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The design and performance of the electromagnetic calorimeters in Hall C at Jefferson Lab

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Abstract.

The design and performance of the electromagnetic calorimeters in the magnetic spectrometers in Hall C at Jefferson Lab are presented. For the existing HMS and SOS spectrometers, construction information and comparisons of simulated and experimental results are presented. The design and simulated performance for a new calorimeter to be used in the new SHMS spectrometer is also presented.

We have developed and constructed electromagnetic calorimeters from TF-1 type lead-glass blocks for the HMS and SOS magnetic spectrometers at JLab Hall C. The HMS/SOS calorimeters are of identical design and construction except for their total size. Blocks of dimension 10 cm × 10 cm × 70 cm are arranged in four planes and stacked 13 and 11 blocks high in the HMS and SOS respectively. The energy resolution of these calorimeters is better than $6\%/\sqrt{E}$, and pion/electron (π/e) separation of about 100:1 has been achieved in energy range 1 – 5 GeV. Good agreement has been observed between the experimental and GEANT4 simulated energy resolutions. The HMS/SOS calorimeters have been used nearly in all Hall C experiments, providing good energy resolution and a high pion suppression factor. No significant deterioration in their performance has been observed in the course of use since 1994.

For the SHMS spectrometer, presently under construction, details on the calorimeter design and accompanying GEANT4 simulation efforts are given. A Preshower+Shower design was selected as the most cost-effective among several design choices. The preshower will consist of a layer of 28 modules with TF-1 type lead glass radiators, stacked in two columns. The shower part will consist of 224 modules with F-101 type lead glass radiators, stacked in a “fly’s eye” configuration of 14 columns and 16 rows. The active area of 120 × 130 cm² will encompass the beam envelope at the calorimeter. The anticipated performance of the new calorimeter is simulated over the full momentum range of the SHMS, predicting resolution and yields similar to the HMS calorimeter. Good electron/hadron separation can be achieved by using energy deposition in the Preshower along with total energy deposition in the calorimeter. In this case the PID capability is similar to or better than that attainable with HMS calorimeter, with a pion suppression factor of a few hundreds predicted for 99% electron detection efficiency.

1. Introduction

The experimental program at Jefferson Lab focuses on the studies of the structure of nucleons and nuclei. The initial base equipment of Hall C is well suited to the JLab scientific program that required high luminosity, intermediate detector acceptances and resolution [1]. A magnetic spectrometer pair points to a common pivot with scattering chamber. The Short Orbit Spectrometer (SOS) accesses a momentum range of 0.3 - 1.7 GeV/c, and an angular range of 13.3° - 168.4°. The High Momentum Spectrometer (HMS) covers a momentum range 0.5 -

7.3 GeV/c, and angular range between 10.5° - 80° . The JLab 12-GeV Upgrade [2] envisages a Hall C scientific program focused again on high luminosity measurements, with detection of high energy reaction products at small forward angles. The SOS will be superseded by the newly built Super High Momentum Spectrometer (SHMS), capable of achieving a minimum scattering angle of 5.5° and a maximum momentum of 11 GeV/c.

The detector packages in the HMS and SOS are comprised of a pair of drift chambers for particle tracking, two pairs of x-y scintillator hodoscopes for triggering and time-of-flight measurements, and a gas Čerenkov detector and an electromagnetic calorimeter for electron/hadron separation. Hall C experiments typically demand detection efficiencies of better than 99%, and background particle suppression of 1,000:1 in e/π separation. This can be achieved by combining 100:1 suppression in the calorimeter, with the remaining suppression in the gas Čerenkov counter.

The detector package of the SHMS will be a near-clone of the HMS, and includes a heavy gas Čerenkov for hadron selection, and a noble-gas Čerenkov and lead-glass electromagnetic calorimeter for electron/hadron separation. The approved experiments demand a suppression of pion background for electron/hadron separation of 1,000:1, with suppression in the electromagnetic calorimeter alone on the level of 100:1.

2. HMS and SOS Calorimeters

The calorimeters for the HMS and SOS spectrometers were installed in 1994, becoming the first operational detectors at JLab. The detectors are of identical design and construction (see Fig. 1) except for their total size. The thickness, ~ 14.6 radiation lengths, is enough to absorb the major part of energy of electrons within the HMS/SOS momentum ranges. To avoid shower leakage, the lateral dimensions of the calorimeters were extended by 5 cm beyond the sizes required by spectrometer acceptance. This gave calorimeter physical areas of $70 \times 130 \text{ cm}^2$ for the HMS and $70 \times 110 \text{ cm}^2$ for the SOS.

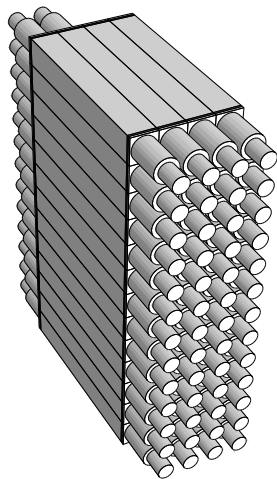


Figure 1. A sketch of the HMS calorimeter. The front of detector is at left. The far side PMTs in the first two layers were added in 1998.

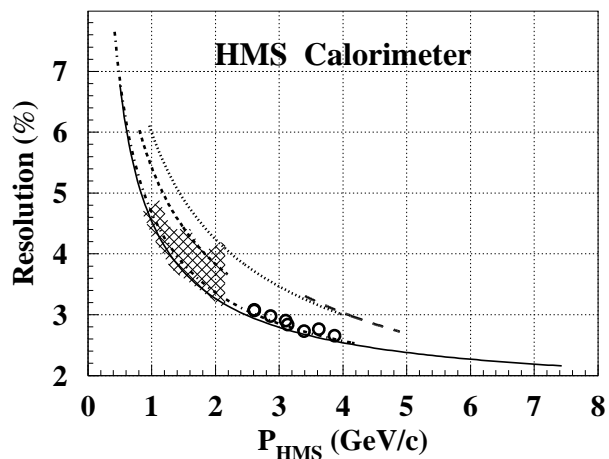


Figure 2. Resolution of the HMS calorimeter from the GEANT4 calculations (solid line) and from Hall C experiments E89-008 (\cdots), E00-116 ($- - -$), E04-001 ($- \cdot -$), E01-006 ($- - -$), E01-004 (\circ) and E03-003 (cross-hatched area).

The Čerenkov radiator is of TF-1 type lead glass blocks (index of refraction ~ 1.65 , radiation length 2.74 cm, density of 3.86 g/cm^3). The light attenuation length of TF-1 varies significantly in the range of sensitivity of the PMT photocathode, and is $\sim 100 \text{ cm}$ at the peak of sensitivity

~ 400 nm. The blocks are wrapped in $25\ \mu\text{m}$ thick aluminized Mylar and $40\ \mu\text{m}$ thick Tedlar type film for light-tightness. High viscosity silicone grease ND-703 from Bicon is used for the PMT – block optical contact (index of refraction ~ 1.46).

The calorimeter signals are read out by 3" Philips XP3462B PMTs, with semitransparent bi-alkaline photocathode with peak quantum efficiency of $\sim 29\%$ at 400 nm , and 8-stage linear focused cube dynode structure. The operating voltages were set in the range $\sim 1.4\text{--}1.8\text{ kV}$ to match the gain $\sim 10^6$. The PMT base is of a purely resistive, high current (2.3 mA at 1.5 kV), surface mounted ($\sim 0.640\text{ M}\Omega$) design, operating at negative HV and linear to within $\sim 2\%$ up to the peak anode current of $120\ \mu\text{A}$ ($\sim 5 \times 10^4\text{ pe}$). The dark current is typically less than 3 nA .

The readout electronics were identical for both calorimeters. The raw anode signals from the phototubes were taken to the electronics room through ~ 480 feet RG coaxial cables, then split 50/50, with one output sent through 400 ns delay cable to a LeCroy 1881M Fastbus ADC module, and the other to a Philips 740 linear fan-in modules to be summed. Data from the Fastbus modules were acquired in the "sparsified" mode, in which only data above a threshold were read from each ADC channel. Signals from the whole calorimeter and from the front layer alone are summed for use as an option in the first level electronic trigger for e/π discrimination [3].

The calorimeter calibration is performed with electrons selected in the gas Čerenkov detector. The standard calibration algorithm [4] is based on minimization of the variance of the estimated energy with respect to the calibration constants, subject to the constraint that the estimate is unbiased. The calorimeter energy corresponding to a track is divided by the track momentum and used for particle identification.

The simulation code for the calorimeters is based on the GEANT4 package, version 9.1 [11], and the QGSP_BERT physics list [5]. The code closely emulates the geometry and the

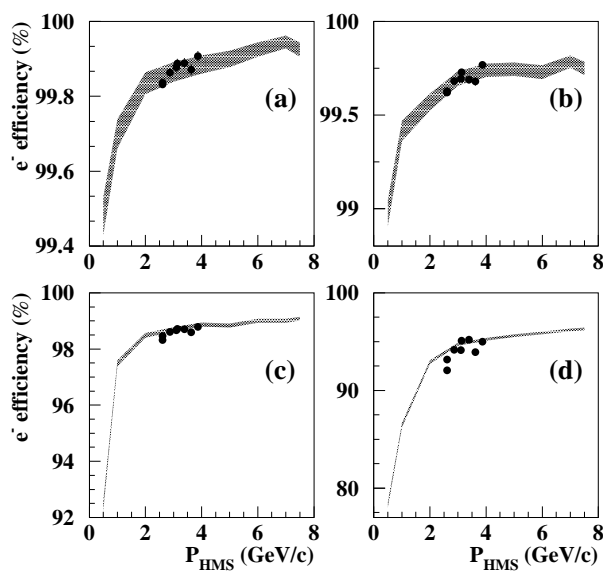


Figure 3. Efficiency of electron detection in HMS calorimeter at different momenta, for cuts on the normalized energy deposition 0.7 (a), 0.8 (b), 0.9 (c), 0.95 (d). The shaded areas represent results from GEANT4 simulations. The symbols are data from Hall C experiment E00-104.

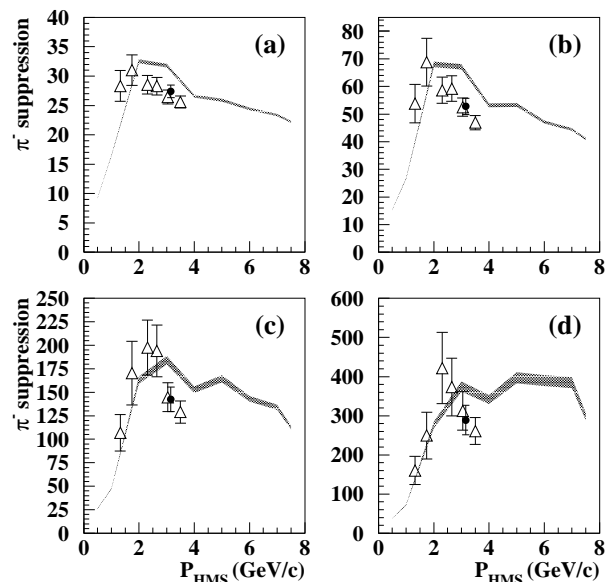


Figure 4. Pion suppression factor of HMS calorimeter versus momentum of the spectrometer, for cuts on the normalized energy deposition 0.7 (a), 0.8 (b), 0.9 (c), 0.95 (d). The GEANT4 simulation (shaded area) is compared to data from Hall C experiments E00-108 (Δ) and E00-104 (\bullet).

composition of the detector, and electronic effects in readout electronics. The projectiles are generated at the focal plane of the spectrometer, then pass through the material between the focal plane and calorimeter.

The resolution of the HMS calorimeter (shown in Fig. 2) is close to the resolution of the lead-glass calorimeters of similar thicknesses. The 3-parameter fit [8] to the simulated resolution (in %) gives dependence on energy in the form $3.75/\sqrt{E} \oplus 1.64 \oplus 1.96/E$. Experiments before the modification of the counter in 1998, such as E89-008 shown in the figure, report a resolution of $\sim 6\%/\sqrt{E}$ (E in GeV) ([3], [6]). Experiments carried out afterward found improved energy resolution. As for the SOS calorimeter, on-line data analyses of a number of Hall C experiments gave resolution $6\%/\sqrt{E} + 1\%$ within the range of SOS momentum $0.5 - 1.74$ GeV/c. Another experiment reported a resolution of $\sim 5\%/\sqrt{E}$ for momenta $1.2 - 1.7$ GeV/c [7].

The experimental efficiency of electron detection, at momenta within the range $2.8 - 4.1$ GeV/c, for different cuts on energy deposition is in reasonable agreement with the simulation (see Fig. 3). The simulation predicts a steady rise of e^- detection efficiency with energy due to the improvement in resolution. Both experiment and simulation show a momentum dependence of the π^- suppression factor peaking at several GeV/c (see Fig. 4).

The HMS/SOS calorimeters' resolution shows only slight changes during the years of usage (see Fig.2). These changes include variations in electronics, calibration technique and possible degradation of the calorimeter components. Stability of both calorimeters has also been evaluated by tracking changes in the ADC pedestals and PMT gains. No significant degradation of HMS/SOS calorimeters' performances after 15 years of operation have been noticed.

3. SHMS Calorimeter

The newly designed SHMS calorimeter consists of two parts (see Fig. 5): the main part at the rear (Shower), and Preshower before the Shower to augment particle identification capability of the detector. The Shower is 18.2 radiation length deep, which almost entirely absorbs showers from ~ 10 GeV electromagnetic projectiles, and the Preshower is 3.6 radiation length thick.

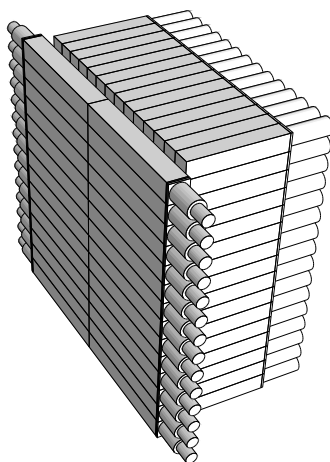


Figure 5. A sketch of SHMS calorimeter, consisting of a lateral Preshower detector and a projective Shower detector.

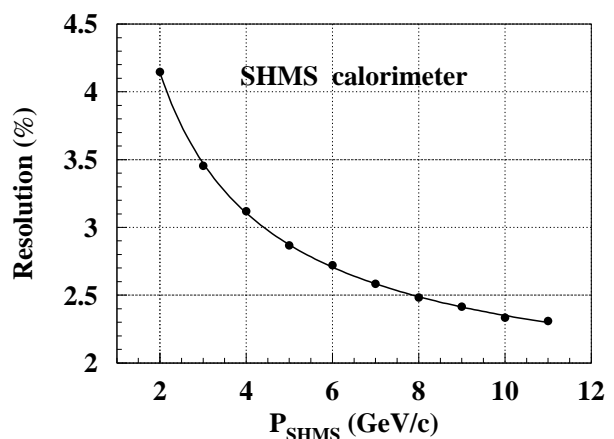


Figure 6. Resolution of the modeled SHMS calorimeter. The bullet symbols are data from the GEANT4 simulation, the line is a fit to them in the form $5.04/\sqrt{E} \oplus 1.71 \oplus 2.46/E$.

The Preshower radiator consists of a layer of TF-1 type lead glass blocks from the calorimeter of the retired SOS spectrometer, stacked in an aluminum enclosure (not shown in Fig. 5). 28 PMT assemblies, one per block, are attached to the left and right sides of the enclosure.

The Shower part consists of 224 modules from the decommissioned HERMES detector [9]. $\sim 120 \times 130 \text{ cm}^2$ of effective area of detector covers the beam envelope at the calorimeter.

The optical insulation of the TF-1 blocks in the Preshower is optimized to minimize the dead material between them. The PMT assembly tubings are screwed in 90 mm circular openings on both sides of the enclosure. The 3" XP3462B PMTs are optically coupled to the blocks using ND-703 type Bicon grease of refractive index 1.46.

The HERMES modules to be used in the Shower part are similar in construction to the HMS/SOS modules but differ in details. The radiator is an optically isolated $8.9 \times 8.9 \times 50 \text{ cm}^3$ block of F-101 lead-glass, which is similar to TF-1 in physical parameters and fractional composition. The small amount of Cerium, added in F-101 for the sake of radiation hardness ([10]), absorbs light at small wavelengths, and thus restricts the band of optical transparency to a higher wavelengths. Each block is coupled to a 3" XP3461 PMT from Photonis, with a green extended bialkali photocathode, of the same sizes and internal structure as the XP3462B the Preshower. Silgard-184 silicone glue of refractive index 1.41 is used for optical coupling of the PMTs to lead-glass blocks. See [10] for details on the construction of the HERMES module.

As both SOS and HERMES modules have been in use for more than 14 years under conditions of high luminosity, the lead glass blocks and the PMTs were checked for possible degradation. No sign of noticeable damage had been observed.

The simulation code is again based on GEANT4 package (version 9.2) [11] and the QGSP_BERT physics list [5]. The calibration algorithm is similar to the HMS calorimeter.

Resolution of the modeled SHMS calorimeter (Fig. 6) is analogous to the other lead-glass shower counters, though it is somewhat lower compared to the HMS calorimeter due to the excess of the light absorption in the F-101 lead glass in the Shower.

Electron detection efficiency improves with momentum (see Fig. 7, top), which is consistent with better resolutions at higher energies. Meanwhile, pion rejection tends to worsen because

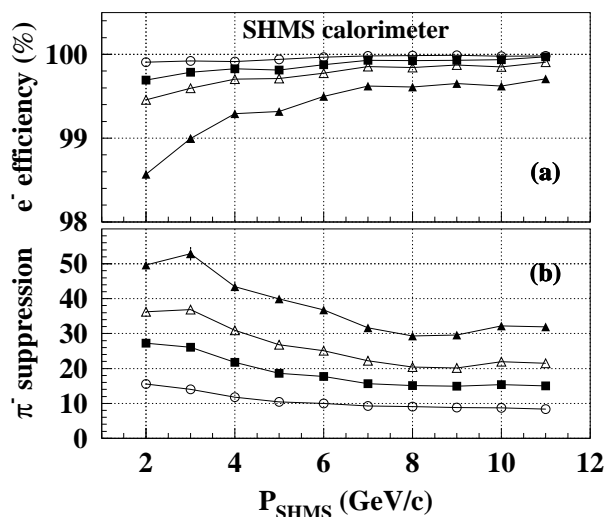


Figure 7. Electron detection efficiency (a) and pion suppression factor (b) of the SHMS calorimeter versus spectrometer's momentum setting for cuts on the normalized total energy deposition at 0.7 (○), 0.8 (■), 0.85 (△) and 0.9 (▲).

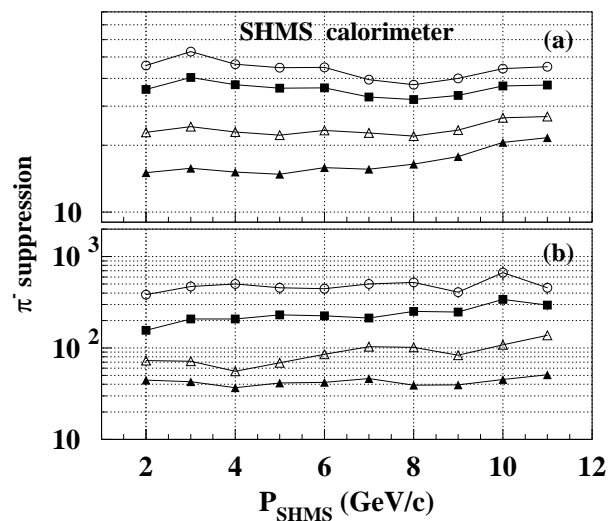


Figure 8. Pion suppression factor versus SHMS momentum setting for electron detection efficiencies 99% (○), 99.5% (■), 99.8% (△) and 99.9% (▲), by cutting on the normalized total energy deposition only (a), and by use of energy deposition in the Preshower in addition (b).

of the increase in electromagnetic component of hadron induced cascades (Fig. 7, bottom).

Combining the total energy deposition with deposition in the Preshower significantly improves the pion rejection (compare top and bottom panels in Fig. 8). A gain in suppression by a factor of 2 - 10 is achievable, dependent on momentum and the chosen electron detection efficiency.

4. SUMMARY AND CONCLUSIONS

We have developed and constructed electromagnetic calorimeters from TF-1 type lead-glass blocks for the HMS and SOS magnetic spectrometers at JLab Hall C. An energy resolution better than $\sigma/E \sim 6\%/\sqrt{E}$ and a pion suppression $\sim 100:1$ (for $\sim 99\%$ e^- detection efficiency) have been achieved in the 1 - 5 GeV energy range. Performance of the HMS calorimeter within the full momentum range of the spectrometer is modeled. Within the limited momentum range, the calculated resolution and π^- suppression factor are in good agreement with experimental data. The HMS/SOS calorimeters have been used in nearly all the Hall C experiments, providing good energy resolution and high pion suppression factor. No significant deterioration in the performance is observed in the course of operation since 1994.

Design and construction of the electromagnetic calorimeter for the newly built SHMS spectrometer in Hall C have been finalized. Preshower+Shower configuration was selected. A Monte Carlo program for the counter was developed, and simulations have been conducted with realistic parameters of the detector. The predicted resolution is slightly lower than that for the HMS calorimeter. Good electron/hadron separation can be achieved by using energy deposition in the Preshower along with total energy deposition in the calorimeter. A pion suppression factor of a few hundreds is predicted for 99% electron detection efficiency.

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