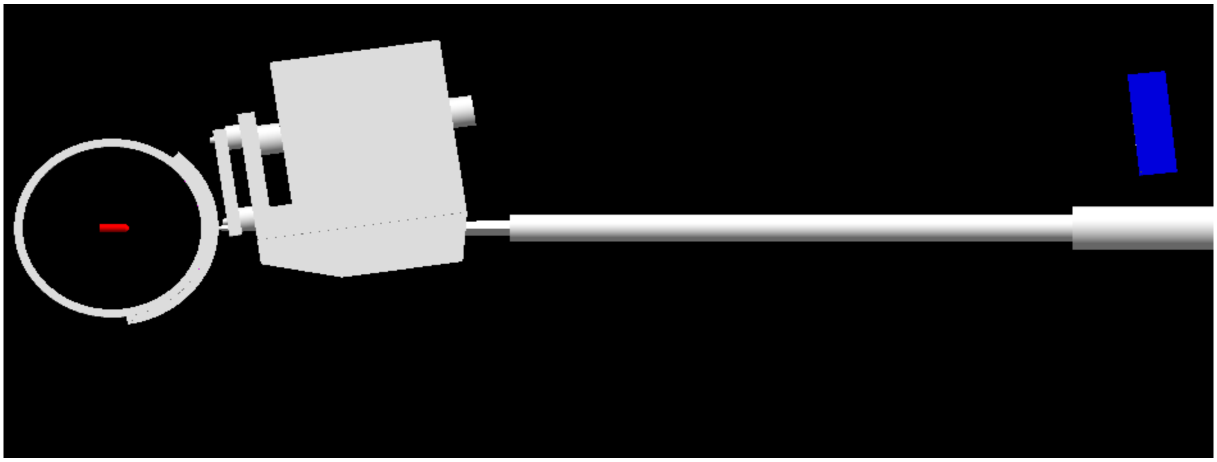
Table 1: Run plan of the DVCS in Hall C [3].

	Energy Dependence at fixed (Q^2, x_B)												Low-x_B				High-Q^2		
x_B	0.36					0.50			0.60				0.2				0.36	0.50	0.60
$Q^2\,(\mathrm{GeV})^2$	3.0			4.0		3.4		4.8	5.1			6.0	2.0			3.0	5.5	8.1	10
k (GeV)	6.6*	8.8	11	8.8*	11	8.8	11	11	6.6	8.8*	11	11	6.6	8.8	11	11	11		
k' (GeV)	2.2	4.4	6.6	2.9	5.1	5.2	7.4	5.9	2.1	4.3	6.5	5.7	1.3	3.5	5.7	3.0	2.9	2.4	2.1
θ_{Calo} (deg)	11.7	14.7	16.2	10.3	12.4	20.2	21.7	16.6	13.8	17.8	19.8	17.2	6.3	9.2	10.6	6.3	7.9	8.0	8.0
D_{Calo} (m)	3	3	3	4	3	3	3	3	3	3	3	3	6	4	4	6	4	4	4
I_{beam} (μA)	28	28	28	50	28	28	28	28	28	28	28	28	11	5	50	11	50	50	50
$\mathrm{N_{evt}}$ (10^5)	1.5	8.8	8.2	2.1	7.9	7.3	11	5.1	0.2	0.2	2.7	2.6	3.5	3.6	64	3.4	6.1	0.8	0.4
$\sigma_{M_X^2}$ (GeV^2)	0.13	0.13	0.12	0.15	0.15	0.09	0.09	0.11	0.09	0.09	0.09	0.09	0.17	0.17	0.17	0.22	0.19	0.15	0.13
Days	1	2	1	1	3	3	2	5	5	1	5	10	1	1	1	1	5	5	12

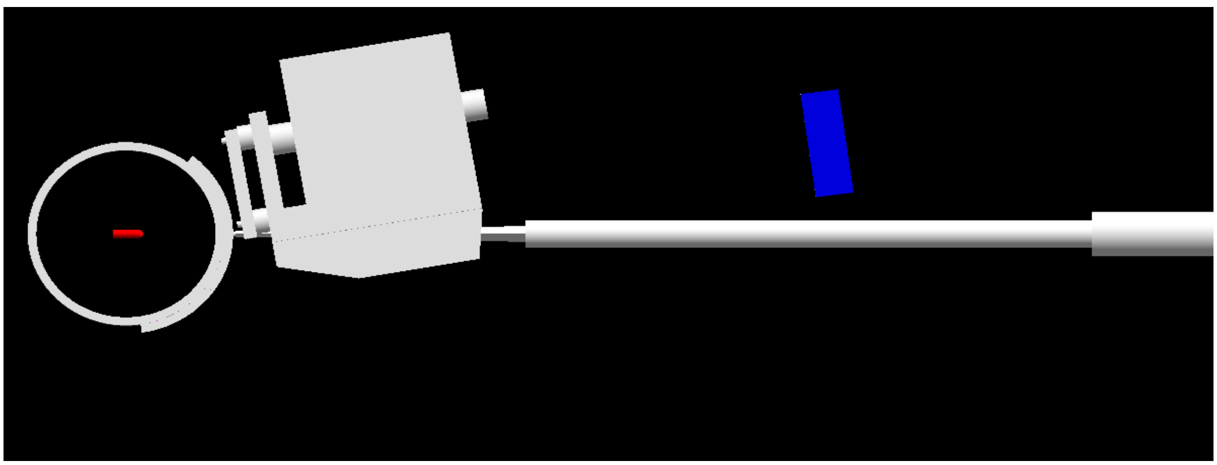
In this document, low-x_B with Q^2 = 3.0 GeV^2 and high-Q^2 with Q^2 = 5.5 GeV^2 were used.

1.2.1 Geometry

The geometries of the simulation for the two kinematic settings (low-x_B and high-Q^2) are shown in Figure 6. There are LH2 target(red), its chamber, sweeping magnet with magnetic field (from Bogdan), beam pipe, and the EM calorimeter(blue). The volumes except target chamber and beam-pipes are filled with air.



(a) Low-x_B with Q^2 = 3.0 GeV^2



(b) High-Q^2 with Q^2 = 5.5 GeV^2

Figure 6: Geometries of two kinematic settings.
Red : LH2 target, blue : EM calorimeter

1.2.2 Dose rate calculation

From total energy deposition of the particles in each crystal($PbWO_4$) and the number of beam electrons used, dose rate can be calculated. "Edep" in equation 4 means energy deposition of the particles to the crystals.

$$\frac{Edep[MeV]}{Crystal}\,N_e^{-1} \;\rightarrow\; \frac{Edep[J]}{Crystal\ mass[kg]}(Dose)\ N_e^{-1} \tag{4}$$

From equation 4, also by converting the number of beam electrons to beam current, dose rate can be obtained. Dose rate in each crystal for both kinematic settings with and without magnetic field is shown in 7.

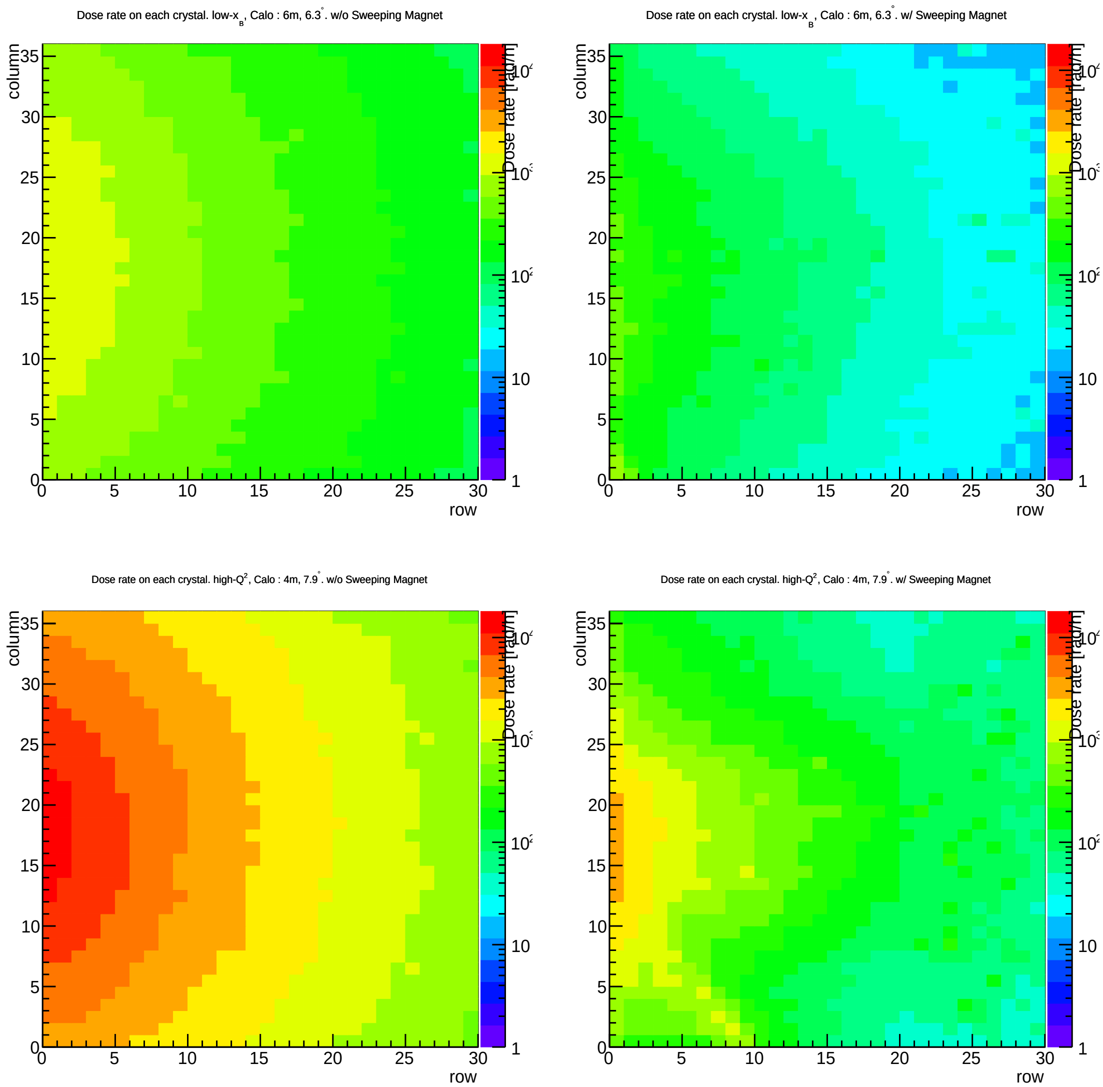


Figure 7: Dose rate in each crystal for the low-x_B and the high-Q^2 settings.
All physical volumes(target chamber, beam-pipe) are in the simulation.
Field ON : Sweeping magnet is also simulated. Field OFF : No sweeping magnet.

In Figure 8, the maximum dose rate on the crystal from each individual column of crystals form Figure 7 is plotted.

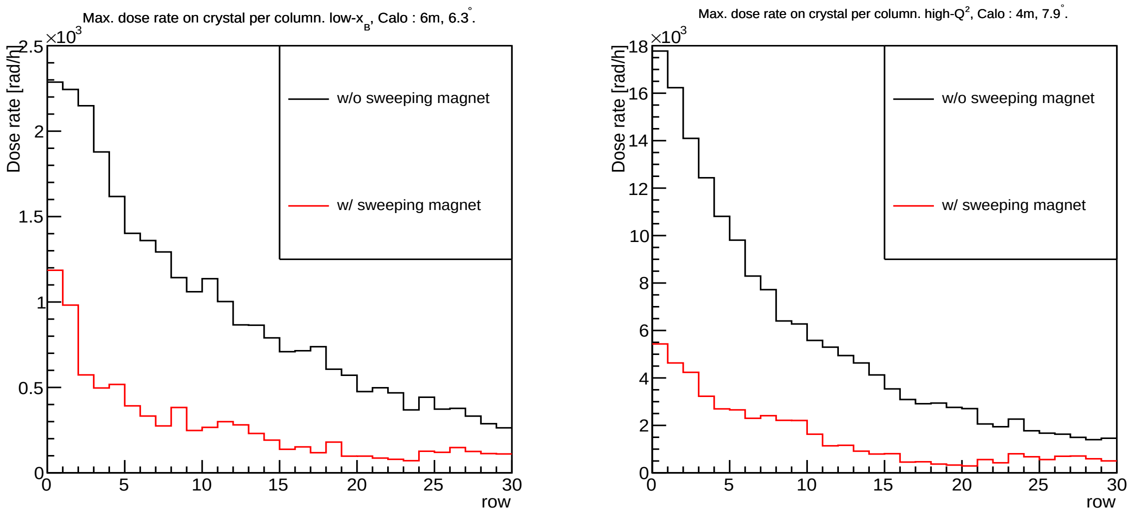


Figure 8: Maximum dose rate in each column of crystals for the low-x_B and the high-Q^2 settings.
All physical volumes(target chamber, beam-pipe, etc.) are in the simulation.
Field ON : Sweeping magnet is also simulated. Field OFF : No sweeping magnet.

1.3 Comparison of two different methods

The two methods mentioned in this document agree each other in an order of magnitude, although the first method has no geometries. It is due to the length of the calorimeter's crystal which absorbs 95% of the 10 GeV particles as can be seen in Figure 9.

Since the second method implements all essential geometries of Hall C, it is more realistic.

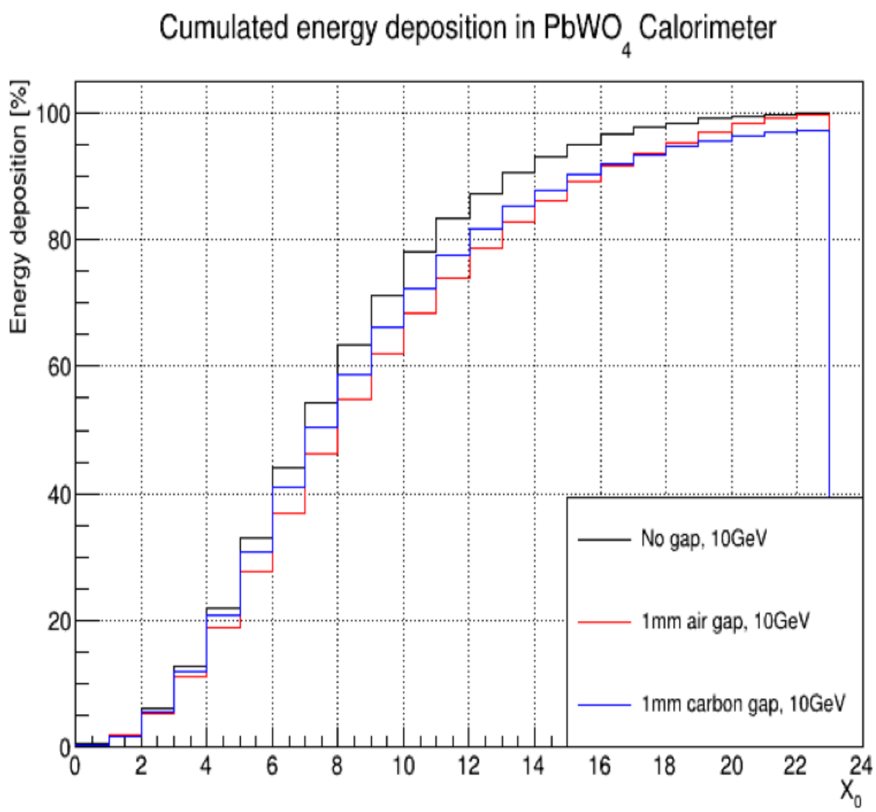


Figure 9: For this document, the crystals in the calorimeter were separated with 1mm carbon material.
Radiation length (X_0) of $PbWO_4$: 0.89 cm

Appendices

A Previous calculation of dose rate on each crystals

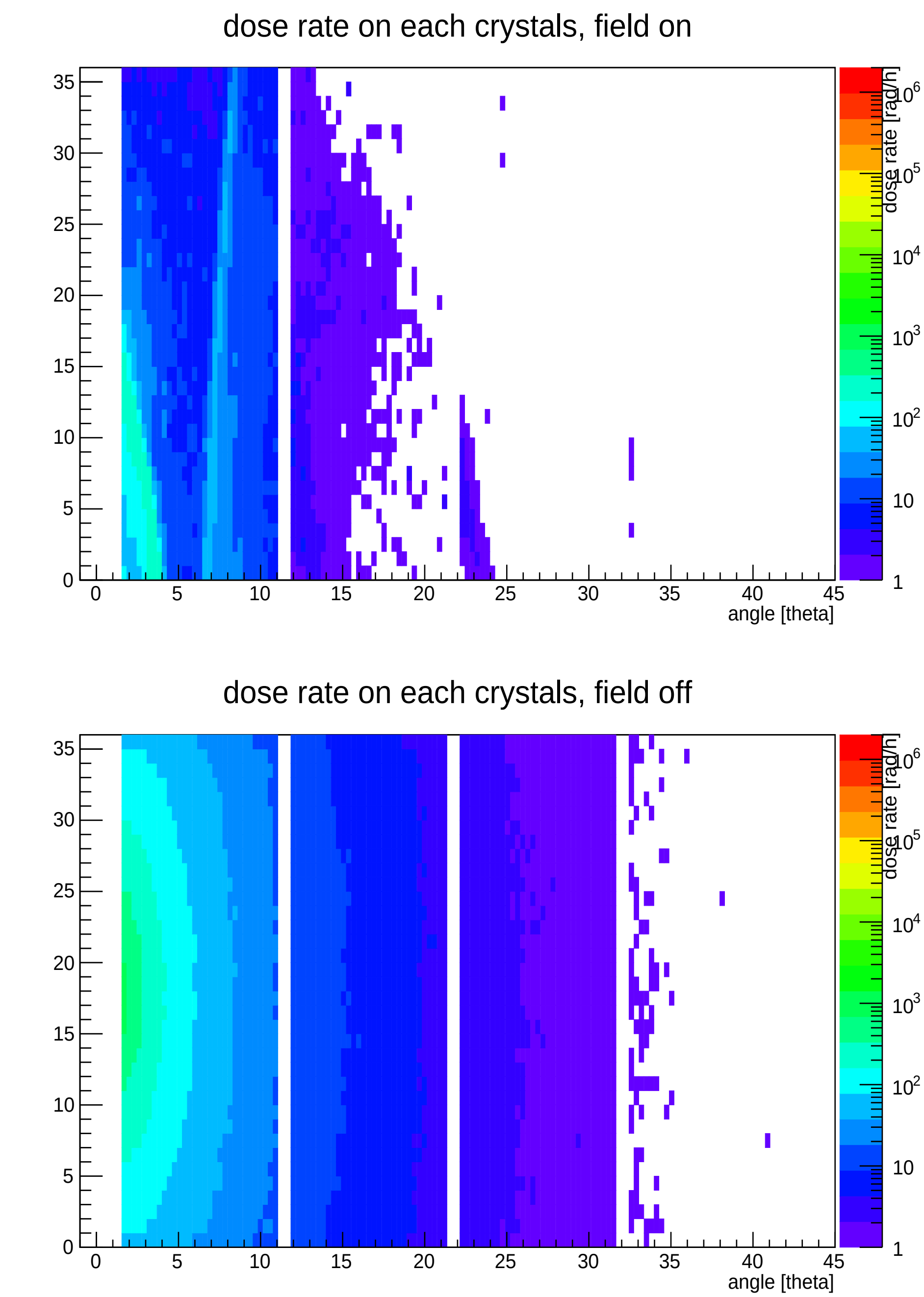


Figure A.1: Dose rate in each crystal. Previous calculation
Geometries : target and EM calorimeter. 1μA, 4m away from the target

To calculate the dose rate in Figure A.1, the mass of crystal was used to convert energy deposition in each crystal to dose rate. As can be clearly seen, when the sweeping magnet's magnetic field is off, the dose rate distribution in one column becomes homogeneous after $\sim 8^\circ$. Since the dose rate is higher at the center of the column of crystals when the angle is small, the dose rate discrepancy less than the factor of 36 in small angle in Figure 5(please, look at only the red plot in (a) when comparing with (b)) can be explained.

References

[1] ICRP publication 103, *The 2007 Recommendations of the International Commission on Radiological Protection*, glossary, 2007

[2] ICRP publication 21, *Data for Protection against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15*, 1971

[3] Munoz Camacho, *Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C* Proposal to Jefferson Lab PAC 40. PR12-13-010 (2013)