Liquid argon calorimeter performance at high rates

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CALOR 2012
1. The ATLAS experiment at the LHC

- 2011: 7 TeV, ~ 5 fb\(^{-1}\) recorded
- 2012: 8 TeV, ~ 15 fb\(^{-1}\) expected
- inst. luminosity reached: \(6.5 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\)

- Planned to be reached after shutdown 2013/2014:
  - 13 TeV, \(L = 1-2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) inst. luminosity
    (nominal design: \(10^{34} \text{ cm}^{-2} \text{s}^{-1}\))
2. Upgrade plans

Phase II: Instantaneous luminosity of $5-7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Problems with rates and average energy deposits in calorimeter endcap region.

Ion build-up, HV drop, boiling Argon and space-charge effects in ATLAS FCal.

Confirm operation of Endcap and FCal calorimeters

Replace FCal with sFCal or install additional miniFCal
2. Upgrade plans

**LAr calorimeter system**

- **Liquid-Argon sampling calorimeters**
  - EM Barrel + EM Endcap (EMEC)
  - Hadronic Endcap calorimeter (HEC)
  - Forward calorimeter (FCal)

- Highest particle flux in forward region (EMEC, HEC, FCal)

Operation after Phase II upgrade need to be tested.
2. Upgrade plans

**Simulations:**

- Particle flux at $> 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is expected to be too high for current FCal with 250 $\mu$m gaps.

**FCal1 structure:**

**Operation performance with increased luminosity:**

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[Diagram of FCal1 structure]

[Graph showing Relative Current vs. time (t) with different luminosities and HV values]
3. Hilum project

- Hilum project at U-70 accelerator in Protvino, Russia
- Goal: test EMEC, HEC and FCal in HL-LHC environment

INTAS Project INTAS-CERN 05-103-7555

Hilum ATLAS LAr Endcap Collaboration:
- Univ. of Arizona
- Univ. of Dresden
- JINR Dubna
- IEP Košice
- Univ. of Mainz
- LPI Moscow
- MPI Munich
- BINP Novosibirsk
- IHEP Protvino
- TRIUMF Vancouver
- Univ. of Wuppertal
3. Hilum project

- Proton beam of 50 GeV
- Bunch structure with every 6\textsuperscript{th} bunch filled → \(\sim 1\mu s\) bunch spacing
- Extract one accelerator fill in \(\sim 1.2\) s spill
- \(\sim 10\)s spill cycle time
- Intensity range: \(10^6 - \sim 3\times10^{11}\) p/spill
- Beam extraction with bent crystal technique
3. Hilum project

**Setup in experimental area**

**Goal:** simulate particle flux through calorimeters in dependence of $\eta$ as in ATLAS

*→* Testbeam setup and absorber thickness was optimized in MC simulations, using the 2D-gaussian beam size of 10mm.
3. Hilum project

The calorimeter test modules

HEC module

EMEC module

FCal1/sFCal module

60×60 mm²
4 readout channels
4 HV channels

70×70 mm²
4 readout channels
3 HV channels

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

Each module is housed in a separate movable cryostat.
3. Hilum project

Beam intensity monitoring

- Bunch based: Cherenkov counter with fast ADC-readout
  - Resolution of single bunches possible
  - Important due to bunch-to-bunch variations

- Absolute calibration done with activation of AL foils:
  - Reaction: \(27\text{Al}(p,3p3n)\text{22Na, } 22\text{Na} \rightarrow \gamma \) (1275 keV)
  - Overall precision: 15%.
Readout signal shapes

- Charged particles passing the LAr detectors produce typical triangular pulse at the detector
  - This is shaped by the front-end electronics
- Readout done with two 25ns sampling ADCs
- Main mode + delayed mode → effective: 12.5ns
- 2 gains: low and medium gain
  - Understanding of the whole readout chain is rather good

- In addition a charge flow in the gap needs to be compensated by the HV system (→HV DC current).

Response of one readout channel of the HEC to a calibration pulse (black)
Corresponding model function (red)
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Prediction for signal behaviour

Problem of positive ion buildup:
- D is ionization rate per volume
- \( D_c \) is critical ionization rate \( \rightarrow \) charge build-up in gap is equal to charge on electrodes
- Relative rate \( r = D/D_c \)
- \( w \): recombination rate
- Signal \( S \): \( 1 \) for \( r \leq 1 \) and \( 1/r^{1/4} \) for \( r > 1 \)

Prediction of HV currents:
Above critical intensity \( I_c \) \( \rightarrow \) space charge limit. Current drawn at \( I_c \) is critical current \( i_c \)

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

J. Rutherfoord, NIM A 482 (2002) 156-178:

Analytic calculations (curves) and simulations (dots) for different recombination rates \( w \)

More details on that: Presentation by John Rutherfoord
3. Hilum project

**Prediction for signal behaviour (2)**

Simulations of charge density and electric field over 2mm LAr gap of EMEC module for different beam intensities.

Assumed: HV = 1.2kV
- ion mobility: $\mu_+ = 10^{-3}$ cm$^2$/Vs
- reco. rate constant: $k_r = 10^{-5}$ cm$^3$/s

**Current** and shaped pulse for 2mm LAr gap of EMEC module for different beam intensities.

Scale factors of 3.3 ($10^8$ p/s) and 10 ($3 \times 10^8$ p/s) are used for better comparison of the effects.
3. Hilum project

Results – Readout signal shapes EMEC
3. Hilum project

Results – Readout signals

EMEC

Pulse Height, ADC/proton vs Beam Intensity, protons/s

Critical Intensity = (1.64 \pm 0.77) \times 10^8

HV corrected critical intensity

nominal LHC

HEC

Pulse Height, ADC/proton vs Beam Intensity, protons/s

Critical Intensity = (1.78 \pm 0.7) \times 10^8

HV corrected critical intensity

nominal LHC

FCal 250 \( \mu \)m gap

Pulse Height, ADC/proton vs Beam Intensity, protons/s

Critical Intensity = (9.8 \pm 0.3) \times 10^8

nominal LHC

Critical intensity

FCal 100 \( \mu \)m gap

Pulse Height, ADC/proton vs Beam Intensity, protons/s

Critical Intensity > 1.0 \times 10^{10}

nominal LHC
3. Hilum project

Results – HV currents

FCal (250μm gap)
Result from testbeam run 2008

- FCal current increases linearly with beam intensity
- Has become one of the standard methods for relative luminosity measurement in ATLAS

EMEC
Result from testbeam run 2010

- Behaviour of EMEC currents as predicted
- Prediction: \( i = i_c \times \left( \frac{I}{I_c} \right)^{0.75} \) for \( I > I_c \)
- Fit: Exponent \( p = 0.76 \pm 0.03 \)
4. Summary and Conclusion

  - Observed pulse shapes follow closely the expectations.
  - Signal behaviour of EMEC and HEC is flat up to $\sim 5-8 \times$ nominal LHC intensity (within present uncertainties).
  - $\text{FCal}(250\mu\text{m gap})$ amplitudes drop already slightly above nominal LHC intensity.
  - Proposed $\text{FCal}(100\mu\text{m gap})$ test module shows very stable behaviour until $10 \times$ nominal LHC luminosity.
  - HV currents of EMEC behave well as predicted in dependence of intensity.

- **Recent run in 2012 (analysis ongoing) allows to reduce the systematic uncertainties at both low and high intensities.**
References


2. Upgrade plans

Simulated neutron flux in ATLAS

![Neutrons in ATLAS detector at $L = 10^{34}$ cm$^{-2}$ s$^{-1}$](image)
Cryogenic and LAr purity monitoring

- Temperature, pressure and level of LAr was monitored.
- Purity has to be < 1ppm O₂ equivalent to prevent signal bias due to space charge effects.
  - sufficient and stable enough over the time.
3. Hilum project

Results – Readout signal shapes HEC

![Graphs showing response vs time for different bunch conditions and voltages.](image-url)
3. Hilum project

Results – Readout signal shapes FCal(269)
3. Hilum project

Results – Readout signal shapes FCal(119)
Lumi monitoring with HV currents

- Was possible to show, that FCal HV current depends linear on beam intensity with non-linear part < 0.36% (95% CL) at $10^9$ p/spill $\approx 10^{34}$ LHC Lumi.

- Results are published in JINST:
  
  http://iopscience.iop.org/1748-0221/5/05/P05005

  ➔ including systematic uncertainties a precision of $\sim 0.5\%$ might be possible in ATLAS at nominal luminosity

- Relative luminosity in ATLAS is measured using HV currents with < 1% precision.