Development of GSO calorimeters for the LHCf experiment

（LHCf実験とGSOをもちいたカロリーメータの開発）

Takashi SAKO (堀)
(STEL/KMI, Nagoya University)

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### Brief history of the LHCf calorimeters

<table>
<thead>
<tr>
<th>Year</th>
<th>Arm 1</th>
<th>Arm 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>LHC 7TeV p-p</td>
<td>LHC 7TeV p-p</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>GSO upgrade</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td>LHC 5TeV p-Pb</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td>GSO upgrade</td>
</tr>
<tr>
<td>2015</td>
<td>LHC 13TeV p-p</td>
<td>LHC 13TeV p-p</td>
</tr>
</tbody>
</table>

- **plastic scintillator base**
- **GSO scintillator base for 13TeV operation**

**Target of GSO based calorimeters** is “SAME performance” to the plastic based ones except radiation hardness.
Contents

- Introduction to the LHCf experiment
  - story of LHCf upgrade to GSO-based calorimeters
- Radiation hardness of the GSO scintillators
  - increase of the light intensity
  - recovery
- Structure of the GSO-based calorimeters
- Calibration of light collection non-uniformity at HIMAC
- Calibration for energy measurement at CERN SPS
- Summary
Short introduction to the LHCf experiment
Motivation

- Cosmic-rays with $E>10^{15}$ eV are observed through atmospheric air shower
- Energy and mass of 1ry particles are determined from the ground observations
- Interpretation relies on the MC simulation of air showers
- Hadronic interaction, especially forward particle production, is a key of the MC simulation
The LHC forward experiment

Two independent detectors at either side of IP1 (Arm#1, Arm#2)

- All charged particles are swept by dipole magnet
- Neutral particles (photons and neutrons) arrive at LHCf
- Target energy is 100GeV-7TeV
LHCf Detectors

- Imaging sampling shower calorimeters
- Two calorimeter towers in each of Arm1 and Arm2
- Each tower has 44 r.l. of Tungsten, 16 sampling scintillators (with HAMAMATSU R7400U) and 4 position sensitive layers (≈3% sampling)

Arm#1 Detector
- 20mmx20mm+40mmx40mm
- 4 XY SciFi+MAPMT

Arm#2 Detector
- 25mmx25mm+32mmx32mm
- 4 XY Silicon strip detectors
Performance Summary

Hadronic shower (MC)
- Position resolution
  - Black: X-plane
  - Red: Y-plane
  - $\Delta E/E \approx 40\%$

Energy resolution
- $\sigma_E/E \approx 40\%$ because of $1.6\lambda$

EM shower (MC)
- Position resolution
- $\Delta E/E < 5\%$

PID technique
- 400 GeV photon
- 1 TeV neutron
  - Identification of incoming particle by shower shape

$\pi^0$ reconstruction
- $M_{??} \sim M_{\pi^0}$
LHCf calorimeters
- rad-hard upgrade with GSO -
Radiation Damage

- Peak dose in 2010 7TeV operation $\sim 70\text{Gy}$
- Expected dose in 2015 13TeV operation (same $\mathcal{L}$) $\sim 700\text{Gy}$ ($\propto E^3$)

Excess from 135MeV $ightarrow$ talk by Matsubayashi

3% decrease in 2 months $ightarrow$ radiation damage

History of invariant mass peak in 2010 run, LHCf, IJMPA, 28 (2013) 1330036
## Selection of scintillators

The table below compares various properties of different scintillators used in the original LHCf experiment.

<table>
<thead>
<tr>
<th>Property</th>
<th>GSO</th>
<th>EJ-260</th>
<th>BGO</th>
<th>PWO</th>
<th>CeF3</th>
</tr>
</thead>
<tbody>
<tr>
<td>density (g/cm³)</td>
<td>6.71</td>
<td>1.023</td>
<td>7.13</td>
<td>8.28</td>
<td>6.16</td>
</tr>
<tr>
<td>r.l. (cm)</td>
<td>1.38</td>
<td>14.2</td>
<td>1.12</td>
<td>0.92</td>
<td>1.68</td>
</tr>
<tr>
<td>decay constant (ns)</td>
<td>30-60</td>
<td>9.6</td>
<td>300</td>
<td>2,7,26</td>
<td>5,15</td>
</tr>
<tr>
<td>intensity (NaI=100)</td>
<td>20</td>
<td>19.6</td>
<td>12</td>
<td>0.26</td>
<td>7</td>
</tr>
<tr>
<td>λ em (nm)</td>
<td>430</td>
<td>490</td>
<td>480</td>
<td>430</td>
<td>305</td>
</tr>
<tr>
<td>reflective index (@ λ em)</td>
<td>1.85</td>
<td>1.58</td>
<td>2.15</td>
<td>2.16</td>
<td>1.68</td>
</tr>
<tr>
<td>radiation hardness (Gy)</td>
<td>$10^6$</td>
<td>100</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>melting point (°C)</td>
<td>1950</td>
<td>—</td>
<td>1050</td>
<td>930</td>
<td>1460</td>
</tr>
</tbody>
</table>
Irradiation test at HIMAC (Carbon beam)
(Kawade et al., JINST, 6, T09004, 2011)

- No decrease of light intensity up to 1MGy, but 20% increase at O(10kGy)
- Increase was also reported by Tanaka et al., NIM A404, 283 (1998) using gamma-ray irradiation
Recovery measurements with Carbon beam at HIMAC

- 20% increase after a 7.4kGy (O(10kGy)) irradiation is confirmed
- second irradiation (10.7kGy) resulted a smaller increase
- day-scale natural recovery is confirmed
- recovery does not seem to converge to 1
Detail view of the recovery phase

\[ I = I_0 + A \times \exp\left(-\frac{t}{\tau}\right) \]

dotted lines

\[ I = 1 + A \times \exp\left(-\frac{t}{\tau}\right) \]

<table>
<thead>
<tr>
<th></th>
<th>( I_0 )</th>
<th>( A )</th>
<th>( \tau ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAY1 A</td>
<td>1.13</td>
<td>0.09</td>
<td>13,000</td>
</tr>
<tr>
<td>DAY1 B</td>
<td>1.13</td>
<td>0.09</td>
<td>11,000</td>
</tr>
<tr>
<td>DAY2 A</td>
<td>1.14</td>
<td>0.05</td>
<td>5,600</td>
</tr>
<tr>
<td>DAY2 B</td>
<td>1.12</td>
<td>0.05</td>
<td>8,800</td>
</tr>
</tbody>
</table>

- \( \tau \approx 10,000 \) sec is consistent with Kawade et al. using UV light
- \( I_0 = 1.13 \) is also consistent with Kawade et al. (short measurement with UV) and Tanaka et al. (sparse but months-scale measurement with gamma)
# Fit results with errors

<table>
<thead>
<tr>
<th></th>
<th>FIT1</th>
<th>FIT2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\chi^2$/DOF</td>
<td>$I_0$</td>
</tr>
<tr>
<td><strong>DAY1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSO-A</td>
<td>54.6/46</td>
<td>1.129</td>
</tr>
<tr>
<td></td>
<td>(0.18)</td>
<td>(0.005)</td>
</tr>
<tr>
<td>GSO-B</td>
<td>72.3/44</td>
<td>1.126</td>
</tr>
<tr>
<td></td>
<td>$(4.5\times10^{-3})$</td>
<td>(0.008)</td>
</tr>
<tr>
<td><strong>DAY2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSO-A</td>
<td>50.1/98</td>
<td>1.137</td>
</tr>
<tr>
<td></td>
<td>$(&gt;0.99)$</td>
<td>(0.002)</td>
</tr>
<tr>
<td>GSO-B</td>
<td>70.2/98</td>
<td>1.119</td>
</tr>
<tr>
<td></td>
<td>(0.98)</td>
<td>(0.004)</td>
</tr>
<tr>
<td><strong>DAY1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GSO-A</td>
<td>49.0/45</td>
<td>1.187</td>
</tr>
<tr>
<td></td>
<td>(w/o RUN8)</td>
<td>(0.31)</td>
</tr>
<tr>
<td>GSO-B</td>
<td>59.7/43</td>
<td>1.187</td>
</tr>
<tr>
<td></td>
<td>(0.047)</td>
<td>(0.003)</td>
</tr>
</tbody>
</table>
LHCf GSO calorimeter
- mechanical structure -
LHCf Calorimeters

Acrylic fibers connected to MAPMT

Position sensor 40x1mm² SciFi bundle

Acrylic guide + fibers connected to PMT

Calorimeter plastic scintillator (EJ260)
LHCf Calorimeters

Acrylic fibers => Quartz fibers

SciFi => GSO bar (talk by Makino)

light guide acrylic => quartz

3mm^t plastic scintillators => 1mm^t GSO scintillators
Structure of GSO calorimeters

- supporting fragile 1mm-thick elements
- holding elements in a compact space with a necessary alignment precision
- keeping longitudinal structure same as before
(without tungsten)
Non-uniformity of light collection must be calibrated.

(without tungsten)
Non-uniformity calibration at HIMAC

- Calorimeters WITHOUT tungsten layers were scanned over the ion beam.
- Signal intensity as a function of the position was extracted.
Non-uniformity result (sample)

- Essentially same characteristics with the plastic scintillator
- Amplitude of variation is larger than that of plastic scintillators
- By taking this result in a calibration, this does not deteriorate the detector performance
GSO calorimeter
- energy measurement -
Full detector (Arm1) with Tungsten
Setup of SPS beam test

- Calorimeters were exposed to the SPS electron (100-200GeV), proton (350GeV) and muon (150GeV) beams
- Calorimeters were scanned over the beams
- Impact points were measured using a silicon strip tracker
Channel to channel calibration
Beam test results vs. MC simulation

Charge => energy factors are determined by scaling the MC results to the experimental data
Energy resolution for EM shower

$\sigma$ is defined as energy resolution

$\sum_{i} E_i$ is calculated for each event and converted to the incident energy by a function $E = f(\sum_{i} E_i)$ determined by MC (f is almost linear function)
Energy resolution (preliminary)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC (pede 考慮せず)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>3%</td>
<td>2.7%</td>
</tr>
<tr>
<td>150 GeV</td>
<td>2.3%</td>
<td>2.4%</td>
</tr>
<tr>
<td>180 GeV</td>
<td>2.1%</td>
<td>2.1%</td>
</tr>
</tbody>
</table>

BW; results of original detector
Mase et al., NIM A671 (2012) 129-136

➢ Energy resolution same as the previous detector is achieved
Good (preliminary) linearity is achieved for 100-200GeV EM showers

\[ E = f(\sum E_i) \] must be determined

Arm2 analysis ongoing in parallel
Ready for operation!

- LHCf detectors were successfully installed into the LHC tunnel in November
- Commissioning was also successful
- Waiting dedicated 13TeV run in May 2015
Summary

- LHCf measures forward neutral particles at LHC to understand hadronic interactions for CR physics
- LHCf uses compact EM calorimeters to measure photons and neutrons of 0.1-7TeV
- LHCf replaced plastic scintillators with GSO scintillators for 2015 operation at LHC
- LHCf studied radiation hardness of GSO
  - 20% increase after $O(10kG)$ was confirmed
  - recovery up to 13% with $\tau=10^4$ sec time scale was measured
- LHCf succeeded to construct compact EM calorimeters using GSO scintillators
  - non-uniformity in light collection is calibrated using HIMAC test
- LHCf calorimeters were tested for SPS beam
  - energy resolution consistent with the previous detectors and MC were obtained at 100-200GeV EM showers
  - Good linearity is obtained
Backup
CR spectrum and structures
(D’Enterria et al., APP, 35, 98-113, 2011)

- Knee (10^{15} \text{eV})
- Ankle (10^{18} \text{eV})
- Cutoff (10^{20} \text{eV})
Measurements

- $N_e \rightarrow E$; helped by air shower simulation
- $I_{\text{fluor.}} \rightarrow E$; calorimetric, no air shower simulation, but emissivity calibration
- $N_\mu - N_e, E < \langle X_{\text{max}} \rangle \rightarrow$ Mass; helped by air shower simulation
LHCf; $\pi^0$ $P_T$ distribution (6 rapidity bins)
$M_{\gamma\gamma}$ in the 2010 data

IJMPA, 28 (2013) 13300366

PRD 86, 092001 (2012)

IJMPA, 28 (2013) 13300366
シンチレータ：EJ260

PMT R7400U

12mm

16mm

20mm
HV ディバイダー
回路の改良

等分配デバイダ
改良

後段（ダイノード間の粒子数が多い）の電位差を大きくしたテーパーデバイダー

一般的なボックス型PMTの模式図

ディバイダー（電圧分配器）
紫外N2レーザーを用いたPMT線形ダイナミックレンジ性能評価システム

N2レーザー: スペック（KEN-1020, 300psec）
波長: 337.1nm

目的
• PMTの光量と出力の対応を調べる
• 70000粒子相当光量
測定結果

HVにおける光量とADC値の関係

β線により測定

LowRangeADC (0.025pC)
70000粒子相当光量まで非線形性が5%以内のシステムが完成!!
先行研究: $^{60}$Co γ線照射に対する反応

Tanaka et al., NIM, A404, 283-294, 1998

- ガンマ線照射とCビーム照射による増光は同じ現象だろう
- 注意: Tanaka et al.では、τ~80時間を報告
which is the luminescence center. The increase in the light yield caused by irradiation could be explained through a hypothesis that there exist certain number of intermediate energy levels due to impurities or host ions in the energy gap, and they usually absorb some fraction of the energy. If the excited electrons drop to the intermediate levels and then undergo non-radiative transitions to the ground levels, they do not contribute to scintillation. If such intermediate levels are occupied by irradiation, the energy transfer efficiency to Ce$^{3+}$ increases, resulting in an increase in the light output. The time scale of the recovery is determined by the stability of the occupied states. Since we

Tanaka et al., NIM, A404, 283-294, 1998

加熱による回復 (Tanaka et al.)

> >100°Cに加熱することで、トラップされていた電子が追い出されて発光する
> 加熱前 1.10±0.02 の増光があったが、加熱後 1.01±0.02 に回復
Energy resolution (plastic scintillators)

High gain operation

Low gain operation

NIM A671 (2012) 129-136
Leak-in, leak-out correction

②シャワー漏れ出し/漏れ込み補正

- シミュレーションによるシャワー漏れ出し/漏れ込み量の見積もり
  →シャワー発達が実際と異なれば、正しく補正できていないことになる。