Liquid-Argon Calorimeters for High Luminosity

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Instantaneous luminosity - $5 - 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

→ mean pile-up of 140-200 events

>25 years of operation instead of anticipated 10 years

Scoping document - ATLAS Phase II Upgrade → 3 Scenarios: Reference, Middle & Low Cost
Motivation for the HL-LHC to extend and improve the physics program

Probing the Higgs sector
- more precise coupling measurement
- rare decays
- self coupling

New physics beyond the Standard Model (SUSY and extra dimensions)

Maintain optimal trigger system

Challenges:
→ High instantaneous luminosity
→ High pile-up
→ Radiation damage
→ Higher trigger rates
→ More complex trigger algorithms
Liquid Argon Calorimeters

- Active medium → Liquid Argon (LAr)

- **The barrel** cryostat
  - two electromagnetic (EMB) halves → lead-LAr

- **The endcap** cryostat
  - Electromagnetic calorimeter halves/endcaps (EMEC) → copper/LAr
  - Two hadronic calorimeter wheels (HEC) → copper/LAr
  - three forward calorimeter wheels (FCal) → copper-tungsten/LAr

188 × 10^3 cells in total
LAr technologies

EM Cal Structure

HEC Structure

FCal Structure

Pb Absorber
• Honeycomb spacer
• Cu/Kapton electrode

Cu Absorber

Honeycomb spacer &
• Cu/Kapton electrode

Electrode Rods & Absorber Matrix
Cu (FCal1) + LAr 269 µm gap
W (FCal2/3) + LAr 376/508 µm gap
LAr Signal Pulse Shapes

Diagram showing a section of a liquid argon detector, labeled with components such as readout electrode, absorber, outer copper layers, inner copper layer, kapton, stainless steel, glue lead, liquid argon gaps, and HV connections.

Graph on the right showing detector pulse, shaped and sampled signal, and time axis in nanoseconds (0-600 ns).
LAr & Tile Calorimeters

- The LAr and Tile calorimeter electronics upgrades are mandatory → all scenarios of Phase II

- Replacement of FCal1 with high-granularity sFCal1
  - Boiling is almost excluded

- New device in front of endcap: HGTD - High granularity timing detector

<table>
<thead>
<tr>
<th>Calorimeters</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAr Calorimeter Electronics</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Tile Calorimeter Electronics</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Forward Calorimeter</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>High Granularity Precision Timing Detector</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
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</tbody>
</table>

High Granularity Timing Detector

HLR front-end

high granularity small-gap LAr forward calorimeter (sFCal)
sFCal Option

- **Degradation - most inner radius:**
  - $\text{Ar}^+$ build-up → **field & signal distortion**
  - High HV currents

The FCal is planned to be replaced by a high-granularity sFCal in order to improve the physics performance, if installation and radiation risks are found to be sufficiently small.
sFCal Option

- **sFCal** - A finer granularity copy of the existing FCal1 - 100µm
- **The only option** to improve the current performance
  - Improved granularity in $(\Delta \eta \times \Delta \phi)$ → by removing summing boards → will assist in pile-up reduction
  - Lower protection resistors, new cooling loops
Problem of positive ion buildup:

**D** - ionization rate per volume

**Dc** - critical ionization rate → charge buildup in gap = to charge on electrodes

Relative rate \( r = \frac{D}{D_c} \)

**Signal S:**

1 for \( r \leq 1 \) and \( (1/r)^{1/4} \) for \( r > 1 \)

\[
\frac{i}{i_c} = \begin{cases} 
\frac{I}{I_c} & \text{for } I < I_c \\
(I/I_c)^{3/4} & \text{for } I > I_c
\end{cases}
\]
The Calorimeter Test Modules

HEC

- 60×60 mm²
- 4 readout channels
- 4 HV channels

EMEC

- 70×70 mm²
- 4 readout channels
- 3 HV channels

FCal1/sFCal

- 90×60 mm²
- 2x4 readout channels
- 2x4 HV channels

Each module is housed in a separate movable cryostat.
Setup in experimental area


Test beam setup and absorber thickness was optimized in MC

Current talk is on the basis of 2013 Data
HiLum R&D Project

IHEP/Protvino proton beam comes in bunches beam of 50 GeV

Bunch structure with every 6\textsuperscript{th} bunch filled → ~1 μs bunch spacing

Studies without pileup.

Extract one accelerator fill in ~1.2 s spill

\begin{align*}
\text{Intensity range:} & \quad 10^6 - 3 \times 10^{11} \text{ p/spill}
\end{align*}
Hilum: Liquid argon calorimeter performance at high rates

From minimum bias events at LHC we obtain for a LHC luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ a corresponding beam intensity at Protvino of $6.7 \times 10^8$ p/s ($8.9 \times 10^7$ p/s, $4.8 \times 10^7$ p/s) for the FCal(269) (EMEC,HEC) with $\sim$46% MC uncertainty.
HV Current Measurement

Device is installed between the HV power supply and the Filter Boxes of the Calorimeter modules

Measurement of the 3 EMEC HV channels in March 2013 run

Four 24-bit ADCs → Digital resolution of 1.2nA

Measurement rate: 10Hz / channel

Time-stamp of internal clock was synchronized with DAQ clock to ±1s

Stable and solid running
HV Current from EMEC mock-up over very wide range of beam intensity

Expected $\sim 0.75$

$$i/i_c = \begin{cases} 
\frac{I}{I_c} & \text{for } I < I_c \\
(I/I_c)^{3/4} & \text{for } I > I_c
\end{cases}$$

Prediction $\rightarrow$ Above critical intensity $I_c \rightarrow$ space charge limit.

Current drawn at $I_c$ is critical current $i_c$

<table>
<thead>
<tr>
<th>Protons/spill</th>
<th>$10^7$</th>
<th>$10^8$</th>
<th>$10^9$</th>
<th>$10^{10}$</th>
<th>$10^{11}$</th>
<th>$10^{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons/bunch</td>
<td>5</td>
<td>50</td>
<td>500</td>
<td>5000</td>
<td>5 \cdot 10^4</td>
<td>5 \cdot 10^5</td>
</tr>
<tr>
<td>LHC lumi equal [cm$^{-2}$ s$^{-1}$]</td>
<td>$10^{32}$</td>
<td>$10^{33}$</td>
<td>$10^{34}$</td>
<td>$10^{35}$</td>
<td>$10^{36}$</td>
<td>$10^{37}$</td>
</tr>
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Test to Destruction

- Run IHEP proton beam with highest intensity for several days
- Compare HV currents before and after
- Roughly equivalent to worst place in EMEC after about 1000 fb$^{-1}$

![Graph showing relationship between HV Current [μA] and Cherenkov Intensity [10$^9$ p/s]]
Conclusions

Ar+ ion build-up is actually a problem for linearity for Liquid Argon Calorimetry

- LAr Calorimeters are intrinsically radiation tolerant (was shown after test for destruction)

- Critical intensity for ATLAS EMEC $\sim 1.6 \times 10^8$ p/s and for FCal1 is under investigations