Test beam study of the Si/W calorimeter for the PHENIX forward upgrade

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Abstract. The Si/W calorimeter prototype for the PHENIX forward upgrade has been tested using the electron beam of various energies available from PS and SPS at CERN. The measured energy shows a good linearity and the obtained energy resolution $\sigma_E/E$ can be parametrized as $3.8\% \oplus 22\%/\sqrt{E(\text{GeV})}$. The energy deposition profile measured for 6 GeV electron beam features a characteristic electromagnetic shower and agrees with the Monte Carlo simulation based on GEANT4. Position and angle of the incident electron can be reconstructed from the measured energy deposition profile. The resolution of the obtained position is 2 (mm).

1. Introduction
The PHENIX experiment at the relativistic heavy ion collider is considering an electromagnetic calorimeter FOCAL as the forward upgrade. The calorimeter is expected to replace the 20 cm thick copper absorber located at 40 cm forward from the nominal collision location. A compact calorimeter is a necessity for the upgrade due to the large particle multiplicities at forward and close proximity to the collision location. A Si/W sandwich sampling calorimeter is the natural choice to meet the needs [1].

The lateral and longitudinal segmentation of the calorimeter enables reconstruction of the electromagnetic shower initiated by the incident electron as well as its energy measurement. We can determine the incident position and angle of the beam electron up to a high precision to promote the calorimeter to a tracking device.

Possible enhancement in the PHENIX measurement capabilities achieved by FOCAL is under investigation along with the prototype performance study. General aspects of the detector FOCAL will be described in another write-up of the current proceedings [2]. This write-up focuses on the beam test of the prototype.

2. Experimental Setup
We describe relevant information and define nomenclatures for the later discussions.

2.1. Test beam
Test was performed at CERN in the July of 2009. Data collection for electron beams of lower energies (1, 2, 3, 4, 5, 6 GeV) was made at PS T10 site. Data collection for electron beams of higher energies (20, 30, 40, 50, 60, 75 GeV) was made at SPS H2 site. Total duration of data collection was 13 days.

Two homemade scintillators were positioned in front of the calorimeter and valid beam events required coincident signals from them in addition to the valid beam logic by the beam line detectors. Electron identification was also obtained from the beam line detectors. Calorimeter was rotated by 5°, 10°, 15°, 20°, and 25° to get electron beam with the corresponding incidence angle. 10k – 50k valid beam events were recorded for a given collection setting. Offline data analysis tagged and rejected about 20% of the recorded SPS events as the hadron event.

2.2. Detector and readout electronics
The prototype detector is a Si/W sandwich sampling calorimeter and has the longitudinal and lateral structure relative to the beam direction. The longitudinal direction refers to $z$(beam) direction, and the lateral direction refers to $x$(horizontal) or $y$(vertical) direction perpendicular to beam direction.

Longitudinal structure of the detector is depicted in Fig. 1 (a). The detector contains 21 sandwich layers where each sandwich layer includes a 4 mm thick tungsten plate (black) and a 525 micron thick silicon pad sensor layer (yellow). Additional silicon strip sensor layers were inserted as depicted in figure, but not included in the current analysis. Fig. 1 (b) shows an actual Si sensor. Each Si sensor layer is patched and covered by this Si sensor unit with the areal size of 6 cm x 6 cm. Each Si sensor unit is segmented into 16 pads with the areal size of 1.5 cm x 1.5 cm each.

Signals from pads at the same lateral location in the first, the middle, and the last 7 sensor layers are electrically summed and labeled as segment 0, 1, and 2. The minimum detector granule pad tower is associated to this signal. The signal produced by a given pad tower is processed by the preamp a trans-impedance amplifier circuit, digitized by the 64 MHz flash ADC, and recorded with the valid beam trigger. ADC values recorded for 20 sample time bins around beam trigger are displayed in Fig. 2. The signal shape matches the preamp circuit simulation by the SPICE[5] program, and we attribute the signal shape to the preamp electronics.

Figure 1 Longitudinal detector structure (a), and Si sensor unit (b).

Figure 2 ADC signal distribution around beam trigger.
2.3. Calibration and Monte Carlo simulation

ADC values recorded for each pad tower is fit with the predetermined signal shape after pedestal subtraction (Fig. 2). The fit parameter is the amplitude, and this signal amplitude is the energy response of the pad tower. The energy response is considered to be proportional to the energy deposited in the pad tower. The proportionality constant converts the detector signal into the energy.

We ignore variation of the proportionality constants over pad towers after exploring two equalization methods. The approach to utilize the penetrating muon signals can see only crude variations due to the low preamp gain and the finite ADC dynamic range. The other approach was to seek the optimized proportionality constant set to minimize electron energy resolution. However, no significant improvement in electron energy resolution was observed from the minimization process.

We ignore variation of the proportionality constant over time. Sensor and readout electronics are expected to be stable over time, and the method to utilize penetrating muon signals is not accurate to determine the difference.

GEANT4 [3] program is utilized to simulate the energy deposition into pad towers by the electron beam. Simulation includes the detailed description of detector and all processes involved with energy deposition. Beam transport in the beam line is not included in the current simulation.

3. Calorimeter performance

We discuss key characteristics of the calorimeter, the energy measurement and the trajectory determination.

3.1. Energy measurement

We sum signal amplitudes obtained for all pad towers to get the energy sum.

![Fig. 3 Energy sum, the distribution (a), the relation to beam energy (b), and the resolution (c). Data (Red solid line), Fit (Blue dotted line)](image)

3.1.1. Line shape

The distribution of energy sum for 75 GeV electron beam is depicted in Fig. 3 (a). The shape is characterized by a clear peak and the long lower energy tail. According to the simulation study, energy leakage such as detector inefficiency causes the tail. We determine the mean energy response $E$ and the absolute resolution $\sigma_E$ by fitting the peak with Gaussian distribution as shown. The Centroid (width) of the Gaussian distribution corresponds to $E$ ($\sigma_E$).

Conversion constant to absolute energy is determined from the 75 GeV electron beam run by adjusting $E$ to 75 GeV the nominal beam energy.

3.1.2. Linearity & resolution

The mean energy response $E$ is shown for various test beam energies in Fig. 3 (b). $E$ increases linearly with the beam energy and deviation from the line fit $y = ax$ is by less than 2.5% for all test setting.
Another fit by the function \( y = ax(1 + bx) \) with the nonlinearity parameter \( b \) was also performed. Non-linearity parameter \( b \) was determined to be 0.085%/GeV.

The (fractional) energy resolution \( \sigma_E/E \) is shown for various test beam energies in Fig. 3 (c). Solid lines are fit by the function \( \frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \), where \( E \) is in GeV. The coefficient \( a \) (\( b \)) is 22% (3.8%).

The contribution from stochastic fluctuation term dominates the resolution at low energies and is comparable to the one from constant term at the highest energy.

3.2. Trajectory determination
The measured energy deposition profile for electron beam features the electromagnetic shower in the longitudinal and the lateral direction. The calorimeter can determine the incident position and angle of the shower initiating particle accurately.

3.2.1. Lateral and longitudinal energy deposition profile
Fig. 4 shows the measured longitudinal and lateral energy response profile for 6 GeV electron beam. Measured energy sum are displayed for data (red) while mean energy depositions are displayed for simulation (blue).

The energies distributed in segment 0, 1, and 2 add up to 6 GeV the beam energy. Segment 0 contains the largest fraction of energy and segment 2 contains 1% of the total energy. Simulation suggests the electromagnetic shower initiated by the incident electron reaches maximum quickly within segment 0 and decays slowly along the longitudinal direction.

Figure 4 Longitudinal and lateral energy response (data in red) and deposition (simulation in blue)
The lateral energy response shows strong peak within ±1 pad unit from maximum. Pad size 1.5 (cm) was chosen to match the Molière radius of the calorimeter and the observed feature is consistent to the characteristics of the typical electromagnetic shower [4]. Simulated lateral energy deposition profile also agrees with data.

An interesting fact is noted. Agreement between the data and the simulation matches best when we add material of 0.3 radiation length thickness (1 mm thick tungsten plate) in front of the calorimeter. Detectors used to define valid beam adds up to 0.1 radiation length and was not included in the simulation.

3.2.2. Position and angle measurement

Each pad tower has a well defined lateral coordinate \((x_{i}, y_{i})\). We construct effective lateral position \((x_{CG}, y_{CG})\) of the electron beam by weighting pad tower positions with their energies and summing

\[
x_{CG} = \frac{\sum_{i} E_{i} x_{i}}{\sum_{i} E_{i}},\quad y_{0,CG} = \frac{\sum_{i} E_{i} y_{i}}{\sum_{i} E_{i}},\quad \text{and} \quad x_{1,CG} = \frac{\sum_{i} E_{i} x_{i}}{\sum_{i} E_{i}}.
\]

\(x_{0,CG}\) (\(y_{1,CG}\)) denotes weighted sums over the segment 0(1) pad towers. Similar definition is given to \(y_{CG}, y_{1,CG},\) and \(y_{2,CG}\).

\(x_{CG}\) has relation to the true x position \(x_{true}\). An example is shown in Fig. 5 (a). The plot is generated from the simulation for normal beam incidence case and the correlation is between \(x_{CG}\) and the incident beam x position (= \(x_{true}\)). Inherent nonlinearity in \(x_{CG}\) can be corrected by empirically parameterized function \(y = x + a \sin \left(2\pi \cdot \frac{(x - x_{0})}{1.5 (cm)} \right)\) and subsequent fit (red line). We get \(x_{cal}\) the estimator of \(x_{true}\) after the nonlinearity correction to \(x_{CG}\). Fig. 5 (b) shows distribution of the difference between \(x_{true}\) and \(x_{cal}\) for the simulated events. Judging from this plot, we estimate 2.0 mm as the \(x_{cal}\) resolution.

Estimation of the incident angle is also possible using \(\Delta x\) the difference between \(x_{0,cal}\) and \(x_{1,cal}\). Fig. 5 (c) shows the relation between the incident angle and \(\Delta x\) for data (red) and for simulation (blue).
Simulation explains the relation clearly. \( x_{0,\text{cal}} (x_{1,\text{cal}}) \) represents mean of the lateral shower profile at some effective longitudinal position \( z_{0,\text{eff}} (z_{1,\text{eff}}) \) positioned inside segment 0(1). Simulation estimates \( \Delta z \), the difference between \( z_{0,\text{eff}} \) and \( z_{1,\text{eff}} \) to be 42 mm for 6 GeV electrons. The \( \Delta x \) increases as the incident beam angle and hence the shower slope \( \Delta x/\Delta z \) increases.

Some broadening occurs in \( \Delta x \) due to the finite resolution in \( x_{0,\text{cal}} \) and \( x_{1,\text{cal}} \). The amount of broadening is depicted as error bars in Fig. 5 (c) for data (red) and for simulation (blue). This agreement asserts the \( x_{0,\text{cal}} \) (\( x_{1,\text{cal}} \)) variable resolution is properly simulated supporting the previously estimated \( x_{\text{cal}} \) resolution of 2 (mm).

4. Conclusions
We performed beam test of the Si/W calorimeter prototype for the PHENIX forward upgrade. Detailed study on energy measurement and tracking by the prototype calorimeter was made using electron beam.

Measured energy shows a good linearity and the achieved resolution meets the design goal. We measured the longitudinal and lateral energy response profile, which features a typical electromagnetic shower and agrees with the GEANT4 simulation. Incident electron position and angle can be calculated from the calorimeter measurements. Resolution for the incident x position is estimated to be 2.0 mm.

To achieve the results, we utilized simultaneous longitudinal and lateral segmentation of the prototype allowed for the Si/W calorimeter while adopting simple calibration process. We recognize these characteristics as the strength of current prototype.

References
[1] G.Barbiellini et al. Energy resolution and longitudinal shower development in a Si/W electromagnetic calorimeter, Nucl.Instr. and Meth.in Phys. Res. A 235(1985), 55
G.Ferri et al. The structure of the lateral shower development in Si/W and Si/U calorimeters, Nucl.Instr. and Meth.in Phys. Res. A 273(1988), 123
[2] See contribution by E. Kistenev
[3] S. Agostinelli et al. GEANT4-a simulation toolkit, Nucl.Instr. and Meth.in Phys. Res. A 506(2003), 250
J.Allison et al. Geant4 developments and applications, IEEE Transactions on Nuclear Science 53(2006), 270
[4] C. Amsler et al., The Review of Particle Physics, Physics Letters B667(2008), 1
[5] http://en.wikipedia.org/wiki/SPICE