Nuclear Instruments and Methods in Physics Research A 1063 (2024) 169278

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Novel 4x4 SiPM array readout with integrated preamplification stage, optimized for the PWO detectors of the EIC EEEMCal☆

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ARTICLE INFO

Keywords:
Lead tungstate
PWO
PbWO4
SiPM readout
MPPC readout
Silicon photomultiplier
EEEMCAL detectors
High energy physics detectors
Fast SiPM readout

ABSTRACT

We are reporting on a new readout circuit developed for the lead tungstate (PbWO4) scintillation detectors for the Electron Ion Collider (EIC) Electron Endcap Electromagnetic Calorimeter EEEMCal. The high magnetic field region precludes the use of photomultiplier tubes while the detector requirements specify good spectral resolution performance and fast pulse integration over a large dynamic range. We selected a silicon photomultiplier (SiPM) from Hamamatsu and produced a matrix of 4 x 4 sensors to cover the 20 mm × 20 mm scintillator coupling surface. Signal acquisition and amplification electronics boards were designed and integrated with the sensor board to produce a compact high performance readout package. A prototype detector was built and tested at Jefferson Lab with encouraging resolution and timing performance results.

1. Introduction

The Electron Ion Collider (EIC) is a new installation based on the existing RHIC, which is under construction at Brookhaven National laboratories. The head-on collisions between ion and electron beams will help probe the structure of matter at the smallest scale. For example, the highly energetic collisions between electrons and nuclei will be able to release quarks and gluons from the particle structure. The color charged quarks and gluons released into the quantum vacuum will undergo changes before reverting to colorless matter. The study of these changes will bring new knowledge to the physics of matter at the smallest scale, such as the difference between quark and gluons behavior and interactions in vacuum and within a large nucleus. The collision products from the collisions are detected using several detector assemblies, one of them being the EEEMCal. This detector is built around many 20 mm × 20 mm x 200 mm PbWO4 scintillation crystals. Due to the high magnetic field in the detector region, vacuum tube photomultipliers (PMT) cannot be used and instead semiconductor photodetectors are required. These silicon-based photomultipliers, also called Multi-Pixel Photon Counters (MPPC) consist of arrays of avalanche photodiodes (APD) pixels operating in Geiger mode. The output signal consists of the sum of all signals from the pixel that have been activated during the input light pulse. SiPM devices operate differently than PMTs. The photosensor selection was performed so that the detector performance would meet the preliminary requirement criteria for dynamic range and signal integration time window with the highest spectral resolution and

☆ This work was supported by the Department of Energy, USA. Jefferson Science Associates, LLC operated Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-06OR23177. The project is finance by Technology Agency of the Czech Republic , Project TREND FW01010218.

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https://doi.org/10.1016/j.nima.2024.169278
Received 30 June 2023; Received in revised form 13 March 2024; Accepted 19 March 2024
Available online 26 March 2024

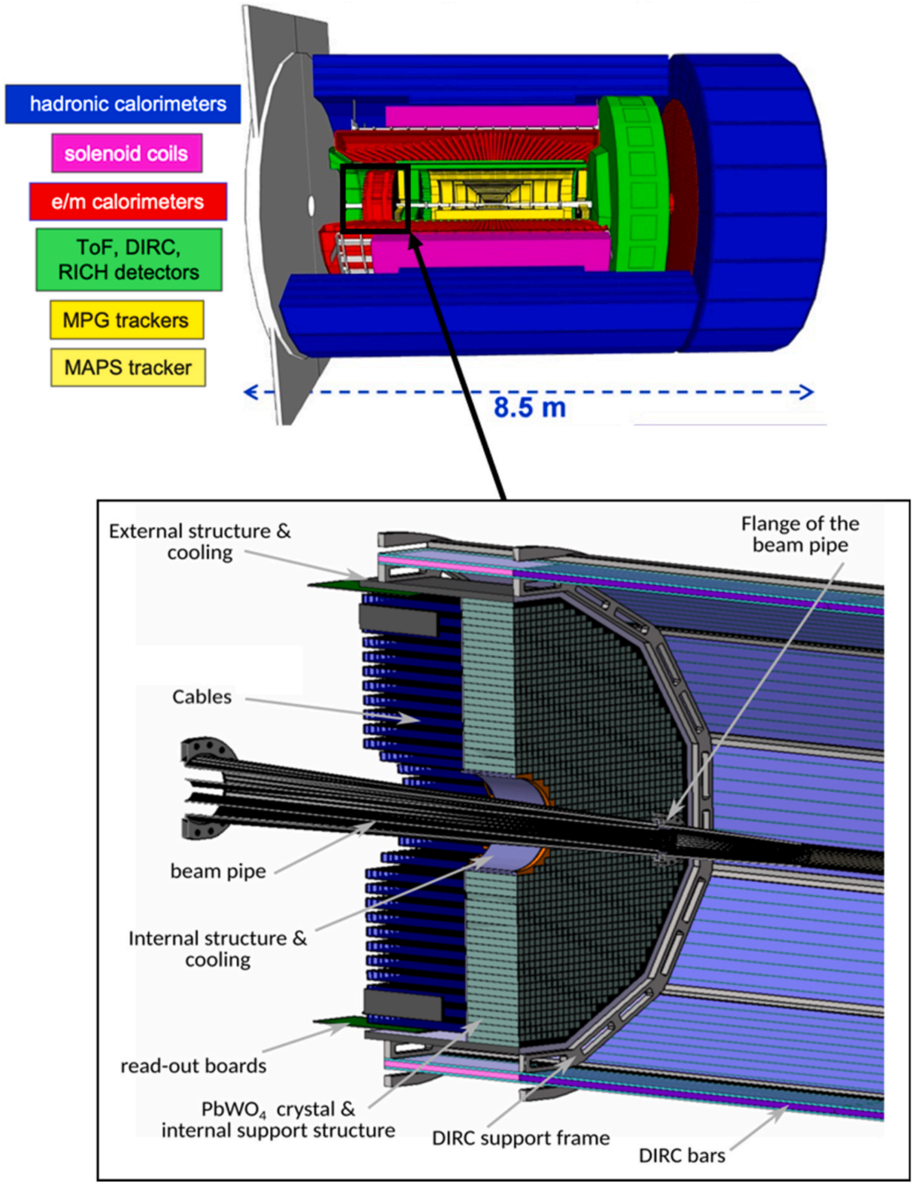
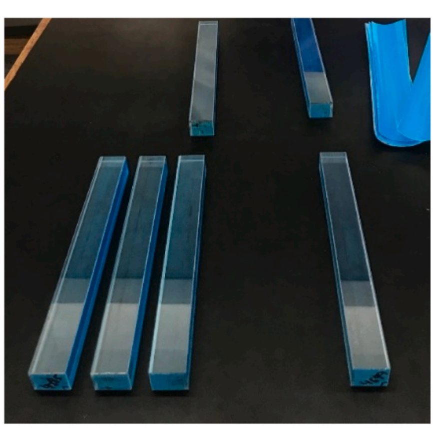


Fig. 1. EIC detectors and closeup detailed sketch of the EEEMCAL assembly (color online).



Density (g/cm^3)	8.28
Hardness (Moh)	4
Refractive index	2.17
Melting point (°C)	1123
Crystal structure	Tetragonal symmetric
Hygroscopic	No
Wavelength max emission (nm)	420
Decay constant (ns)	5 - 15
Photon yield (ph/MeV)	15 - 25
Molière radius (cm)	2.0

Fig. 2. PbWO4 crystals and table of the material's relevant properties.

Table 1
EIC geometry for the LD EMCal in the Central Detector section.

Component	WBS	Length (cm)	Inner Radius (cm)	Outer Radius (cm)	Offset from Center (cm)	Physical Start (cm)	Physical End (cm)	Volume (m^3)	Weight (kg)	Technology	Notes
LD EMCal	6.10.05	60	9	63	−174	−234	−174	0.73	4738	PbWO4	Offset: measured from face nearest to interaction point Weight: estimated as 85% lead glass and 15% steel
Service Gap		10			−320	−320	−330				Offset: measured from location nearest to interaction point

Table 2
Overview of initial EEEMCal Design Specifications.

Coverage: • -3.4< eta < -1Rin = 15 cm, Rout = 49 cm Egamma: •20 MeV–20 GeV Energy Resolution: •1% = 2.5%/sqrt(E) + 1%/E Spatial Resolution: •1 mm = 3mm/sqrt(E) Maximum Annual Dose at top luminosity: •EM: ~3 krad/year (30 Gy/year) •Hadron: 10^10 n/cm^2	Signal Dynamics: •2V dynamic range •ADC 14 bit Signal Rate: •=< 1 MHz/channel Digitization gate: •~(100–200) ns Sampling Rate: •250 MHz Data sparsification/feature extraction: •Peak •Integral •Time •Pedestal •Number samples •Pulse quality •Pileup detection and recovery

response linearity. A readout assembly was built with a 4x4 SiPM array directly coupled to a preamplification stage. In addition, the compact electronics module includes the bias control for the SiPMs and adjustable gain and offset controls via a USB and RS485 interface. The design was optimized for high performance with a small footprint and low energy consumption/heat dissipation. The choice of SiPM sensor, the design of the SiPM signal extraction, summation and amplification were critical for this performance optimization. The electronics assembly requires no active cooling for stable operation, which is an important feature for future implementation at EIC, requiring compactness of assembly of several thousands of modules in a barrel shape. The bias voltage is fixed, and the preamplifier gain and offset settings are saved locally on EEPROM and are adjustable externally through the communication port. A detector prototype was constructed with a 3x3 array of 20 mm × 20 mm x 200 mm PbWO4 crystals coupled to individual sensor arrays and readouts. The detector was tested at the Thomas Jefferson National Accelerator Facility with 5 GeV positrons.

2. The EIC EEEMCal and initial design specifications

The EEEMCal is still in the design stages, but the structure and a set of initial specifications are available. This calorimeter is part of a larger detector assembly with details shown in Fig. 1.

An overview of the science requirements and detector concepts for the EIC are available in the EIC Yellow Report [1]. The lead tungstate crystals for the instrument are grown by double Czochralski method where the material is purified during the first growth which produces the starting material for the second growth. This is necessary to produce crystal of the highest purity that can meet the radiation hardness required for the instrument. In addition, the consistent light yield and optical properties produce good spectral resolution in the GeV range and enable measurements at photon energies in the MeV range. Fig. 2 shows PbWO4 crystals elements next to a table with the material's relevant properties.

The geometry of the calorimeter as of January 2023 is summarized in Table 1.

An overview of the design specifications for the scintillation detector section is shown in Table 2. The parameters guiding the SiPM sensor choice are the large dynamic range from 20 MeV to 20 GeV, the high energy resolution, and the high signal rate with short digitization gate.

3. Readout concept and architecture

The parameters guiding the SiPM sensor selection included devices with high photodetection efficiency (PDE) to maximize signal collection

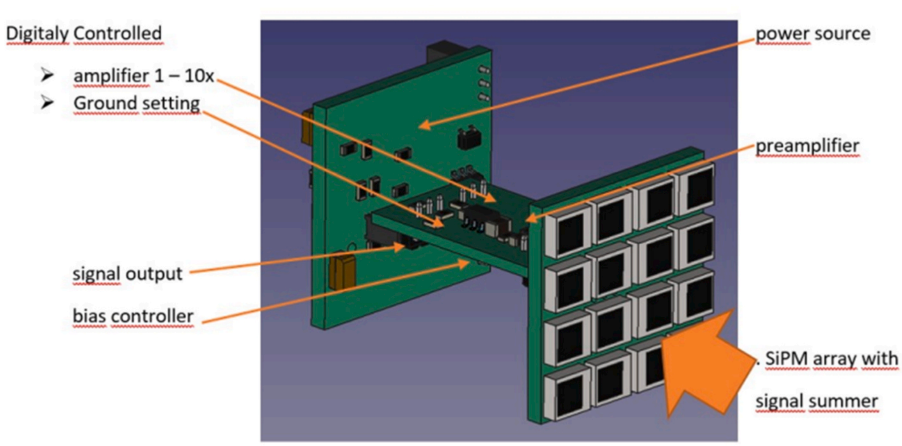


Fig. 3. Sketch of the readout electronics mechanical assembly.

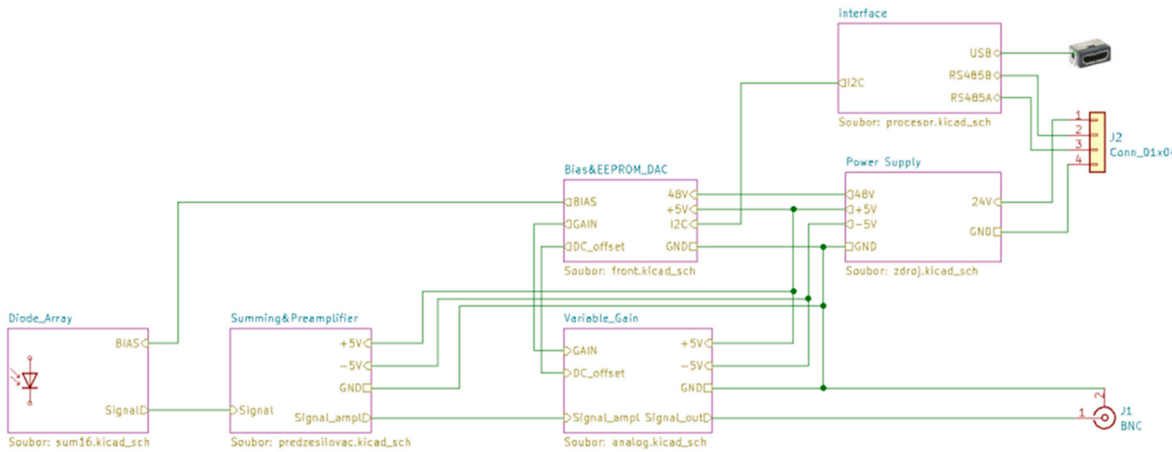


Fig. 4. Functional diagram of the electronics circuit.

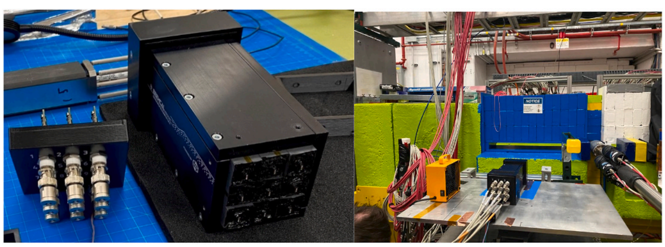


Fig. 5. 3 x 3 crystals prototype open to show the optically sealed photosensor boards and installed in Hall D at Jefferson Lab.

for high spectral resolution, low capacitance for fast signal collection, small cell size and large number of cells for high dynamic range and good response linearity, a high fill factor for enhanced signal collection, low noise and low dark counts for a good signal to noise ratio, and finally a good format to fill the 20 mm $\times$ 20 mm crystal coupling face area. The Hamamatsu S14160-3015 was selected as the best compromise. The sensitive area of 3 mm $\times$ 3 mm is populated with 39,984 15 μm microcells. The photon detection efficiency (PDE) is 32% at 450–500 nm and 30% at the 420 nm maximum emission wavelength of PbWO4. The terminal capacitance is reasonably low at 530 pF. The dimensions of the package are 4.35 mm $\times$ 3.85 mm, which allows for the fabrication of a 4 x 4 SiPM matrix to cover the 20 mm $\times$ 20 mm coupled face of the scintillator crystal. A sensor board was developed with the 16 SiPM units on one side and a signal collection circuit in the back. This board is connected to a second board housing the preamplification stage, the bias controller and an amplification stage with adjustable gain and offset, and a temperature sensor with a temperature correction feedback circuit to regulate the SiPM bias voltage for constant amplification. A third board includes the power supplies and a communication port for signal output, temperature signal and gain and offset adjustments for the amplifier. Fig. 3 shows a sketch of the mechanical assembly and Fig. 4 shows the functional diagram for this custom readout electronics circuit.

4. Detector prototype with 3 x 3 PbWO4 crystals and readout assemblies

A detector prototype was built with a 3 x 3 matrix of PbWO4 crystals, each coupled to a SiPM readout assembly. The crystals were packaged according to a technique which enhances light collection and minimizes optical cross talk with a minimum thickness of material between neighboring crystals [2]. The crystals were wrapped with 60 μm thick Enhanced Specular Reflector film from 3 M, which provides 98.5% reflectivity over the visible spectrum. The reflectorized crystals are

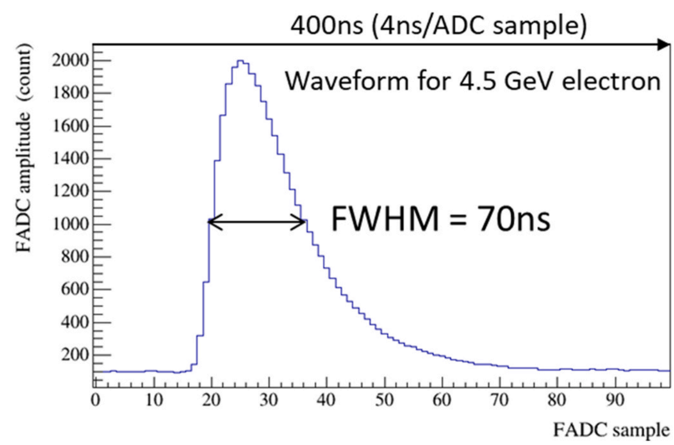


Fig. 6. Digitized waveform for a 4.5 GeV positron detection.

wrapped in a 25 μm layer of Tedlar extending over the SiPM board to provide optical isolation between adjacent detector assemblies. The photosensor boards are optically coupled to the crystals and optically sealed in the Tedlar wrap using a black RTV as shown in Fig. 5.

5. Detector test in the positron beam at Jefferson Lab

The prototype was tested using a beam of positrons provided by the Pair Spectrometer [3], which is a key component of the GlueX detector in the experimental Hall D at Jefferson Lab. The detector was installed in Hall D as shown in Fig. 5, downstream of the pair spectrometer. Electron-positron pairs are produced by the primary photon beam interacting with a beryllium converter. Lepton pairs are deflected in a 1.5T dipole magnet and detected using two layers of scintillation counters positioned symmetrically around the photon beam line. Each arm consists of 8 coarse counters and 145 high-granularity counters. The high-granularity hodoscope is used to measure the lepton momentum. The position of each counter corresponds to the specific energy. Each detector arm covers the lepton momentum range 3–6.2GeV/c. The energy resolution of the Pair Spectrometer is estimated to be better than 0.6%. The vertical spread of the positrons is about 7 mm. The position of the prototype was surveyed and aligned with respect to the beam line and the center of the pair spectrometer magnet, such that the lepton beam spot is focused on the center row of the prototype, perpendicular to the front face of the crystals. Therefore, the center of an electromagnetic shower is situated in one of the modules in the central row (and contains the largest energy). This results in much higher ADC

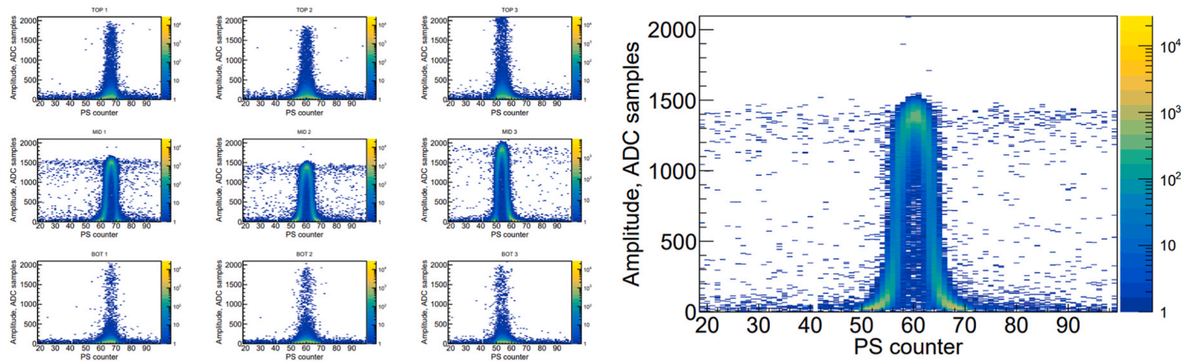


Fig. 7. Charge response of the 3x3 channels (left) and central cell (right) vs. pair spectrometer hodoscope counter number (energy).

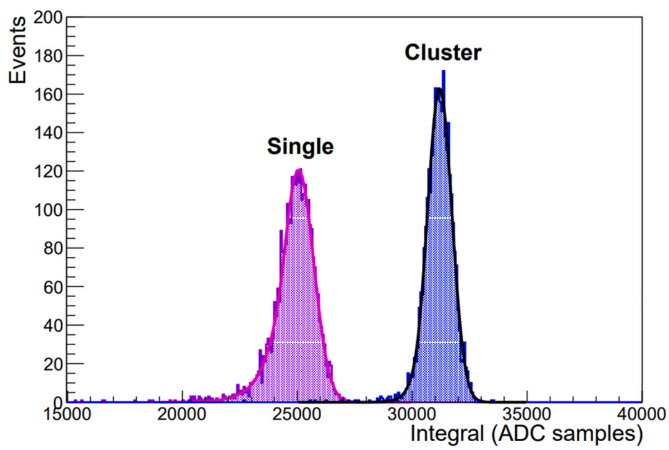


Fig. 8. Energy resolution for 5.8 GeV positrons for the central cell and for the sum of all 9 cells.

amplitudes in the central row compared to that in the top and bottom. The detector amplifier output is routed via a 50 ft cable to the JLab fADC250 digitizer with 1V dynamic range and 12-bit ADC [4]. A digitized waveform for a 4.5 GeV positron detection is shown in Fig. 6 and demonstrates the fast signal rise and fall times, meeting the requirement of the 100–200 ns digitization gate for EEEMCal detectors.

The charge response was acquired for all channels and recorded against the pair spectrometer hodoscope counter number indicating the positron energy. The charge response plots are shown in Fig. 7 for the 3x3 matrix with a closeup view of the central cell response. From this data, histograms of the pulse height for a specific energy can be obtained and the spectral energy resolution figures are computed. The central module in the shower contains about 80% of the overall deposited energy. This can be seen from Fig. 8, which presents the energy distribution in the central cell of the shower and the energy summed over 3x3 cells around the central cell (E1/E9 ∼ 2500/31000–0.8). As expected, the relative energy resolution (i.e., the width of the energy distribution over the mean) is significantly improved when the energy is summed over an array of 3x3 cells. The resolution for the sum of the 9 cells was computed to be 1.71%. Additional measurements were performed at 4.542 GeV with a resolution of 2.15%. The results are plotted in Fig. 9 against reference performance measurements from a PMT based prototype and the complete PMT based calorimeter results measured during the PrimEx – eta experiment [2]. The measured differences in spectral resolution between the PMT based calorimeters and the SiPM prototype are essentially due to the different sensitive areas and quantum efficiencies of the photosensors. The sensitive area of the prototype readout is comprised of 16 SiPMs of active dimensions 3 mm × 3 mm with a photodetection efficiency of 30% at 420 nm. The Hamamatsu R4125 PMT used for the calorimeter during the PrimEx experiment has an

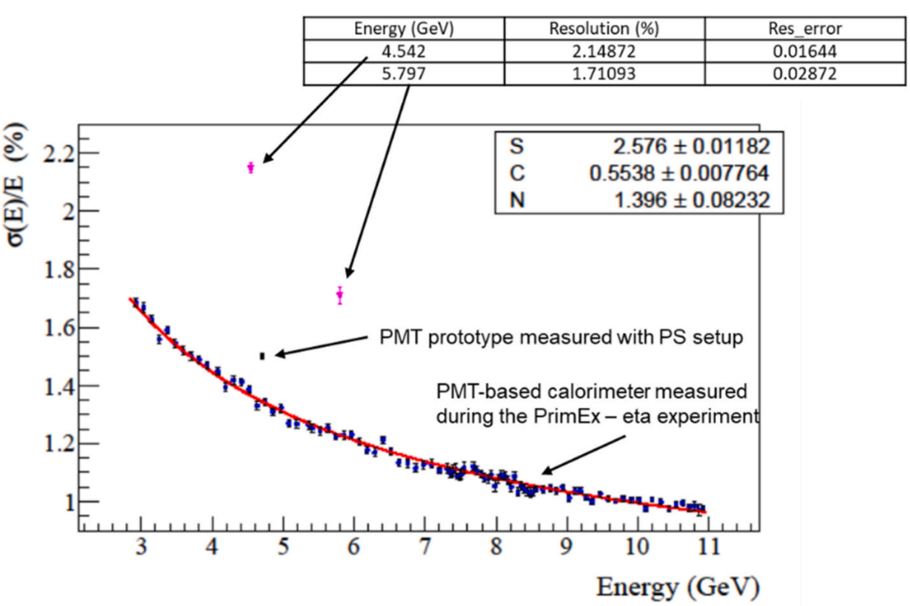


Fig. 9. detector resolution performance vs. positron energy plotted against a 3x3 PMT based prototype and a complete PMT based calorimeter [2].

entrance window diameter of 19 mm and a typical quantum efficiency of 27% at 420 nm. The overall efficiency of the SiPM array can be defined as the product of the sensitive area (16 × 3 mm x 3 mm), and the photodetection efficiency (0.30) divided by the crystal face area (20 mm × 20 mm). Similarly, the efficiency of the photomultiplier is the input window area multiplied by the photocathode quantum efficiency divided by the crystal face area. The detection efficiency ratio between the SiPM array and the photomultiplier can be computed and gives a result of 0.564. A 3 x 3 crystal on PMT prototype array had been tested and produced a resolution of 1.5% at 4.7 GeV as indicated by the black square on Fig. 9. As a first order approximation, let's consider that spectral resolution scales with the square root of the signal level. The same PMT based prototype array would produce a resolution of 1.5% x sqrt(4.7/4.54) = 1.53% at 4.54 GeV. If we now compute what the resolution would be at 4.54 GeV if the sensitivity were reduced by a factor 0.564 (the relative sensitivity of our SiPM array), the result is 1.53%/sqrt(0.564) = 2.03%, which is close to the 2.15% measured during our experiment.

6. Summary

We are reporting the first beam test results with a PWO/SiPM prototype using a 4 x 4 array of S14160-3015 units to cover the 20 mm × 20 mm crystal face with an active coverage of 36%. The use of SiPMs enables detector positioning in high magnetic field environments without the need for high voltage cables. The custom readout electronics assembly is compact, modular, and scalable with low power consumption and allows for simple maintenance and replacement. The 3 x 3 PWO prototype was successfully tested in the high energy positron beam at JLab and met the goal of validating the electronics design and performance for high-energy physics applications. The results on energy resolution are promising. Further tests are planned for different energy ranges <1 GeV with precise calibration of each module for the defined energy. Further improvements will be investigated where lower temperatures from active cooling could bring lower noise levels from the SiPM while getting higher signal and better resolution from the PWO crystals. The readout threshold can also be optimized further. Finally, a 5 x 5 PWO crystal array prototype will produce better performance by capturing the particle shower fully with better energy deposition and energy resolution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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