Performance and upgrade of the ATLAS Tile Calorimeter

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on behalf of the
ATLAS Tile Calorimeter System

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Tile Calorimeter - central hadronic calorimeter in ATLAS

- Hadronic sampling calorimeter: iron/scintillator ~ 5:1
- 3 cylinders with coverage: $|\eta|<1.0$ in barrel, $0.8<|\eta|<1.7$ in extended barrel
  - 64 independent modules in every cylinder
  - thickness along radius – $7.4\lambda$ (1.54 m instrumented part)
- Aim for jet energy resolution: $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 3\%$

Dimensions
- Diameter: 8.5 m
- Length: 12 m
- Weight: 2900 T

Principle of TileCal:
Measure light produced by charged particles in plastic scintillators (tiles)

Role of TileCal:
Perform precise measurements of hadrons, jets, missing transverse energy as well as provide input signal to Level 1 Calorimeter Trigger

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- Diameter: 8.5 m
- Length: 12 m
- Weight: 2900 T
• Every scintillating tile in 11 rows is read out by 2 wavelength shifting fibers
• Fibers go along both sides of every module to outer radius and are grouped together into pseudo-projective geometry cells in 3 layers
• Granularity $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in first two and 0.2x0.1 in outermost layer
  • number of tiles in one cell varies from 16 to 300
• 5182 cells, 9852 channels in total (double readout for normal cells, single readout for special cells E1-E4, so called gap and crack scintillators)
• Readout is organized in four partitions
  • barrel is split in two partitions called LBA for $\eta > 0$, LBC for $\eta < 0$
  • two extended barrels called EBA and EBC
TileCal signal processing and calibration

• Signal from PMT is passed to front-end electronics (FEE) for shaping, amplification (2 gains 1/64 ratio) and digitization (10-bit ADC)
• Optimal Filter (OF) algorithm reconstructs amplitude and time of the signal from 7 consecutive measurements
  \[ A = \sum_{i=0}^{n} a_i S_i \quad \tau = \frac{1}{A} \sum_{i=0}^{n} b_i S_i \]
• Deposited energy is evaluated based on reconstructed amplitude in ADC counts and calibration coefficients
  \[ E [\text{GeV}] = A [\text{ADC}] \times C_{\text{ADC} \rightarrow pC} \times C_{\text{Cs}} \times C_{\text{laser}} \times C_{pC \rightarrow \text{GeV}} \]
• \( C_{\text{ADC} \rightarrow pC} \) is provided by Charge Injection System (CIS) which monitors stability of electronic chain
• \( C_{\text{Cs}} \) is provided by Cesium Calibration System which monitors all optic components - tiles, fibers, PMTs
• \( C_{\text{laser}} \) is provided by Laser Calibration System which monitors stability of PMTs between Cesium calib runs
• \( C_{pC \rightarrow \text{GeV}} \) conversion factor was measured in 2001-2003 when 11% of all TileCal modules were brought to the testbeam at the SPS
• CIS calibration is performed ~weekly by injecting pre-defined charge into readout chain
  • design values: 800 pC = 1023 counts in Low gain, 12.5 pC = 1023 counts in High gain
  • channel-to-channel variation ~ 1.6 %
  • very stable: RMS/mean of detector-wide average over whole RUN2 is 0.03-0.04%
• Cesium calibration is performed using movable radioactive sources (done 2-3 times per year now)
  • independent readout chain - uses integrator (with $\tau = 10$ ms) and 12bit ADC
  • measures total drift in tiles/fibers/PMT, which allows to set correct EM scale every year
• Laser calibration is performed by injecting laser light into every PMT
  • done in special calibration runs as well as in empty bunches during physics runs
  • allows to correct for PMT drift between Cesium runs (up to 2.5% per year in normal cells)
  • it is used also for monitoring of synchronization between LHC clock and digitization time
• Minimum Bias System
  • measure PMT current during data taking and gives information about instantaneous luminosity
  • shares readout with Cesium system, also used to set “Cesium” calibration constants for E-cells
  and other special cells which are not calibrated by Cesium source
• The response of high momentum isolated cosmic muons verifies the measured energy at the EM scale

• Isolated hadrons are used as a probe of the hadronic response. The detector response uniformity and linearity are observed.
**Pileup noise, timing, lumi measurements**

- Electronic noise in TileCal measured in dedicated pedestal runs is at the level of 20-40 MeV
- Pile-up noise is measured with zero-bias triggered events (as expected, it scales as $\sqrt{\mu}$)
- Time resolution studied with multijet events is within 1 ns for the cells with energy above 30 GeV
- TileCal participates in luminosity measurements, integrated current in all cells is measured
- Profile of lumi coefficients vs $\eta$ in physics runs reproduces profile of cell degradation measured by Cesium: cells with higher currents are drifting faster
LHC Schedule

**LS2: Phase-I Upgrade goals**
- $\mathcal{L} \cong 3 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- $\langle \mu \rangle \cong 80$
- Keep L1 trigger (max) 100 kHz; latency $\leq 3 \mu$s

**TileCal: Replacement of Crack Scintillators**

**LS3: Phase-II Upgrade goals**
- $\mathcal{L} \cong 7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- $\langle \mu \rangle \cong 200$
- Upgrade trigger (L0/L1) to 1 MHz; latency $\cong 10 \mu$s

**TileCal: Full electronics upgrade**
TileCal Phase I upgrade

- Crack scintillators (E3/E4) provide energy correction of electrons/photons/jets passing through the inter-cryostat region
  - resulting in a significant improvement in the energy resolution
- They are placed in relatively high radiation zone and require replacement for RUN3
- In addition, $\eta$ coverage will be extended from $1.2 < |\eta| < 1.6$ to $1.2 < |\eta| < 1.72$ to allow resolution improvements in that critical region
- New scintillators are currently being installed in the ATLAS detector

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TileCal in Phase II upgrade

- Full electronics replacement, both on and off detector
  - Higher trigger rate (1-4 MHz), extended data pipelines (35 s, moved off detector)
  - Full calorimeter information read out at 40 MHz: full granularity to trigger
  - Higher radiation levels, improved reliability and robustness of electronics
  - Increased bandwidth: 4096 up-links (9.6 Gbps) and 2048 down-links (4.8 Gbps)
- New modular mechanics: 4 mini-drawers in one super Drawer
- Data and power redundancy to improve system stability
- New low voltage and high voltage power supplies systems due to higher radiation requirements
  - HV Power Supply: better temperature and voltage stability, remote control -1024 new cables
  - LV Power Supply (LVPS): lower noise, better reliability and point-of-load regulators
- All kinds of radiation tests with new electronics components (especially LVPS) showed stable voltages, no destructive errors or latch-ups
- Also in plans: replacement of most degraded PMTs (~10%) and crack scintillators
Electronics layout of the HL-LHC TileCal

- Mini-drawer (MD) hosts 12 PMTs and 12 Front-End Boards (FEB) named FENICS - Front-end electronics
- FENICS card performs signal shaping and amplification (2 gains, 1/32 ratio)
- MainBoard: digitizes the front-end two-gain outputs at 40 MHz with 12bit ADCs (i.e. 17 bit effective range)
- Daughterboard (DB) transfers bi-gain output from 12 channels every 25 ns to the back-end via 4 x 9.6 Gbps links, distributes LHC clock settings, liaise the on- and off-detector electronics.
- Tile PPr (Preprocessor) buffers data from all MD in pipelines located off-detector; evaluates signal at the full 40 MHz rate; calculates trigger objects; distributes the sampling clock and detector control information.
- TDAQi interfaces with trigger and ATLAS TDAQ, sends accepted data to the FELIX (Front End LInkeXchange).
Testbeam measurements

- TileCal modules equipped with Phase-II upgrade electronics together with modules equipped with the legacy system were exposed to different particles and energies in 7 testbeam campaigns at SPS during 2015-2018

- Half-module (LBC65) was equipped with new electronics since 2015
- Extended barrel (EBC65) was equipped with new electronics in 2018 (latest generation of front-end cards)
Testbeam results

- Overall, good performance has been demonstrated
  - Agreement between legacy and new electronics in terms of energy calibration
  - Signal to noise ratio is improved with respect to legacy system (factor of ~2) and muon signal is very well visible
  - Different response for each hadron type compatible with previous testbeams

Response to electrons at different energies

Correct EM scale for electrons

Separation of particles of different types is possible thanks to upstream Cherenkov counters
In July 2019, a prototype of the TileCal drawer (so-called demonstrator) was inserted in the ATLAS detector for evaluation of its performance and functionality.

The prototype includes the HL-LHC electronics and the remote HV control and the current-style data-taking scheme, calibration and monitoring systems.

The 3-in-1 FEB is a predecessor of the FENICS including analog trigger output for the present ATLAS trigger system.

The Tile PPr demonstrator (1/8 of the full-size HL-LHC PPr) provides data to the current DAQ (ROD) and transmits triggered events to the FELIX.

The prototype will take data during Long Shutdown 2 (till 2020) and will be evaluated for RUN3.
Conclusions

• TileCal was performing very well during RUN2 in 2015-2018
  – Calibration is well understood
  – Response to single particles and jets agrees with MC

• Right now Phase I upgrade is ongoing, it involves replacement of crack
  scintillators of TileCal with bigger $\eta$ coverage

• All TileCal on- and off-detector electronics will be replaced in 2024-2026
  during Phase II upgrade for the HL-LHC era
  • R&D is done, initial tests demonstrate good performance
  • One Demonstrator drawer with new electronics was inserted in the
    ATLAS detector and its functionality is being evaluated
  • The main elements for Phase II upgrade are about to enter
    pre-production.