The Liquid Argon Calorimeter for the ATLAS experiment at CERN

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Outline

• The Large Hadron Collider (LHC) at CERN: Overview
• Physics at LHC
• The ATLAS experiment
• ATLAS Liquid Argon Calorimeters
• The EM Barrel calorimeter
• Readout Electronics
• Performances of the detectors in testbeam
• Status and perspectives
• Conclusions
LHC: Overview
• Re-use of the LEP tunnel
• LEP closeout: Nov. 2000
• Last dipole removed: Feb 2002
• 40000 tons removed (30k from LEP, 10k from the exper. areas)
LHC: Layout

- LEP/LHC tunnel: 27km circumference
- \(\sim 100\)m underground
- \(1.3^\circ\) tilt towards the lake to reduce the depth at the north side (Jura)
- Booster-PS-SPS as proton injectors
- 2 Transfer lines
- 8 Interaction Points:
  - 4 equipped for experiments (IP1, IP2, IP5, IP8)
  - IP3, IP7: betatron and momentum correction system, IP4 RF, IP6 damping
- Reuse of LEP caverns for Alice/LHCb
- New constructions:
  - CMS, Atlas caverns
  - Transfer lines
  - Beam-Dumping at IP6
Excavations completed, Atlas cavern delivered (CMS, Jul 2004), all CE for LHC machines completed in summer 2003
LHC: Magnets

- 2 Beam-pipes / 27km circumf.
- 1200 supercond. dipole magnets

<table>
<thead>
<tr>
<th>L [m]</th>
<th>$T_{\text{top}}$ [K]</th>
<th>$B_{\text{nom}}$ [T]</th>
<th>$I_{\text{nom}}$ [A]</th>
<th># elem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.3</td>
<td>1.9</td>
<td>8.3</td>
<td>11796</td>
<td>1232</td>
</tr>
</tbody>
</table>

- Coils made of Nb-Ti cables
- Dipoles and quadrupoles interconnected so as to form a continuous cryogenic pipe
- Magnets immersed in a Superfluid Helium bath. Low pressure liquid helium heat exchanger
- Colder than dark outer space (2.7K)
- In all, LHC cryogenics will need 40,000 leak-tight pipe junctions, 12 Ml of LN$_2$ will be vaporised during the initial cooldown of 31ktons of material. LHe total inventory 700,000 litres
LHC: Magnets (2)

Superconducting cable 3

Updated 31 May 2003

Data provided by A. Verweij  AT-MAS
## General Parameters (Protons)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy at collision</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Energy at injection</td>
<td>450 GeV</td>
</tr>
<tr>
<td>Dipole field at 7 TeV</td>
<td>8.33 T</td>
</tr>
<tr>
<td>Coil inner diameter</td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between aperture axes (1.9 K)</td>
<td>194 mm</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1 E34 cm⁻¹s⁻¹</td>
</tr>
<tr>
<td>Beam beam parameter</td>
<td>3.6 E-3</td>
</tr>
<tr>
<td>DC beam current</td>
<td>0.56 A</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>7.48 m</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>24.95 ns</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>1.1 E11</td>
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<tr>
<td>Normalized transverse emittance (r.m.s.)</td>
<td>3.75 μm</td>
</tr>
<tr>
<td>Total crossing angle</td>
<td>300 μrad</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>0 h</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>7 keV</td>
</tr>
<tr>
<td>Critical photon energy</td>
<td>4.1 eV</td>
</tr>
<tr>
<td>Total radiated power per beam</td>
<td>3.8 kW</td>
</tr>
<tr>
<td>Stored energy per beam</td>
<td>350 MJ</td>
</tr>
<tr>
<td>Filling time per ring</td>
<td>4.3 min</td>
</tr>
</tbody>
</table>

[from L.R. Evans presentation at the 2003 Particle Accelerator Conference, Portland, USA, 12-16 May]
### LHC Parameters: A-A beam

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Injection</th>
<th>Collision</th>
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<tbody>
<tr>
<td>Energy per charge</td>
<td>E/Q</td>
<td>0.45</td>
<td>7</td>
</tr>
<tr>
<td>Energy per nucleon</td>
<td>E/A</td>
<td>0.18</td>
<td>2.76</td>
</tr>
<tr>
<td>Centre-of-mass-energy</td>
<td>E_{cm}</td>
<td>73.8</td>
<td>1148</td>
</tr>
<tr>
<td>Dipole field</td>
<td>B_{max}</td>
<td>5.391</td>
<td>8.386</td>
</tr>
<tr>
<td>Transverse normalized emittance at IP</td>
<td>10^{-4} m</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>r.m.s. beam radius at IP</td>
<td>10^{-6} m</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>10^{-6} m</td>
<td>280</td>
<td>16</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>10^{-3} rad</td>
<td>&lt; 100</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>10^{-1} eVs/charge</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>10^{-6} cm</td>
<td>11.5</td>
<td>7.5</td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>10^{-3} E</td>
<td>0.468</td>
<td>0.114</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>10^{-9} ns</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Bunch harmonic number</td>
<td>h_{b}</td>
<td>891</td>
<td>891</td>
</tr>
<tr>
<td>Number of bunches per ring</td>
<td>n_{b}</td>
<td>592</td>
<td>592</td>
</tr>
<tr>
<td>Filling time in the LHC</td>
<td>min</td>
<td>9.8</td>
<td>-</td>
</tr>
<tr>
<td>Number of ions per bunch</td>
<td>N_{b}</td>
<td>10^7</td>
<td>7.0</td>
</tr>
<tr>
<td>Number of ions per beam</td>
<td>N</td>
<td>10^{10}</td>
<td>4.1</td>
</tr>
<tr>
<td>Ion intensity per beam</td>
<td>mA</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Initial luminosity per bunch</td>
<td>10^{24} cm^{-2}s^{-1}</td>
<td>-</td>
<td>1.7</td>
</tr>
<tr>
<td>Total initial luminosity</td>
<td>L_{0}</td>
<td>10^{27} cm^{-2}s^{-1}</td>
<td>-</td>
</tr>
<tr>
<td>IBS emittance growth</td>
<td>h</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>Luminosity half-life</td>
<td>h</td>
<td>-</td>
<td>4.2</td>
</tr>
</tbody>
</table>

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L.R. Evans, CERN EDMS Document No. 381951

[from L.R. Evans presentation at the 2003 Particle Accelerator Conference, Portland, USA, 12-16 May.]
LHC experiments

First beams: Apr 2007
5 experiments under construction

- **2 General Purpose experiments:**
  - **ATLAS:** (A Toroidal LHC Apparatus)
  - **CMS** (the Compact Muon Solenoid)

- **ALICE** (A Large Ion Collider Experiment)

- **LHCb** (CP violation in the b-quark sector)

- **Totem** (total pp cross-section (CMS cavern))
LHC capability to discover new physics or simply verify current theories is unprecedented. Even during the 1st year of running \( (L = 2 \cdots 10^{33} \text{cm}^{-2}\text{s}^{-1}) \) with an integrated luminosity of \( 10 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
<th># Events</th>
<th>Total statistics collected at previous machines by 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W \to e\nu )</td>
<td>30</td>
<td>( 10^8 )</td>
<td>( 10^4 \text{ LEP} / 10^7 \text{ Tevatron} )</td>
</tr>
<tr>
<td>( Z \to ee )</td>
<td>3</td>
<td>( 10^4 )</td>
<td>( 10^7 \text{ LEP} )</td>
</tr>
<tr>
<td>( \bar{t}t )</td>
<td>2</td>
<td>( 10^7 )</td>
<td>( 10^4 \text{ Tevatron} )</td>
</tr>
<tr>
<td>( \bar{b}b )</td>
<td>( 10^6 )</td>
<td>( 10^{12-10^{-13}} )</td>
<td>( 10^9 \text{ Belle/BaBar} )</td>
</tr>
<tr>
<td>( H \ (m=130\text{GeV}) )</td>
<td>0.04</td>
<td>( 10^5 )</td>
<td></td>
</tr>
<tr>
<td>( \tilde{g}\tilde{g} \ (m=1\text{TeV}) )</td>
<td>0.002</td>
<td>( 10^5 )</td>
<td></td>
</tr>
</tbody>
</table>

- Electroweak Symmetry Breaking, Higgs Boson
- Supersymmetry
- New Particle Search
- Extra-dimensions
- top/bottom
- Heavy Ion
Golden Channel: $H \rightarrow ZZ^* \rightarrow 4\ell (e/\mu)$
Atlas: Detector Overview

Diameter 25mt, Barrel Toroid length 26mt, Weight 7000 tons
... as tall as a 5 stories building
Atlas: Installation/Pit

BNL Instrumentation Division Seminar - Jun 11th, 2003- pag. 16
- Installation of TX1S shield beg. April
- Cavern delivered in schedule
Atlas: Inner Detector
- Silicon Pixels: 3 barrel layer modules + 3*2 disk modules
- Silicon Tracker
- Transition Radiation Tracker (straw tubes with Xe/CO₂/O₂ mixture)
Atlas: Superconductive Solenoid

- Field: 2T, Energy Stored: 38MJ
- Fully tested
- Ready for integration in the barrel EM cryostat by end of 2003
- Cryogenics chimney tested in summer 2002
Atlas: Tile Calorimeter

- Irons as absorber and scintillating tiles as active material
- Tiles placed perpendicular to the beam
- Boths sides readout by wavelength shifter into 2 separate PMs
Atlas: Toroids
Atlas: Muon Spectrometer

- Muon Spectrometer instrumented separately with precision chambers and fast trigger chambers.
- Momentum measurement: MDT in the barrel/EC, CSC in the forward region.
- Critical aspect: accuracy needed in positioning the chambers and sophisticated alignment measurement.
Atlas: LAr calorimeters

- EM barrel and EC: “accordion” geometry
- Hadronice Endcap
- Forward Calorimeter
LAr EMB: Calorimetry requirements

- Rapidity coverage
- Energy Range (16 bits):
  - Pileup noise in single readout cell: $\sigma \simeq 50\text{MeV}$
  - No significant degradation from readout electronics
  - $Z^*$ reconstruction ($M \simeq 5\text{TeV}$) sets the upper limit on the energy to be measured in a readout element
- Absolute em energy scale/linearity 0.1% for W,top mass measurement
- Energy Resolution:
  \[
  \frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
  \]
  - Stochastic term: $a \leq 10\%$
  - Noise term ($b \leq 200\text{MeV}$)
  - Constant term ($c \leq 0.7\%$)

$H \rightarrow \gamma\gamma$: $\sigma_{m_H} \simeq 1\%$
Angular Resolution

\[ \sigma_\theta \leq \frac{50 \text{mrad}}{\sqrt{E(\text{GeV})}} \]

resolution affects the accuracy on H mass reconstruction

\( \gamma \) reconstruction and direction measurements: fine \( \eta \) granularity of the first sampling layer + presampler

Fast Response:

- minimize the effects of pileup noise from minimum bias events through fast shaping
- bipolar shaping \( \rightarrow \) zero area signal \( \rightarrow \) no baseline shift from pileup

Coherent Noise: leq 5% of total incoherent noise per channel

jet and \( \tau \) reconstruction requires summing up to 1000 cells

Radiation resistance

- neutron fluence: \( 10^{12} \text{cm/yr} \)
- total dose: 20Gy/yr
LAr EMB: Cryostat (2)
- Etching of the inner layer (signal)
- Bonding
- Etching of the 2 outer layers (HV)
- Tolerances:
  - overall size: 0.4mm
  - accuracy of etching pattern: 0.2mm
  - relative alignment of the 3 layers: 0.2mm
  - clearance between cells: 0.1mm
- Screen printing HV distribution resistors, pads and bridges (*high resistivity ink: $\rho \simeq 1M\Omega/\square$*)
- Connector crimping to extract signals
LAr EMB: Kapton Bending
LAr EMB: Absorber preparation

- 2 nominal thicknesses (1.5mm, 1.1mm for $\eta \leq (\geq) 0.8$ respectively
- Lead sheets: (Online X-measurements to control flatness. Max. $\pm 30 \mu m$)
- Lead preparation: water brushing with alumina powder, rinsing, drying (done just before use because of fast lead oxidation)
- Steel (0.2mm thick) preparation before gluing:
  - Chemical degreasing (FINOX)
  - Passivation (NETINOX)
  - Rinsing and Drying
- Lead-steel sandwich by gluing with 0.13mm (0.33mm) thick prepreg (fiberglass cloth pre-impregnated with epoxy resin).
- Total thicknesses 2.16mm for both configurations
- Bending
- Encasing in G10 bars to hold in place
LAr EMB: Wheel Assembly
LAr EMB: Wheel Rotation
LAr EMB: Insertion
Access space limited during installation. Maintenance and operation is not going to be easy...
LAr EMB: Front-End Board

- 32 hybrid (4 preamplifier each) bipolar discrete technology
- 32 shaper (BiCMOS AMS): bipolar (RC)-(CR)^2 (\(\tau \approx 13.1\, \text{ns}\))
  - 4 input channels
  - 3 gain settings (1/10/100) to cover the 16 bit dynamic range needed
  - Integral non-linearity (\(\leq 0.2\%\))
- Analog pipeline: 40MHz sampling, SCA store samples during L1 latency
- Upon arrival of a L1 signal a train of samples digitized by 12-bit ADCs
- Gain Selector algorithms guarantee all the samples of a channel and event are digitized using the same gain scale
- Digitized data are serialized and transmitted to the ROD (1.6Gb/s optical link)
- First level of analog summing for the L1 trigger through pluggable Layer Sum Board. Signals sent through the baseplane to the Tower Builder Board
- **Crate fully loaded dissipates 3kW \(\rightarrow\) water cooling (leakless, i.e. negative pressure circulation system)
LAr EMB: Cooling
LAr EMB: Calibration Board

• 128 indep. current pulsers onboard: uniformity $\leq 0.11\%$ (after shaping)
• Programmable through a 17 bit DAC (DMILL technology)
• Pulse generated through switches synchronized to the 40MHz clock
• Exponential shape through an RL circuit ($\tau \simeq 365\text{ns}$)
• DAC voltage converted to DC current through custom static low-offset ($10\mu\text{V}$) operation amplifiers (DMILL technology)
• Control Registers sets calibration patterns, DAC amplitudes and set delay chips to change the relative phase of the pulse with respect to the 40MHz clock
- Analog summing (4 layers in depth) to reconstruct the $E_T$ deposited in a tower
- Tower size are: $\Delta \eta \Delta \phi = 0.1 \times 0.1$ for $\eta \leq 2.5$ ($\Delta \eta \Delta \phi = 0.2 \times 0.2$ for higher $\eta$)
- Conversion from deposited energy to $E_T$:
  - linear mixer gain on the LSB
  - final adjustment in the TBB
- Summing over the layers can be done only after pole zero correction (to compensate for the different $t_p$ due to a wide range of detector capacitance) and gain correction.
- Programmable delay settings can optimize the relative phase of the input signals from the different layers
- Signal outputs sent to Trigger Cavern Receiver boards will compensate for the attenuation along the cables (70m).
LAr EMB: Controller Board

- Board settings and monitoring (through a custom serial protocol, SPAC)
- Distribution of the Trigger signals
- 280V power supply in USA15
- 70mt of cables down in the exp. hall
- DCDC converter installed on the top of the crates
  - Rad. qualification: 300kRad, SEE/SEB
  - Magnetic Field
- Monitoring of the voltages and of the temperatures through custom *embedded* local monitoring board (ELMB) communicating through CANBus to the main monitoring framework
• Boards approaching production: formal review (PRR)
• System test in progress here in BNL to validate the readout architecture and the overall performances as a system
LAr EMB: TestBeam Results

- For the barrel calorimeter, see B. Aubert et al., NIM A500 (2003) 202-231.
- For the EC calorimeter, see B. Aubert et al., NIM A500 (2003) 178-201.
LAr EMB: TestBeam Results (3)

\[ \eta = 0.0875 \]
\[ \sigma(E)/E = a \sqrt{E} + b \]
\[ a = 9.11 \pm 0.12 \text{ GeV}^{1/2} \]
\[ b = 0.47 \pm 0.02 \% \]

\[ \eta = 0.3625 \]
\[ \sigma(E)/E = a \sqrt{E} + b \]
\[ a = 9.24 \pm 0.10 \text{ GeV}^{1/2} \]
\[ b = 0.23 \pm 0.04 \% \]

\[ \eta = 0.5375 \]
\[ \sigma(E)/E = a \sqrt{E} + b \]
\[ a = 9.23 \pm 0.09 \text{ GeV}^{1/2} \]
\[ b = 0.21 \pm 0.02 \% \]
• Optimal Filter Coefficient to calculate energy/time

\[
E = \sum \alpha_i \cdot (S_i - p) \\
E_T = \sum \beta_i \cdot (S_i - p)
\]

\[
\alpha = \frac{A^{-1} \cdot g}{G} \\
g = h \star i_{DET}
\]

\[
G = g^T A^{-1} g
\]  

• Pb.: Correct extraction of the detector response from calibration
- 1M events
- Equivalent to $\Delta \eta \times \Delta \phi = 1.2 \times 0.075$
- Unfolding of the constant term: 0.78%