Dual-Readout Calorimeter

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On behalf of the IDEA proto-collaboration
Outline

✦ Dual Readout Calorimeter Performance
   ✦ Electromagnetic performance
   ✦ Hadronic performance
   ✦ Jet performance
✦ Update on calorimeter development
   ✦ Mechanics
   ✦ Readout
   ✦ Prototype plans

IDEA: Innovative Detector for Electron-positron Accelerator
Dual-readout in a nutshell

- Compensation achieved without construction constraints
- Calibration of a hadron calorimeter just with electrons
- High resolution EM and HAD calorimetry

Cherenkov light (C)
- only produced by relativistic particles, dominated by electromagnetic shower component

Scintillation light (S)
- measure $dE/dx$

- Measure the electromagnetic fraction event by event to equalize the response off-line
- Charged hadrons ($\pi^+, \ldots$), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)
Dual-readout in a nutshell

Simultaneous measurement on event-by-event basis of elm fraction of hadron showers

\[ S = \left[ f_{em} + (h/e)_s \times (1 - f_{em}) \right] \times E \]
\[ C = \left[ f_{em} + (h/e)_c \times (1 - f_{em}) \right] \times E \]

\( e/h \) ratios \((c = (h/e)_c \text{ and } s = (h/e)_s)\) for either Cherenkov or scintillation structure) can be measured

\[ \cotg \theta = \frac{1 - (h/e)_s}{1 - (h/e)_c} = \chi \]

\( \Theta \) and \( \chi \) are independent of both energy and particle type

It is possible to evaluate

\[ f = \frac{c - s(C/S)}{(C/S)(1 - s) - (1 - c)} \]

and

\[ E = \frac{S - \chi C}{1 - \chi} \]
G4 Simulation for performance studies

Theta coverage up to ~0.1 rad
75 projective elements x 36 slices = 2700 tower

\[ \Delta \theta = 1.125^\circ \]
\[ \Delta \phi = 10^\circ \]

Copper + scintillating and Cherenkov fibers

Read out the single fiber: 130 M channels
1. Equalization constants are extracted per each tower by sending electrons of known energy and collecting signals (photo-electrons).

2. Electrons energy reconstructed by summing over all towers’ signals multiplied by the tower calibration constant….

3. Calibration constants are rescaled to take into account the different response while sampling electromagnetic showers tails.
Em. Performance: energy resolution

Cherenkov and scintillation sample the em. shower independently ➡ can be combined

\[
S: \quad \frac{\sigma}{E} = \frac{15.5\%}{\sqrt{E}} + 1.2\%
\]

\[
C: \quad \frac{\sigma}{E} = \frac{18.3\%}{\sqrt{E}} + 0.5\%
\]

\[
\frac{\sigma}{E} = \frac{11.0\%}{\sqrt{E}} + 0.8\%
\]

![Graph showing the energy resolution for Cherenkov and scintillation](image)
Response uniformity:
- Fibers pointing to interaction point
- Constant sampling fraction
- Constant sampling frequency

Reco vs True energy

σ/E @40 GeV vs tower num
Em. Performance: angular resolution

Position of impinging particle reconstructed with barycentre method with both scintillation and Cherenkov signals (combination of two signals)

All the fibers are readout independently (to be revaluated if grouping applied)

\[\sigma_\theta = \frac{1.4}{\sqrt{E}} + 0.018 \text{ (mrad)}\]

\[\sigma_\phi = \frac{1.8}{\sqrt{E}} + 0.088 \text{ (mrad)}\]
Had. Performance: pion energy resolution

Simulated 100 GeV π in IDEA calo (FTFP-BERT phys list)

- Scintillation
- Cherenkov
- DR method

Had. Performance: pion energy resolution

Energy resolutions pion:

\[ \frac{\sigma}{E} \sim \frac{33\%}{\sqrt{E}} \]

- Energy fluctuations
- Cherenkov fluctuations
- Scintillation fluctuations

RD52 TB data - Lead-fibers module
NIMA 866, 76 (2016)

- 30x30 cm\(^2\) lead/fibers module
- Containment ~ 90%
- not corrected for fiber attenuation length
Had. Performance: jet energy resolution

Jet reconstruction:

✦ Jet generated with PYTHIA8, tuned to LEP measurement

✦ Propagated in GEANT4 calorimeter

✦ Obtain C and S response + (θ,φ) of the tower ➞ get jet 4-momenta

✦ Clustering with FASTJET (Duham kt algorithm)

<table>
<thead>
<tr>
<th></th>
<th>Average (GeV)</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Truth</td>
<td>45.01</td>
<td>1.11</td>
</tr>
<tr>
<td>DR method</td>
<td>44.94</td>
<td>2.40</td>
</tr>
<tr>
<td>Scintillation</td>
<td>38.98</td>
<td>2.80</td>
</tr>
<tr>
<td>Cherenkov</td>
<td>29.37</td>
<td>5.30</td>
</tr>
</tbody>
</table>

\[ e^+ e^- \rightarrow q\bar{q} \]

90 GeV center-of-mass
Had. Performance: jet energy resolution

PYTHIA8 + GEANT4 + FASTJET

\[ \frac{\sigma}{E} = 38\% \]

\[ \frac{p_0}{\text{mean}} = 0.3815 \pm 0.004098 \]

\[ \chi^2 / \text{ndf} = 7.931 \times 10^{-6} / 3 \]

Material Budget:
- \( X_0 \) at 90°

No Material Budget

IDEA Preliminary

Rec. jet energy - true jet energy (GeV)
W and Z reconstruction

\[ e^+ e^- \rightarrow WW \rightarrow \mu \nu jj \]

Monte Carlo Truth
DR method

W Peak
80.38 GeV

<table>
<thead>
<tr>
<th></th>
<th>Average (GeV)</th>
<th>std</th>
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</thead>
<tbody>
<tr>
<td>W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC Truth</td>
<td>79.3</td>
<td>4.2</td>
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<tr>
<td>DR method</td>
<td>79.14</td>
<td>5.1</td>
</tr>
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</table>

\[ e^+ e^- \rightarrow HZ \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 jj \]

Monte Carlo Truth
DR method

<table>
<thead>
<tr>
<th></th>
<th>Average (GeV)</th>
<th>std</th>
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</thead>
<tbody>
<tr>
<td>Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC Truth</td>
<td>91.24</td>
<td>4.32</td>
</tr>
<tr>
<td>DR method</td>
<td>91.32</td>
<td>5.43</td>
</tr>
</tbody>
</table>
W/Z/H 2-jets final states

\[ e^+ e^- \rightarrow HZ \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 jj \]
\[ e^+ e^- \rightarrow WW \rightarrow \nu_\mu \mu jj \]
\[ e^+ e^- \rightarrow HZ \rightarrow bb\nu\nu \]

PYTHIA8 + GEANT4 + FASTJET

Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal

Only decays to u,d,s,c

c semileptonic decays excluded
Next step: prototype in 2020

10x10 cm² divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S)
♦ 2mm outer diameter, 1mm inner diameter
♦ Material: brass CuZn37
Readout:
♦ 1 central tower readout by SiPM
♦ 8 surrounding towers readout by PMT (à la RD_52)
SiPM Readout: RD52 TB

- Dual-layer SiPM readout in previous TB
  - Avoids optical cross-talk
- Saturation studied with dedicated test beams
  - 25 µm pixels OK for Cherenkov
  - Yellow filter used to control saturation in Scintillation channel

The sensors used were 25 µm cell pitch (S13615-1025)
First test with new SiPM

We tested new SiPMs using our standard equipment (SP5600 and DT5720A from Caen) together with an automatic software tool developed to characterize SiPMs (JINST 10, C08008)

Sensor: S14160-1315PS
   Cell size =15μm
   Vbias = 42 (≈ 4 V over breakdown)
   Signal amplification: 40dB
   Measured Xtalk = 2%

Sensor: S14160-1310PS
   Cell size =10μm
   Vbias = 42.5 (≈ 4.5 V over breakdown)
   Signal amplification: 40dB
   Measured Xtalk = 1.8%
If the Citiroc1A qualification will fulfil our requirements we still need a compact and scalable solution for a test beam: the FERS-5200 system from CAEN could be a possible solution.

**FERS: A5202**

**The basic principle**
- 2 Citiroc1A (64 ch)
- Timing with a TDC implemented into the FPGA ($\approx 0.5$ ns)
- 2 ADC to measure the charge
- 1 HV power supply (20–100V) with temperature compensation
- Interface for readout
Challenges in 2020 prototype

Verify changes in mechanical construction procedure

Challenges in the Readout

- Improve the linearity response:
  - SiPMs with larger dynamic range (smaller cell-size)
  - ... in addition to yellow filters to attenuate the scintillating light
- Increased number of channels looking for a scalable and cost effective solution
  - The use of CITIROC 1A is under study
  - The SiREAD could allow for the longitudinal segmentation using the timing
- Signal grouping
  - possibility to be studied in order to reduce the number of channels to readout
Summary

Dual-readout calorimetry development in the IDEA framework

✦ A number of new performance studies with full simulation, tuned on TB data
  ✦ EM E resol. 11%/\sqrt{E} uniform in the whole detector;
  ✦ Optimal angular resolution (1.4/\sqrt{E} mrad in \theta and 1.8/\sqrt{E} mrad in \varphi ) when all the fibers are readout
  ✦ Good di-photon separation and Particle ID
  ✦ Hadronic energy resolution as good as 33%/\sqrt{E} to single particle, and 38%/\sqrt{E} to jets

✦ Detector and Readout development
  ✦ TB in 2020 on new 10x10x100 cm$^2$ prototype includes all new proposed solution
    ✦ Detector unit based on 2mm capillary with fiber core
    ✦ SiPM readout of 320 channel with dedicated electronics
Before Correction

- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and energy which one would obtain if fem=1 (em scale calibration)
**Dual-Readout approach at work**

200 GeV “jets” in DREAM

\[ \cot \theta = \frac{1-(\bar{h}/e)_S}{1-(\bar{h}/e)_C} = \chi \]

\[ E = \frac{S - \chi C}{1 - \chi} \]
Em. Performance: energy resolution

Scintillation

Cherenkov

Simulated 40 GeV e- in IDEA calo

θ=φ=1.5°
The sensors used were 25 μm cell pitch (S13615-1025)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>S13615</th>
</tr>
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<tbody>
<tr>
<td>Effective photosensitive area</td>
<td>-</td>
<td>1.0x1.0</td>
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<tr>
<td>Pixel pitch</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>Number of pixels / channel</td>
<td>-</td>
<td>1584</td>
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<tr>
<td>Geometrical fill factor</td>
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<td>47</td>
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<table>
<thead>
<tr>
<th>Parameters</th>
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<th>S13615</th>
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<tr>
<td>Spectral response range</td>
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<td>320 to 900</td>
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<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td>450</td>
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<tr>
<td>Photon detection efficiency at λp³</td>
<td>PDE</td>
<td>25</td>
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<tr>
<td>Breakdown voltage</td>
<td>V_{BR}</td>
<td>53 ±5</td>
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<tr>
<td>Recommended operating voltage</td>
<td>V_{GD}</td>
<td>V_{BR} + 5</td>
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<tr>
<td>Dark Count</td>
<td>-</td>
<td>50</td>
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<tr>
<td>Crosstalk probability</td>
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<td>1</td>
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<tr>
<td>Terminal capacitance</td>
<td>C_{t}</td>
<td>40</td>
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<tr>
<td>Gain(^{15})</td>
<td>M</td>
<td>7.0x10(^5)</td>
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<td></td>
<td></td>
<td>1.7x10(^6)</td>
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## New sensors: SI4160-1310PS / SI4160-1315PS

<table>
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<th>Parameter</th>
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<th>SI4160</th>
<th>SI4160-1310PS</th>
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<th>SI4160-3015PS</th>
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<td>3 x 3</td>
<td>1.3 x 1.3</td>
<td>3 x 3</td>
<td>mm</td>
<td></td>
<td></td>
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<tr>
<td>Pixel pitch</td>
<td>10</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>µm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>16675</td>
<td>90000</td>
<td>7296</td>
<td>40000</td>
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<tr>
<td>Geometrical fill factor</td>
<td>31</td>
<td>49</td>
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<td></td>
<td></td>
<td>%</td>
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<tr>
<td>Package</td>
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<tr>
<td>Window</td>
<td>Silicone resin</td>
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<td></td>
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<tr>
<td>Window refractive index</td>
<td>1.57</td>
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<tr>
<td>Spectral response range</td>
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<td>290 to 900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nm</td>
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<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td>460</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nm</td>
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<tr>
<td>Photon detection efficiency at λp²</td>
<td>PDE</td>
<td>18</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Breakdown voltage²³</td>
<td>VBR</td>
<td>38±3</td>
<td>44±3</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Recommended operating voltage²³</td>
<td>Vop</td>
<td>Vbr + 5</td>
<td>Vbr + 4</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
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<tr>
<td>Vop variation within a reel</td>
<td>±0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Dark count rate²⁴</td>
<td>typ. DCr</td>
<td>120</td>
<td>700</td>
<td>120</td>
<td>700</td>
<td></td>
<td>kcps</td>
</tr>
<tr>
<td></td>
<td>max. DCr</td>
<td>360</td>
<td>2100</td>
<td>360</td>
<td>2100</td>
<td></td>
<td></td>
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<tr>
<td>Direct crosstalk probability</td>
<td>Pct</td>
<td>&lt; 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Terminal capacitance at Vop</td>
<td>Ct</td>
<td>100</td>
<td>530</td>
<td>100</td>
<td>530</td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Gain</td>
<td>M</td>
<td>1.8 × 10⁵</td>
<td>3.6 × 10³</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Temperature coefficient of Vop</td>
<td>ΔTVop</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mV/°C</td>
</tr>
</tbody>
</table>

*2: Photon detection efficiency does not include crosstalk and afterpulses.

*3: Refer to the data attached for each product.

*4: Threshold=0.5 p.e.
Optimization of hadronic simulation, based on comparison to RD52 test beam data

Promising preliminary results with FTFP_BERT_TRV and QBBC new phys list

60 GeV π FTFP-BERT \( \chi = 29 \)

100 GeV π FTFP_BERT \( \chi = 29 \)
The dual-readout fiber 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 \( \lambda_{\text{int}} \)

2012 RD52

Lead, 9 modules
Each module: 9.3 * 9.3 * 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 \( \lambda_{\text{int}} \)
The dual readout fiber calorimeters

2 Cu modules

Pb 3*3 matrix
Test on tublets

Under the test 2 tubes were cut with electro erosion in pieces 1cm long. 12 such pieces were measured twice with microscope + measuring system.

- **Outer Diameter**: Average: 2.015 mm, STD 3 μm
- **Inner Diameter**: Average: 1.063 mm, STD 7 μm
- **Concentricity Offset**: Average 19 μm, STD 8 μm
Depth at which light is produced in had shower fluctuate at the level of a $\lambda_{int}$ (~25 cm in RD52 calo)

Costant term (~ 1%) due to light attenuation (8m per Scintillation and 20m for Cherenkov)

Particles travel ~ c
Light in media travel at $c/n$
Using PMT signal starting time it is possible to correct for light attenuation effect
Signal linearity results

Measurement conditions (containment correction not applied):

\[ V_{\text{op}} = 5.5 \ V_{\text{ov}} (57.5 \ V) \] and \[ \text{PDE}_C \sim 25\% \ (440\text{nm}) - \text{PDE}_S \sim 20\% \ (556\text{nm}) \]

Temperature stability correction:

\[ \Delta T < 0.5^\circ \text{C} \] during a single run (negligible) \[ \| \Delta T \sim 1^\circ \text{C} \] during the full scan (considered)

Cherenkov Light Yield (2017) \( \sim 28.6 \pm 0.4 \text{ Cpe/GeV} \)

Scintillation Light Yield (2018) \( \sim 41.9 \pm 0.3 \text{ Spe/GeV} \)

Hottest fibre: \( \sim 9.8 \pm 0.1 \text{ Spe/GeV} \) Linear within 1%
Signal grouping

Full scale module: $O(10^8)$ readout channel
Analogic signal grouping to reduce channel number under study
Critically requiring linear working regime
• No way to apply correction on summed signals
• Need to guarantee multi-photon spectrum detection
• Push for higher dyn range (25 to 5 μm)

Multi-Photon spectrum preserved also with 9 grouped SiPM.

SiPM number 1 4 8
Space granularity (mm$^2$) 4.5 18 36
### Readout: Citiroc1A

<table>
<thead>
<tr>
<th>Detector Read-Out</th>
<th>SiPM, SiPM array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Channels</td>
<td>32</td>
</tr>
<tr>
<td>Signal Polarity</td>
<td>Positive</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Trigger on 1/3 of photo-electron</td>
</tr>
<tr>
<td>Timing Resolution</td>
<td>Better than 100 ps RMS on single photo-electron</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>0-400 pC i.e. 2500 photo-electrons @ 10^6 SIPM gain</td>
</tr>
<tr>
<td>Packaging &amp; Dimension</td>
<td>TQFP160-TFBGA353</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>225mW - Supply voltage: 3.3V</td>
</tr>
</tbody>
</table>

**Inputs**
- 32 voltage inputs with independent SiPM HV adjustments

**Outputs**
- 32 digital outputs (for timing)
- 2 multiplexed charge output, 1 multiplexed hit register and 2 trigger outputs

**Internal Program. Features**
- 32 HV adjustment for SiPM (32x8bits), Trigger Threshold Adjustment, channel by channel gain tuning, 32 Trigger Masks, Trigger Latch, internal temperature sensor