Dual-Readout Calorimetry for High-Quality Energy Measurements

Status report of the RD52 (DREAM) Collaboration*

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*DREAM (RD52) Collaboration:
Cagliari, Cosenza, Como, Pavia, Pisa, Iowa State, TTU, Korea University
RD52 is a **generic** detector R&D project **not** linked to any experiment

**Goal:**

Investigate + eliminate the factors that prevent us from measuring hadrons and jets with similar precision as electrons, photons

And thus develop a calorimeter that is up to the challenges of future experiments in particle physics

**Outline:**

- New paper (hadronic performance)
- New experimental results (1 week in October 2016)
- Plans for the future
**Dual-Readout Method**

**What:** avoid spoiling em resolution in order to get $e/h = 1$ (i.e. keep $e/h > 1$) *BUT* measure $f_{em}$ event-by-event

→ eliminate effects of fluctuations in $f_{em}$ on calorimeter performance

**How:**

1) exploit the fact that $(e/h)$ values for a sampling calorimeter based on scintillation light or Čerenkov light are (very) different *(e.g. protons contribute to S but not to Č signals)*

2) calibrate separately S and Č response with electrons only
Dual-Readout w/ Sampling Fibre Calorimeters

2003 DREAM
Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%

2012 RD52
Copper, 2 modules
Each module: 9.3 * 9.3 * 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

2012 RD52
Lead, 9 modules
Each module: 9.3 * 9.3 * 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}

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RD52 DR Fibre Calorimeters

2 Cu modules

Pb 3*3 matrix
Hadron detection with a dual-readout fiber calorimeter

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Abstract

In this paper, we describe measurements of the response functions of a fiber-based dual-readout calorimeter for pions, protons and multiparticle “jets” with energies in the range from 10 to 180 GeV. The calorimeter uses lead as absorber material and has a total mass of 1350 kg. It is complemented by leakage counters made of scintillating plastic, with a total mass of 500 kg. The effects of these leakage counters on the calorimeter performance are studied as well. In a separate section, we investigate and compare different methods to measure the energy resolution of a calorimeter. Using only the signals provided by the calorimeter, we demonstrate that our dual-readout calorimeter, calibrated with electrons, is able to reconstruct the energy of proton and pion beam particles to within a few percent at all energies. The fractional widths of the signal distributions for these particles ($\sigma/E$) scale with the beam energy as $30%/\sqrt{E}$, without any additional contributing terms.


Key words: Dual-readout calorimetry, Čerenkov light, optical fibers

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Principles of Dual Readout Calorimetry

\[ S = \left[ f_{em} + \left( \frac{h}{e} \right)_S \times (1 - f_{em}) \right] \times E \]

\[ C = \left[ f_{em} + \left( \frac{h}{e} \right)_C \times (1 - f_{em}) \right] \times E \]

- Hadronic data points (S, C) are located around a straight (red) line.

\( 100 \text{ GeV} \pi^- \) (leakage corr.)
\[
\cotg \theta = \frac{1 - (h/e)_s}{1 - (h/e)_c} = \chi
\]

\(\Theta, \chi\) independent of both:

i) energy (!!)

ii) type of hadron (!!)

\[
E = \frac{S - \chi C}{1 - \chi}
\]

is universally valid
Dual Readout at Work (2)

80 GeV $\pi$

- Entries: 6391
- Mean: 50.53
- RMS: 10.54

Cerenkov
rms/mean = 21%

80 GeV $p$

- Entries: 9348
- Mean: 46.41
- RMS: 9.256

Cerenkov
rms/mean = 20%

Number of events per bin

Calorimeter signal (em GeV)

$\sigma/E = 8.2\%$

$\sigma/E = 8.4\%$

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Effects of the dual-readout method

Signal linearity

![Graph showing signal linearity vs energy (GeV)]
the Rotation Method

- Fit experimental data with a straight line
- Determine coordinates of \( P \)
  (intersection with \( C=S \) line)
- Rotate data points about \( P \)
  over angle \( (90^\circ - \theta) \)
- Project data points on horizontal \( (S) \) axis

\( \theta \) is independent of \( E \)
and particle type!!
\[ \text{Don't need this info!!} \]
Applications of the Rotation Method

80 GeV $\pi^+ / p$

(a) Entries: 1647
Mean $x$: 64.44
Mean $y$: 51.49
Std Dev $x$: 7.562
Std Dev $y$: 10.78

(b) Entries: 1647
$\chi^2$/ndf: 184.5/172
Mean: 80.73 ± 0.07
Sigma: 2.596 ± 0.060

(c) Entries: 2291
Mean $x$: 61.34
Mean $y$: 47.08
Std Dev $x$: 6.418
Std Dev $y$: 9.4

(d) Entries: 2291
$\chi^2$/ndf: 173.5/170
Mean: 80.36 ± 0.06
Sigma: 2.686 ± 0.051

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Single-Particle Hadronic Resolution

Hadronic Resolution (Pb Module)

\[ \sigma = \frac{53\%}{\sqrt{E}} + 1.7\% \]

to be corrected for:
- light attenuation
- lateral leakage

Jet energy resolution \( \sim \) few \% at \( \sim 100 \text{ GeV} \)

(4th Concept Detector LOI quotes 30\%/\sqrt{E} for jets)

Jet resolution should also be studied coupled w/ tracking information
(high granularity \( \rightarrow \) “particle-flow friendly”)

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The PMT readout of the DREAM calorimeter
PMT vs. SiPM Readout

**SiPM advantages:**
- compact readout (no fibres sticking out)
- longitudinal segmentation possible
- operation in magnetic field
- larger light yield (number of Čerenkov p.e. limits resolution)
- very high readout granularity → particle flow “friendly”

**SiPM (potential) disadvantages:**
- signal saturation (digital light detector)
- cross talk between Čerenkov and scintillation signals
- dynamic range
- instrumental effects (stability, afterpulsing, ...)

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First SiPM RD52 Readout

8 x 8 array of 1 mm² Hamamatsu SiPMs, 50 μm pixels (400/SiPM)

1 fiber per SiPM

MODULE 1: All channels equipped (32 scintillating + 32 Čerenkov fibers)

MODULE 2: Only Čerenkov fibers connected (32)
First SiPM RD52 Readout

Event displays in 8x8 mm² regions →
Showering electrons deposit 50% of their energy in this region

A short summary of the data taking conditions:

- two modules, both based on the array with 50 μm pitch cells:
  - module 1: both scintillating and Cherenkov fibres connected to the pixels of the array
  - module 2: Cherenkov fibers only were connected

Driven by two main reasons:
- the saturation of the sensors connected to the scintillating fibres
- the study of the optical cross talk

Recorded data:

<table>
<thead>
<tr>
<th>Module 1</th>
<th>Module 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>e⁺:</strong></td>
<td><strong>e⁺:</strong></td>
</tr>
<tr>
<td>20 GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>(&gt; 54,000 events)</td>
<td>(&gt; 178,000 events)</td>
</tr>
<tr>
<td>40 GeV</td>
<td>40 GeV</td>
</tr>
<tr>
<td>(&gt; 146,000 events)</td>
<td>(&gt; 300,000 events)</td>
</tr>
<tr>
<td>60 GeV</td>
<td>60 GeV</td>
</tr>
<tr>
<td>(&gt; 173,000 events)</td>
<td>(420,000 events)</td>
</tr>
<tr>
<td><strong>µ⁺:</strong></td>
<td><strong>µ⁺:</strong></td>
</tr>
<tr>
<td>180 GeV</td>
<td>180 GeV</td>
</tr>
<tr>
<td>(&gt; 100,000 events)</td>
<td>(&gt; 340,000 events)</td>
</tr>
<tr>
<td></td>
<td>100 GeV</td>
</tr>
<tr>
<td></td>
<td>(300,000 events)</td>
</tr>
</tbody>
</table>
Optical Cross Talk and Signal Saturation

(module 2)

Čerenkov light yield ~ 60-70 p.e./GeV (2 x PMT)
~ 25% optical x-talk to neighboring SiPM.s
~ 8% non-linearity due to saturation
2017 RD52 Plans

a) Eliminate x-talk by using separate SiPM arrays
   crucial issue: fibre feed-thru

b) Eliminate / strongly reduce saturation effects by using
   SiPM with 4 x larger dynamic range (4 x smaller pixel area)

c) Possibly develop an electronic board to integrate up to 9
   sensors in a single readout channel
Goals 2017 beam tests

In addition, we want to test two new full-scale copper-fiber calorimeter modules, built at Iowa State University (standard PMT readout)

For both components of our experimental program, we request electron beams, with energies from 10 - 100 GeV
More on Future

**INFN initiative for R&D for future accelerators (RD_FA):**
open a 3-year (2018-2020) working package on DR
→ first step: simulate a conceptual detector (IDEA) for CepC/FCCee

Activities already started (within RD52 groups and plans) ...

**collaboration growing**

- Setting up collaboration with CepC people
- in order to include the DR option in CepC CDR

- Setting up collaboration with FCCee people (Gigi, Mogens)

*Need a CERN official project!*
2017 Simulation Plans

Fully simulate a testbeam copper module (w/ full optical propagation and conversion, at least for Čerenkov light)

Implement a 4π geometry description for the IDEA detector → estimate W/Z resolution capability

Evaluate combined performance w/ a $2X_0$ preshower (Si or MPDG) detector in front
Copper grooving still an issue!
We don’t have yet a viable solution for massive production …

Thinking about bronze

Other issues:
When/How build a full-containment detector ?
When/How develop projective geometry ?
About the read-out of $O(10^3-10^4)$ fibres ?