

ATLAS Tile Calorimeter Upgrades for the High-Luminosity LHC Era

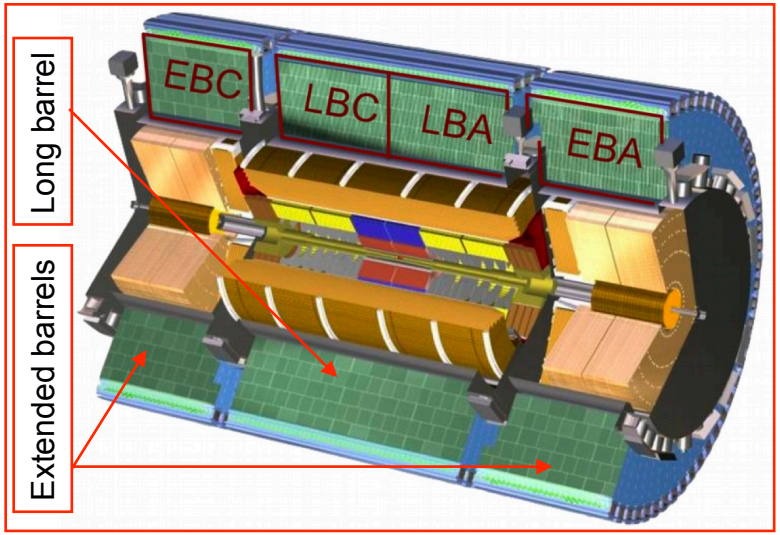
Seyedali Moayedi, on behalf of the ATLAS Tile Calorimeter System

University of Texas at Arlington

International Workshop on Future Linear Colliders – 11 November 2026

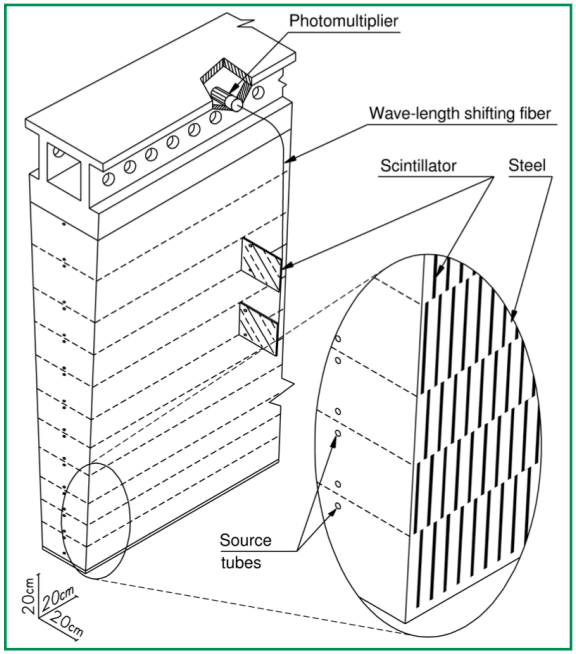
Introduction: ATLAS Tile Calorimeter

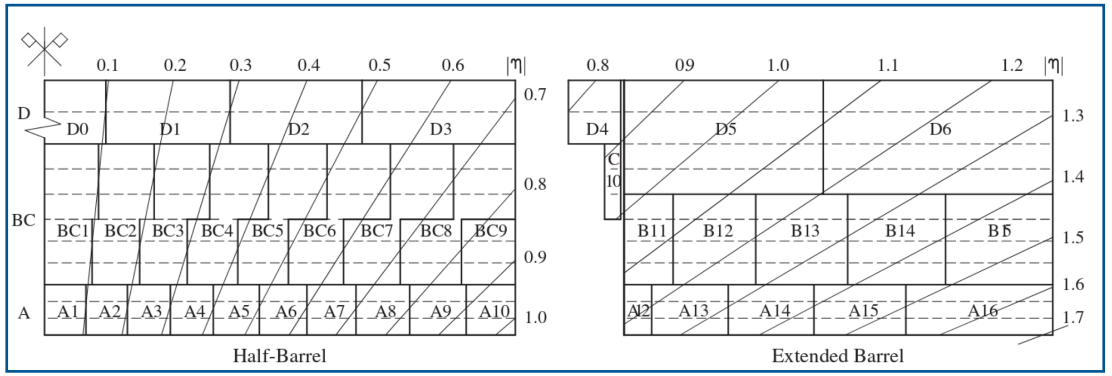
- The ATLAS Tile Calorimeter*, a hadron non-compensating sampling calorimeter, composed of wedge-shaped modules arranged in one long and two extended barrels, uses scintillating tiles and WaveLength Shifting (WLS) fibers to transfer light to the PhotoMultiplier Tubes (PMTs) inside the modules
- The WLS fibers are bundled to define cells, each cell read out by two PMTs
- Cell granularity down to 0.1 x 0.1 $\Delta\eta \times \Delta\phi$



ATLAS Tile Calorimeter drawing

Tile Calorimeter wedge module





Mapping of Tile Calorimeter cells

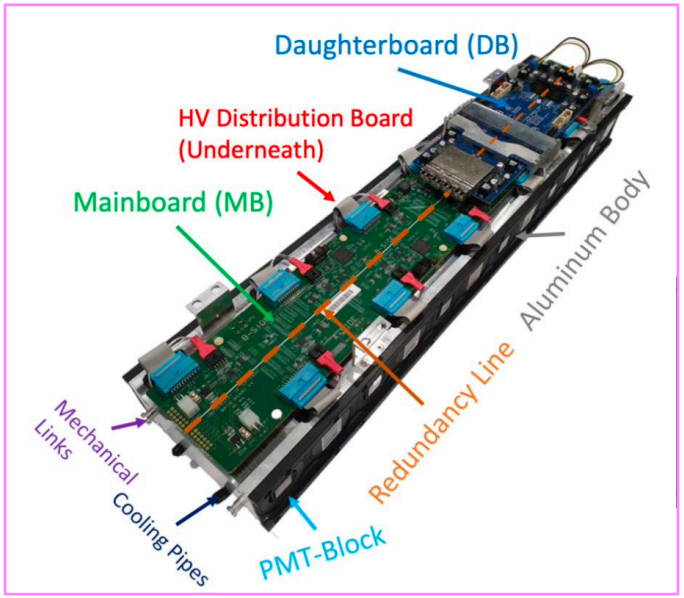
*Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter, https://cds.cern.ch/record/2285583/files/CERN-LHCC-2017-019.pdf

Tile Calorimeter HL-LHC Upgrade Overview

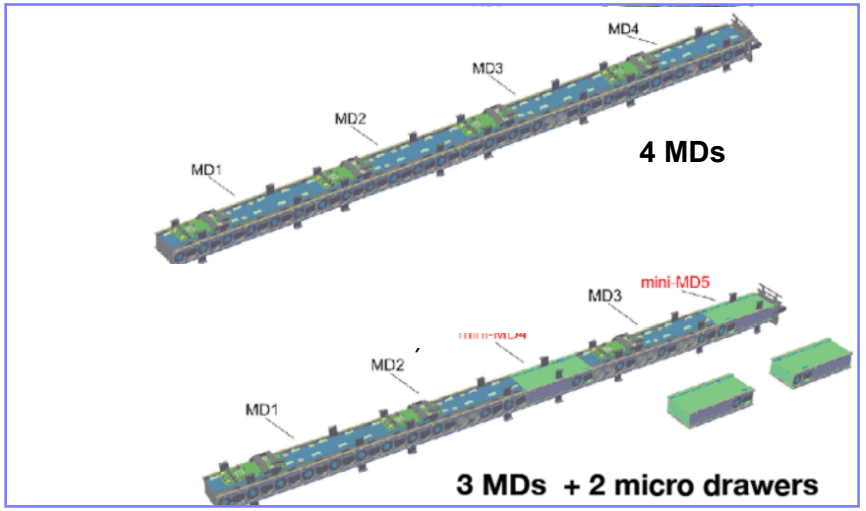
- New on- and off-detector electronics
- 40 MHz continuous data readout
- Fully digital trigger output for Level 1 trigger
- Improved radiation hardness
- Upgraded calibration systems

- Improved accessibility with new mechanical supports for front-end electronics, i.e., Mini-Drawers (MD)
- 896 independent mini-drawers instead of 256 super-drawers
- Improved redundancy and reduced single points of failure
- Replacement of 10% of PMTs
- New power supplies for High and Low Voltage (HV and LV)

Mini-drawer with assembled on-detector electronics

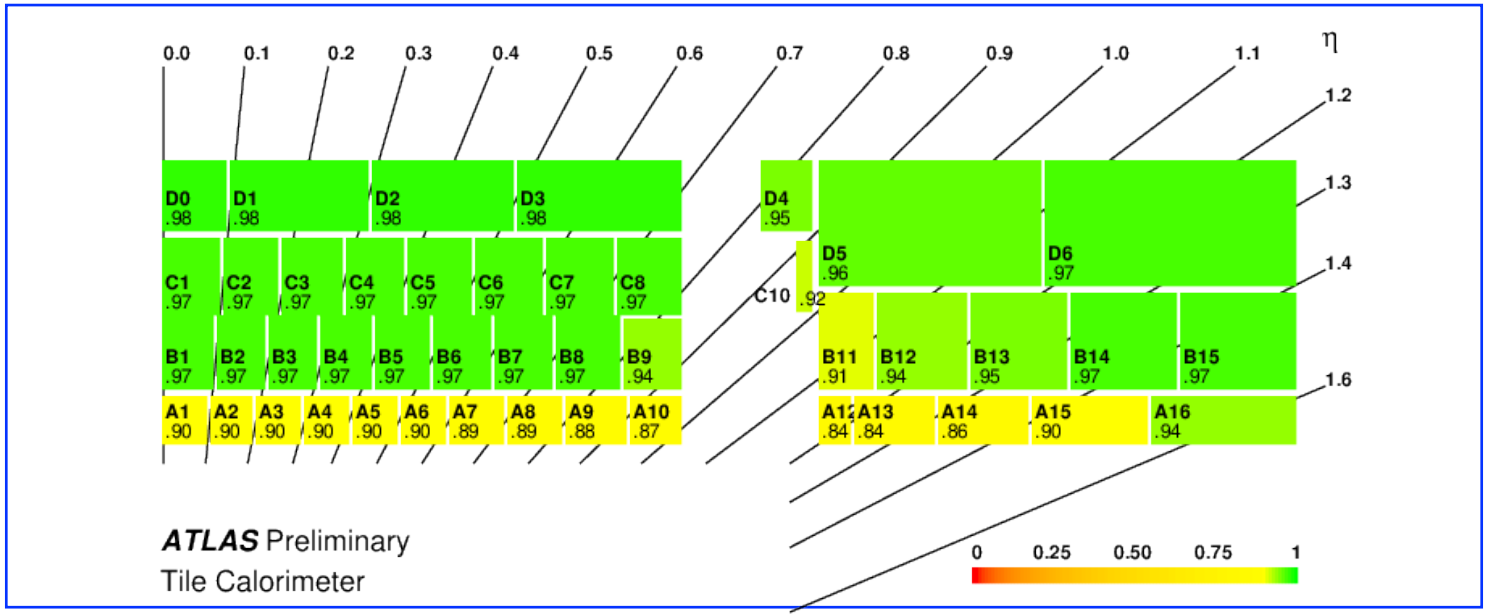


Mini-drawers on long barrel and extended barrel modules



Optics Robustness

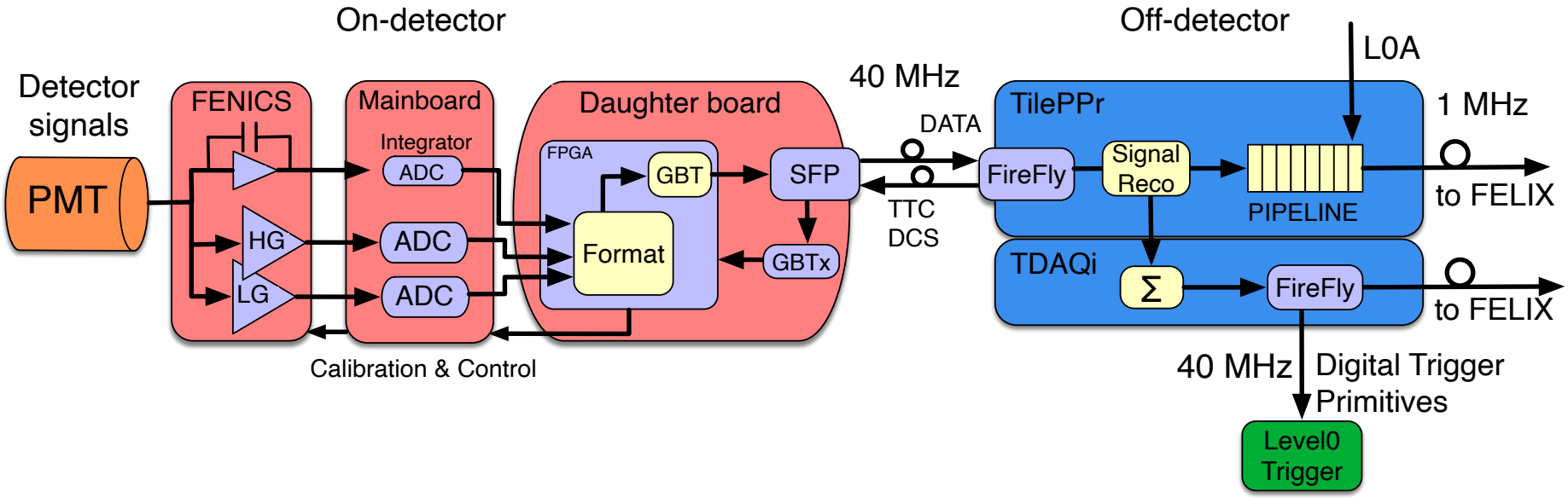
- Radiation damage degrades TileCal scintillators and WLS fibers
- The scintillating light output of the cells over time with respect to the beginning of Run 2 is studied for different cells
- Continuous degradation of scintillators with no recovery between Run 2 and Run 3 was observed
- TileCal optics robustness/evolution toward HL-LHC is well understood
  - 10% of the PMTs in the highly irradiated areas will be replaced



Average relative light yield measurement for the long barrel cells in Nov. 2024 wrt Feb. 2015*

*ATLAS Tile Calorimeter Public Results: Radiation Hardness https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileRadiationHardness

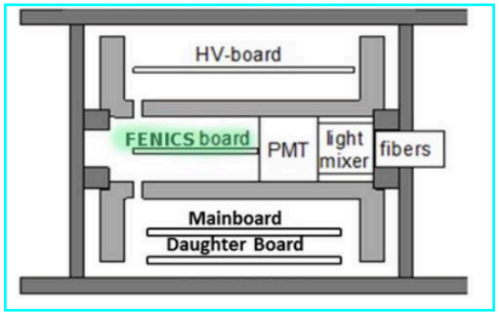
Readout Electronics



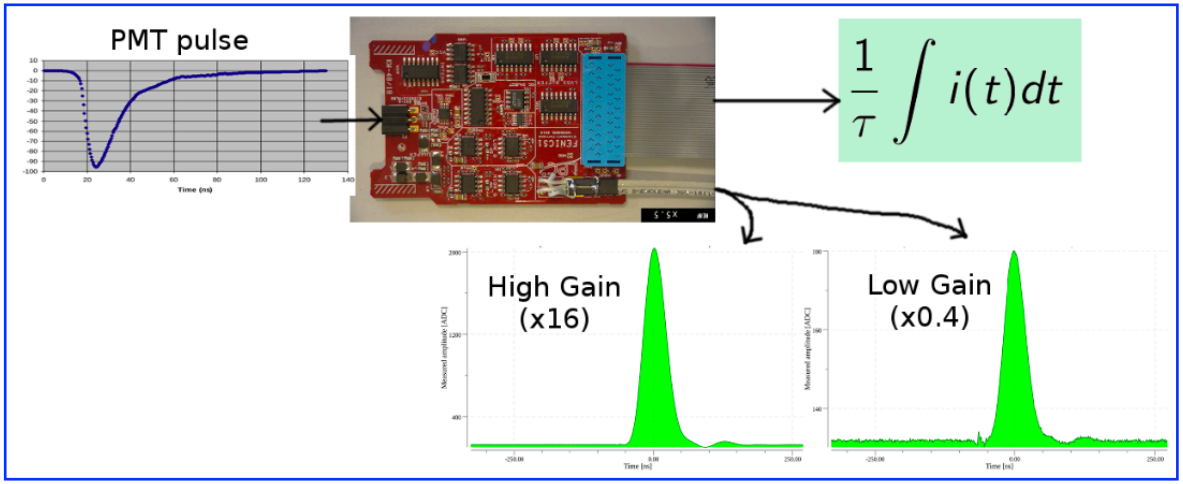
On-Detector Electronics: FENICS

- The FENICS board conditions and amplifies PMT signals
- Shaping fast signal from PMT (FWHM = 50 ns after shaping)
  - amplification with two gains → wide dynamic range (0.2 – 1000 pC)
- Current integration (luminosity measurement and cesium calibration)
  - five available gains → huge dynamic range (0.02 – 13000 nA)
- Charge or current injection for calibration of both channels
  - Fast channels: 5.1 pF (0.005 – 20.9 pC) and 220 pF (0.2 – 901 pC)
  - Slow channel: 5 MΩ (0.04 – 164 nA) and 60.4 kΩ (3.3 – 13560 nA)
- A total of 9852 FENICS boards will be used (maximum 12 per MD)
  - The FENICS boards production have almost been completed

FENICS board in Mini-drawer cross section

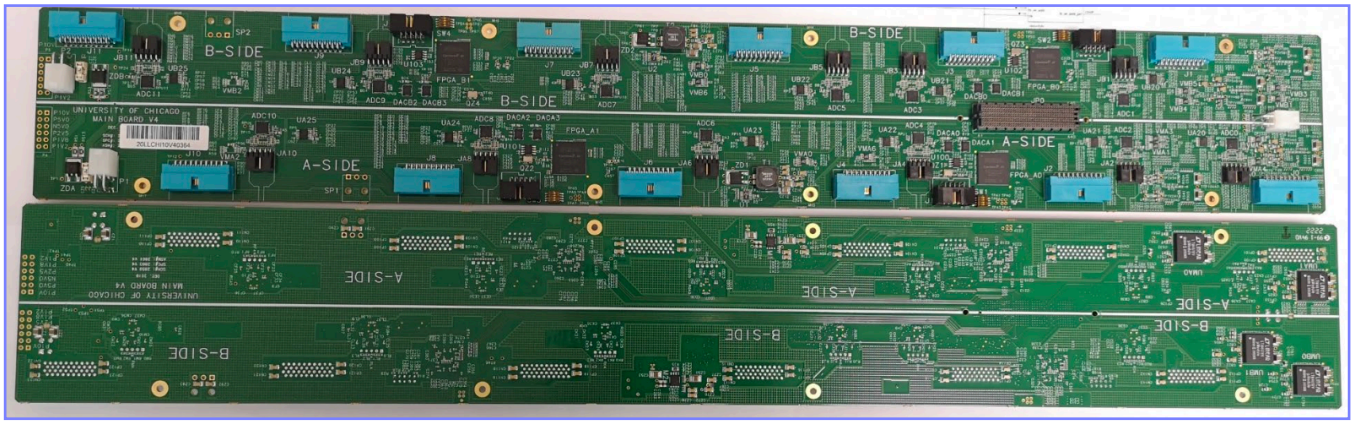


FENICS readout channels



On-Detector Electronics: Mainboard

- Mainboards are the backbone of the on-detector electronics
  - Receives analog signals from 12 FENICS front-end cards
    - Digitizes and serializes them to the daughterboard
    - Uses Fast 12-bit 40 MS/s ADC and slow 16-bit SAR ADC
  - Receives 10 Volts feed from LVPS and generates logic voltages
    - Routes 10 V to DB; provides LV levels for FENICS
- 69 cm x 10 cm PCB conforms to mini-drawer profile and PMT positions
  - 16-layer PCB to shield analog/digital signals
  - FPGAs used for FENICS calibration configuration and MB clocks
  - 896 Mainboards to be used and production already completed



Top and bottom side of the mainboard

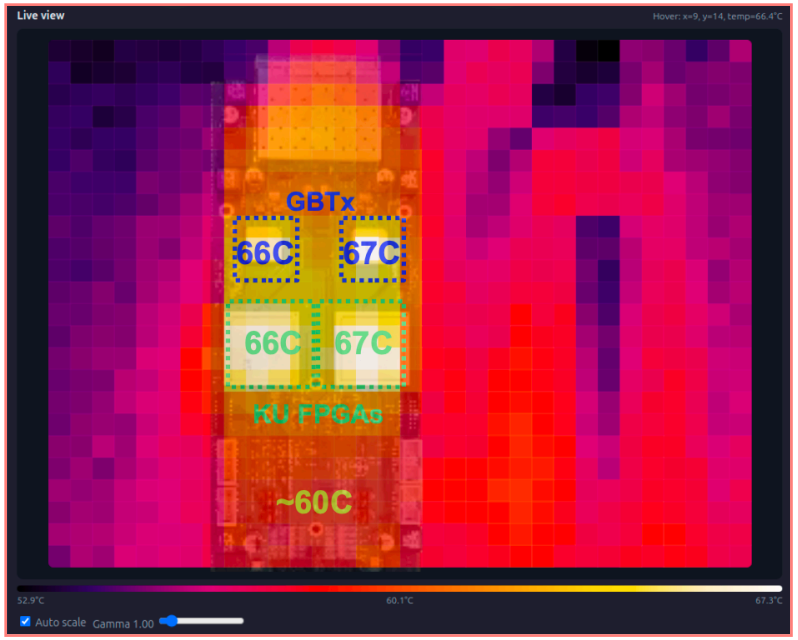
On-Detector Electronics: Daughterboard

- Receives and distributes the LHC clock to the ADCs on the mainboard
- Collects the ADC data, formats it and sends it to off-detector electronics
- Receives the configuration commands for the front-end
- Has two independent sides (A/B) for robustness
- Uses Kintex™ UltraScale™ FPGA, GBTx rad-hard ASIC for high speed communication, SFP+ transceiver to send data at 9.6 Gb/s to off-detector via optical links
- Radiation hardness tests are now complete
- Final version DB6v5 is in production and going through burn-in
- Firmware is being developed



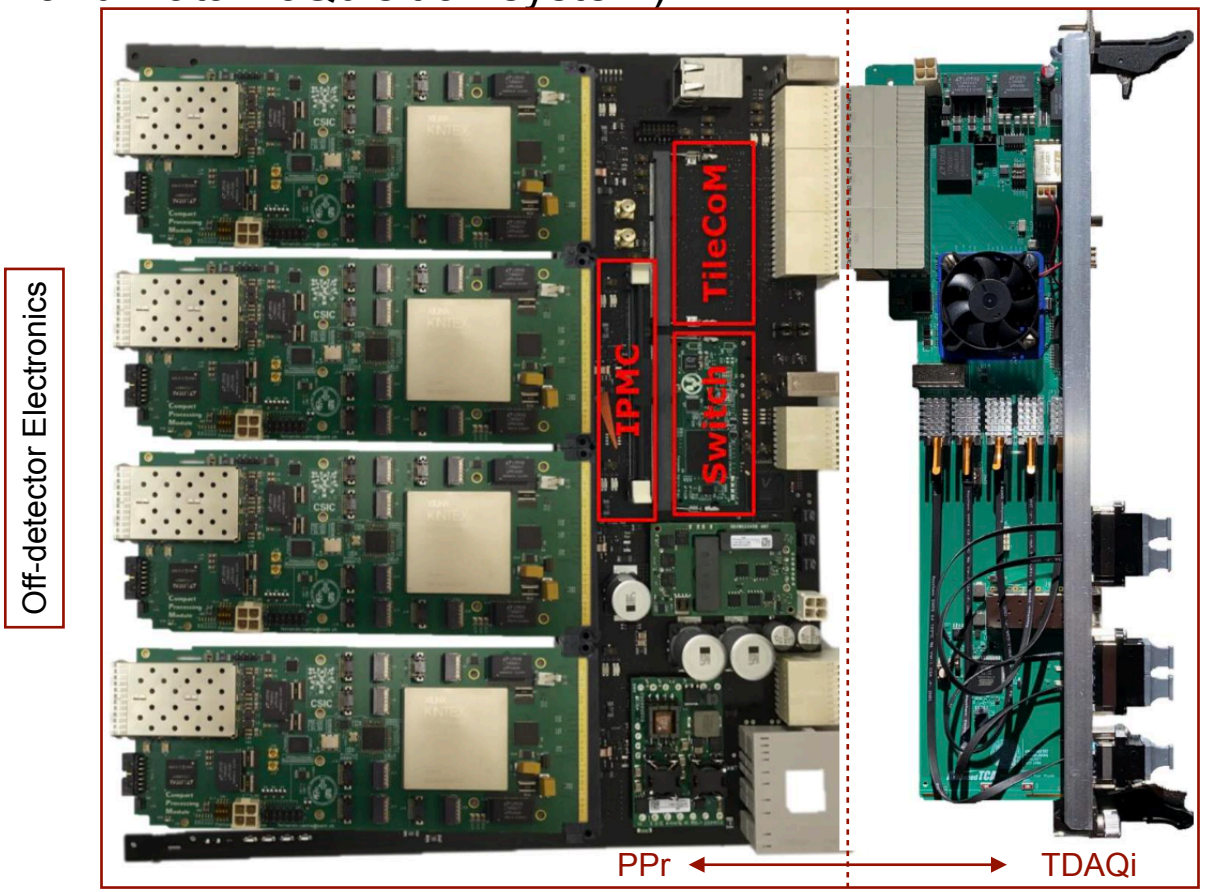
Final Version of daughterboard

Daughterboard temperature during burn-in



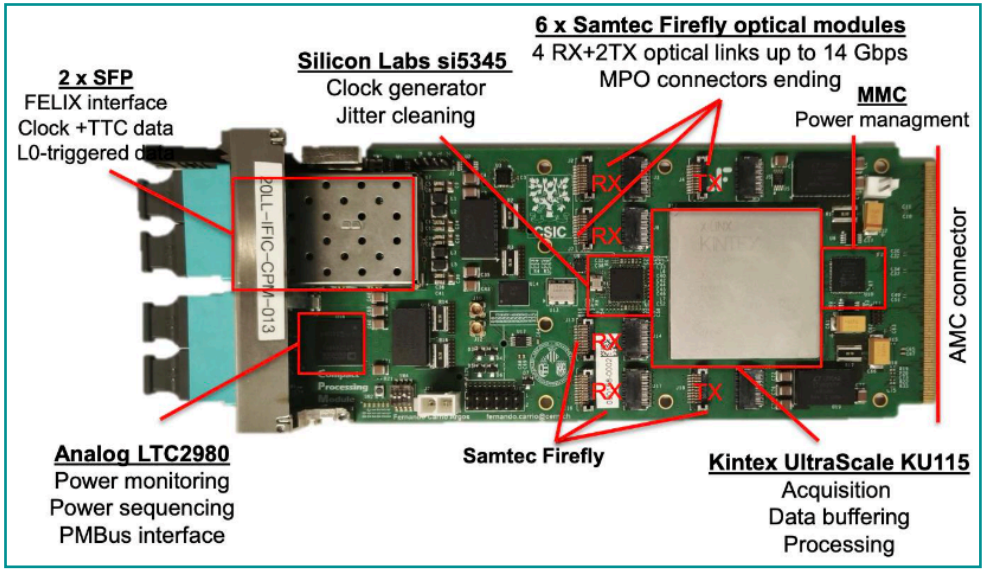
Off-Detector Electronics

- Includes PreProcessor (PPr) and TDAQi
- Preprocessor includes an ATCA carrier board to host 4 CPMs (Compact Processing Modules), in addition to mezzanine boards, i.e., IPMC, GbE switch, and TileCoM (Tile Computer on Module)
- TDAQi is the rear board in the ATCA crate to provide interface to TDAQ (Trigger and Data AcQuisition system)



Off-Detector Electronics: PPr

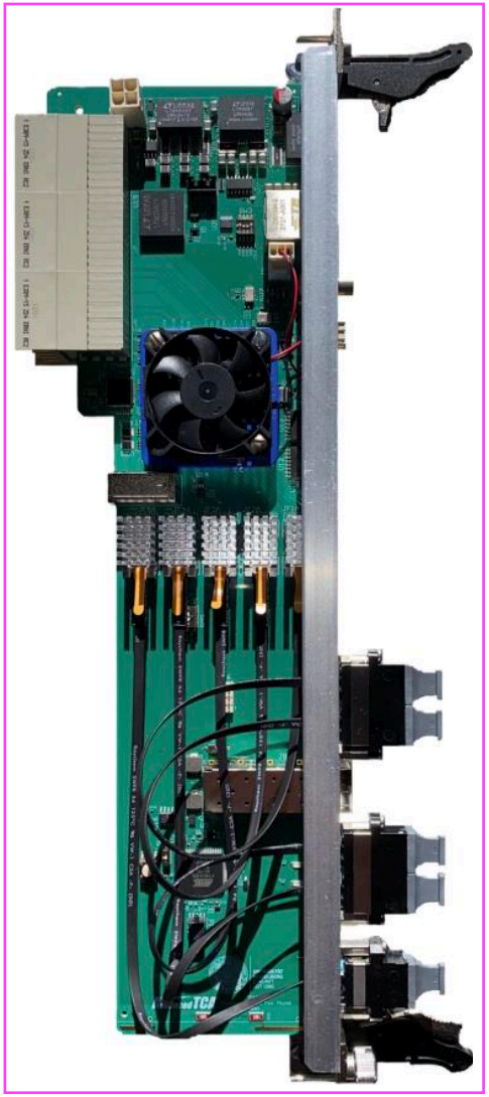
- Compact Processing Module (CPM)
  - Connects with one LB and one EB daughterboards via optical fibers (Samtec FireFly modules)
  - Distributes the LHC clock and reads data at the full 40 MHz rate from the on-detector electronics
  - Stores data in pipeline memories and performs online reconstruction (FPGA)
  - Collects and distributes DCS information
  - Performs on-detector electronics configuration and control, including remote FPGA programming
- ATCA carrier board
  - Hosts 4 CPM modules and mezzanine boards
  - Provides connection between CPMs and the TDAQi RTM board
- Production to start soon



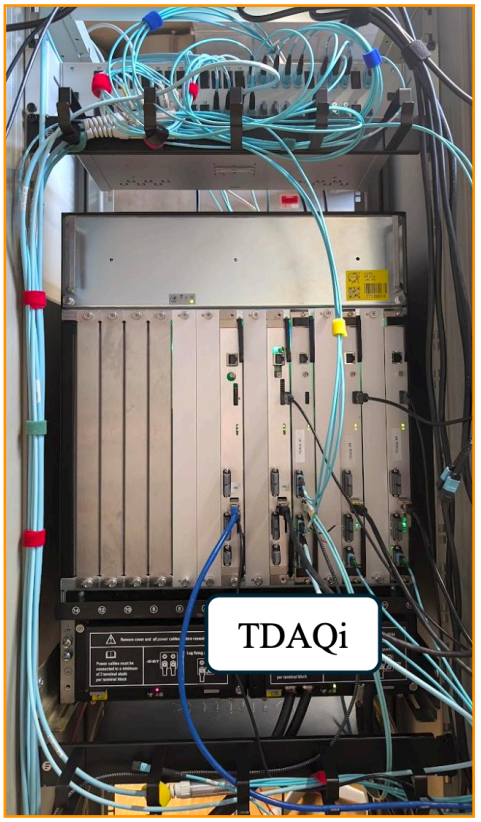
Compact Processing Module

Off-Detector Electronics: TDAQi

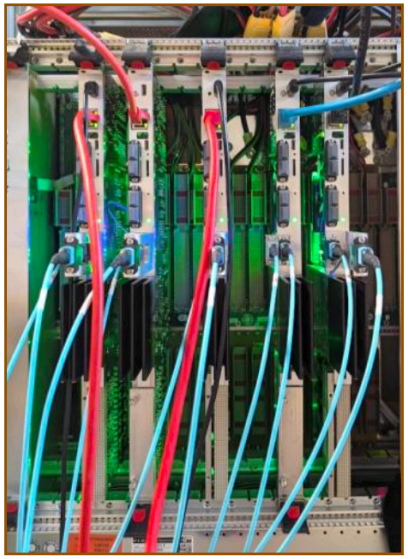
- TDAQi collects reconstructed energies from CPMs, calculates trigger primitives and sends trigger information to L1 trigger systems (electrons, jets, muons, and cell energies)
- Form factor is ATCA RTM board with FPGA and optical links
- Measured latency is less than 250 ns
- Production to start soon



TDAQi

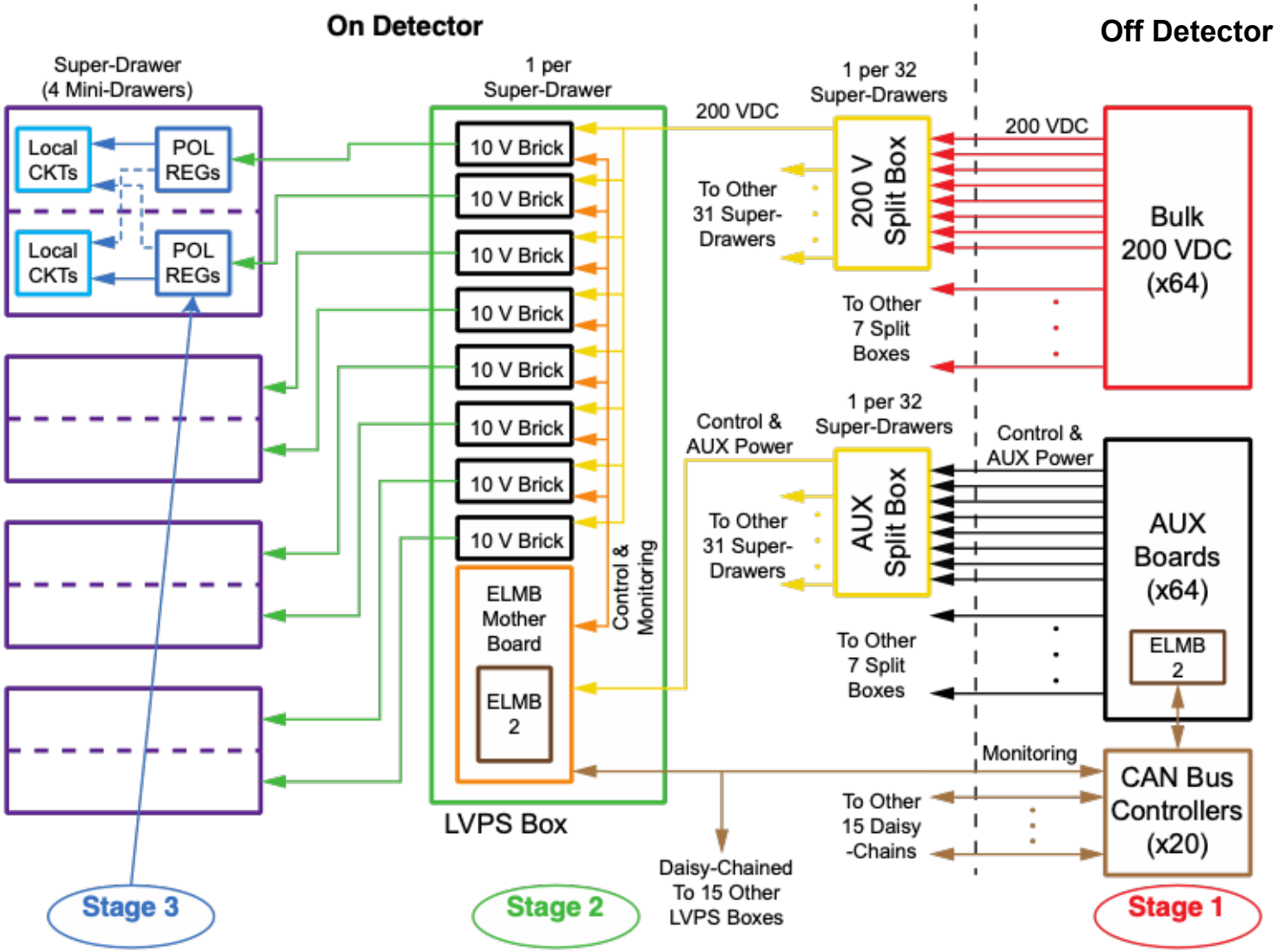


Fiber Patch Panel



TDAQi tests with Trigger data

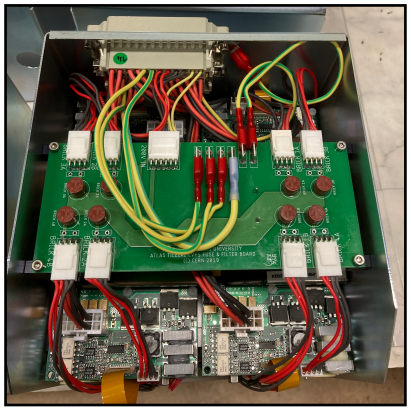
Low Voltage Distribution System



Low Voltage Power Supply

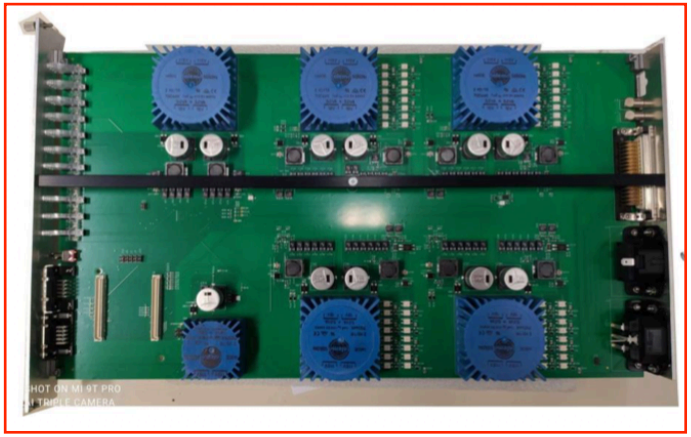
- Three-stage low-voltage (LV) system
  - Bulk 200V AC-DC (TDK-Lambda)
  - Rad-hard 10V DC-DC converters (bricks) sitting inside the LV box (production almost completed)
    - Aux boards used for control and monitoring (production complete)
    - 8 different bricks and 8 different voltages provided to front-end electronics in the legacy system
    - 8 identical bricks provide 10 V to one module (each brick powers half a mini-drawer)
      - Thanks to redundancy, even with 4 out of 8 bricks running a module will still be able to read out all the cells (half the PMTs)
  - Point-of-load regulators on front-end electronics convert 10 V to different voltages

LV box (no lid)



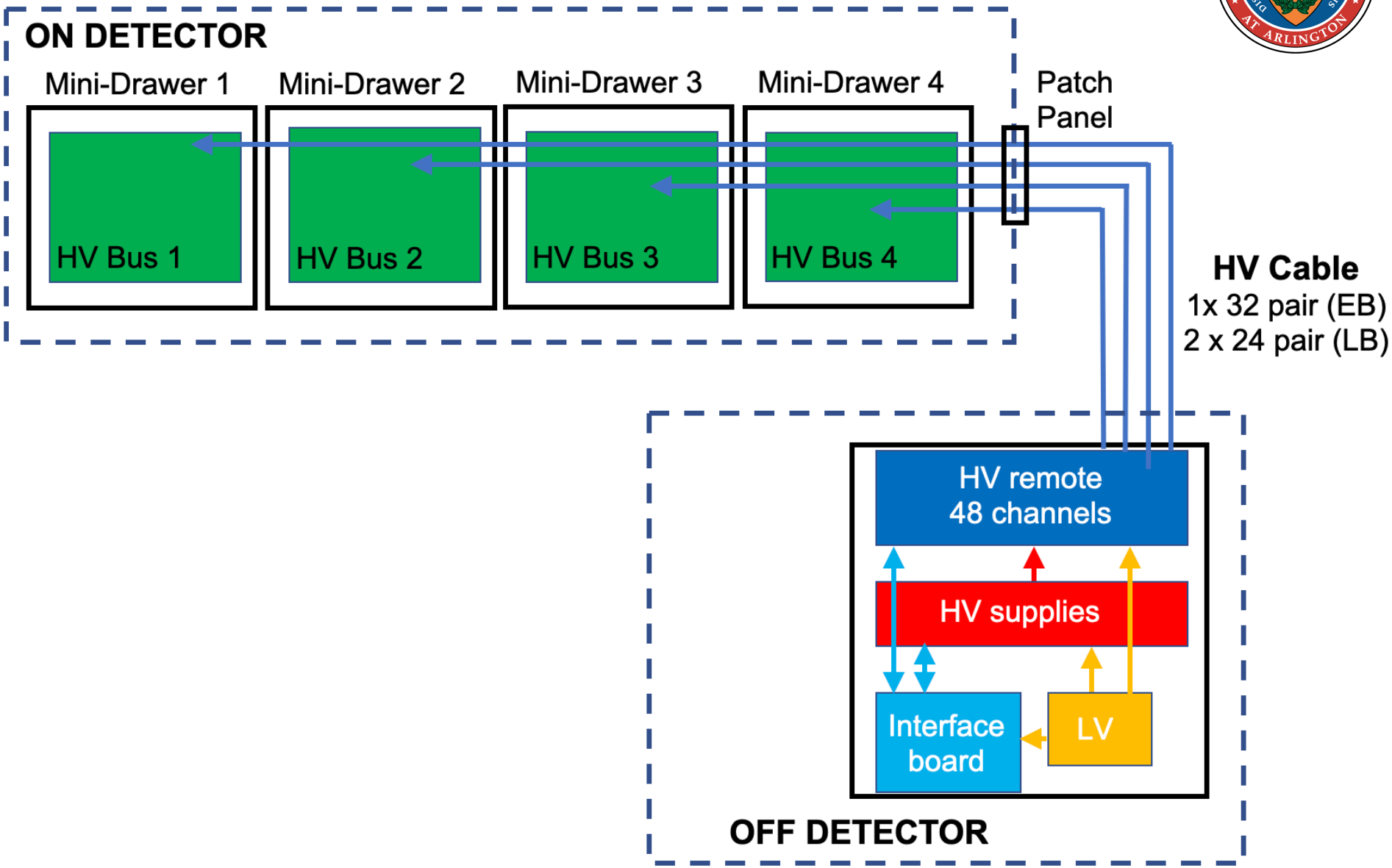


LVPS brick top view



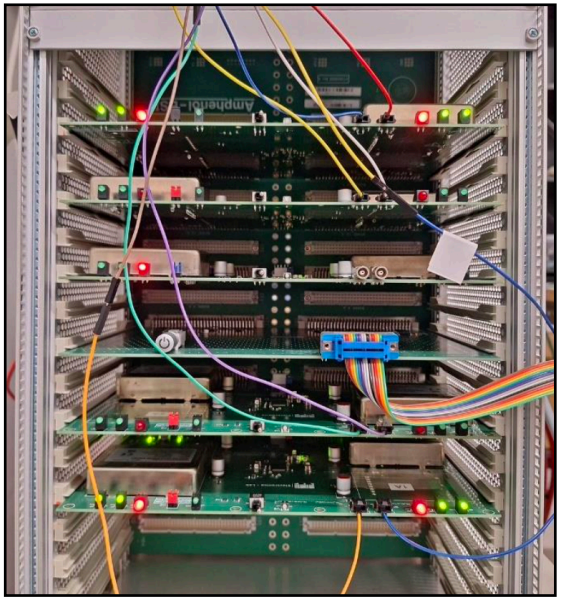
Aux board (off-detector)

High Voltage Distribution System

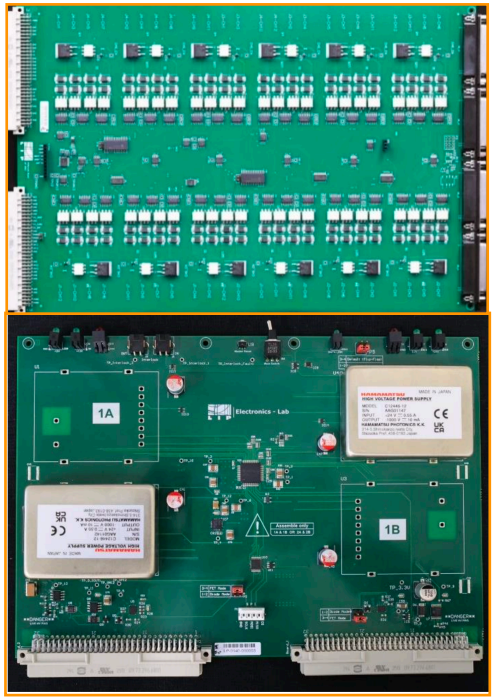


High Voltage Power Supply

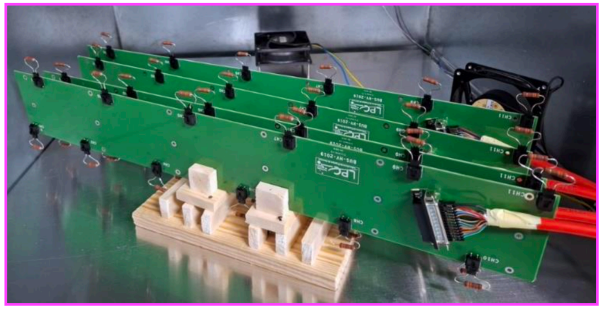
- Remotely regulated high-voltage (HV)
  - 0.6-1kV over 100m cable for ~10k channels
  - On-detector passive HV distribution (HV bus board)
  - Off-detector remote regulation for individual channels using HV supply, HV remote, and HV interface boards inside a crate
  - Hamamatsu bulk HV supply units
  - Special 24- and 32-pair cables
  - Preproduction and tests ongoing



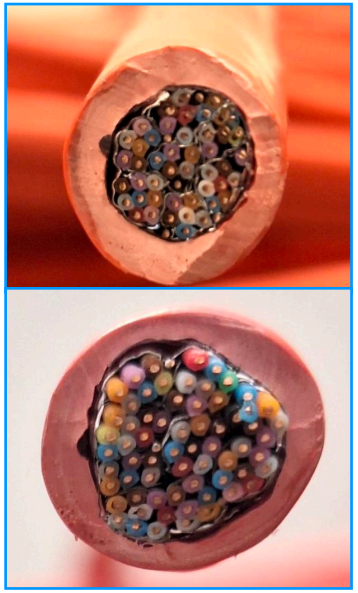
HV boards inside the crate



HV supply and HV remote board



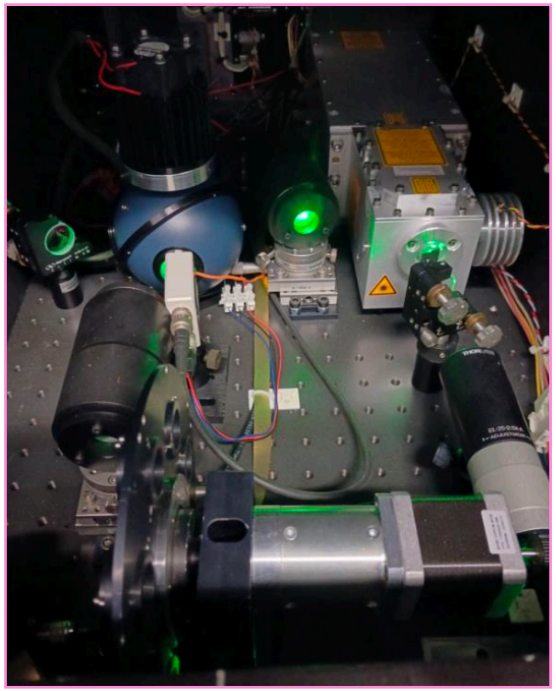
HV bus boards



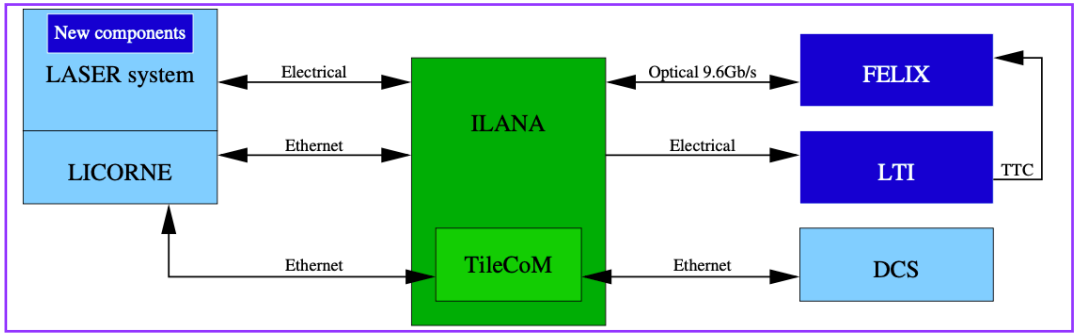
24 and 32 pair special cables

Calibration System: Laser

- Laser calibration system for PMTs
  - Optical line to mix DC light from the new LED matrix and pulsed light via integrating sphere for pile-up “simulation”
  - New control system and TDAQ interface (ILANA)
    - ILANA Using TileCoM SoC (System on a Chip) mezzanine
  - Production ongoing



Optical line with new LED matrix and sphere inside the optics box



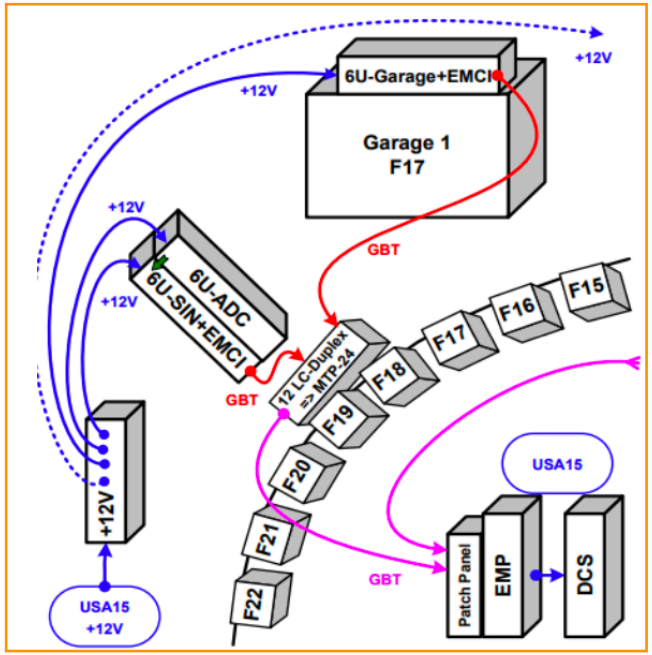
Laser system block diagram



ILANA prototype

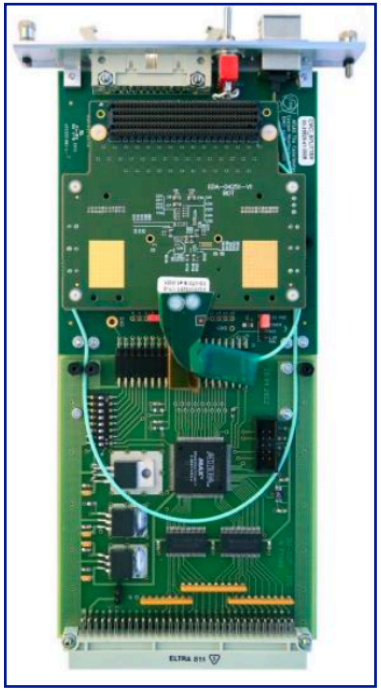
Calibration System: Cesium

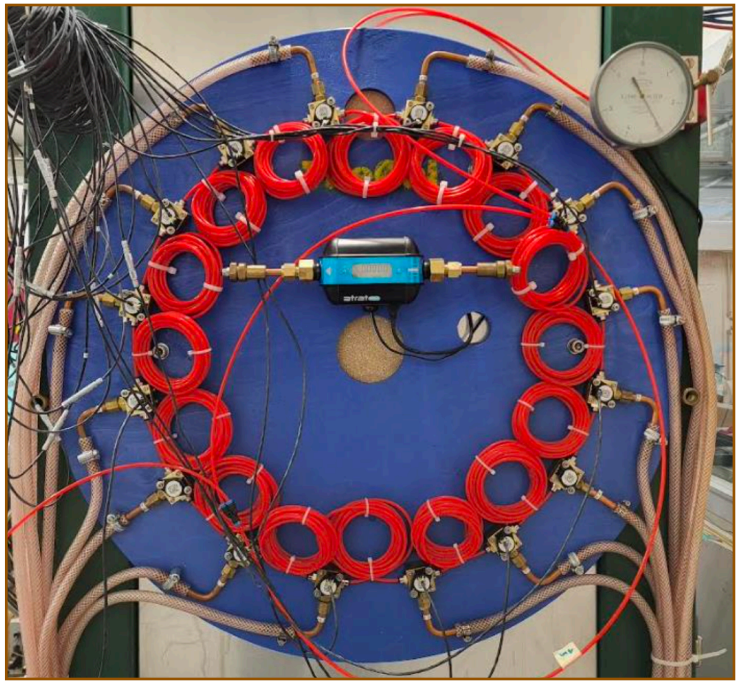
- Cesium system uses a ^{137}Cs movable source
  - New on- and off-detector electronics using optical links, EMCI/EMP
  - Production is completed and tests are ongoing with updated hydraulics
    - Hydraulic tests, using mock-up and simulation, converged to the final design of the hydraulic system
      - No bypass shut-off valves
      - Optimized valve opening



Cesium system block diagram

Cesium system control board

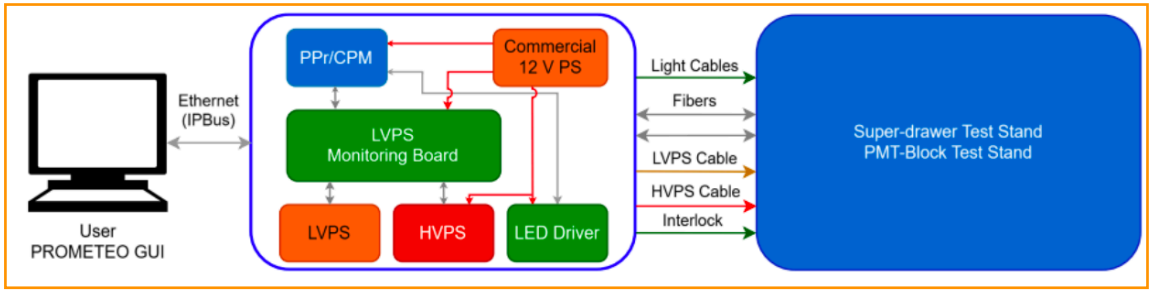




Mock-up system used for hydraulic tests

Tests and Certifications

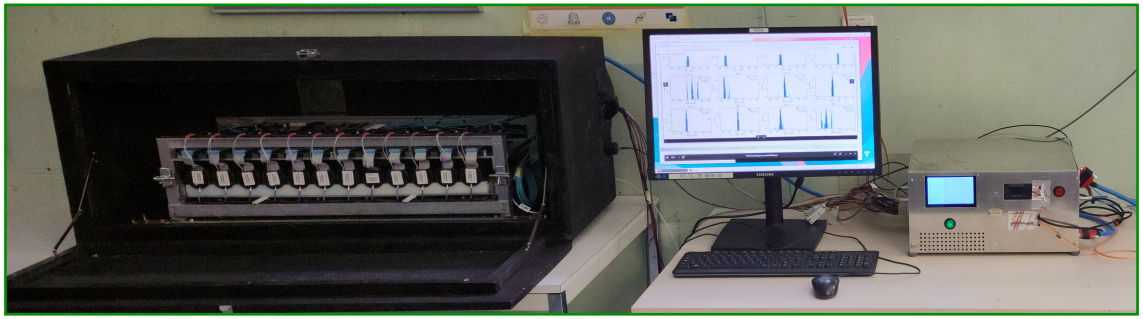
- Front-end electronics is to be assembled from multiple components into mini-drawers before installation
  - Tests performed on PMT block test bench and super-drawer test stand
- PROMETEO portable test bench is used to certify the functionality and performance (Production is starting) for installation and future maintenance
- Test results and board IDs to be saved in the assembly and installation database



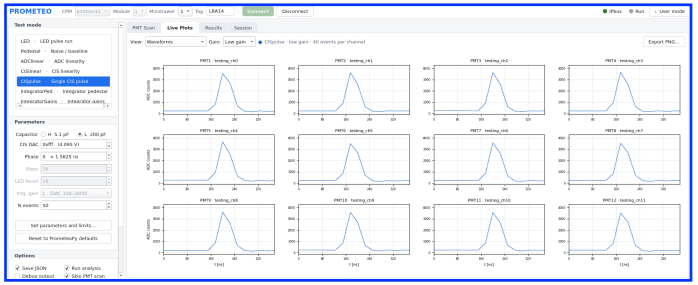
PROMETEO block diagram

PROMETEO portable box





PMT block test bench



PROMETEO GUI

Test Beam Campaigns

- Several test beam campaigns were held between 2015 to 2025 to test the performance of the electronics for the HL-LHC





Upgrade LB, upgrade EB, and demonstrator modules used in the test beams



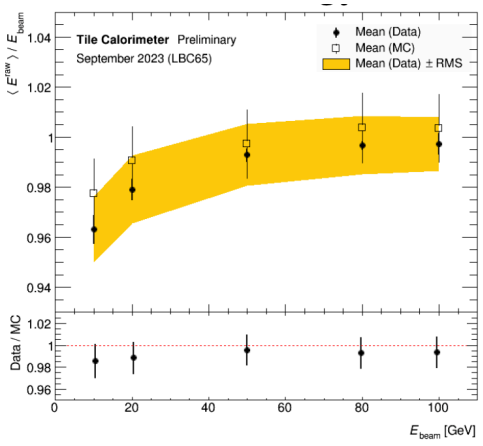


Test Beam Results

- Test beam data analysis was performed for different beams to study electronics performance and detector response

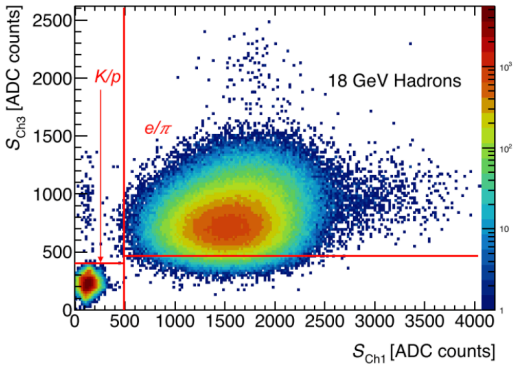
Electron Beams*

- Crucial to model electromagnetic components in the hadronic showers
- Verify linearity of the response vs initial beam energy
- Validate electromagnetic (EM) scale



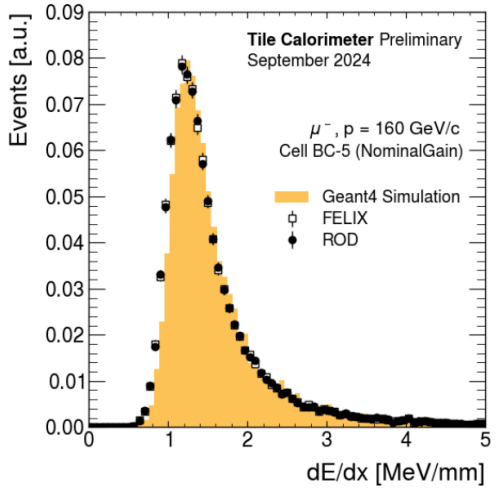
Hadron Beams**

- Important to accurately measure response to hadrons in TileCal
- Identify pions, kaons and protons → compare to the predictions from Geant4 simulations
- Study response and resolution to validate/ improve modeling in the simulation



Muon Beams*

- Well understood interaction of muons with matter (MIP)
- Study detector response uniformity using through-going muons
- Verify the new electronics performance



**Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV https://link.springer.com/article/10.1140/epjc/s10052-021-09292-5

*ATLAS Tile Calorimeter Public Results: Test Beam https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsTileTestBeamResults

Production Status

Deliverable	Production [%]	Notes
Mini-drawers	100	Accepted at CERN
PMT	100	Accepted at CERN
FENICS	97	Production almost finished
Mainboard	100	Accepted at CERN
Daughterboard	50	Production/testing ongoing
PPr/TDAQi	0	Production to start soon
Laser Calibration	30	Production/full system integration ongoing
Cesium Calibration	~100	Full slice tests ongoing
LVPS Bricks	90	Production almost done
LVPS Box	65	Assembly and testing ongoing
Aux boards	100	Accepted at CERN
HVPS	0	Preproduction and tests ongoing
Mini-drawer Assembly line	100	Accepted at CERN
Handling and Tools	100	Accepted at CERN
PROMETEO	0	Production starting

Summary

- ATLAS Tile Cal is being upgraded for the HL-LHC starting in 2030
  - Going from 256 independent readout modules to 896 independent mini-drawers (can read out all the connected cells even when half-powered)
  - On-detector electronics (FENICS, mainboard, and daughterboard) are upgraded to provide 40 MHz continuous readout
  - Off-detector electronics (PPr and TDAQi) are upgraded to provide fully digital trigger output
  - LV system is upgraded to provide higher radiation hardness and improved power distribution
  - HV system is upgraded to provide off-detector HV regulation and control
  - Calibration systems (laser and Cesium) are upgraded to provide updated calibration requirements
  - Test and certification systems are upgraded to be compatible with the upgrade electronics
  - Test beams performed to verify the performance of the electronics
  - 10% of PMTs to be replaced due to radiation degradation
- While decommissioning of legacy electronics has already started, components will be ready for assembly and installation in 2027/2028 and commissioning in 2029

Thank You!