Monte Carlo Simulation for SHMS Calorimeter
Part I (Version 2a-2d)

A.H. Mkrtchyan, V. Tadevosyan

Abstract

The results of MC Simulation based on standard GEANT 3 program for SHMS shower counter are presented. For several considered versions the energy resolution, efficiencies and pion/electron separation capabilities in the momentum range 1-11 GeV/c are determined. It was shown that the lead glass calorimeter with Preshower is the best for π/e rejection. An improvement in the energy resolution due to increase in thickness of lead glass radiator behind 40 cm was not observed.

Introduction

The SHMS magnetic spectrometer is aimed to cover small forward angles and higher momentum settings not available so far in Hall C[1]. When identifying electrons at this settings, good particle identification is needed to suppress high hadrons background. Lead glass electromagnetic calorimeters are well suited to this purpose. A charged particle moving in lead glass with relative to light velocity \( \beta > 1/n \) (n is for refractive index of the medium) radiates Cherenkov light proportional to track length. The light propagates through the glass and is detected in PMT. Absorption of light in the glass causes PMT signal to be dependent on the distance that the light propagates. This may be corrected in an analysis code. Properly calibrated, the calorimeter provides Deposited Energy spectrum for particle identification in off-line analysis. The modular construction of the calorimeter provides additional information on the shower development which is beneficial to the identification.

General requirements for SHMS Calorimeter are:

- Effective area: 120x140 cm\(^2\)
- Total thickness: ~20 rad. length
- Dynamic range: 1.0 - 11.0 GeV/c
- Energy resolution: ~6% at 1 GeV/c
- Pion rejection: ~100:1 at P > 1.5-2.0 GeV/c
- Electron efficiency: > 98%

A possible choice for SHMS calorimeter is construction similar to existing HMS and SOS calorimeters. An alternative choice is a calorimeter similar to HERMES[2] and Hall-A[3] shower counters. The goal of this study was to explore a few proposed versions for SHMS Calorimeter based on commercially produced and used elsewhere lead glasses. The configurations considered here are of a total absorption part (dabbled Shower in the sequel), or a combination of preshower and shower parts (Preshower+Shower in the sequel). The Preshower is a slab of few radiative length thick lead glass before the Shower part. For each version the energy resolution, electron detection efficiency and pion/electron separation capabilities are determined. Each component consists of a number of the modules. The module in turn consists of an optically isolated rectangular lead glass block and an optically coupled to it PMT. The lead glass type and block size could differ in Preshower and Shower.
Monte Carlo Simulation

The Monte Carlo program is based on GEANT-3.21 simulation package[^4]. It was developed and used originally for the simulation of the HMS and SOS calorimeters. The GEANT part of the code is for electromagnetic and hadron shower developments, the Cherenkov light generation as well, and a custom made part of the code is for the realistic optics tracing of the light photons in the rectangular geometry of the glass block. Absorption in the lead glass, reflection off the optical coating of the modules, passage through the the optical coupling to the PMT are scrupulously simulated in the tracing code based on the conventional optics[^9]. A survived light photon knocks off a photo-electron off the PMT photo-cathode according to its quantum efficiency.

The part of the code for detector description was modified for adapting it to the SHMS calorimeter simulations, and a separate bride was created for each of the versions described below.

The program outputs signals in photo-electrons from the constituent modules, on event-by-event basis. These are fed to a calibration code, quite similar to the codes for HMS and SOS calorimeters in the Hall-C standard analysis code. Then the calibration constants are used to reconstruct the energy deposition in the modules which are used in the subsequent analysis.

**Version 2a. TF-1 10x10x40 cm³ blocks. Shower only**

This version is an assembly of the total 182 modules to cover all the acceptance of SHMS. The blocks are 10x10x40 cm³ TF-1 type lead glasses (see fig.3). The modules are oriented longitudinally with respect to the central ray of the spectrometer (a “hodoscope” configuration) with PMTs looking upstream. The calorimeter is 14.6 radiative length deep. The chemical composition and relevant physical properties of the glass are listed in table 1. The attenuation length that was measured on the sample of the blocks for SOS and HMS calorimeters is shown in fig. 2.

Figure 3 shows results of the simulation in the SHMS momentum range. The resolution $\sigma/E = 3.6(\%) + 1.9(\%)/\sqrt{E}$ for the electron peak of the total energy deposition in the calorimeter is somewhat better than expected. The electron detection efficiency is 99% when $\pm 3\sigma$ cut around the peak is applied. For the same cut the pion rejection factor is $\sim 2 \cdot 10^{-3}$ as expected.

![Fig. 1. Calorimeter with total absorption part only (without Preshower), consists of 182 modules of TF-1 type Lead Glass blocks of the size 10x10x40cm³ (version 2a).](Image)
Table 1. Chemical composition and physical properties of the TF-1\textsuperscript{[10]}.

<table>
<thead>
<tr>
<th>Chemical composition (weight %)</th>
<th>Fractions atomic units</th>
</tr>
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<tbody>
<tr>
<td>PbO</td>
<td>51.2</td>
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<tr>
<td>SiO$_2$</td>
<td>41.3</td>
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<tr>
<td>K$_2$O</td>
<td>3.5</td>
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<tr>
<td>Na$_2$O</td>
<td>3.5</td>
</tr>
<tr>
<td>As$_2$O$_3$</td>
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<tr>
<td>Radiation length (cm)</td>
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<tr>
<td>Density (g/cm$^3$)</td>
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<tr>
<td>Critical energy (MeV)</td>
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</tr>
<tr>
<td>Refraction index</td>
<td>1.6476</td>
</tr>
</tbody>
</table>

Fig. 2 Attenuation lengths of TF-1 type lead glass blocks, the best and the worst among measured HMS/SOS blocks. The average of the two has been used in the simulation.
Version 2b. TF-1 10x10x50 cm$^3$ blocks. Shower only

This version is similar to the previous except the lead glass blocks are taken 50 cm long instead of 40 cm. The deeper calorimeter the less energy leak of the electromagnetic shower from the radiator, but the more light loss due to absorption in the glass and reflections. Both factors, the shower leakage and the light loss, are crucial to the detector performance. Therefore it should be an optimum in the longitudinal size of the detector. For the GAMS and HERMES calorimeters of the similar construction and in the similar energy range it was found that the optimum is at ~40 cm$^3$\cite{5,6}.

Figure 5 shows the distributions of the total number of photoelectrons for the two cases, 40 and 50 cm deep calorimeters, for 9 and 11 GeV incident electrons. It is clear that in terms of the strength of the signal the shorter calorimeter is preferable. But in terms of the resolution the longer is still little bit better (3.61% versus 3.73% at 9 GeV and 3.47% versus 3.77% at 11 GeV).
Fig. 4. Calorimeter with total absorption part only (without Preshower), consists of 182 modules of TF-1 type Lead Glass blocks of the size 10x10x50cm$^3$ (version 2b).

Fig. 5. The expected number of photo-electrons for TF-1 Lead Glass blocks with thickness 40cm and 50cm at 9 and 11GeV.
Version 2c. F-1 9x9x50 cm$^3$ blocks. Shower only

This version is similar to the two cases described above except the blocks are 9x9x50cm$^3$ F-101 lead glasses (see fig.6) as it is in HERMES calorimeter. The F-101 lead glass is quite similar to TF-1 (see table 2 for the glass properties) except the improved radiative hardness which is beneficial for the SHMS forward angle kinematics. These type of blocks are produced in Lytcarino factory of optical glasses (Russia). Measurement of the radiation hardness of F-101 blocks with γ-rays$^{[7]}$ and high energy hadrons$^{[6]}$ have shown that an accumulated dose of 2000 rad produces a degradation of transmittance less than 1%. Thus F-101 is from 10 to 50 times less susceptible to radiation damage than SF-2 or TF-1 glasses.

We assumed the same absorption length for the light in F-101 as before for TF-1. Though the optical properties of F-101 (see table 2 and fig.7) may differ from those of TF-1 due to the small ingredients for the hardness.

![Fig. 6. Calorimeter with total absorption part only (without Preshower), consists of 224 modules of F-101 type Lead Glass blocks of the size 9x9x50cm$^3$ (version 2c).](image)

<table>
<thead>
<tr>
<th>Chemical composition (weight %)</th>
<th>Fraction atomic units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb$_2$O$_4$</td>
<td>51.23</td>
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<tr>
<td>SiO$_2$</td>
<td>41.53</td>
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<tr>
<td>K$_2$O</td>
<td>7.0</td>
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<td>Ce</td>
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<tr>
<td>Radiation length (cm)</td>
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<td>Density (g/cm$^3$)</td>
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<td>Critical energy (MeV)</td>
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<td>Moliere radius (cm)</td>
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<tr>
<td>Refraction index</td>
<td>1.65</td>
</tr>
<tr>
<td>Thermal expansion coefficient (C$^{-1}$)</td>
<td>8.5·10$^{-6}$</td>
</tr>
</tbody>
</table>
Fig. 7 Transmittance for 8.9 cm thick F-101 Lead Glass blocks\textsuperscript{[14]}.

The results of simulations are shown in Fig.8. Overall the performance of the calorimeter is in the stream of the previous two cases.

We checked the optimum for the longitudinal size of the calorimeter as previously by comparing simulation results for 40 cm and 50 cm deep detectors with 9 GeV and 11 GeV incident electrons. The results are presented in Fig.9. Again, 50 cm case is worse in terms of the strength of the sum signal but is slightly better in terms of resolution.

Fig. 8 Energy resolution (a), electron detection efficiency at $\pm 3\sigma$ cut around electron peak (b) and pion rejection factor (c) for calorimeter “shower only” with blocks of 9x9x50cm$^3$ F-101 lead glass.
Fig. 9 Number of detected photoelectrons for the 9 GeV and 11 GeV incident electrons on the calorimeter of 40 cm and 50 cm long F-101 lead glass blocks.

Version 2d. Shower of 9x9x50cm³ F-101 blocks with Preshower of 10x10x70cm³ F-101 blocks

The calorimeter considered here is a combination of a Shower and a Preshower. The Preshower is one layer of modules with 10x10x70cm³ TF-1 type lead glass blocks oriented transversely to the incident particles. The modules are stacked in two columns to cover the acceptance of the spectrometer. The PMTs, one per module, are attached to the left and right sides of Preshower. The total number of modules in Preshower is 26. Shower part, identical to version (2c), consists of the modules with 9x9x50cm³ F-101 lead glass blocks oriented longitudinally, with total number of blocks in it 224. Fig.10 sketches the geometry of the calorimeter.

There is significant coordinate dependence in both Preshower and Shower as it is found in the early simulations[^11]. In the Preshower the signal depends mostly on the X coordinate of the impact point only (see Fig.10 for coordinate convention). While in the Shower it depends on both X and Y, and probably on both pitch angles. In the calculations presented below the signals of the modules in Preshower are corrected for X coordinate, while in the Shower no any correction is applied.
Fig. 11 shows results of the simulations. The resolution for incident electron is better at high momentum settings when compared to the previous versions. The particle identification is done using combination of energy depositions in Preshower and Shower. A flavor of Kernel Machines\textsuperscript{[12]}, Support Vector Machine SVM\_Light\textsuperscript{[13]} has been used for optimization of the separation in the plane.

When compared to the Shower only case of the version (2c) (Figure 8), a significant improvement in the pion rejection at the same electron detection efficiency could be noticed, especially in the range of momentum settings greater than 2 GeV/c. This could be understood by looking at Preshower and Shower energy depositions (Fig.12). The Preshower is thick enough (3 rad. length) for the incident electron to initialize an electromagnetic shower and hence to deposit significant fraction of the energy. While for the incoming hadron it is slim enough (in units of hadron interaction length) to let it pass without interaction as a minimum ionizing particle. This difference in energy depositions in the Preshower, especially at high energies, augments the separation capability of the Shower part.
Fig. 11 Energy resolution (a), electron detection efficiency (b) and pion rejection factor (c) for calorimeter Preshower+Shower (version 2c).
Fig. 12 Number of photoelectrons produced (a) in Shower at 1 GeV/c, (b) in Preshower at 1 GeV/c, (c) in Shower at 9 GeV/c, (d) in Preshower at 9 GeV/c by incident electron and pion.

**Conclusion**

Monte Carlo simulations for the different versions of the calorimeter, based on the lead glass blocks found elsewhere, with and without Preshower, for SHMS spectrometer project have been performed. A hint for the optimum of the thickness of the calorimeter without Preshower at ~40cm is observed. The energy resolution of 2-5%, \( \pi/e \) rejection factor \( \sim 2 \times 10^{-2} \) at electron detection efficiency \( \sim 99\% \) for the case without Preshower are expected within the range 1-11 GeV/c of the spectrometer momentum setting. Adding Preshower dramatically improves \( \pi/e \) rejection factor. The energy resolution for versions with and without Preshower are similar. The use of radiative hard F-101 type lead glass blocks from HERMES will be an optimal solution. A good choice is also to use TF-1 type blocks for the assembly, but in this case an additional time and expenses should be allotted. No significant deterioration in the performance is observed in the course of exploitation of the HMS and SOS calorimeters since 1995. The Yerevan Collaboration takes responsibility for the construction and assembly of SHMS calorimeter.
References

[4] GEANT -- Detector Description and Simulation Tool, CERN Program Library Long Write-up W5013.