NEW DETECTING TECHNIQUES AND DETECTING MATERIALS FOR FUTURE CALORIMETRY

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Demand for a high time resolution in future experiments

Limits of inorganic scintillators for time resolution in HEP

Scintillation rise time analysis benefits

From exploiting of spontaneous processes to external picosecond probe

Active materials radiation damage in collider experiments.

Demand for a new materials.
The situation is however complex as collisions in a bunch crossing vary both in time and in longitudinal position: The TOF gives a relation in the z-time plane

(Courtesy of P. Bloch, Report at CMS Upgrade Week, Karlsruhe, 31/03/14)

Time resolution, radiation hardness to high energy hadrons and price for materials for high granularity detectors become crucial.
Interaction of 100GeV electron with scintillator similar to LSO:Ce.
For simplicity: $X_0 = 1\text{cm}$; density $7\text{g/cm}^3$; rise time 0.3 ns; decay time 40ns; LY = 30ph/keV

Ionization and bremsstrahlung versus penetration distance

Ionization and bremsstrahlung versus time

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Number of photons emitted by scintillation in LSO:Ce due to Ionization and bremsstrahlung

Case of a simple approximation of the scintillation pulse:
rise time-0.3ns, decay time- 40ns.

No chance to use these phenomena to get high time resolution.
GEANT4 simulation of the 100GeV e⁻ interaction with virtually sliced scintillator.
(10 slices of 3mm long wafers, each wafer is equivalent to 10 ps of particle flight)

Deposited energy per particle
(average for 3000 Incident particles).

Shower beginning
Relative error of the amplitude measurement at the beginning of the 100 GeV electron shower development

- +/-10% is reachable at 30ps with scintillator like LSO:Ce

Relative error of amplitude measurements.
The scintillator Internal Time Resolution (ITR) at registration of 100GeV electrons

Relative Error of Time measurements.

Absolute Error of Time measurements.

Time resolution FWHM is 2,3*AET. AET~Time interval at 8-9 ps.

No HEP experimental data are available yet. The best time resolution is near 130ps in medical imaging PETs exploiting photo-absorption of the soft gammas.
The time resolution of a single PWO detector module as a function of the deposited energy of PANDA ECAL (R. Novotny et al., NIM A 648 (2011) 77)

Current ECAL time resolution (EE) (Courtesy of P. Bloch, Report at CMS Upgrade Week, Karlsruhe, 31/03/14)

Time resolution at registration of high energy gamma quanta is better than 100 ps!

Daniele del Re, O 1.04 CALOR 2014

Rise time is becoming a limiting factor!

\[ X_0 = 0.89 \text{ cm}; \text{Rise time} < 100 \text{ ps}; LY = 0.3 \text{ ph/keV} (100 \text{ times less than LSO}); \text{Decay time} 10 \text{ ns} \]
Requirements for crystal pairs:
1. Close $X_0$ and density;
2. Minor transmission radiation damage in the spectral range of scintillation;
3. A possibility of spectral discrimination of scintillation from different crystals.

Possible combinations:
BSO/LSO; BSO/PWO; CeF$_3$/BaF$_2$; LuAG/LuAG(undoped)

<table>
<thead>
<tr>
<th>Property</th>
<th>Lu$_2$SiO$_5$:Ce (LSO)</th>
<th>Bi$_4$Si$<em>3$O$</em>{12}$ (BSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Yield, Ph/MeV</td>
<td>30000</td>
<td>1200</td>
</tr>
<tr>
<td>Decay constant of scintillation kinetics, ns</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Emission maximum, nm</td>
<td>420</td>
<td>480</td>
</tr>
<tr>
<td>density, g/cm$^3$</td>
<td>7.4</td>
<td>7.12</td>
</tr>
<tr>
<td>$X_0$, cm</td>
<td>1.3</td>
<td>1.15</td>
</tr>
<tr>
<td>Zeff</td>
<td>60</td>
<td>74</td>
</tr>
</tbody>
</table>

Refraction indexes $n_{BSO} \sim n_{LSO}$, Spectral discrimination is possible!
BSO transmission damage does not affect luminescence in the spectral range longer than 3.2eV (400nm)!

Stokes shift:
LSO - 3500 cm\(^{-1}\) (0.44eV)
BSO - 22400 cm\(^{-1}\) (2.8eV)

No significant change of the optical transmission of LSO:Ce crystals longer than 3.2eV (400nm)!

Optical transmission spectra of LSO#2619 (highly Ce doped) sample measured at room T before (1) and after (2) irradiation with protons.

Optical transmission spectra of LSO#2620 (slightly Ce doped) sample measured at room T before (1) and after (2) irradiation with protons.

LSO Scintillation pulse: GEANT4 simulation

50 GeV e- scintillation pulse from 10 LSO:Ce plates
BSO Scintillation pulse: GEANT4 simulation

50 GeV e- Scintillation pulse from 10 BSO plates
Structure of the signal rise time in LSO/BSO module: GEANT4 simulation

Initial part of scintillation pulse from 10 BSO plates of module (zoom of first nanosecond of time scale)

Initial part of scintillation pulse from 10 LSO plates of module (zoom of first nanosecond of time scale)
Ionising radiation produces several transient phenomena occurring in a time interval of about $10^{-12}$ s or shorter. In case of dielectric materials the relevant process is a short term polarization.

Small shifts of the atoms due to polarization of the media under ionization can change band gap for a short time. Shift $\sim 0.2\text{Å}$ at time less than $10^{-12}$s.

Change of the two photons absorption conditions in the media for a short time.

Two photons absorption - an effective tool to exploit ultrafast changes in the dielectric transparent media. Hot carriers evolution in insulating material due to ionizing radiation.
Two photons absorption in PWO

Experimental bench to prove the concept

Two photons (2,97+3.16eV) absorption in 1 cm thick PWO.

R&D to combine ionization and picosecond two photons absorption is planned Within AIDA-II and TICAL: 4D Time Imaging Calorimeter ERC project.
How it can work and what may be the benefits?

1. Fibers can have different refraction index to control light speed

2. Fibers can be also scintillating

3. Registration can be managed in a regime of standing or travelling wave
CERN + Giessen + Mainz+ KEK+ Minnesota+ Minsk jointed efforts to study:

- Transmission deterioration of the crystals after proton irradiation;
- Color centers creation and their recovery;
- Phosphorescence (mostly in LSO and YSO);
- Energy deposition from the radioisotopes induced in different inorganic scintillation elements;
- Energy deposition in scintillators from the radioisotopes induced in construction materials like W, Pb;
- Radioisotopes induced radio-luminescence in detecting cells of different designs after irradiation.
## Summary of the crystal damages after irradiation with protons

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Transmission damage /cutoff shift</th>
<th>Phosphorescence</th>
<th>Radioisotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWO</td>
<td>Yes/Yes</td>
<td>weak</td>
<td>More than 20</td>
</tr>
<tr>
<td>PWMO</td>
<td>Yes/Yes</td>
<td>weak</td>
<td>More than 20</td>
</tr>
<tr>
<td>BSO</td>
<td>Yes/Yes</td>
<td>weak</td>
<td>More than 20</td>
</tr>
<tr>
<td>PbF$_2$</td>
<td>Yes/Yes</td>
<td>no</td>
<td>More than 20</td>
</tr>
<tr>
<td>LSO:Ce</td>
<td>Yes/Yes</td>
<td>strong</td>
<td>More than 10</td>
</tr>
<tr>
<td>YSO :Ce</td>
<td>Yes./(No data)</td>
<td>weak</td>
<td>One dominating</td>
</tr>
<tr>
<td>$Y_2$O$_3$(ceramics)</td>
<td>Yes./Yes</td>
<td>no</td>
<td>One dominating</td>
</tr>
<tr>
<td>YAP:Ce</td>
<td>Yes./(No data)</td>
<td>weak</td>
<td>One dominating</td>
</tr>
<tr>
<td>YAG:Ce</td>
<td>Yes./(No data)</td>
<td>weak</td>
<td>One dominating</td>
</tr>
</tbody>
</table>

(Details are presented in reports: E.Auffray et.al. SCINT 2013 & IEEE NSS MIC 2013)

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Optical transmission damage due to charged hadrons is proportional to the fluence of the particles through detecting cell.

Concentration of the new defects in scintillators is proportional to the number of the charged hadrons passed scintillator.

- **Homogeneous cell**: damage overall volume of scintillator;
- **Shaslik type cell**: all scintillator wafers are damaged but with the effect progressively decreasing from front to rare part of the cell;
- **Combined Fibers Calorimeter (CFC) cell**: damage in fibers is proportional to the fluence of the particles through fibers only, moreover, only forward part of the fibers will be damaged: 30-40 cm in the fiber material with density 4g/cm³.

Damage Profile (D)
# Scintillators in terms of damage effects: request for new middle heavy scintillators

<table>
<thead>
<tr>
<th>Scintillation materials</th>
<th>Average atomic number</th>
<th>Light yield</th>
<th>Expected damage effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Damage of optical transmission</td>
</tr>
<tr>
<td>Cross luminescent</td>
<td>Low</td>
<td>Low</td>
<td>Large</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Low</td>
<td>Large</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Low</td>
<td>Large</td>
</tr>
<tr>
<td>Doped</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Large</td>
<td>Moderate</td>
</tr>
<tr>
<td>Self-activated</td>
<td>Low</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>Large</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

**DSB:Ce**

**CeF$_3$**

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# Single crystals versus inorganic fibers

<table>
<thead>
<tr>
<th>Cost drivers</th>
<th>Single crystalline materials</th>
<th>Inorganic fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion of the raw material mass in the final phase (pulling rate)</td>
<td>up to 5mm/hour</td>
<td>Up to 5mm/sec</td>
</tr>
<tr>
<td>Additional mechanical treatment</td>
<td>Yes</td>
<td>Practically no in a case of cladded species</td>
</tr>
<tr>
<td>Crystal growth techniques</td>
<td>Well developed</td>
<td>Transfer from laboratory techniques to industrial production</td>
</tr>
<tr>
<td>Raw materials specification</td>
<td>The same</td>
<td>The same</td>
</tr>
</tbody>
</table>
There is a strong demand for breakthrough in high time resolution techniques for future experiments at collider experiments.

These techniques have to be adequate to operate in a high dose rate irradiation environment containing strong hadron component.

New materials for future calorimetry have to be not only surviving in a high dose rate environment but also suitable for implementation of high time resolution techniques.