Simulations for the Study of Mirror Misalignments for the SHMS Heavy Gas Cherenkov Detector

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Abstract

The purpose of this report is to present the SHMS Heavy Gas Cherenkov (HGC) detector Geant4 simulation results pertaining to a variety of mirror misalignment positions. Simulation results were obtained for pions at two SHMS central momenta: p = 3.0GeV/c and p = 7.0GeV/c. Also, the HGC detector was set to contain C_4F_{10} at a pressure of P = 0.95atm for all simulation configurations. Mirror positions were calculated based on two possible misalignment configurations which included a shift along the z-axis by $z = \pm 3.0$mm and an angular tilt about the y-axis by $\theta = \pm 0.3^o$.

The coordinate system used throughout this report is based on the axes convention for charged particle transport in dispersive magnetic systems. In this convention, the z-axis points in the direction of the charged particle as it traverses the spectrometer, the x-axis points in the direction of increasing particle momenta, and the y-axis can be deduced as $\vec{y} = \vec{z} \times \vec{x}$. Thus, the $+x$-axis points downward and the $+y$-axis points leftward with respect to the HGC detector frame. Further information regarding this convention and its relation to the HGC detector can be found in Ref. [1].

The HGC detector is composed mainly of the detector body, 2 aluminum windows, 4 PMTs, and 4 mirrors. Each mirror has dimensions 60cm$\times$55cm with a radius of curvature of 110cm and

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a thickness of 3mm. In order to prevent any possible gaps at the joint locations, the mirrors were interleaved in the order of mirror number: 4, 3, 2, 1. Here, mirror 4 is in the ($-x$, $-y$) quadrant, mirror 3 is in the ($-x$, $+y$) quadrant, mirror 2 is in the ($+x$, $-y$) quadrant, and mirror 1 is in the ($+x$, $+y$) quadrant. The closest mirror to mirror approach is between 7-10mm and there is a 5cm overlap between mirrors 1 and 2 as well as between mirrors 3 and 4 in the y-direction. The optimal mirror positions were chosen based on 7.0GeV/c pion simulations in C_4F_8O at P = 0.95atm.

The top mirrors (3 and 4) were paired together and the simulations were configured based on the aforementioned parameters. This was performed while keeping the bottom mirrors (1 and 2) fixed in their optimal positions. Similarly, the top mirrors were held fixed while the bottom mirrors were repositioned as a pair. Only one position misalignment parameter was applied per configuration in order to isolate the effects of a misaligned mirror. This resulted in a total of 16 simulation data sets which can be found in Table 1.

Within Geant4, mirrors were positioned in the HGC detector reference frame by their geometrical center along with an angular tilt about the y-axis. A shift along the z-axis was simply calculated by adding or subtracting 3mm to the z-coordinate. In order to change the angular tilt of the mirrors by θ = $\pm0.3^o$, three steps were used to recalculate the geometrical center position. First, each mirror was translated by an amount corresponding to the initial position of its interleaving corner. This relocated each mirror from the detector reference frame to the mirror reference frame. Second, each mirror was rotated by $\pm0.3^o$. Lastly, each mirror was translated back by the amount corresponding to the initial position of its interleaving corner. This relocated each mirror back to the detector reference frame.

The simulation results from each configuration were qualitatively and quantitatively analyzed and compared to the nominal results for pion momenta at p = 3.0GeV/c and p = 7.0GeV/c. Quantitative comparisons included the pion detection efficiency, the number of uncaptured photons, the total pion event distribution, and the pion event distribution for each individual PMT. A qualitative comparison was performed pertaining to missed photons which reached the back plane of the

Configuration	π Momentum p (GeV/c)	Mirrors Moved	Mirrors Fixed	Shift
1	3.0	1 & 2	3 & 4	z = +0.3mm
2	3.0	1 & 2	3 & 4	z = -0.3mm
3	3.0	1 & 2	3 & 4	θ = +0.3^o
4	3.0	1 & 2	3 & 4	θ = -0.3^o
5	3.0	3 & 4	1 & 2	z = +0.3mm
6	3.0	3 & 4	1 & 2	z = -0.3mm
7	3.0	3 & 4	1 & 2	θ = +0.3^o
8	3.0	3 & 4	1 & 2	θ = -0.3^o
9	7.0	1 & 2	3 & 4	z = +0.3mm
10	7.0	1 & 2	3 & 4	z = -0.3mm
11	7.0	1 & 2	3 & 4	θ = +0.3^o
12	7.0	1 & 2	3 & 4	θ = -0.3^o
13	7.0	3 & 4	1 & 2	z = +0.3mm
14	7.0	3 & 4	1 & 2	z = -0.3mm
15	7.0	3 & 4	1 & 2	θ = +0.3^o
16	7.0	3 & 4	1 & 2	θ = -0.3^o

Table 1: Simulation Configurations

detector.

Each simulation employed 200000 pion events. From these events, the mean total number of detected photo-electrons (p.e.) per pion event were analyzed along with the mean number of detected p.e. per pion event for each individual PMT. It should be noted that the sum of the mean number of detected p.e. for each PMT exceeds the mean total number of detected p.e. per pion event. This is due to the fact the Cherenkov radiation cone created by a single pion event can be reflected by multiple mirrors, resulting in multiple registered pion events. The percent difference between the nominal and misalignment simulation results is presented in Table 2 in which the percent difference was calculated as

$$\%_{Difference} = \frac{Simulated\,Value - Nominal\,Value}{Nominal\,Value} \times 100. \quad (1)$$

On an individual PMT basis, the angular tilt of the mirror has a greater effect on the mean number of detected p.e. when compared to a shift along the z-axis. It can also be seen that the mean total number of detected p.e. per pion event is larger for the 7.0GeV/c configurations when compared to the 3.0GeV/c configurations. This is due to the larger Cherenkov radiation cone angle produced at 7.0GeV/c. Furthermore, a misalignment in mirrors 1 and 2 has a greater affect on the mean number of detected p.e. per pion event since a greater number of photons is being focused on mirrors 1 and 2. The misalignment information obtained by each individual PMT is presented in the case that when the detector is calibrated, one can use this information to make a qualitative comparison to the experimental data. This information can be made more useful by combining it with the tracking data from the drift chambers.

The pion detection efficiency was determined based on the optimal threshold cut and then compared to the nominal pion detection efficiency. Please refer to Ref. [2] for further information on the determination of the threshold cut. The optimal threshold cuts were found to be 3.75 p.e. and 22.32 p.e. at p = 3.0GeV/c and p = 7.0GeV/c respectively. This corresponds to a respective pion detection efficiency of e_π = 98.99% and e_π = 99.55%. Table 3 presents the detection efficiency as well as the percent difference when compared to the nominal efficiency. Also included in Table 3

Configuration	Mean Number of Detected Photo-Electrons per Pion Event $\%_{Difference}$ (%)				
	PMT 1	PMT 2	PMT 3	PMT 4	Total
1	2.72	2.52	0.18	-0.17	1.77
2	-3.31	-2.39	0.09	0.00	-2.01
3	4.63	3.27	0.00	-0.09	2.58
4	-6.95	-5.62	0.09	-0.17	-4.40
5	0.05	0.21	0.88	0.60	0.24
6	0.00	0.25	-0.79	-0.68	-0.14
7	0.09	0.08	0.09	0.26	0.00
8	-0.18	0.34	-0.53	-1.11	-0.19
9	3.85	3.92	0.06	0.20	2.22
10	-4.34	-4.19	0.06	0.34	-2.26
11	7.68	6.97	0.06	0.17	3.87
12	-8.73	-8.88	-0.19	0.23	-4.87
13	-0.08	0.12	2.11	3.18	1.14
14	0.05	-0.10	-2.52	-3.43	-1.22
15	-0.03	0.10	2.08	5.22	1.30
16	0.00	-0.05	-4.57	-6.66	-2.22

Table 2: Percent Difference in the Mean Number of Detected Photo-Electrons per Pion Event Compared to the Nominal Configuration

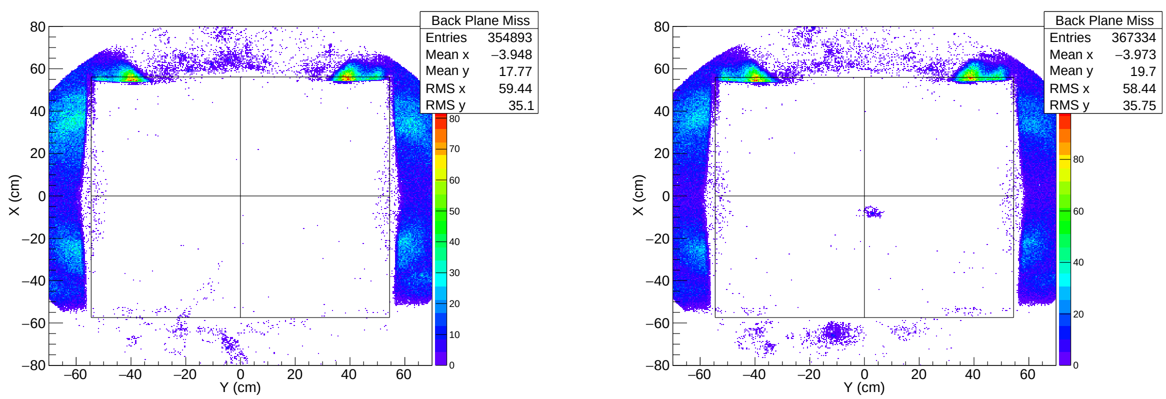
is the percent difference for the number of uncaptured photons.

Configuration	π Detection Efficiency		Number of Uncaptured Photons
	e_{π} (%)	$\%_{Difference}$ (%)	$\%_{Difference}$ (%)
1	99.02	0.02	0.04
2	99.03	0.04	0.08
3	99.00	0.01	-0.27
4	99.01	0.01	-0.60
5	99.07	0.08	0.13
6	98.96	-0.03	-0.07
7	98.94	-0.05	0.10
8	99.04	0.05	-0.01
9	99.64	0.09	-0.13
10	99.42	-0.13	0.14
11	99.62	0.07	-0.54
12	99.08	-0.47	0.80
13	99.62	0.07	-0.02
14	99.45	-0.10	0.02
15	99.53	-0.01	-0.14
16	99.37	-0.18	0.26

Table 3: Pion Detection Efficiency at the Optimal Threshold Cut and the Percent Difference in the Efficiency and Number of Uncaptured Photons Compared to the Nominal Configuration

There is no significant change in the pion detection efficiency at p = 3.0GeV/c when the mirrors are misaligned by z = ±3mm or θ = ±0.3^o. However, configuration 12 shows that at higher momentum, a misalignment in the angular tilt of mirrors 1 and 2 results in a decrease to the pion detection efficiency by nearly 0.5%. This is due to the fact that charged particles with a relatively high momentum are deflected by a smaller angle than particles with a relatively low momentum after exiting the SHMS superconducting dipole. Therefore, the majority of the Cherenkov radiation will be directed towards mirrors 1 and 2 at higher particle momenta.

A visual comparison was performed to analyze the missed photons along the back plane of the HGC detector which is a virtual plane located behind the mirrors. The nominal missed photons along the back plane are displayed in Fig. 1 (a) whereas Fig. 1 (b) displays the missed photons along the back plane corresponding to configuration 11. Configuration 11 was selected for presentation due to the size of the region of missed photons between mirrors 3 and 4. This configuration emphasizes the worst case among all back plane missed photons within the region of the four mirrors. Some configurations had similar spots between mirrors 3 and 4 while others had a negligible amount of missed photons (less than 30) or no considerable missed photons within the region of the four mirrors.



(a) Nominal

(b) Configuration 11

Figure 1: (a) Nominal back plane missed photons. (b) Configuration 11 back plane missed photons. The approximate mirror boundaries are shown by the overlying grid. A spot can be seen between mirrors 3 and 4 due to leakage in the interleave gap between the mirrors. It is an estimate of approximately 50-150 photons which is negligible compared to the number of photons generated by the total number of simulated pion events. Note that the coordinate axes are flipped with respect to the coordinates of the charged particle transport convention. Therefore, mirror 1 is in the top right corner and mirror 4 is in the bottom left corner.

Conclusion

None of the mirror misalignment possibilities explored in this report significantly affect the total pion detection efficiency at the studied pion momenta of p = 3.0GeV/c or p = 7.0GeV/c. When comparing the experimental data to the simulation results, significant deviations from the expected results during detector commissioning will imply that the misalignment of the mirrors is greater than the possible misalignment configurations studied in this report. Alternatively, it may indicate a malfunctioning PMT. To investigate the possible misalignment of the mirrors or a malfunctioning PMT, partial disassembly of the HGC detector will be required. This must be consulted with the HGC construction group led by Dr. Garth Huber at the University of Regina.

References

[1] W. Li, *Heavy Gas Cherenkov Detector Construction for Hall C at Thomas Jefferson National Accelerator Facility*, JLAB-PHY-12-1697, 2012.

[2] M. Strugari, *Simulations for π/K Separation for the SHMS Heavy Gas Cherenkov Detector*, HallC-doc-804-v1, 2016.