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The Calorimeter System of the new muon *g-2* experiment at Fermilab

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Abstract

The electromagnetic calorimeter for the new muon $(g-2)$ experiment at Fermilab will consist of arrays of PbF_2 Čerenkov crystals read out by large-area silicon photo-multiplier (SiPM) sensors. We report here the requirements for this system, the achieved solution and the results obtained from a test beam using 2.0 – 4.5 GeV electrons with a 28-element prototype array.

Keywords: Lead-fluoride crystals, Silicon photomultiplier, Electromagnetic calorimeter
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1. Requirements on the Calorimeter system

The new muon $(g-2)$ experiment, E989, at Fermilab will measure the muon anomaly a_μ to a precision of 0.14 ppm [1]. It will require 24 electromagnetic calorimeter stations placed on the inside radius of a magnetic storage ring. The muon precession frequency data is obtained from the decay of 3.1 GeV/c muons repeating many $\sim 700\,\mu$s "fills." The calorimeter system is composed by a segmented lead fluoride calorimeter readout by silicon photo-multipliers (SiPM). The primary physics goal of the calorimeter is to measure energy and hit time of daughter positrons. The requirements on the energy and time measurements are:

- Relative energy resolution of the reconstructed positron energy summed accross calorimeter segments must be better than 5% at 2 GeV.
- Timing resolution of the hit time extracted from the fit of the SiPM current pulse must be better than 100 ps for positrons with kinetic energy greater than 100 MeV in any combination of temporal and spatial pileups.
- The calorimeter must be able to resolve two showers by temporal or spatial separation. The calorimeters must provide 100% efficiency in the discrimination of two showers with time separations greater than 5 ns. Showers that occur closer in time than 5 ns must be further resolved spatially in more than 66% of occurrences.
- The gain (G) stability requires a maximally allowed gain change of $\frac{\delta G}{G} < 0.1\%$ within a 200 μs time period in a fill.

2. Design of the calorimeter system

The electromagnetic calorimeter system consists of 24 stations, each made of 54 lead fluoride (PbF_2) crystals in a 6 high by 9 wide array, with each crystal read out on the rear face using a large-area SiPM coupled directly to the crystal surface.

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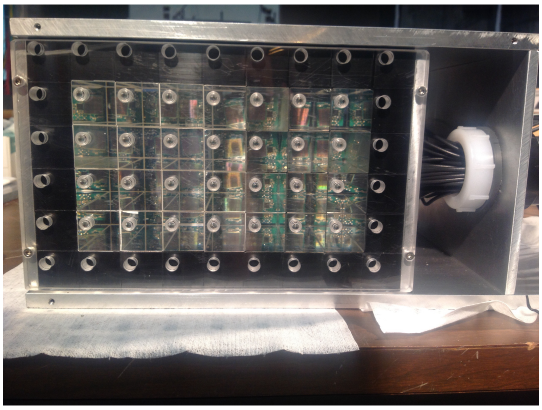

Figure 1: A prototype of the $(g-2)$-calorimeter, tested at SLAC. This test-box consisted of a 4×7 PbF_2 crystal array with each crystal coupled to a Hamamatsu SiPM.

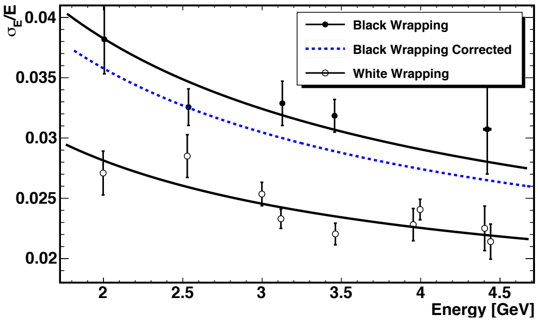

Figure 2: Energy resolutions of 3×3 arrays of PbF_2 crystals with black and white wrappings as a function of energy. Fit functions are of the form $\sigma_E^2/E^2 = (1.5\,\%)^2 + a^2/(E/\mathrm{GeV})$. The blue dashed line is the result of correcting the black-wrapped curve for dead SiPM channels.

PbF_2 has very high density (7.77 g/cm^3), a 9.3-mm radiation length (X_0), and a Molière radius of $R_M^E = 22\,\mathrm{mm}$. The fast nature of the purely Čerenkov radiation aids in reducing pileup. In fact, the intrinsic pulse width from photon arrivals is affected noticeably by the choice of wrapping [2]. To verify the overall gain stability, each of the 24 stations must be equipped with a calibration system that must monitor the gain continually during the muon spills with a precision of $\sim 0.04\%$ [3].

3. Result from test beam

To characterize the performance and properties of this detector, we completed a study of a prototype array at SLAC's End Station Test Beam Facility. The facility provides a well-collimated beam of electrons at a user-defined rate with a typical rate of $5-10\,\mathrm{s}^{-1}$. Energies from 2 to 4.5 GeV were used in the present study. At each setting the beam energy was known to about 50 MeV and stable to better than 1 %.

The calorimeter prototype tested at SLAC was a 4×7 array of $2.5\times2.5\times14\,\mathrm{cm}^3$ ($15X_0$) high-quality PbF_2 crystals, grown by SICCAS[5] (see Fig. 1). Each crystal in the first four consecutive columns was wrapped in a single, non-overlapping layer of reflective white Millipore® paper, whereas each crystal in the remaining three columns were wrapped in matte black absorbing Tedlar™. The Millipore Immobilone-P is a polyvinylidene fluoride membrane with 0.45 μm pores, and acts as a Lambertian (diffusive) mirror. The upstream face for all crystals was left unwrapped to permit the injection of light from a calibration system. Each crystal was viewed by a monolithic 16-channel Hamamatsu MPPC[6] (SiPM). The SiPM used has 57,600 50-μm-pitch pixels in a $1.2\times1.2\,\mathrm{cm}^2$ area, an entrance window made from epoxy resin with a refractive index of 1.55, and was optically matched to PbF_2 via NuSil LS-5257 optical grease. When a photon strikes a SiPM pixel, it can cause an avalanche that is summed together with the other struck pixels in a linear fashion to produce the overall response. Quenching resistors are intrinsic to the device to arrest the avalanche and allow a fired pixel to recover with a time constant typically in the 10's of ns. The pixel recovery time is very much dependent on the SiPM fabrication properties. For good near-linear operation, the number of pixels must exceed greatly the highest photon count that is expected to reach a device. A deviation from linearity at high light levels is caused by pixel saturation, that is, the suppressed ability for a single pixel to have more than one avalanche within a single recovery period. For our crystals, we anticipated approximately 1 pe/MeV, where pe (short for photo-electron) represents a converted photon. The $(g-2)$ highest single electron energy is $\sim 3100\,\mathrm{MeV}$, which implies a maximum pixel occupancy fraction near 5 %. The results obtained at the Test Beam were:

- The energy resolution, light yield, and linearity characteristics of a PbF_2 calorimeter coupled with SiPM readout is found to either exceed or meet performance of previous PMT-coupled arrays.
- The absolute energy scale in units of photo-electron per pulse-integral can be obtained using only the laser system, independent of beam, and the calibration system can monitor the gain to a relative precision of better than 10^{-4} per hour.
- White-wrapped crystals exhibited an energy resolution σ/E of $(3.4\pm0.1)\,\%/\sqrt{E/\mathrm{GeV}}$, with nearly twice the light yield compared to black-wrapped crystals, that had a resolution of $(4.6\pm0.3)\,\%/\sqrt{E/\mathrm{GeV}}$ (see Fig. 2).
- The crystal wrapping affects more than just the light yield; it affects the pulse-shape as a function of impact position, in particular with a white diffusive wrapping.

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[6] Multi-Pixel Photon Counter Model number S12642-4040PA-50 [4].

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