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Development of the upgraded LHCf calorimeter with Gd_2SiO_5 (GSO) scintillators

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The Large Hadron Collider forward (LHCf) experiment was motivated to understand the hadronic interaction relevant to the cosmic-ray air shower development. LHCf has installed compact calorimeters at the LHC and observed neutral particles emitted around zero degree during 0.9, 2.76 and 7 TeV pp collisions and 5 TeV pPb collisions. Since the next operation in 2015 is expected under much higher radiation dose, we have upgraded the detectors, especially their scintillators, to be radiation harder. In this paper, we report the performance of the new imaging sensor, GSO-bar hodoscope tested by heavy-ion beam and 50-250 GeV electron beams. As the result, shower-peak position resolution of 123 μm for 100 GeV electron induced showers was achieved that is satisfactory for our physics goal.

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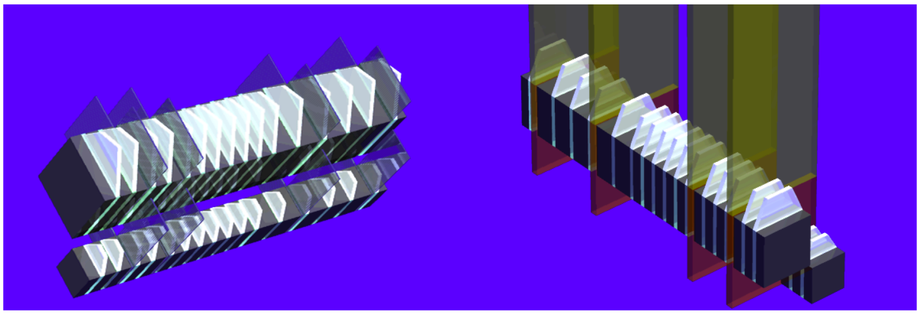

Figure 1: Schematic views of the current Arm1 (left) and Arm2 (right) detectors. The transverse sizes of the calorimeters are 20 × 20 mm^2 and 40 × 40 mm^2 in Arm1 and 25 × 25 mm^2 and 32 × 32 mm^2 in Arm2. Although plastic scintillators used in the current sensors are replaced with GSO after upgrading, basic design of the detector does not change.

1. Introduction

The Large Hadron Collider forward (LHCf) is an experiment dedicated to measure the hadronic production cross-sections of neutral particles emitted in forward angles (pseudorapidity, $\eta > 8.4$) in proton-proton collisions at the LHC, CERN [1]. The energy spectra of forward particles can be used to improve the hadronic interaction models used for modeling the cosmic-ray air shower development and hence are helpful in the further understanding of the Ultra-High-Energy Cosmic Rays. LHCf has reported energy spectra of forward photons and neutral pions at $\sqrt{s}$ = 900 GeV and 7 TeV pp collisions and $\sqrt{s_{NN}}$ = 5.02 TeV pPb collision [2–5]. LHCf will measure the forward spectra of $\sqrt{s}$ = 13 TeV pp collision planned in 2015. With this collision energy, irradiation to the detector will be fatal, especially to the plastic scintillators used in the current detectors [6]. Therefore, we have developed the new detectors with high radiation resistivity. The performance of the upgraded detectors was studied by beam tests. The basic optical properties of the new scintillators are different from current ones.

2. LHCf detectors

2.1 The current detectors

LHCf has two independent detectors, named Arm1 and Arm2, installed in the instrumental slots of the neutral particles absorbers (TANs) located at ±140 m from interaction point 1 (IP1). In the TANs, neutral particles produced at IP1 and emitted in the pseudorapidity range from 8.4 to infinity are observed. Each detector has two sampling and imaging calorimeter towers composed of 44 radiation lengths of tungsten and 16 sampling layers of 3 mm thickness plastic scintillator plates (EJ-260). The transverse sizes of the calorimeters are 20×20 mm^2 and 40×40 mm^2 in Arm1 and 25×25 mm^2 and 32×32 mm^2 in Arm2. Four layers of imaging sensors, scintillating fibre belts (SciFi, KURARAY SCSF-38) for Arm1 and silicon micro-strip sensors for Arm2 [1], are sandwiched in the calorimeter for measuring transverse positions of the showers (Fig.1). The current detectors have energy and position resolutions for the electromagnetic showers better than 5 % and 200 μm, respectively, in the energy range >100 GeV. More detail of the current detectors is described in [1].

Figure 2: Right figure shows the GSO-bar hodoscope under construction. Left figure shows a completed one layer of the GSO-bar hodoscope. Fibers from the GSO-bars were bundled with epoxy glue.

LHC plans $\sqrt{s} = 13$ TeV proton-proton collision in 2015. Once the LHC increases the collision energy to 13 TeV in 2015, maximum radiation dose to the detectors will be about 30 Gray / nb^{-1}. Considering this irradiation rate, current detectors are not suitable for this operation, because plastic scintillators begin its degradation of light yield for doses above 10^2 Gray. Therefore, to measure the energy of the particles precisely, plastic scintillators must be replaced with more radiation-hard ones for the next physics run. We decided to use Gd_2SiO_5 (GSO) scintillators for the new detectors.

2.2 Upgraded detectors with GSO scintillators

GSO is an inorganic and crystal scintillator, and this is one of the radiation hardest scintillator among known scintillators. GSO has no degradation in scintillation properties at 10^6 Gray and this is at least 10^4 times higher than EJ-260. The radiation hardness of GSO was verified by accelerator beam test [6, 7]. Plastic scintillator plates used in Arm1 and Arm2 and SciFi in Arm1 were replaced with GSO-plates and GSO-bar hodoscopes, respectively. Although each component of the calorimeter was replaced, the basic design of the calorimeters was not changed before and after the upgrade. In this paper, we focus on the performance of the GSO-bar hodoscope of upgraded Arm1. The study of the GSO-plates is described in [8].

The upgraded Arm1 has four GSO-bar hodoscope layers for imaging showers developed in the calorimeters (Fig.2). The GSO-bar is a 1 mm×1 mm×20 mm (40 mm) long and thin scintillator bar and is not covered with any coatings or cladding materials. One layer of GSO-bar hodoscope consists of two orthogonally aligned belts. Each belt consists of 20 GSO-bars with 20 mm length and 40 GSO-bars with 40 mm length for the 20 mm and 40 mm calorimeters, respectively. The GSO-bar belts were fastened with the black acrylic holder and they are covered by mirror-like optical enhancement film (enhanced specular reflector, 3M Company) to optically screen two belts. 4

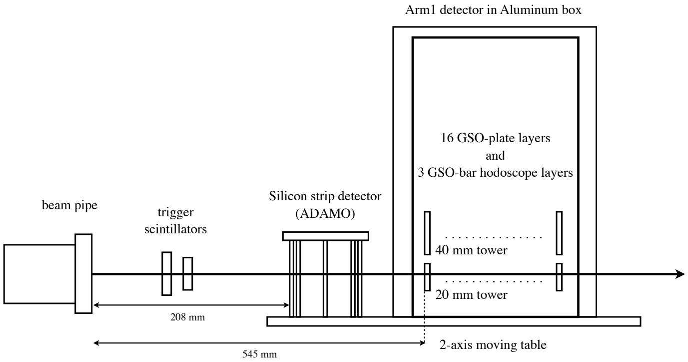

Figure 3: The setup of the SPS beam test. Arm1 detector was on the two-axis movable table. Although the 3rd layer of the GSO-bar hodoscope was missed in this beam test, this is not problem for measurement of electro-magnetic shower because later layers (3rd and 4th) of the GSO-bar hodoscopes are used for hadron-induced shower

GSO-bar hodoscopes with 480 ch were read out by 8 of 64-anode photomultiplier tubes (HAMAMATSU H7546, hereafter MAPMT) through 0.71 mm diameter silica fuzed optical fibers.

2.3 Crosstalk on GSO-bar hodoscope

Because GSO-bars have no cladding materials different from SciFi, the GSO-bar hodoscope has non-negligible crosstalk between neighboring GSO-bars. Crosstalk also occurs on the MAPMT surface by the leakage of light to neighboring pixels from fiber end. As the result of the accelerator test with heavy-ion beam (^{12}C, 400 [MeV/n]) at Heavy Ion Medical Accelerator in Chiba (HIMAC) at National Institute of Radiological Science (NIRS), about 8-9 % of crosstalk adjacent to the channels was observed. A crosstalk matrix for its correction was determined after the measurement of crosstalk in all channels [8].

3. Performance study of the upgraded detector

3.1 Setup

The beam test for performance study was carried out at CERN Super Proton Synchrotron (SPS) North area T2H4 beam line in August, 2012. In this beam test, the detectors on a two-axis movable table were exposed to 50-250 GeV of electron, 150 and 200 GeV of muon and 350 GeV of proton beams. A silicon strip tracker (ADAMO tracker, [10]) was placed in front of the detector to determine the particle-incident position on the calorimeters (Fig.3) as a reference to the position determination.

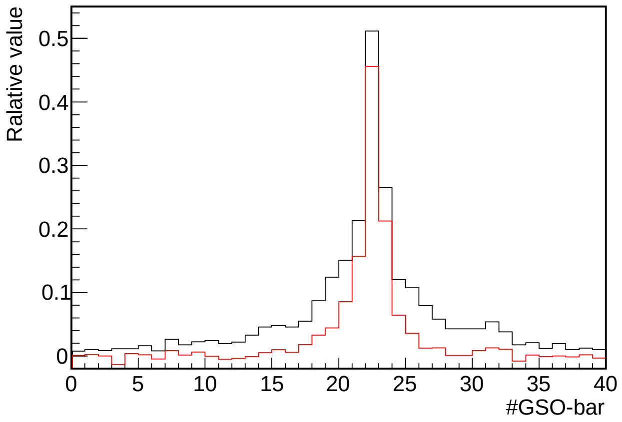

Figure 4: Lateral distributions of the cascade shower developed in the 40 mm calorimeter. The black line shows the raw distribution with relative gain correction and the red distribution is after crosstalk correction.

3.2 Determination of the shower-peak position

A incident shower position is determined using the lateral distribution measured with each GSO-bar hodoscope layer. The black histogram of Fig.4 is a lateral distribution of a cascade shower developed in the 40 mm calorimeter observed by the first layer of the GSO-bar hodoscope. This distribution after relative gain correction is still broader than the expected distribution due to smearing by crosstalk effect. Applying crosstalk correction, the distribution becomes sharper as shown in the red histogram in Fig.4. Crosstalk is corrected by subtract the crosstalk component of each channels. The distribution was fitted by an empirical function based on the Cauchy distribution to determine the shower peak position. Note that the cross talk does not deteriorate the position resolution significantly. On the other hand, to identify the events recording more than 1 shower in a single calorimeter cross talk correction improves the analysis. Performance of this multi-hit analysis was described in [11].

3.3 Position resolution

True beam position was determined using the ADAMO tracker. Because the position resolution of ADAMO tracker, about 30 μm in this study, is better than that of the LHCf calorimeters, position resolution was defined as the standard deviation of the residual distribution between the shower-peak positions determined by the GSO-bar hodoscope and the ADAMO tracker. Figure 5 shows comparison of the position resolutions between the GSO-bar hodoscope and the current imaging layer, SciFi. In this figure, the black circles and the open squares show the position resolutions of the GSO-bar hodoscope and SciFi, respectively. The position resolution of the GSO-bar hodoscope meets the requirement of the LHCf experiment, less than 200 μm, and is better than that of SciFi in the whole energy range. Improvement of the analysis method such as crosstalk correction, design of the support structure and the accuracy of the alignment between scintillators led this improved result.

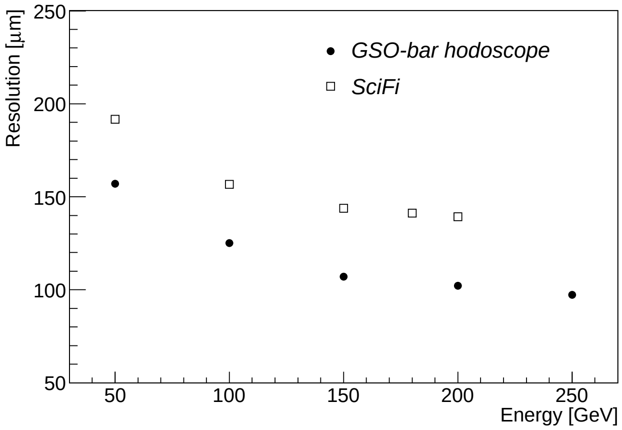

Figure 5: A comparison between SciFi and GSO-bar hodoscope. Horizontal axis is the energy of injected electron and vertical axis is shower-peak position resolution of GSO-bar hodoscope. Filled circles show resolution of GSO-bar hodoscope and open squares show that of SciFi.

4. Summary

The LHCf collaboration has developed the new detectors with GSO scintillators. Performance studies of the new detectors by using accelerator beam were carried out by several hundreds GeV of electron and muon beams. Although the GSO-bar hodoscope has 8 to 9 % of crosstalk adjacent to the next channel, we confirmed that they can be corrected. The GSO-bar hodoscope showed position resolution of 123 μm for 100 GeV electron-induced shower and this performance was better than that of SciFi in all energy range 50-250 GeV used in the beam test. The GSO-bar hodoscope for upgraded Arm1 detector meets requirement of LHCf and is ready for the next operation in 2015.

5. Acknowledgements

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