DREAM Collaboration: Recent Results on Dual Readout Calorimetry.

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In hadronic calorimeters, the fluctuations of the e.m. fraction of the shower \( f_{em} \) dominate the energy resolution for hadrons and jets.

In non-compensating calorimeters (i.e. where \( e/h \neq 1 \)) it is possible to eliminate this effect by measuring \( f_{em} \) event by event.

This was achieved in 2003 in the DREAM Calorimeter with two active media:
- the signal \( S \) in scintillating fibers to measure \( dE/dx \) from all charged particles,
- the signal \( Q \) in clear fibers (quartz or plastic) for Cherenkov light mostly from the e.m. component of the showers.

- Copper – Scintillating and Quartz (clear) fibers
- 19 hexagonal towers,
- each tower: 270 hollow copper rods,
- 2 m (10 \( \lambda_{Int} \)) in depth, radius \( \approx 16 \text{ cm} \) (< 1 \( \lambda_{Int} \)).
If $R = 1$ for e.m. shower, the response of the active media for a hadronic shower is:

$$R(f_{em}) = f_{em} + \frac{1}{e/h} (1 - f_{em})$$

where $e/h$ is 1.3 for Scintill. and 4.7 for clear fibers.

From the ratio of the signals in the quartz (clear) fibers $Q$ and in scintillating fibers $S$:

$$\frac{Q}{S} = \frac{f_{em} + 0.21 (1 - f_{em})}{f_{em} + 0.77 (1 - f_{em})}$$

$f_{em}$ is measured and the energy is corrected.

Resolution was limited by the small Cherenkov photon yield (8-18 ph.e. per deposited GeV).

“Jets” 200 GeV (pions interacting in a target)
Dual Readout in crystals

- In last years extensive studies were performed to extend the Dual Readout in crystals used in homogeneous calorimeters. In these crystals a fraction of the light yield is due to Cherenkov emission (1% in BGO, up to 15% in PWO).
- The peculiar features of the Cherenkov light can be exploited to separate the two types of light:
  - Directionality: \( \cos \vartheta = 1/\beta n \)
  - Timing: Cherenkov light is prompt (few ns) while scintillation light has decay constant.
  - Spectral properties: \( 1/\lambda^2 \) distribution
- One more tool: polarization of the Cherenkov light.
Polarization in dual read out

- Cherenkov light is emitted by molecules that are excited and polarized by a superluminal particle crossing the medium.
- The molecules emit coherent radiation at an angle $\theta_C = \arccos (1/\beta n)$ with respect to the particle direction and with the polarization vector perpendicular to the cone whose central axis is the particle track.

Then the Cherenkov component can be separated from the scintillation light by a polarizer in front of the PMT.

This was done by the DREAM Collaboration in the 2010 test beam. See NIM A 638 (2011) 47-54.
✓ 180 GeV/c pion beam crossing a BSO crystal,
✓ UV filter followed by a polarizer to separate the Cherenkov light.
High density scintillating crystals are used as excellent e.m. calorimeters but they have poor performance for detection of hadrons and jets (very large e/h ratio).

The possibility to separate the Scintillation/Cherenkov components in crystals demonstrated by the DREAM Collab. allows to extend the dual-readout also in e.m. crystals calorimeters.

Extensive studies have been performed in the last years by the DREAM Collaboration on PWO and BGO crystals (see NIMA).

A recent test beam compared two crystals of BSO (Bismuth Silicate) and BGO (Bismuth Germanate) of equal dimensions (2.2 x 2.2 x 18 cm³).

Now on NIM A 640 (2011) 91-98

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Density (g cm⁻³)</th>
<th>Radiation length (mm)</th>
<th>Decay constant</th>
<th>Peak emission</th>
<th>Refractive index n</th>
<th>Relative light output</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSO</td>
<td>6.80</td>
<td>11.5</td>
<td>~100 ns</td>
<td>480 nm</td>
<td>2.06</td>
<td>0.04</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>11.2</td>
<td>~300 ns</td>
<td>480 nm</td>
<td>2.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>
- Faster scintillation in BSO (Scint. yield BGO / BSO ≈ 4),
- Same attenuation length (Cher. and Scint.) ≈ 34 cm,
- Absorption for Cherenkov (1/λ²) smaller in BSO,
- Cherenkov yield BSO / BGO ≈ 5 with U330, less with UG11.

- Crystals on a rotating platform,
- UV filter (UG11/U330) for Cherenkov PMT
- Yellow filter for Scintillation PMT

Deposited Energy (GeV)

C/S
Often in present experiments the e.m. calorimeter is realized with crystals and a hadronic calorimeter is behind.

Since the dual read out was proven to be possible in crystals, the DREAM Collaboration has tested a full size BGO Calorimeter backed by the original DREAM calorimeter.

The e.m. section was a matrix of 100 BGO crystals, 24 cm long and tapered (2.4 x 2.4 cm² – 3.2 x 3.2 cm²) from L3 experiment.

A first test was performed in 2009, see NIMA 610 (2009), 488-501.

In the 2010 test beam 16 PMTs with UV UG11 filters (scintillation strongly attenuated).
Both Scintillation and Cherenkov signals read out in the same PMT: signal from scintillation extracted by a fit on the tail of the signal, Cherenkov = total – scintillation.

Preliminary results for 100 GeV e.m. shower. Scintillation - Cherenkov yields = 67 - 8 ph.e. /GeV

Work on the extension of the dual readout to both e.m. and hadronic sections is in progress.
In 2010 tested also a matrix of seven PbWO₄ crystals doped with 0.3% Molybdenum already characterized (NIM A621,212-221),

Each crystal: (3 x 3 x 20 cm³),

Both wavelength and timing analysis.

PWO Matrix

beam

Cherenkov side
U330 filters

Scintillation side
Yellow filters

σ = 1.2 %

σ = 5.0 %

100 GeV electrons (analysis in progress)
**Dual Readout with Tiles**

Dual Readout can be also implemented in a tile sampling calorimeter. A test of a small prototype $9 \times 9$ cm² was performed in the 2010 test beam.

- Two samplings: $4 \times (4$ mm Lead $+ 4$ mm Quartz $+ 7$ mm Scint), for a total of 6 R.L.
- Separate readout of Cherenkov and scintillation light in each sampling.

Charge distribution in C1 PMT for 180 GeV/c muons

- Fit of a poissonian for the $N\text{phe}$ convoluted with a gaussian with $\sigma^2 = a + b \cdot N\text{phe}$.
- In both modules: $N\text{phe} = 1.3$ for normal beam, 1.6 for 12° tilted detector.
- Average signal for 1 phe = PMT gain.
80 GeV electrons in Quartz – Scint. Tiles

- From a Geant4 simulation: 1.7 GeV / 11.3 GeV deposited in module 1 / 2.
- From average signals in C1 and C2 and PMT gains:
  - 58 Nphe/GeV in module 1,
  - 47 Nphe/GeV in module 2

Cherenkov yield comparable with Cherenkov crystal yield.
The New Dream Calorimeter

The DREAM Collaboration is now preparing a new prototype of fiber calorimeter with better performances.

- Two options: copper or lead (as the module tested in 2010),
- Extensive studies performed for clear fibers to have the largest Cherenkov light yield,
- Sampling fraction: 5% (was 2.6% in the original DREAM calorimeter),
- Quantum efficiency ~ 50% larger,

**Expected 90 Cherenkov phe/GeV, was 8-18 in DREAM**

- 1 module: 46 equal fibers per layer, 46 fiber layers of each type (scintillating/clear)
  - Dimensions of the module: 92 x 92 mm², 2.5 m in length
  - Divided in 4 towers readout for Cherenkov and scintillation signals.

For copper: \( X_0 = 2.31 \text{ cm}, \ R_M = 2.33 \text{ cm}, \ \lambda_{\text{int}} = 22.5 \text{ cm} \)

For lead: \( X_0 = 0.92 \text{ cm}, \ R_M = 2.38 \text{ cm}, \ \lambda_{\text{int}} = 25 \text{ cm} \)

- 21 modules: \( R_{eq} = 23.8 \text{ cm} \)
- 16 modules + 12 half modules: \( R_{eq} = 24.35 \text{ cm} \)
Test of the first New Dream module in the 2010 test beam (Pb absorber)

Constant delay = 2.4 ns from Scintillation de-excitation

2.03 \times 10^{10} \text{ cm/s}

2.05 \times 10^{10} \text{ cm/s}

\theta = 51^\circ

\theta = 51^\circ: \text{Cherenkov angle for } n = 1.6
A new lead module built in Pavia and next week in the test beam.

A copper module in preparation in Pisa will be ready for October test beam.
Conclusions

 ✓ After the pioneering tests of the first Dual Readout calorimeter, the DREAM Collaboration has extensively studied the Dual Readout in crystals.

 ✓ The separation of Cherenkov and Scintillation light can be achieved with several techniques based on the peculiar features of the Cherenkov radiation.

 ✓ Dual Readout e.m. calorimeters composed with crystals have been tested also followed by a hadronic calorimeter (DREAM).

 ✓ Dual Readout can be used also in tile calorimeters.

 ✓ The DREAM Collaboration is now preparing and testing a new fiber Dual Readout calorimeter larger than the original DREAM calorimeter.