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An improved Shashlyk calorimeter

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Abstract

Shashlyk electromagnetic calorimeter modules with an energy resolution of about $3\%/\sqrt{E\,(\mathrm{GeV})}$ for $50-1000\,\mathrm{MeV}$ photons have been developed, and a prototype tested. Details of these improved modules, including mechanical construction, selection of wave shifting fibers and photo-detectors, and development of a new scintillator with improved optical and mechanical properties are described. How the modules will perform in a large calorimeter was determined from prototype measurements. The experimentally determined characteristics of the calorimeter prototype show energy resolution of $\sigma_{\mathrm{E}}/E = (1.96 \pm 0.1)\% \oplus (2.74 \pm 0.05)\%/\sqrt{E}$, time resolution of $\sigma_{\mathrm{T}} = (72 \pm 4)/\sqrt{E} \oplus (14 \pm 2)/E\,(\mathrm{ps})$, where photon energy E is given in GeV units and $\oplus$ means a quadratic summation. A punch-through inefficiency of photon detection was measured to be $\varepsilon \approx 5 \times 10^{-5}$ ($\Theta_{\mathrm{beam}} > 5\,\mathrm{mrad}$).

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1. Introduction

The Shashlyk technique for electromagnetic colorimetry [1] has been in use for several years. In designing a large calorimeter for the KOPIO experiment [2] we have developed an improved Shashlyk module for such a device. This paper describes the design and construction of the module, as well as the unit's performance in prototype tests. It is further development of the work described in Ref. [3].

The requirements of the KOPIO experiment led to the following specifications:

- Energy range: 50–1000 MeV.
- Energy resolution: $\approx 3.0\%/\sqrt{E\,(\mathrm{GeV})}$.
- Time resolution: $\approx 100\,\mathrm{ps}/\sqrt{E\,(\mathrm{GeV})}$.
- Effective noise per channel: $\leqslant 0.5\,\mathrm{MeV}$.
- Photon detection inefficiency: $\leqslant 10^{-4}$.
- Granularity: $\sim 10\,\mathrm{cm}$.
- Size of the calorimeter: $4.4 \times 4.4\,\mathrm{m}^2$.
- Operation in a magnetic field of up to 500 G.

The Shashlyk approach, in which modules are constructed of lead–scintillator sandwiches read out by means of Wavelength-Shifting (WLS) fibers passing through holes in the scintillator and lead is appropriate for such specifications. The performance level can be achieved economically with well understood and reliable techniques. We describe a module with significantly improved performance over previous manifestations for which the technique is well proved by us, e.g. experiment E865 at Brookhaven [1,4], and has been adopted by others, e.g. the PHENIX RHIC detector [5], the HERA-B detector at DESY [6], and the LHCb detector at CERN [7].

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2. Approach to improving the Shashlyk module

At the outset of improving the module a detailed simulation model was developed [3]. This model is based on a GEANT3 [8] description of electromagnetic shower and a special optical simulation of the light collection in the scintillator plates. Input for the model was experimental and test-beam data. The model output correlated well with data. Analyzing the performance of the prototype Shashlyk module with energy resolution of about $4\%/\sqrt{E\,(\mathrm{GeV})}$[1] we found that energy resolution of about $3.0\%/\sqrt{E\,(\mathrm{GeV})}$ could be reached after some optimization of the module's mechanical and optical properties (see details in Ref. [3]).

We revisited the mechanical and optical construction as described below, and optimized the selection of WLS fibers and the photo-detector. A new scintillator with improved optical and mechanical properties was specially developed at the IHEP scintillator facility (Protvino, Russia) [9]. The corresponding improvements to the module design were implemented in the new KOPIO Calorimeter prototype modules, which were equipped with an Avalanche Photo Diode (APD) and Wave-Form Digitizer (WFD) readout.

2.1. Mechanical construction of the improved Shashlyk module

The design of the new prototype module is shown in Figs. 1 and 2. The module is a sandwich of alternating perforated stamped lead and injection-molded polystyrene-based scintillator plates. The cross-sectional size of a module is $110 \times 110\,\mathrm{mm}^2$. There are 300 layers, each layer consisting of a 0.275-mm lead plate and 1.5-mm scintillator plate. The lateral size of a lead or scintillator plate is $109.7 \times 109.7\,\mathrm{mm}^2$. Each plate has 144 holes equidistantly arranged in a 12×12 matrix, in which the spacing between the holes is 9.3 mm. The diameter of the holes is 1.3 mm, both in the lead and the scintillator plates. Inserted into the holes are 72 WLS fibers, with each fiber looped at the front of the module so that both ends of a fiber are viewed by a photo-detector. Such a loop (radius ~2.5 cm) may be approximated by a mirror with a reflection coefficient of about 95% [10]. The fiber ends are collected in one bunch, squeezed, cut and polished, and connected to a photo-detector though a small air gap. The complete stack of all plates is held in compression by four 1-mm stainless steel wires. The module is wrapped with 150-μm TYVEK paper which has light reflection efficiency of about 80%.

The mechanical parameters of the module are summarized in Table 1.

The module is assembled in a special assembling berth that allows one to subject the assembled modules to cyclic longitudinal loadings up to 800 kg. This procedure prevents subsequent longitudinal shrinkage of the assembled modules and provides long-term stability for the length of the module to an accuracy of $\simeq 1\,\mathrm{mm}$.

2.2. Improvements of the module geometry

The mechanical construction of the module was revisited to minimize the insensitive area, to increase the effective radiation density, and to improve the sampling ratio and transverse light collection uniformity.

An important innovation in the mechanical design of the module is the "LEGO"-type locks for the scintillator tiles shown in Fig. 1. These locks, four per tile, maintain the position of the scintillators and the 350-μm gaps, providing sufficient room for the 275-μm lead tiles without optical contacts between lead and scintillator. This mechanical structure enables removal of the 600 paper tiles that were in earlier modules, and allows reduction of the diameter of the fiber holes to 1.3 mm and removal of the compressing steel tapes at the sides of the module. Compared to the earlier Shashlyk module, the holes/cracks and other insensitive areas were reduced from 2.5% to 1.6%, and the module's mechanical properties such as dimensional tolerances and stiffness were significantly improved. By removing the paper tiles, the effective radiation length could be reduced from 4.0 to 3.5 cm.

The sampling, i.e. the relation between thicknesses of lead and scintillator tiles, dominates in the energy resolution of the Shashlyk module. However, one has only limited ability to improve the "pure" sampling contribution to the energy resolution of the Shashlyk module. Decreasing the thickness of the lead will increase the length of the module, while the proportional decreasing both the lead and scintillator thicknesses will reduce the light collection efficiency. Nevertheless, by removing the paper between the lead and scintillator tiles, both the sampling could be improved and the length of the module could be shortened. Compared to the design of the previous module [3], the sampling ratio was improved by a factor of 1.25.

The dominant source of non-uniformity of the light collection is the absorption of light at the edges of a scintillator tile. The reflection efficiency on the edges of the scintillator tile is crucial. In the new module, the WLS fiber density was effectively increased by reducing the size of the tiles to 10.97 cm. This allows the outer fibers to be closer to the edge of the scintillator tile than they were with the "uniform" size of 11.16 cm for 12 fibers with 0.93-cm spacing. In addition, the module was wrapped with TYVEK paper (reflection efficiency about 80%). As a result, the light collection efficiency at the edges of the scintillator tile is only 2.3% smaller than in the center of the tile for the point-like light source. In the case of a 250-MeV photon shower, the difference is only 0.5%, which is negligible compared to the energy resolution of about 6% for such photons.

The experimental results for the light collection uniformity for TYVEK and Xerox copier papers are presented in Fig. 3. The measurements were made with a scintillator

[1]This module was described in details in Ref. [3]. In this paper we will refer to it as to "earlier" Shashlyk module.