Performance of the PHENIX EM Calorimeter

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Abstract

The PHENIX Electromagnetic Calorimeter is a large 15,552 channel lead/scintillator sampling calorimeter based on the shish-kebab optical readout technique[1]. In this report we summarize studies leading to an optimal design for measurement of photons and electrons in the 1 GeV momentum range within the high multiplicity environment expected for events at RHIC. Timing resolutions of $\sim$ 100 ps and a sampling dominated energy resolution of 8% at 1 GeV are featured. We also present a novel scheme for monitoring gain and timing of our entire system.

Test results with a 144 channel preproduction "supermodule" exposed to electron and hadron beams at the AGS are described. The calorimeter is currently under construction in Russia and the US and will be fully installed at RHIC during 1998.

I. Requirements

The central spectrometer of the PHENIX Experiment at RHIC is constructed from two Arms, each subtending a band of $\pm 20^\circ$ about the perpendicular to the beam directions and 90° in azimuth. Outside of the charged particle tracking regions, the electromagnetic calorimeter walls are located 5.3 m from the RHIC colliding beams (Figure 1).

The calorimeter will measure photons and electrons produced in Heavy Ion collisions (where charged multiplicities of up to $\sim$ 200 over the calorimeter area are expected). With our design, th eprobability for showers to overlap is at the 5% level.

The long flight path to the calorimeter allows for some charged particle identification by time-of-flight (TOF) since $\pi^\pm(K^\pm)$ (with an average momenta of $p_t=$ 300 MeV/c) lag behind the "photon flash" by 2(16) nsec. The calorimeter timing measurement complements that of the limited size, high precision TOF scintillator hodoscope. In addition, it provides the only means of measuring the TOF of $\bar{n}$'s and other potential neutral backgrounds to γ's.

[1] This work was supported in part under Department of Energy Contract No. DE-AC02-CH7600016.

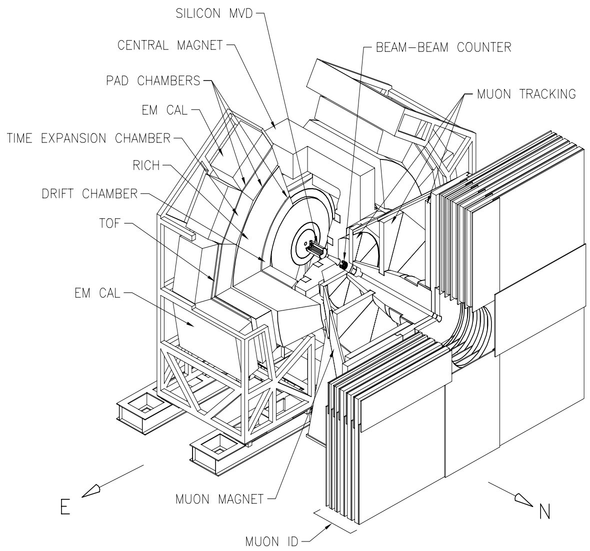

Figure 1: Cutaway view of the PHENIX Experimental layout.

II. Construction

The basic calorimeter element is a module 11.4 cm by 11.4 cm on a side which is optically segmented into 4 independent towers. Each scintillator layer consists of 4 identical 5.52 by 5.52 cm tiles which are injection molded with a pattern of 36-1.3 mm diameter holes for the readout waveshifter fibers. One corner from each tile is flattened in the mold to form a "window" for introducing UV pulses from a lossy optical fiber, used for gain monitoring purposes.

The tiles are arranged with the windows facing the center of the module and this leaves room for a 2 mm diameter optical fiber (seen in the cutaway view of Figure 2) to be passed through the center of the module. Aside from the window, the remaining 4 edges of the tiles are mirrorized using aluminum vapor deposition. This ensures optical isolation of the 4 towers and helps to maintain tower response near the edges.

We used TYVEK paper for an external light reflector on the faces of the scintillators. The modules are assembled by stacking 1.5 mm thick Pb absorber plates, a TYVEK

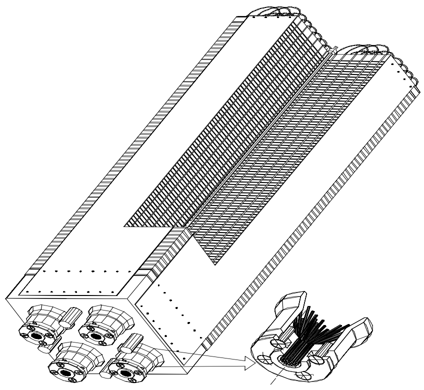

Figure 2: Cutaway view of four tower module assembly.

sheet, the 4 scintillator(4mm thick) quadrants and a second TYVEK reflector in each of the 66 sampling layers.

The module is assembled on a fixture which provides mechanical training of the stack and then the module is tack welded under compression with 0.1 mm thick side straps. End pieces are formed from injection molded plastic with a thin steel shell.

A 6 by 6 array of modules is assembled into a "supermodule" whose structure provides mechanical rigidity and precise location of the calorimeter towers. Each 2 m $\times$ 4 m sector shown in Figure 1 contains 18 supermodules.

III. Readout Principle

Scintillation light produced in the tower is read out through waveshifter doped optical fibers which penetrate the module. A total of 36 fiber penetrations are provided in each tower as part of the scintillator mold. A single, continuous fiber is looped through 2 penetrations so that light emitted in both directions in the fiber will reach the readout end. This increases the size of the light signal and reduces its dependence on shower depth in the calorimeter.

The fiber ends are compressed in a collet, hand polished and phototubes are mounted on the ends with an air gap.

A 12 stage, 30 mm diameter photomultiplier tube was developed for this project [2]. Typical quantum efficiency is 16% at 490 nm and the risetime is 5 nsec. Within the 7 mm diameter illuminated by the fiber bundle the photocathode nonuniformity is $\leq$ 10% and the transit time variation is $\leq$ 2nsec.

A. *Optimization*

The PHENIX group carried out an R&D program to optimize the parameters of the optical system with respect to photostatistics, uniformity and speed of the calorimeter.

Among the scintillator plates which we tested were cast PVT based scintillator (Bicron BC404[3]) with holes drilled for the fiber channels and a variety of injection molded polystyrene (PS) based tiles. Although the PVT

PT (%)	PPO (%)	POPOP (%)	BF203 (%)	I_{mean} BCF99-29A
1.0			0.01	65.7
1.5			0.02	68.0
1.5			0.03	78.7
1.5			0.05	82.2
2.0		0.005		86.9
1.0		0.01		75.5
1.5		0.01		81.5
1.75		0.01		92.9
2.0		0.01		79.6
2.5		0.01		80.2
1.0		0.03		70.2
1.5		0.03		72.4
1.75		0.03		80.0
1.0		0.05		58.6
1.5		0.05		82.6
1.75		0.05		87.2
1.5		0.1		86.4
	1.5	0.01		82.1
	1.75	0.01		84.9
	2.0	0.01		83.2

Figure 3: Light yield (arbitrary units) vs. scintillator composition when read out with BCF99-29A waveshifter fibers.

based scintillator tended to have a higher light yield we chose the PS base because of existing expertise with injection molding of PS scintillator within our collaboration.

Different mixtures of primary scintillator (p-terphenyl) and secondary scintillator (POPOP) were tested for light yield and an optimum of 1.75% : 0.01% was chosen. We injection mold the scintillator using a dry mix of fluors with the polystyrene granules.

A summary of measured light yields is presented in Figure 3. BF203 is a Bicron fluor whose emission spectrum is better matched to the G2 waveshifter used in our readout fibers than that of POPOP.

We selected a waveshifter fluor with a fast (2.8 nsec) decay constant and a 407 nm peak absorption wavelength. The concentration was optimized using a series of fibers provided by Bicron Corp [3] and tested for effective attenuation length (which decreases with concentration) as summarized in Figure 4.

Tyvek and other reflector materials were tested for spectral reflectance in the wavelength region of 300 nm to 600 nm and Dupont 1055B, which was finally selected, was found to give approximately 50% higher light yield than white paper.

IV. Monitoring Scheme

Gain monitoring of the calorimeter will be based on a UV light pulse delivery system which couples to a leaky fiber that illuminates all scintillator tiles in a module . A prototype of this system has been operated at the AGS for over 6 months (Figure 5). The laser calibration was used to check gain stability and also provided a link between calibration runs and beam data taking.

Our goal is to produce the equivalent scintillator light of a 1-2 GeV shower (for gain calibration) in a stable, fast

Fiber	BCF92	BCF99-29a	BCF99-29b	R26	K27
Diameter (mm)	1 and 1.2	1	1	1.2	1.2
Core	PS	–	–	PS	PS
ref. index	1.59	–	–	1.59	1.59
Cladding					
inner	PMMA	–	–	PMMA	PMMA
ref.ind.	1.49	–	–	1.49	1.49
outer	-	-	-	Fluorine	polymer
ref.ind.				1.42	1.42
Fluor	G2, x mg/l	G2, 2x mg/l	G2, 4x mg/l	R26	K27
Num. aperture (%)	3.54	–	–	6	6
Peak Abs. (nm)	407	–	–	450	400-460
Peak Emis. (nm)	492	–	–	530	490
Decay time (ns)	2.8	–	–	11	6.7
L_{att} (m)	3.1	2.7	2.1	2.5	2

Figure 4: Characteristics of WLS fibers tested.

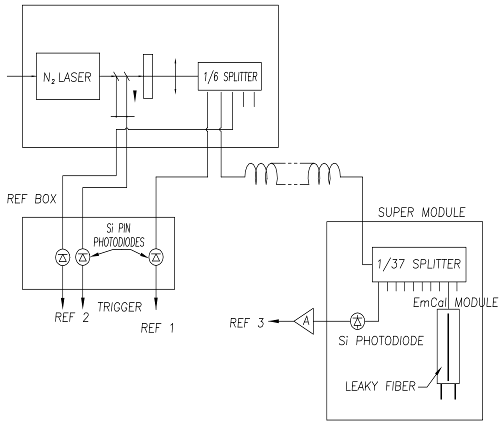

Figure 5: Laser monitoring scheme used for the AGS testbeam run.

timing pulse (for monitoring timing drifts). A relatively low power UV signal can be produced with an N2 laser with a 3nsec pulse width [5]. This was adequate for tests of a 144 channel "supermodule". However, to supply the full 108 calorimeter supermodules, $\sim 50-100$ mJ per pulse is required. For the final system we plan to use an Nd:Yag laser frquency tripled to $\sim$ 355 nm .

In our calorimeter, 1 GeV corresponds to 1600 photoelectrons. The same signal is obtained when 6×10^7 UV photons are delivered to the lossy fiber input. The pulse power requirement of the laser is determined by the measured transfer efficiency of our optical splitters which is approximately 10^{-3} and the goal of up to 10 GeV dynamic range for the laser monitoring pulses.

We make the lossy fibers with a controlled loss profile approximating that of a 1 GeV electromagnetic shower. Acrylic core step-index fibers [4] are inserted in a rotating fixture and a scribe tool scores the cladding at a variable rate of cuts/linear cm of fiber.

V. Testbeam Results

A preproduction supermodule consisting of a 6×6 module array (144 towers total) was assembled at the end of 1994 and installed at the Brookhaven AGS testbeam for the Spring '95 run. Our testbeam measurements emphasized the low energy response of the calorimeter and timing resolution with electrons and hadrons over the range $0.3 \leq p \leq 7$ GeV/c.

Electron tagging in our beamline was provided by a threshold Cerenkov counter. We also used a pair of high resolution ($\sigma_t = 100$ psec) TOF scintillation counters 11.4 m apart for particle identification, one of which was placed directly in front of the calorimeter. Location of the individual timing peaks was used to get a $\sim$ 10MeV level check on the beam momentum.

Calorimeter pulseheight was digitized using LRS 2249W Camac ADC's and timing signals from leading edge discriminators were digitized using LRS 2229A TDC's with 50 psec least count sensitivity.

The initial calibration of the calorimeter channels was obtained with cosmic ray muons selected prior to accelerator startup. A typical cosmic ray event is shown in Figure 6, in which the full supermodule is traversed by a muon track transverse to the tower axis. We are designing the calorimeter electronics to provide an internal trigger based on the number of towers above threshold in a supermodule. The most probable energy deposit is 42 MeV/tower. Calibration constants obtained from the muon peaks were consistent to better than 5% with those obtained by scanning with a 1 GeV electron beam.

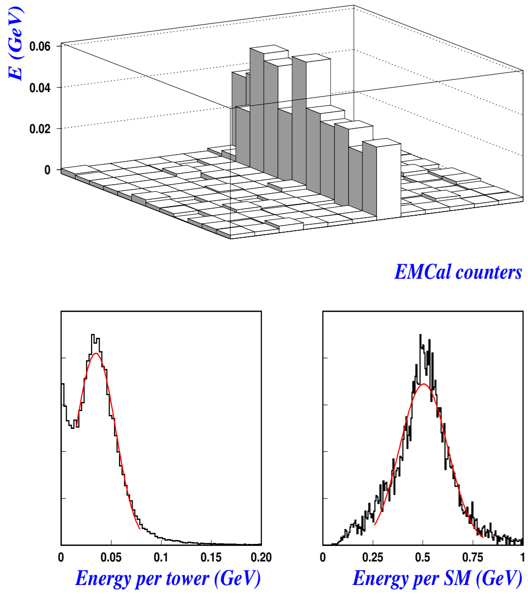

Figure 6: Response to cosmic ray muons traversing the calorimeter- a single event lego plot and the distribution of single channel and channel sums.

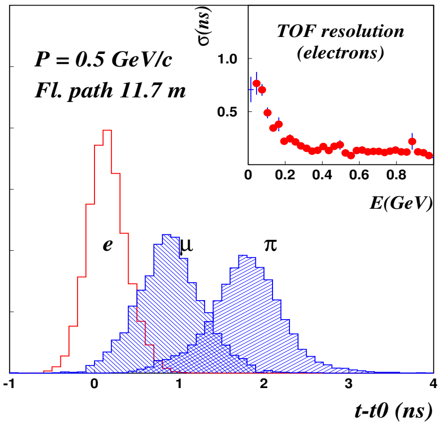

Figure 7: Time-of-flight resolution for electromagnetic showers vs. energy deposit. The lower figure shows the timing channel line shapes for a 300MeV/c beam.

A. *Time resolution*

When a hadron or electron hits the calorimeter, we define a cluster of calorimeter channels centered on the point of impact to make a shower sum. For the results presented here, energy is summed over a 5×5 tower array whenever a channel is above a digital threshold.

The time of arrival is measured using the discriminated pulse (in leading edge mode) from the channel with the maximum pulseheight. The time of arrival was then corrected offline for pulseheight slewing. Figure 7 shows the arrival time distribution measured for 300 Mev/c electrons, muons and pions relative to a scintillation counter placed 11.7 m upstream in the testbeam (twice the flight path in PHENIX).

The timing resolution was found for electromagnetic showers as a function of energy deposit in the corresponding tower. (insert in Fig.7). The resolution which is dominated by photostatistics effects at low energy falls to 100 psec at 1 GeV.

We also studied the calorimeter response to $\pi^{\pm}$,$K^{\pm}$ and $p^{\pm}$ at various energies [6] .Further results will be presented elsewhere.

B. *Response Uniformity and Energy Resolution*

The response uniformity and energy resolution of the calorimeter were measured in an electron beam while recording the impact point of tracks with a beamline tracking system. The variation of light yield in individual scintillators with aluminized edges was measured to be 8% at an edge relative to the center and somewhat larger to a corner. This variation was used to predict the amplitude variation for electromagnetic showers taking also into account dead material in the calorimeter. The calculated

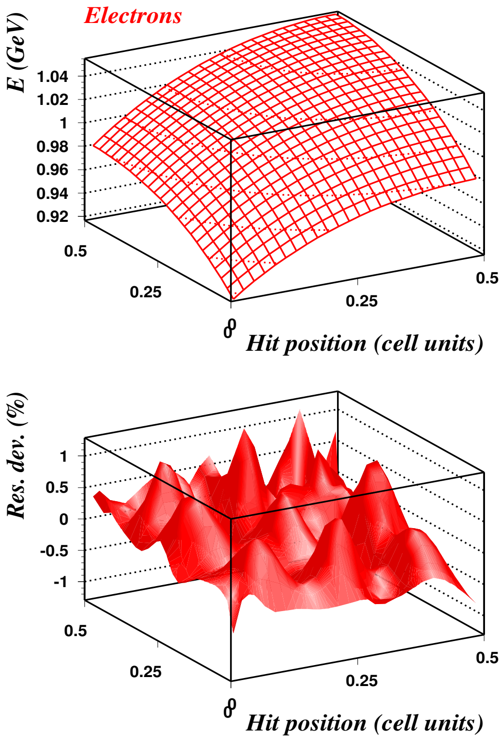

Figure 8: EMCal Uniformity Scan of electrons.

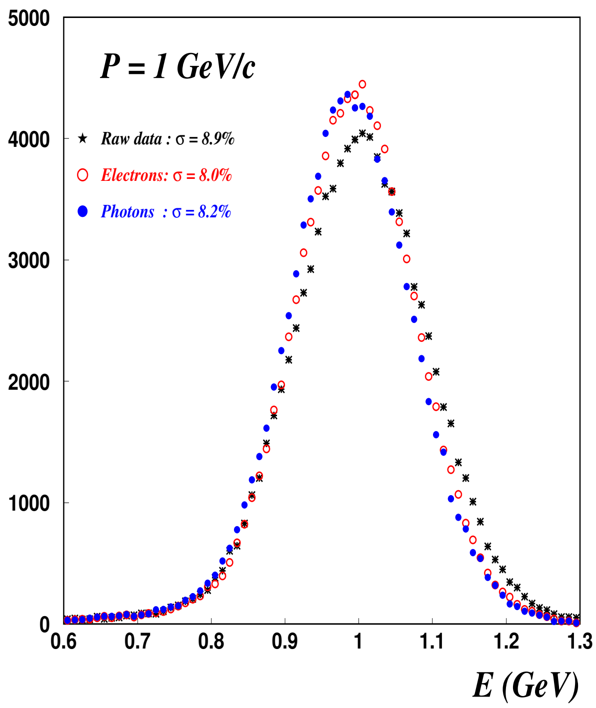

Figure 9: Energy resolution correction for response variations.

overall response map agrees well with a smooth fit to the data shown in the upper half of Figure 8. The response map can then be used to correct calorimeter pulse height as a function of shower impact so long as the impact point can be determined from an external tracking device or from the position resolution of the calorimeter itself (which we measure to be $\frac{1.0cm}{\sqrt{E(GeV)}}$).

As shown in Figure 9, the raw energy resolution of 8.9% at 1 GeV improves to 8.0% for electrons whose position will be determined by the tracking system. If there is no tracking information (as is the case for photon showers) then the resolution worsens to 8.2%. Using a detailed scan of the calorimeter response we also observed deviations from the simple smooth fit which we use in our correction map. The lower half of Figure 8 shows that these deviations which follow the fiber penetration pattern are of the order 1% or less .

VI. Acknowledgements

We wish to thank the AGS staff and particularly our liaison engineer Dave Dayton for excellent support during our test. We also thank Bo Yu, David Whitehouse and Chris Witzig for assistance at various stages of data taking.

References

[1] H.Fessler et al., Nucl. Instr. and Meth. A 240(1985) 284 and G.Atoyan et al., Nucl. Instr. and Meth. A320(1992) 144

[2] G.David et al. IEEE Trans. on Nuclear Sci. 42, No.4, P.306 (1995). The FEU 115M PMT was produced at Moscow Electric Light Plant (MELS), Moscow, Russia.

[3] Bicron Corp. Newburry, Ohio. BCF99-29a denotes a concentration of 2 times that of the product BCF92.

[4] we have used "Raytella" Fiber from Toray(America) 600 third Ave. NYC and "Infolite" from Hoechst-Celanese , Summit, NJ.

[5] VSL-337ND, Laser Sciences Inc, Newton, Ma.

[6] see G.David et al. in Proc. of the Vth Int. Conf. on Calorimetry in High En.Physics., H.Gordon and D.Rueger eds. p.211. and ref. therein.