Test beam study of the PANDA shashlyk calorimeter prototype

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Abstract. The Shashlyk calorimeter prototype for the PANDA experiment has been constructed at IHEP and experimentally tested using the 1-19 GeV electron beam with high precision momentum tagging at the IHEP accelerator. Results of the first measurements for the fine-segmented Shashlyk calorimeter prototype in the wide energy range up to 19 GeV are presented. Fair energy and position resolutions having been obtained are in a good agreement with the Monte-Carlo simulations. Detection inefficiency due to holes for straight light fibers has turned out to be negligible for PANDA. Plans for the near term future including approaching test beam study of $\pi^0$ reconstruction capability of shashlyk prototype are also discussed.

1. Introduction

The physics program of the PANDA project at the international FAIR facility at GSI (Germany) is based on a state-of-the-art universal detector for strong interaction studies at high intensity cooled antiproton beam with an energy up to 15 GeV. This program relies heavily on the capability to measure photons with excellent energy and position resolution. For this purpose PANDA has proposed to employ electromagnetic calorimeters using two different technologies: a compact calorimeter around the target based on lead tungstate crystals and a fine-segmented Shashlyk-type calorimeter in the forward region (Figure 1). PANDA physics program requires $4\pi$ angular coverage of photon detection, which is achieved mainly by the target spectrometer EMC. However, to measure everything in the forward region with angles less than $5^\circ$ in vertical plane and $10^\circ$ in horizontal plane, forward spectrometer EMC is used. The target spectrometer EMC is going to be built from the lead tungstate scintillating crystals (PWO). It has been already realized in the CMS, ALICE and PRIMEX electromagnetic calorimeters [1, 2, 3]. The fine-segmented shashlyk type calorimeter proposed for KOPIO experiment showed a good performance in the energy range up to 1 GeV [4] - energy resolution was about $3%/\sqrt{E}$. Since PANDA requires much wider energy region calorimeter, test beam measurements of the shashlyk calorimeter prototype were carried out at IHEP with the use of electron beam in the energy region from 1 to 19 GeV. The results of energy and position resolution measurements as well as the Monte-Carlo simulation predictions are presented.

In this report we describe a fine-sampling electromagnetic calorimeter prototype with lead absorber, where the thickness of the absorber is significantly smaller than radiation length of lead. Such a small thickness of the absorber layers results in a small interaction probability of
the secondary shower particles. A design of this prototype is close to the KOPIO prototype including the same lateral size of cells. The results of miscellaneous studies of parameters of the prototype in the energy range from 1 to 19 GeV are presented in this report.

2. Shashlyk modules structure

The PANDA forward spectrometer EMC has some specific requirements. Since it is situated outside the target region, seven meters from the interaction point beside the dipole magnet, geometrical size constrains are not so strict as well as position (angular) resolution requirements (see Figure 1). The EMC should cover $\sim 4m^2$ and measure mainly relatively high energy particles in the forward direction. However, the EMC has to keep a good energy resolution in the range of up to 10 GeV, a rather low detection threshold of 10-20 MeV and a fast signal to prevent pile-up effect. One of the most interesting solutions which satisfies all the above requirements and has another advantage of low cost is so called shashlyk calorimeter with fine segmentation.

The modules were assembled from 380 alternating layers of lead and scintillator plates. Lead plates were doped by 3% of antimony to improve their rigidity. Scintillator plates were made of polystyrene doped by 1.5% of paraterphenyle. Scintillator was manufactured at IHEP scintillator workshop by the molding technology (see Figure 2). The physical properties of the modules are presented in Table 1.

Scintillation light was collected by the wave-length shifting (WLS) optical fibers BCF-91A with a diameter of 1.2 mm. Each fiber penetrated through the module along its longitudinal axis twice, forming a loop in front of the module. The radius of the loop was 28 mm. The 72 such looped fibers penetrated through the modules in the longitudinal direction with the spacing of 9.3 mm forming the grid of $12 \times 12$ fibers per module. All 144 fiber ends were assembled into a bundle of a diameter about 10 mm, glued, cut and polished in order to deliver the scintillating light to the photodetector attached at the downstream end of the module. A Hamamatsu photomultiplier R5800 has been chosen as a photodetector for the prototype. The diameter of the photocathode was 25.4 mm, the number of dynodes was 10, the applied high voltage was about 1100 V. Each photomultiplier was monitored by the LED light carried to the photocathodes by a clear polystyrene fiber. The purpose of the LED monitoring system was to check whether the photodetector was working, and to study long-term variations of the LED amplitude.
Table 1. Shashlyk module properties.

| Property                          | Value          |
|-----------------------------------|----------------|
| lead plate thickness              | 0.275 mm       |
| scintillator plate thickness      | 1.5 mm         |
| number of layers                  | 380            |
| effective radiation length, $X_0$| 34 mm          |
| total radiation length            | $20X_0$        |
| effective Moliere radius, $R_M$   | 59 mm          |
| module size                       | $110 \times 110 \times 675$ mm$^3$ |
| module weight                     | 18 kg          |

Figure 2. Shashlyk modules production at IHEP scintillator workshop.

Figure 3. 3×3 matrix of shashlyk modules on movable platform.

3. Prototype test beam setup
The prototype consisted of 9 fine-sampling modules. The modules were assembled into 3×3 matrix installed on the x, y-moving table (see Figure 3). The beam channel 2B of the U-70 accelerator was used to study the performance of the calorimeter prototype. The secondary beam of negatively charged particles of momenta from 1 to 19 GeV/c contained more than 70% of electrons with some fraction of muons, and hadrons (mainly $\pi^-$ and $K^-$. Electron beams available at IHEP have momentum spread of several percent. In order to test high precision calorimeters a dedicated beam tagging setup was constructed at the beam output building [5].

The tagging system is illustrated in Figure 4 and was based on the dipole magnet M and four sets of 2-coordinate drift chambers DC1 to DC4, the bending angle of the magnet was 55 mrad. A trigger of the experimental setup used the coincidence of 4 scintillator counters - S1, S2 and S3 installed upstream before the first drift chamber DC1, and S4 installed after the last drift chamber DC4 in front of the calorimeter prototype (ECAL). This setup was used to measure beam particle momentum with a precision of 0.13% at high energies where multiple scattering was not dominating.

An amplitude information was measured by 15-bit charge sensitive ADC modules LRS2285 over 150 ns gate with a sensitivity of 30 pC/count. To read out a time information from the drift chamber stations, the TDC LRS337 CAMAC modules have been used. Remotely controlled the x, y-moving table positioned the prototype across the beam with a precision of 0.4 mm. Data acquisition system included two crates with ADC and TDC modules as well as control modules to synchronize a read out process. VME crate with CAMAC parallel branch driver and PCI-VME bridge linked all the electronics into the complete system. Detailed description of the data
acquisition system and front-end electronics can be found in [6].

4. Monte Carlo simulations
The relevant simulation tools were developed. These tools, at the first stage, are intended mainly for cross-check of experimental results as well as for tuning of the reconstruction algorithms. Proving consistency of Monte Carlo and real data, we plan to use these tools for further optimization of module design and reconstruction algorithms to provide better performance of the photons and π⁰s reconstruction. Simulation studies were performed with GEANT3 [7] as a Monte Carlo engine with detailed description of materials and module geometry. The developing shower produces light which originates from two different sources:

- scintillation in plastic plates due to continuous energy losses when charged particles pass the active calorimeter material,
- Cherenkov radiation when charged particles pass the WLS fibers.

The simplified technique results in counting energy deposition in the active material (with some corrections to take into account the light attenuation in the fibers) and ignoring Cherenkov radiation inside the fibers. This method is very fast while can not reproduce all the details of the calorimeter response such as non-uniformity due to fibers and cell borders. For these studies, the detailed light propagation was applied taking into account optical properties of materials, reflections at plate borders, light capture by fibers with account of the cladding and the Cherenkov light production and propagation inside the fibers. It was assumed that attenuation length in the scintillator is 70 cm and in the fiber is 400 cm, scintillator refraction index is 1.59, total inner reflection efficiency at large scintillator faces is 0.97 and reflection of diffusion type was assumed at side scintillator faces with the same probability. The mean deposited energy for one optical photon production in the scintillator was assumed to be 100 eV and the Cherenkov photons were generated by GEANT.

5. Calibration
The modules were calibrated by a 19-GeV/c beam. Each module was exposed to the beam using the x, y-moving table. The energy spectrum from one module (Figure 5) shows a sharp peak at 19 GeV corresponding to the energy deposited by electrons. Another peak at low energies is due to minimum ionization loss of muons and charged hadrons. A wide distribution of the deposited energy between the two peaks is due to hadron showers. The best relative calibration coefficients were found by equalizing minimum ionizing particle (MIP) signals, while the absolute calibration was obtained by setting the total measured energy in the 3×3 matrix to 19 GeV. Events where only one module has an energy above the threshold of 100 MeV were selected for the MIP calibration. The energy distribution around the MIP peak (Figure 6) has two contributions, one is caused by the Landau distribution of the ionization energy loss, and another one is due to the finite energy resolution of the calorimeter at low energy. The MIP peak was fitted by the

![Figure 4. Beam tagging system for the shashlyk prototype studies.](image-url)
Landau distribution, and the most probable value of the fitting function served for the relative calibration.

![Figure 5](image1.png)  
**Figure 5.** Energy deposited by the 19-GeV/c beam in one module.

![Figure 6](image2.png)  
**Figure 6.** Energy spectrum near MIP peak position. Fitting function is the Landau distribution.

### 6. Energy and position resolution results

After dedicated calibration runs, where each module was exposed to the 19-GeV/c beam, the ECAL prototype was fixed so that the beam hit the central module, and it was exposed to beams at momenta of 1, 2, 3.5, 5, 7, 10, 14 and 19 GeV/c. For each beam momentum, the magnetic field in the spectrometric magnet M was adjusted to provide the same bending angle of the beam. The momentum of the beam particle $p$ was measured by the magnetic spectrometer, and the energy $E$ measured in the calorimeter prototype is linearly correlated with the momentum $p$, as illustrated by Figure 7. Therefore, in order to obtain a true energy resolution, the measured energy should be corrected by the beam momentum, or the energy resolution can be represented by the width of the distribution of the $E/p$ ratio (Figure 8). The energy resolution is obtained from the Gaussian fit of the right peak around $E/p = 1$. The energy resolution $\sigma_{E}/E$ measured by electrons at the energies from 1 to 19 GeV are shown in Figure 9. Black stars represent the experimentally measured points, and the solid lines (green for experimental and red for MC values) are results of the fit by the function

$$\frac{\sigma_{E}}{E} = \frac{a}{E} + b \sqrt{E} + c, \quad (1)$$

where $E$ is in GeV. The obtained parameters are summarized in Table 2.

There is a good agreement of our experimental results with the MC data and with the previous studies at lower energies [4], where a stochastic term was 2.9%.

A position resolution has been measured by comparison of exact impact coordinate of the beam particle, measured by the last drift chamber DC4, and the center-of-gravity of the electromagnetic shower developed in the calorimeter prototype. Figure 10 shows the dependence of the measured coordinate on the true one. The spatial resolution in the middle of the module is shown in Figure 12. Again, the black stars stand for experimental data points, the curves - for fit by the function:

$$\sigma_{x} = \frac{a}{\sqrt{E}} + b[mm], \quad (2)$$

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Figure 7. Correlation between the measured energy and the beam momentum.

Figure 8. Ratio of the energy E to the momentum p at 19 GeV/c.

Table 2. Parameters describing energy resolution of the prototype [in %].

|                  | Experiment data fit | MC data fit |
|------------------|---------------------|-------------|
| a                | $3.5 \pm 0.3$       | $3.3 \pm 0.1$ |
| b                | $2.8 \pm 0.2$       | $3.1 \pm 0.1$ |
| c                | $1.30 \pm 0.04$     | $1.23 \pm 0.02$ |

Figure 9. Energy resolution dependence on energy.

where $E$ is in GeV. Parameters of the fit are shown in Table 3.

Note that this data is for the worst case position resolution at the module center. Usually resolution near the module edge is 3 times better. The MC result is in good agreement with the experimental data.
Table 3. Parameters describing position resolution of the prototype in the center of the cell [in mm].

|               | Experiment data fit | MC data fit |
|---------------|---------------------|-------------|
| \( a \)       | 13.1 ± 1.0          | 14.1 ± 1.0  |
| \( b \)       | 4.0 ± 0.8           | 3.7 ± 0.9   |

Figure 10. Energy resolution dependence on energy.

Figure 11. Light yield vs amplitude for single module.

Figure 12. Position resolution dependence on energy.

7. Light output measurement
Light yield was measured with the highly stable LED light. The fluctuations of the measured amplitude are due to statistics of detected photoelectrons only. For the measured LED amplitude \( A \) and the dispersion of its distribution \( \sigma_A \), one has a number of detected photoelectrons
expressed by the equation:

\[ n_{\text{p.e.}} = \left( \frac{1.2}{\sigma_A/A} \right)^2. \]  

(3)

A set of runs with six different LED amplitudes has been taken. The dependence of the photoelectron statistics on the LED amplitude for one cell is shown in Figure 11. This plot was fitted by the linear function, and the slope represents the number of photoelectrons per one ADC count. Being divided by the calibration coefficient, one obtains the number of photoelectrons detected by the photomultiplier, when the amount of deposited energy in the module is 1 MeV. The mean value of that number for all 9 modules is \( N_{\text{p.e.}} = 5.3 \pm 0.2 \) per 1 MeV.

8. Detection inefficiency

Due to various mechanical inhomogeneities of the modules one can expect to observe the dependence of the energy \( E \) deposited in the calorimeter on the hit coordinates \((x, y)\). The "hot" zones, if any, should be seen at the WLS fiber positions, at the steel strings, and at the boundaries between the modules. The possible lateral non-uniformity of the energy response was studied with the data collected in the 19-GeV/c beam. The last drift chamber DC4 was used to measure the coordinate of the beam particle incidence onto the calorimeter surface. As the beam contained several particle species which interact differently with the calorimeter medium (see Figure 5), the mean deposited energy was measured as a function of \((x, y)\) for two energy intervals, \( E < 0.5 \) GeV and \( 16 < E < 22 \) GeV corresponding to the MIP peak and that of the electromagnetic shower, respectively. Within the available statistics, lateral non-uniformity of the energy response is observed not more than 1-2%.

9. Conclusions

The measurements of energy and position resolutions of the PANDA forward electromagnetic calorimeter prototype of fine-sampling type have been carried out at the IHEP test beam facility at the Protvino 70 GeV accelerator. The prototype was designed and assembled at IHEP scintillator workshop. The results for \( 110 \times 110 \) mm\(^2\) cell size are the following. Energy resolution: \( \sigma_E/E = 2.8/\sqrt{E} \pm 1.3\% \), position resolution: \( \sigma_x = 13.1/\sqrt{E} \pm 4.0\text{[mm]} \). Monte-Carlo model predictions describe data very well. The results are also consistent with the previous measurements at lower energies [4].

The number of photoelectrons detected by photomultiplier in our measurements is \( N_{\text{p.e.}} = 5.3 \pm 0.2 \) per 1 MeV deposited within one module.

The non-uniformity of the energy response of the prototype due to holes for straight fibers studied with the use of electrons and MIPs has turned out to be negligible. Monte-Carlo simulations are in a good agreement with the obtained experimental results.

The features determined for our calorimeter prototype meet the design goals of the PANDA experiment. However, the final conclusion on lateral sizes of the cells as well as on Shashlyk longitudinal sampling structure could be done only after study of reconstruction efficiency of \( \pi^0 \)-mesons of different energies. We plan to have a shashlyk test beam run in 2008 with a prototype of 8x8 smaller cells (55x55 mm\(^2\)).

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