The New Front-End Electronics For the ATLAS Tile Calorimeter Phase 2 Upgrade

Gary Drake

Argonne National Laboratory, USA

On behalf of the ATLAS TileCal System

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The LHC at CERN

- The Large Hadron Collider at CERN in Geneva, Switzerland
 - 27 km diameter tunnel, ~100 m deep underground Switzerland & France
 - Accelerator capable of colliding proton-proton beams at 14 TeV at 4 locations
 - ~1 billion collisions per second
 - 4 primary experiments along the ring

The ATLAS Experiment

■ The Detector for ATLAS

- Designed to measure particles created from proton-proton collisions at $\sqrt{s} = 14$ TeV energies
- Composed of 6 different detector subsystems wrapped concentrically around the collision point
- Measure trajectory, momentum, and energy of particles, allowing them to be individually identified

- Diameter 25 m -- Length : 46 m
- Barrel toroid length 26 m
- Overall weight 7 000 tonnes
- ~ 100 million electronic channels
- ~ 3 000 km of cables

Higgs Event
→ Decaying Tau Pairs
Measured by the
Hadron Calorimeter

The ATLAS Hadronic Calorimeter (TileCal)

- The Tile Calorimeter – Steel & Scintillating Tiles w/WLS Fibers; PMT Readout

- 256 Modules
- ~48 PMTs/Module
- ~10K readout channels

Electronics for ATLAS TileCal Phase 2 Upgrade – G. Drake – 2015 IEEE NSS, San Diego, CA – Nov. 3, 2015

Current Electronics Architecture

- Each module hosts self-contained instrumentation → “Super Drawer”

Electronics
Drawer
With
PMT Blocks

Signal
Flow

Drivers for the TileCal Phase 2 Upgrade

- **By ~2022, current electronics will have reached end-of-life**
 - Make use of new, modern parts
- **Need for higher radiation tolerance for the future**
 - Planning on X10 increase in radiation tolerance
- **Desire to send ALL data off of detector for every beam crossing**
 - Digitize at Bunch Crossing Rate
 - Part of LAr/L1Calo plans as well
- **Desire to implement a digital trigger**
 - Part of LAr/L1Calo plans as well
- **Desire to implement redundant power supplies in the front-end**
 - Source of problems in current system
- **Desire to reduce single point failures in the front-ends**
 - Data drivers, optical links, dual-sided PMT read-out
- **Desire to improve accessibility of electronics in the drawers**
- **Desire to fix other system and implementation issues in the drawers**
 - We have learned a lot about the current system...

⇒ **4 Themes: Full Data Readout; Digital Trigger; Radiation Tolerance; High Reliability**

Upgrade Electronics Architecture

- Each Module contains 4 “Mini Drawers”

4 Mini Drawers With PMT Blocks

⇒ **“Drop-in” replacement for current instrumentation**

Parameter	Present	Upgrade
Total BW	~ 165 Gbps	~80 Tbps
# Links	256	8192
Data Rate / Link	640 Mbps	9.6 Gbps
# Links / Drawer	1 (+1)	4x4 (+4x4)
Input BW/ROD	5 Gbps	625 Gbps
Out BW/ROD _{DAQ}	2.56 Gbps	~5 Gbps
Out BW/ROD _{L1}	Analog FE	< 80 Gbps

Upgrade Electronics Architecture

- Our plan: Staged Approach → “Demonstrator” → *Interface to Existing System*

Interface to Existing L1Calo - Analog Trigger

Interface to Existing ROD

Interface to Existing DCS

Goals of the Demonstrator Program

- Allows study and development of new electronics using existing infrastructure, including:
 - Digital trigger processing
 - New Trigger Pre-Processor
 - Optical links & serial protocols
 - Redundant power system, & data acquisition
 - Calibrations, slow controls, diagnostics
 - Allows the direct comparison with the old system performance
 - Allows the direct comparison between the different technologies
- ⇒ **A TileCal Goal: To install one or more Demonstrator Modules onto the detector before the Phase 2 Upgrade**
- ⇒ **Will help identify bugs and problem areas before production in ~2020**

Mini Drawers

- **Super Drawers will be composed of 4 mini-drawers, each containing:**

- 12 PMT blocks with active dividers
- 12 Front-End Boards, 6 per side
- 1 Main Board
- 1 Daughter Board
- 1 HV regulation board
- 1 adder base board + 3 adder cards (for the hybrid Demonstrator)

Cross section of a mini-drawer

Required assembly of 45
PMT blocks with new active
dividers

Mini Drawers

⇒ *One of our 1st functional prototypes*

Mini Drawers

Front End Boards

■ Functionality

- Resides inside PMT Blocks
- Short signal path
- Excellent shielding

■ Baseline FEB design: 3-in-1

- Improved version of the present design – made with discrete components
 - Improved linearity
 - Improved radiation tolerance
 - +/- 5V power
- Contains 7-pole passive shaper
- 3 main functions:
 - High and low gain analog outputs
 - Charge injection calibration
 - Integrator to read out Cs calibration data
- Sends analog signals out to Main Board for digitization
- Has analog trigger output, for use in the Hybrid Demonstrator

⇒ **2 Alternative Options being Considered:**

⇒ **QIE ASIC**

⇒ **FATALIC ASIC**

Main Board

■ Functionality

- Interface between FEBs and Daughter Board
- Board is split so that 2 halves independent in data & power for redundancy
- Each cell will be read-out by two PMTs, one on each side of the mainboard

■ Baseline design: Support 3-in-1 FEB

- Contains discrete, commercial ADCs for digitizing FEB analog output signals
 - Samples are transferred serially to the daughterboard at 600 MHz
- Contains FPGA used for slow control and calibration
 - Commands are sent in parallel to 2 control FPGAs on each side
- Contains Point-of-Load (POL) Regulators for regulating +10V to voltages needed by FEB & MB circuits

⇒ **2 Alternative designs for each FE option**

Daughter Board

■ Functionality

- Interface between Main Board and Off-Detector Readout
- Receives data streams from front ends and formats for readout @ 9.6 Gbps
- Handles all clock functions
- Interface for slow controls & calibrations
- Board is split so that 2 halves independent in data & power for redundancy
- Each half board reads out 6 PMTs

■ Baseline design

- Hosts (2) Kintex 7 FPGAs, each of which reads out half of a Main board
→ FPGA provides serialization
→ 2 devices provide redundancy
- Readout uses GBTx and 10 Gbps QSFP+ Luxtera Modulators
- Contains Point-of-Load (POL) Regulators for regulating +10V to voltages needed by DB circuits
- Will use TMR and scrubbing in FPGA to guard against SEU

Optical Links

■ Functionality

- Each has 4 X 10 Gbps bidirectional optical links
- Mach-Zender modulation technology
- Excellent BER: $\sim 10^{-18}$ 1 error in 100 days!

■ Baseline design

- Commercial device: Luxtera Active Optical Link
- Use (2) per daughter Board $\rightarrow$ 8 per Drawer
- Require 8 read-out links per demonstrator
- Fab tech: 130 nm Silicon On Insulator CMOS
- No SEU at TID of 165 kRad and fluence of $8E11$ p/cm²
- PIC microcontroller survives ~ 20 kRad (replacement being developed)

Modulator

PIC Microcontroller

High Voltage System

■ Functionality

- Bulk 900V provided to Drawer
- Can set HV on individual PMTs
- Include HV read back

- Board is split , independent power & data I/O for each half

■ Baseline design

- 12-channel board, 6 channels per side
- Individual control & monitor circuits for each PMT
- Uses microcontroller per channel
 - On-board ADC, DAC, analog circuitry
 - SPI Interface
- Data interface with Kintex 7 on Daughter Board
- Contains on-board POL regulators

⇒ **1 Alternative Option being Considered:**

⇒ **Remote Control (off detector)**

Split Line

Low Voltage Power Supply

3 stage power distribution system design:

- Stage 1 – bulk 200V in USA15
- Stage 2 – LVPS boxes – 8 bricks per box
 - +/- 10V bricks, 7A (14A for redundancy)
- Stage 3 – Point-of-Load regulators
 - Several commercial & custom options being considered
 - Radiation tolerance is critical aspect

Redundancy

- Each brick powers half of a Main Board
- Use Diode-OR on Main Board
- When one brick fails, diodes allow second brick to provide power
- Fuses provide protection in case of short on Main Board

Trigger Preprocessor (PPR)

■ Functionality

- Receives high-speed data from FE
- Provides data to L1/L0CALO
- Saves data in pipelines pending trigger
- Signal reconstruction, L2 algorithms
- Interface with DAQ
- Monitoring, DCS, & TTC to FE

■ Baseline design

- ATCA module – payload card
- Each card services 8 links (1 Drawer)

■ Demonstrator

- Use AMC Demo board
 - 1 Xilinx Virtex 7 FPGA
 - 1 Xilinx Kintex 7 FPGAs
 - 2 GB DDR3 SDRAM
- Compliant with ATCA carrier

Signal Processing

**Final
PPR**

**sROD
Prototype**

Current Status of Design

- Mini Drawer mechanics ⇒ *Design nearly complete; Small production run starting*
 - Front-End Boards
 - 3-in-1 FEB ⇒ *Design complete; Small production run in progress*
 - FATALIC ASIC FEB ⇒ *ASIC in hand; Prototyping in progress*
 - QIE ASIC FEB ⇒ *ASIC in hand; Prototyping in progress*
 - Main Board
 - 3-in-1 MB ⇒ *1st prototype complete; 2nd prototype in progress*
 - FATALIC ASIC MB ⇒ *1st prototype in progress*
 - QIE ASIC MB ⇒ *1st prototype starting; Will use FATALIC MB*
 - Daughter Board ⇒ *1st prototype complete; 2nd prototype in progress
Firmware development in progress; Yet to do: TMR*
 - Optical Links ⇒ *Commercial devices being used for 1st prototype*
 - HV Control
 - Internal option ⇒ *1st prototype complete*
 - Off-detector option ⇒ *1st prototype complete*
 - LVPS & POL regulators ⇒ *Design complete; Small production run in progress*
 - Trigger Preprocessor ⇒ *PPR emulator functional; 1st prototype in hand*
 - Active PMT bases ⇒ *Design complete; Small production run complete*
- ⇒ *~1 year of development, debugging, & testing completed*
- ⇒ *Completed 1st test beam tests at CERN → Data being processed*

A Few Results

- Channel linearity using pedestal DACs

A Few Results

■ Calibration & Noise Measurements

Status of the Radiation Testing

■ Limits

- Limits set for each component type by location
- Order of magnitude (10 year operation with safety factors):
TID: 25 krad; NIEL: 6E12 p/cm²; SEE 1E12 p/cm²

Subsystem	TID	NIEL	SEE	Comments
COTS Regulators	Done – Mostly OK	Not Done	Not Done	Need different -5V Reg CERN FEASTMN is a candidate
3-in-1	Preliminary	Pending	Preliminary	Preliminary tests done; Full Testing Needed
Main Board	Not Done	Pending	Not Done	ADCs tested by BNL; Board size?
Daughter Board	Not Done	Pending	Preliminary	More SEE Testing Needed; TMR not implemented; Scrubbing needs study
Modulator	Done – OK	Pending	Done - OK	No failures, PIC replacement being studied, Some SEUs in received data
HV_Opto	Done - OK	Done - OK	Done - OK	No failures, Some anomalies, Mostly OK
LVPS	(Done for V7.5)	(Done for V7.5)	(Done for V7.5)	Mostly same parts as previous design; Needs Full Testing
Adders	Not Needed	Not Needed	Not Needed	Same as current; Testing Not Needed
Active bases	Done	Done	Not Needed	Good to Go

Summary

- TileCal upgrade goals and specifications are defined
 - Development program is in progress
 - The project has been divided into upgrade tasks, with groups identified
 - Designs and prototypes of each sub-system are progressing well
 - Development program has some options and alternatives
 - Choices will have to be made... → At the time of the TDR (2017)
 - A schedule has been defined for development and testing
 - Prototypes
 - Vertical slice
 - Test beam
 - Tests on-detector → “*Demonstrator*”
 - Radiation tests
- ⇒ *The Demonstrator allows realistic testing of new electronics on the detector*
- ⇒ *1st tests with detector possibly in 2016*
- ⇒ *Goal: Basic design complete by 2018; Production to follow*
- ⇒ *Most significant yet-to-do: Integration with L1Calo, TDAQ, & FELIX*

The TileCal Phase 2 Upgrade project is well underway!