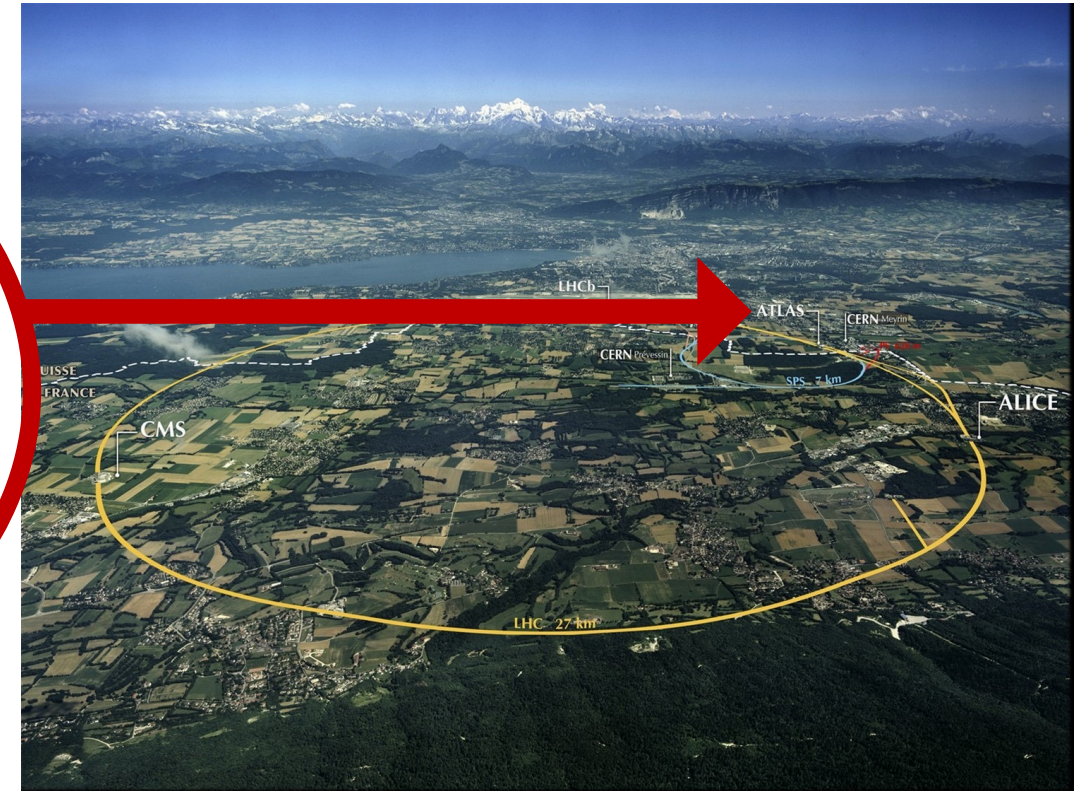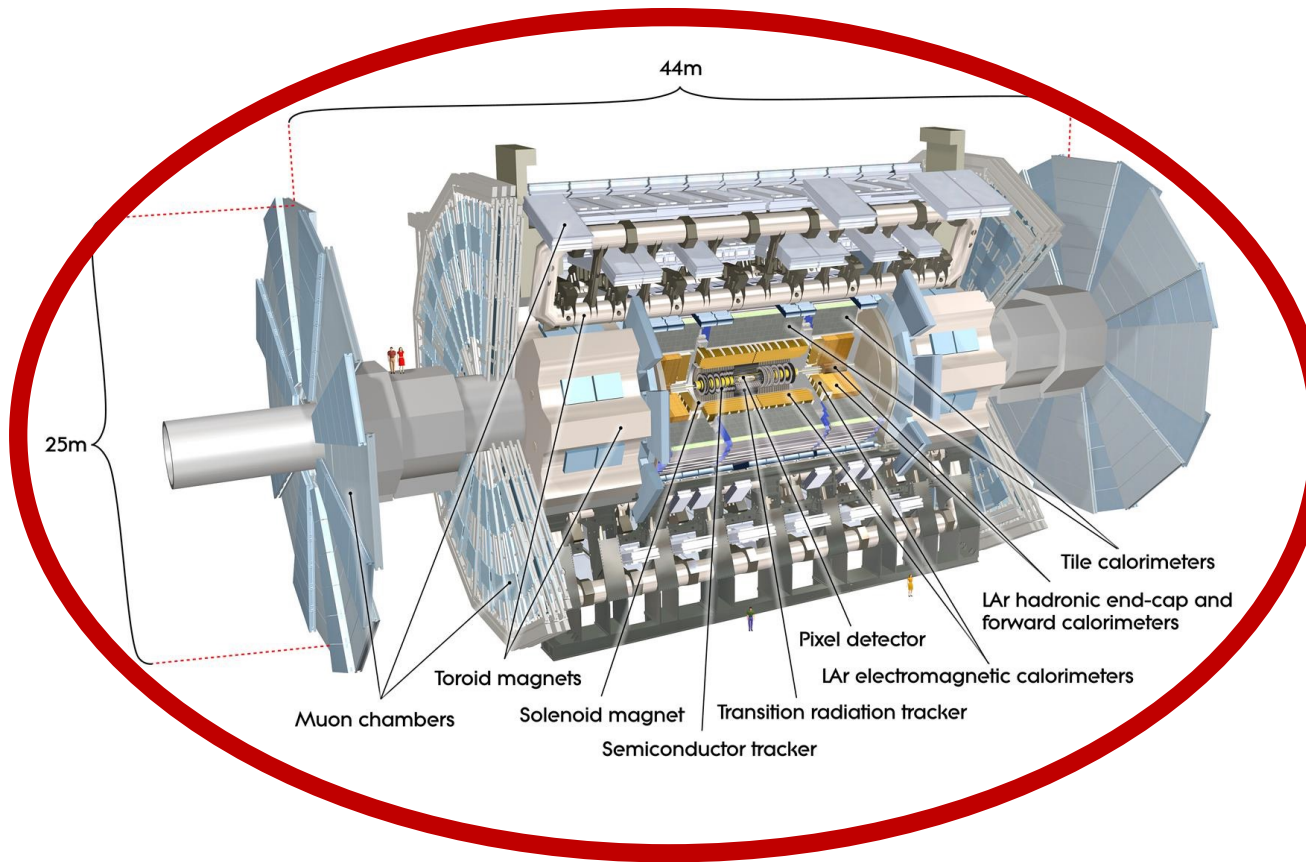# Development of the ATLAS Liquid Argon Calorimeter Readout Electronics for the HL-LHC

Allison McCarn Deiana (Southern Methodist University)

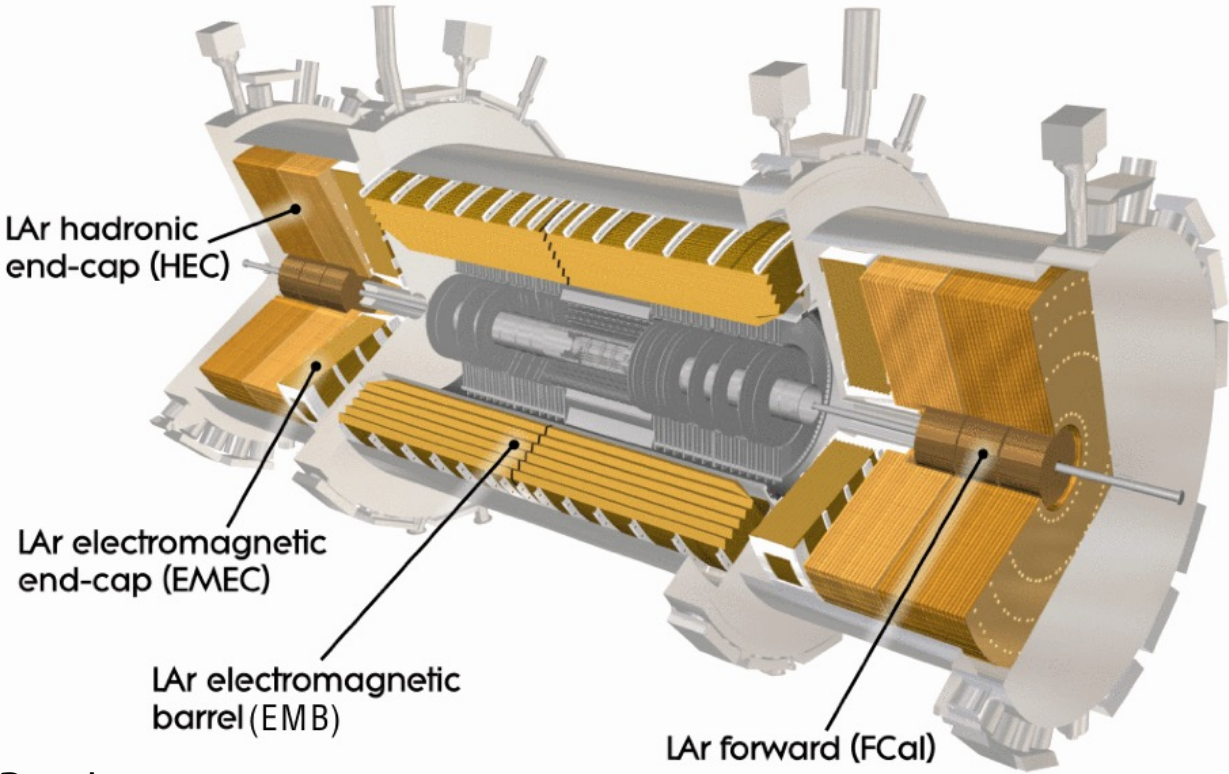On behalf of the ATLAS LAr Collaboration

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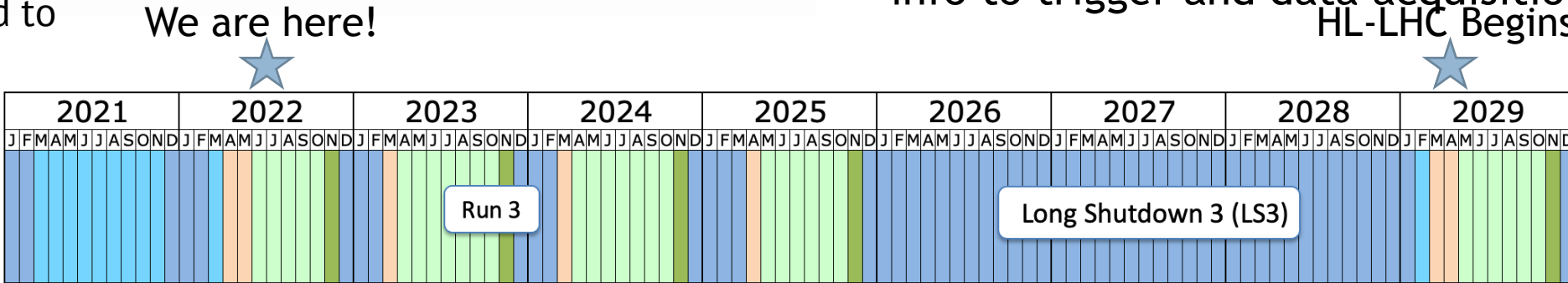# The ATLAS Detector & the Large Hadron Collider (LHC)

The LHC accelerates protons to produce beams of energy up to 7 TeV, which collide in the ATLAS detector with a frequency of 40 MHz.

Overview of Liquid Argon (LAr) Calorimeter

LAr hadronic end-cap (HEC)

LAr electromagnetic end-cap (EMEC)

LAr electromagnetic barrel (EMB)
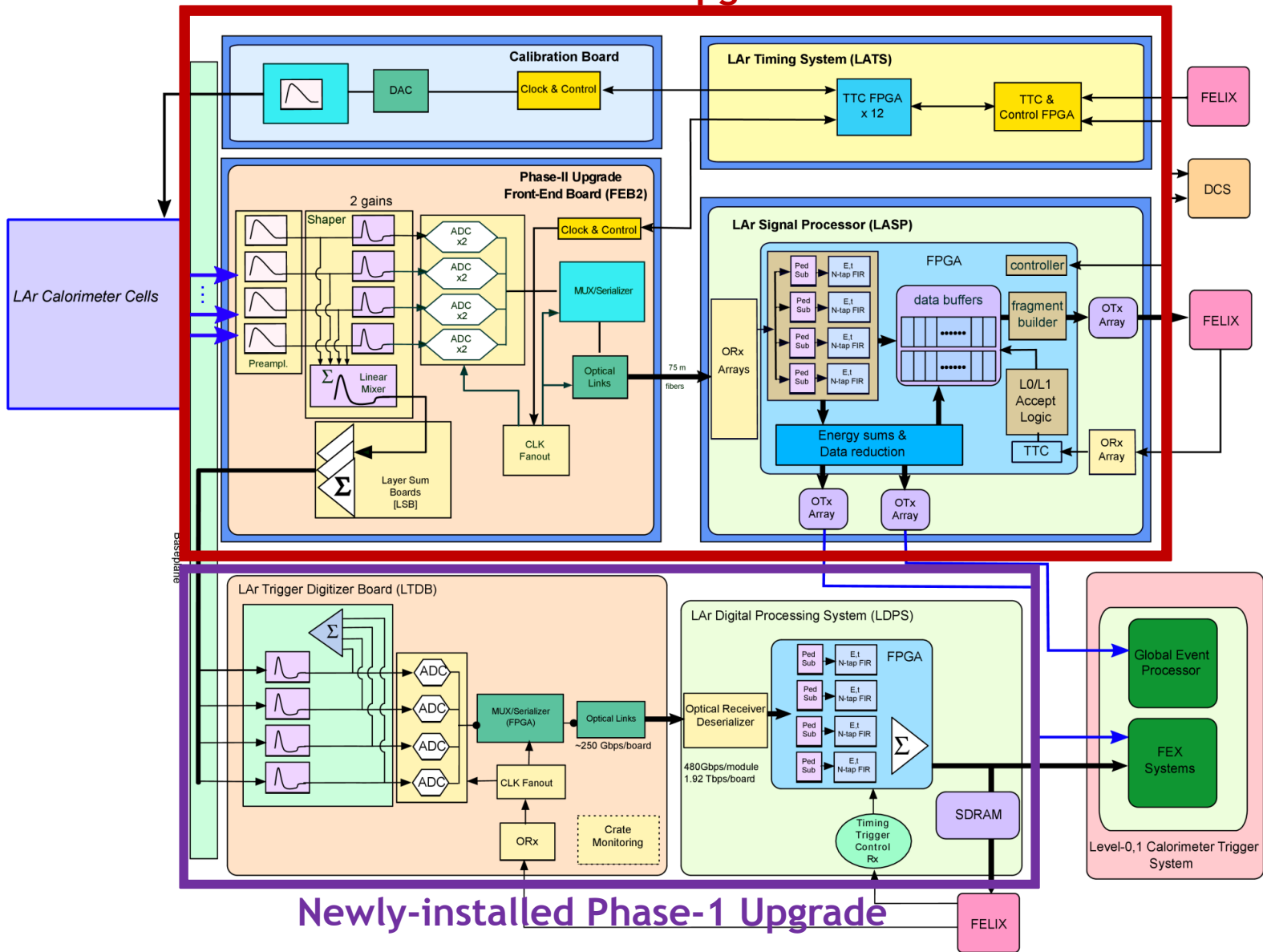
LAr forward (FCal)

- Sampling calorimeter with liquid argon as the active medium.

- Captures energy information of interacting objects (e.g. electrons, photons, jets, for the EM calorimeter)

- This information is processed and propagated off the detector via the **readout electronics** system.

- **On-detector:** Samples cells at 40 MHz and sends digitized pulse off-detector for signal analysis and triggering.

- **Off-detector:** Applies digital filtering to extract energy and time for each cell, passes info to trigger and data acquisition system.

Readout electronics are being upgraded to handle HL-LHC conditions.

We are here!

HL-LHC Begins

Run 3

Long Shutdown 3 (LS3)

2021 2022 2023 2024 2025 2026 2027 2028 2029

LAr HL-LHC Upgrade Overview

- For HL-LHC, full upgrade of main readout chain.

- New readout will provide full granularity of the LAr calorimeter to hardware trigger.
  - Average number of interactions per bunch crossing increasing from 35 to up to 200 in HL-LHC
  - Provide data for trigger improvements, needed to maintain efficiency for physics analysis.

- New on-detector components: Front-End Board 2 (**FEB2**), **Calibration Board**

- New off-detector components: LAr Timing System (**LATS**) and LAr Signal Processor (**LASP**)

Calibration Board

- Used to inject accurate calibrated signals directly in the liquid argon onto the calorimeter cells.
  - Provides pulse of known amplitude and shape for the calibration and testing of the readout board channels
  - 16-bit dynamic range, < 0.1% Linearity, radiation hard up to 14 kGy

- Need to calibrate 180k calorimeter cells = 122 boards with 128 channels each

- Using custom ASICs:
  - CLAROC = creates pulse by opening high frequency switch (180 nm XFAB technology)
  - LADOC = custom 16-bit DAC used to select the calibration current.
  - v4 of these ASICs are being produced to overcome radiation hardness and non-linearity, to be tested this year.

- 32-channel pre-prototype board (CABANON) passed specification review.

- Next up is prototype development and testing.
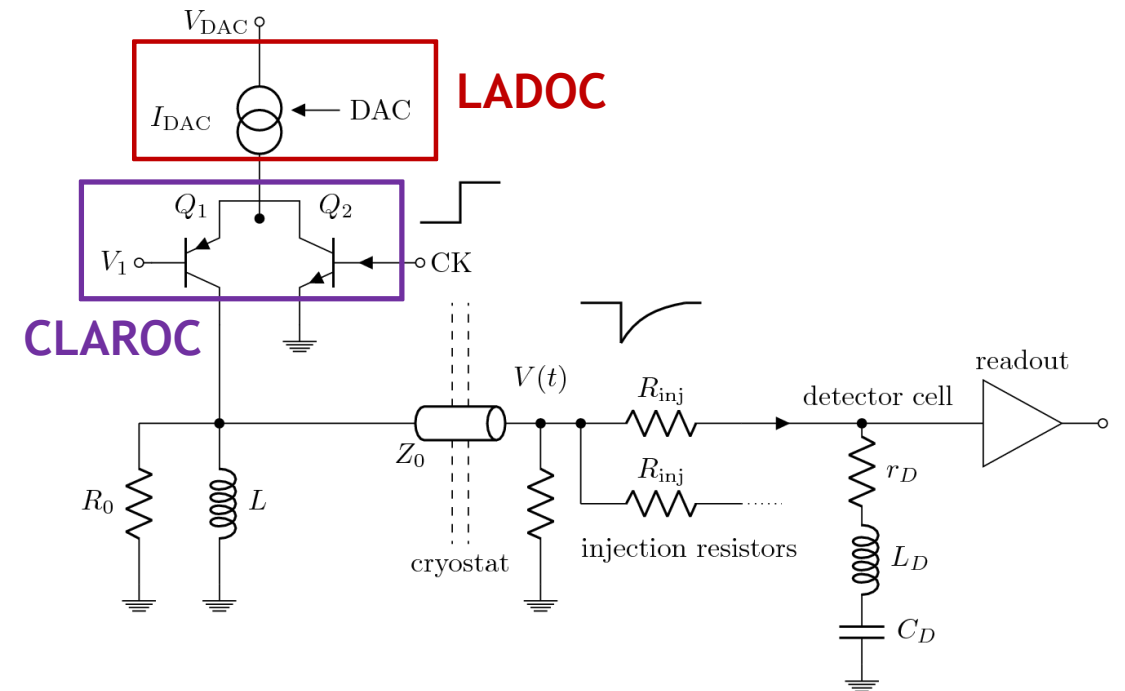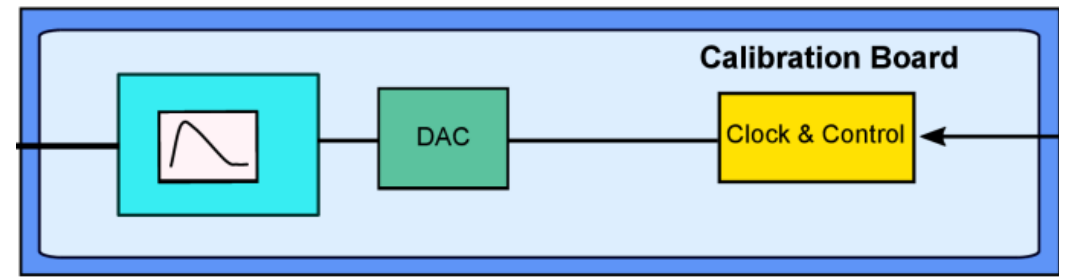
Front End Board (FEB2)

- Each FEB2 board will handle 128 channels (1524 total boards) and includes:
  - pre-amplifier/shaper ASIC (ALFE)
  - ADC ASIC (COLUTA)
  - lpGBT chips connected to bidirectional VersatileLink+ transceiver modules.
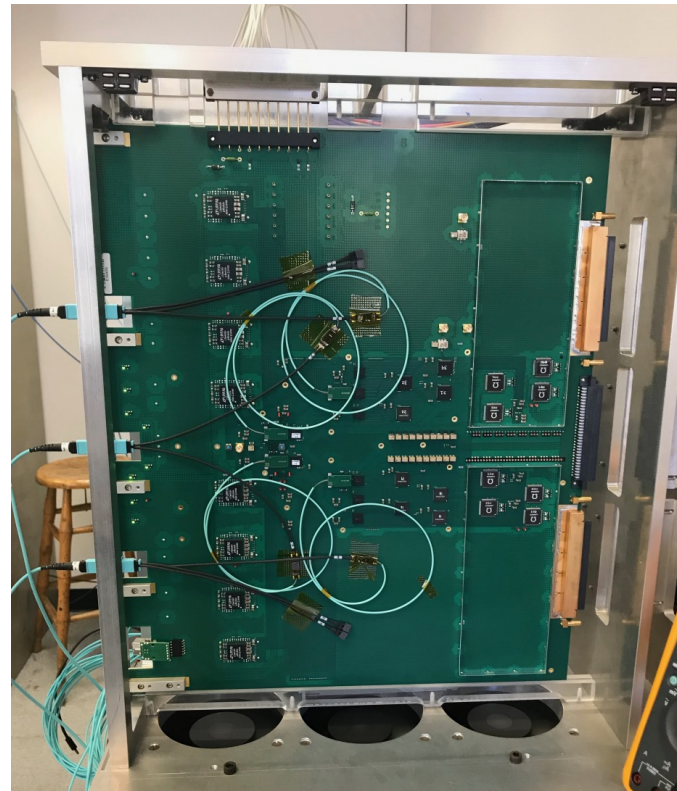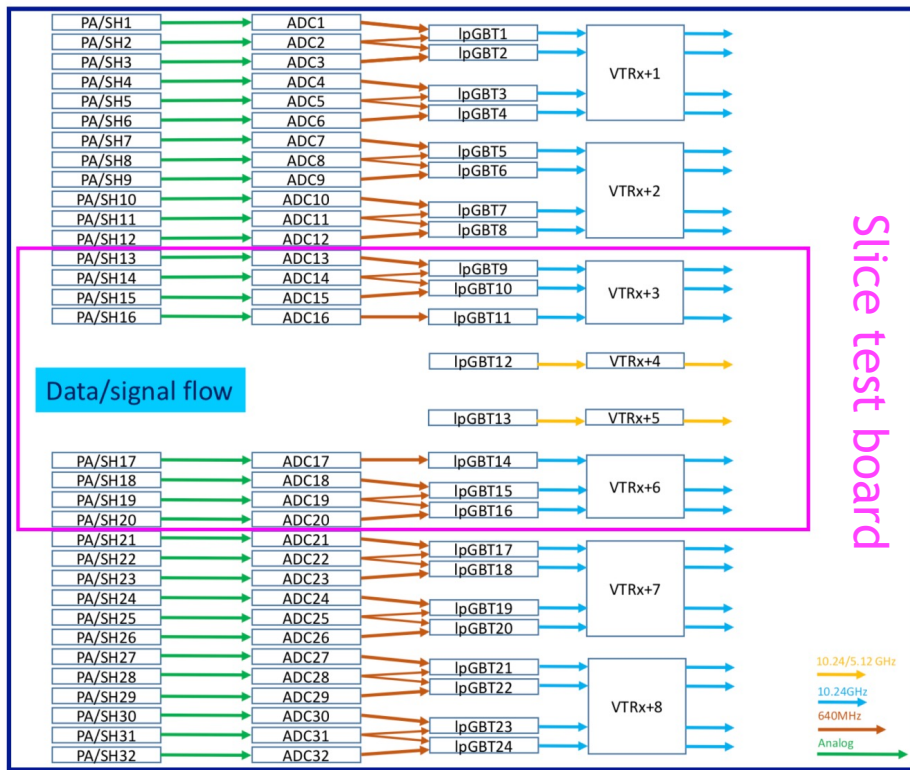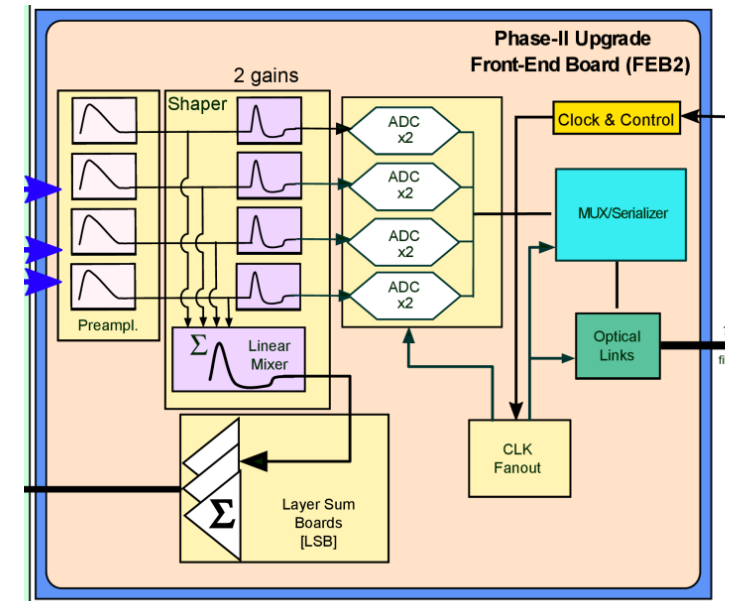
- FEB2 Test Boards produced with 32 channels
  - Validated multi-channel performance.
  - Control and readout on all channels tested.

- Next steps: towards the 128 channel FEB2 prototype

FEB2 ASIC: Pre-Amplifier/Shaper

- Analog processing on signals:
  - Amplifies and shapes ionization pulses in two overlapping gain scales
  - 4 channel summing for hardware trigger
  - CR-RC^2 shaping
  - Large dynamic range : 10 mA for 25 Ω channels and 2 mA for 50 Ω channels
  - Noise : < 350 nA for 10 mA channels, Linearity: < 0.2%
  - Radiation tolerance: performant after 12 kGy dose (c.f. spec. 1.4 kGy)

- ALFE2: Current ASIC version meets analog precision and radiation tolerance specifications.
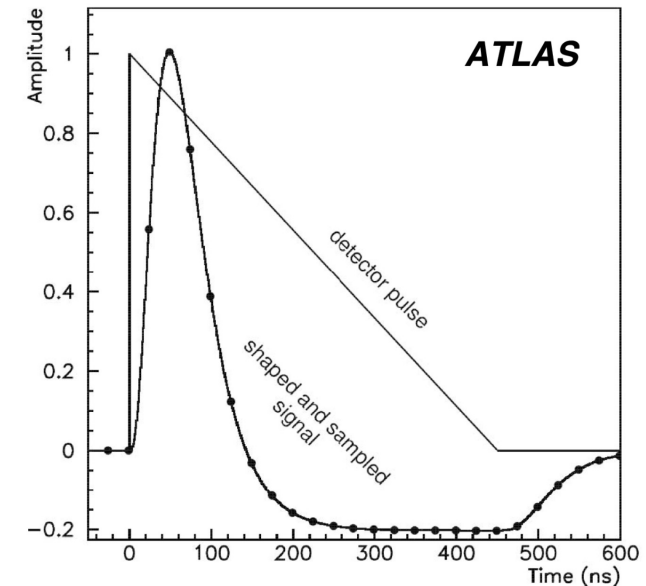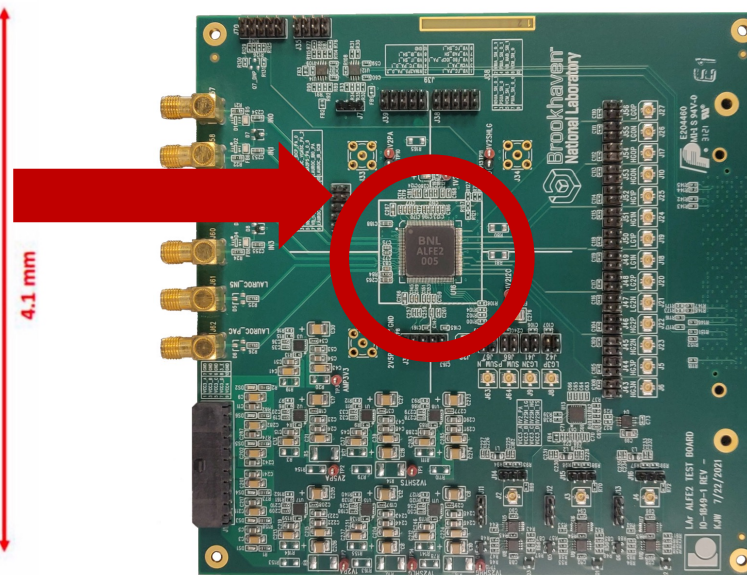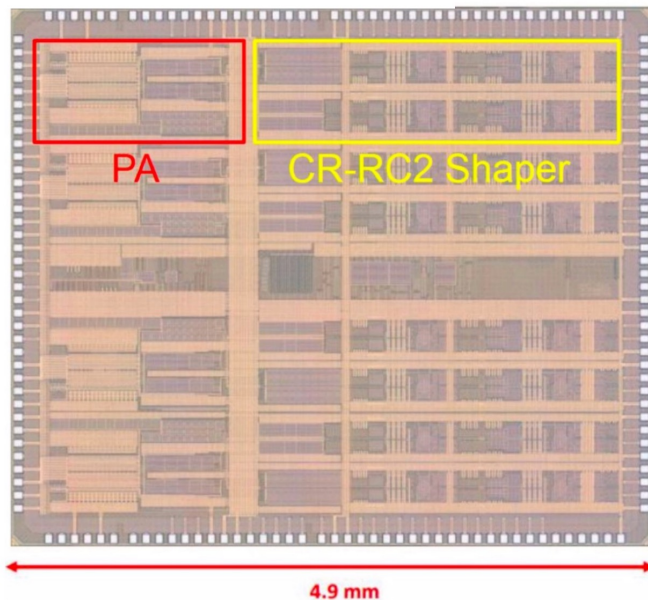
FEB2 ASIC: Analog to Digital Converter (ADC)

- COLUTAv4 ASIC:
  - 8 channel, 15-bit ADC
  - MDAC+SAR+DDPU Architecture
  - TSMC 65nm
  - 40 MSPS
  - 5.854 x 5.456 mm2
  - 4.3 million transistors
  - 1.2 V operation with 2 V_{pp} differential input

- Performance tests:
  - 18 ADCs tested over (almost) full dynamic range → achieved > 11 bit ENOB
  - Pre-amp/shaper integration using ALFEv2
  - Radiation test boards received, tests planned for August
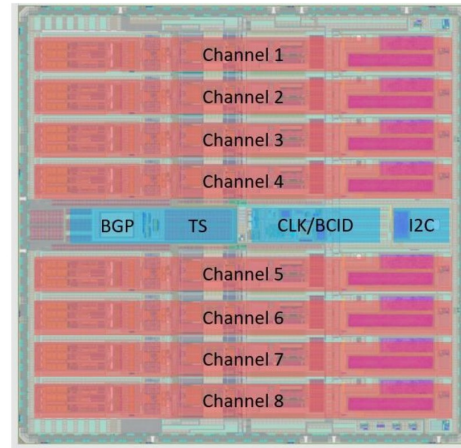
Socketed chip performance
Near full-scale amplitude, frequency of 5 MHz
and measured on channel 1 (transformer input)

ENOB 11.8

Soldered chip achieves ENOB > 12
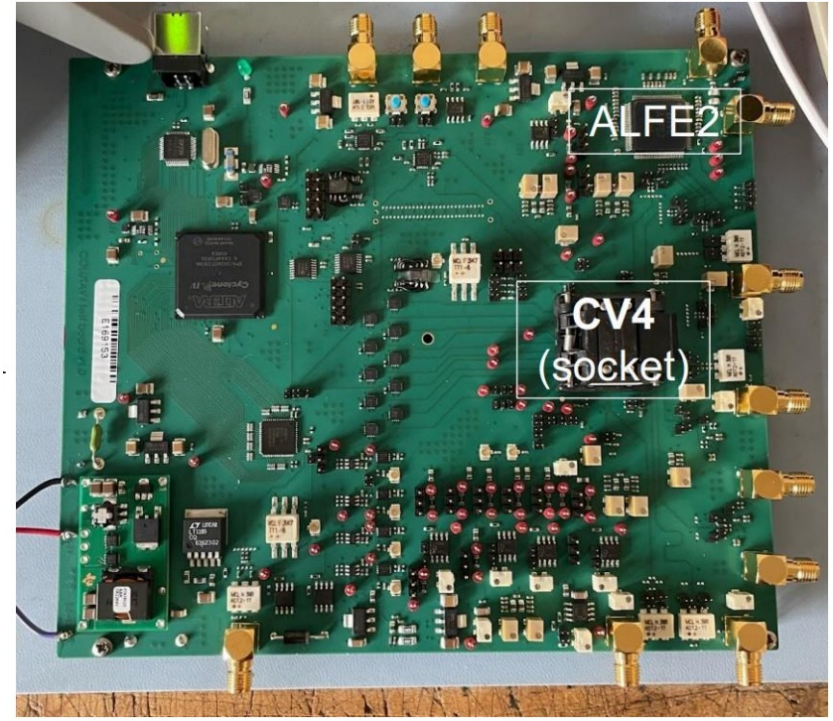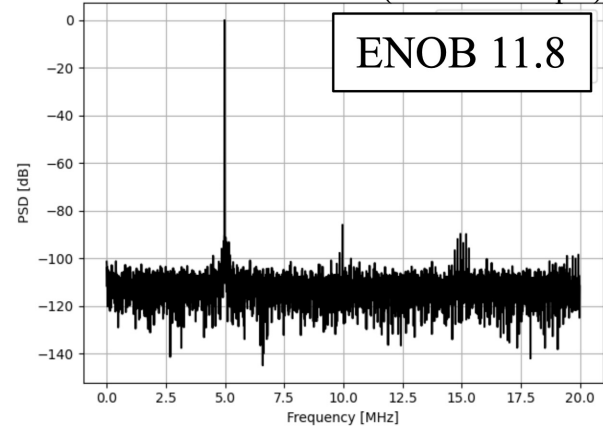

COLUTA v4 ASIC test board

LAr Timing System (LATS)

- Requirements:
  - Trigger, timing and control (TTC) for 1524 FEBs and 122 Calibration boards, 2 links per board, based on lpGBT protocol

- LATOURNETT: ATCA board
  - ~26 total
  - One central and 12 "matrix" Cyclone10 GX FPGAs
  - Schematic design underway & table test bench recently developed

- Current testing status:
  - Central and matrix FPGA firmware validated in simulation
  - Power-up sequence verified with POWERv2 board
  - Temperature tests inside crate

- Next up is prototype submission and integration with on-detector boards!
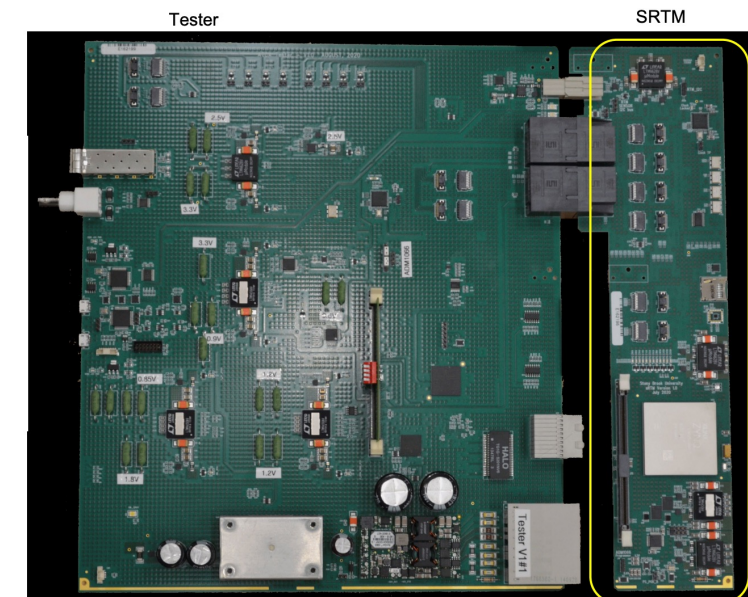

LATOURNETT Power v2: with Fireflys & heatsinks

LATOURNETT
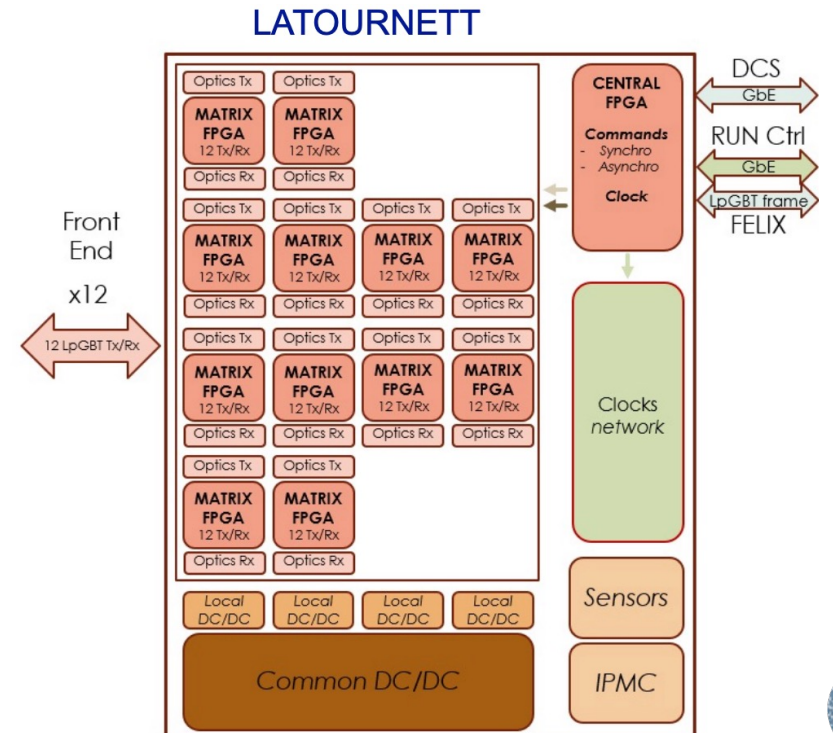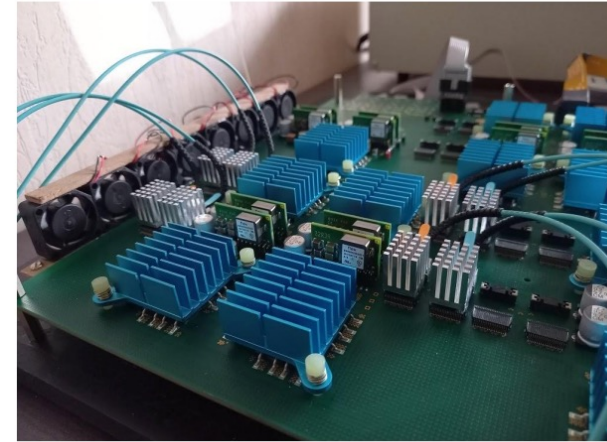
# LAr Signal Processor (LASP) and Smart Rear Transition Module (SRTM)
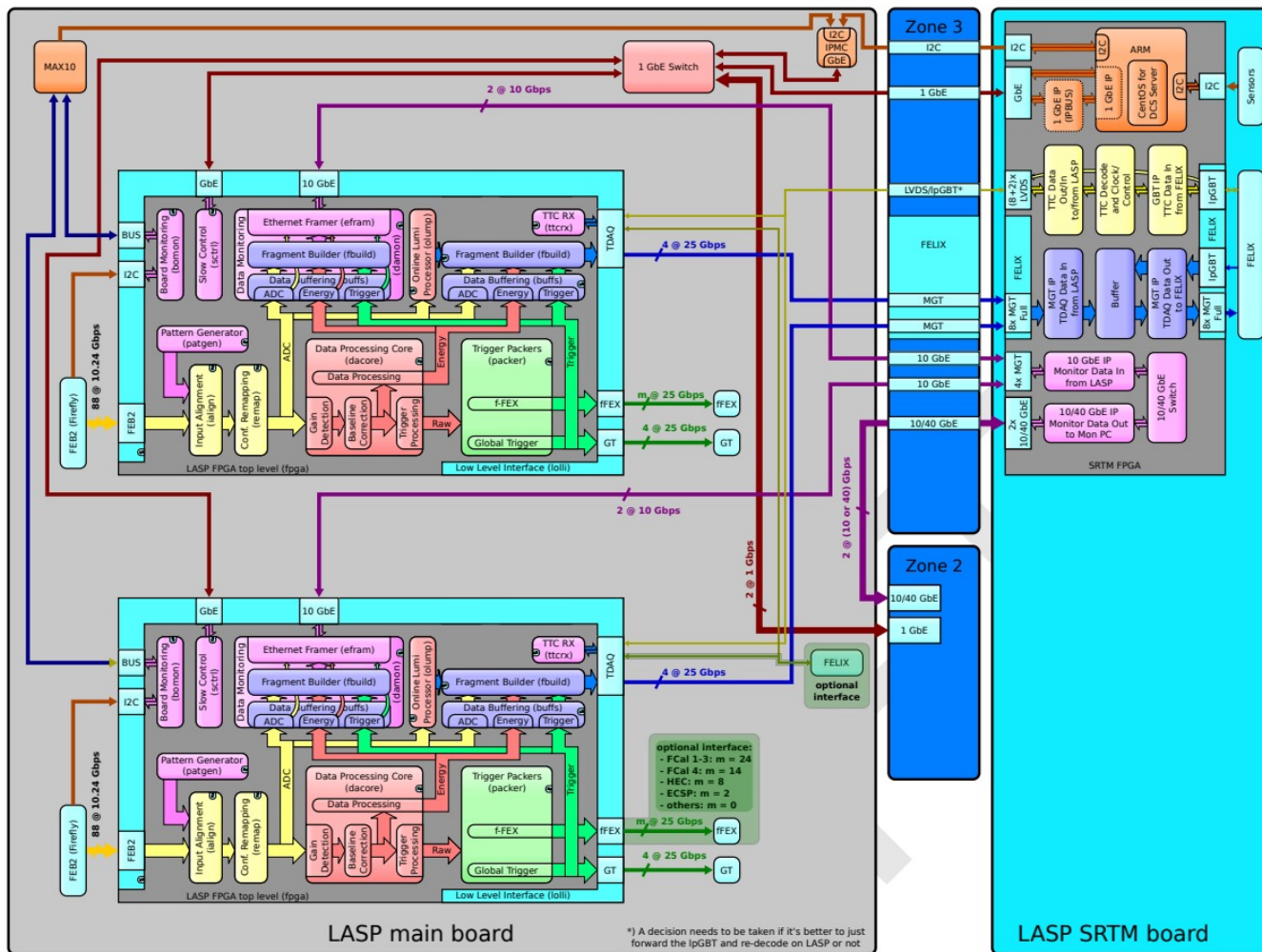
- **Purpose:** Apply digital filtering to digitized waveforms from FEB2, calculate energy & time, and transmit to trigger and DAQ.

- 200-278 of each board, 6 FEB2 per blade (2 FPGAs), outputs to L1 global and forward TDAQ at 25 Gbps.

LAr Signal Processor (LASP) and Smart Rear Transition Module (SRTM)

- Latest results:
  - v1 testboard with full capability: validation of power sequencing, i2c sensors, clock, FPGA configuration
  - Switched from Stratix-10 FPGA to Agilex.
  - Slice-test firmware developed to receive and process data from a FEB2 slice testboard (32 LAr cells, 6 data fibers)

- Next up are more measurements with test board and full prototype design
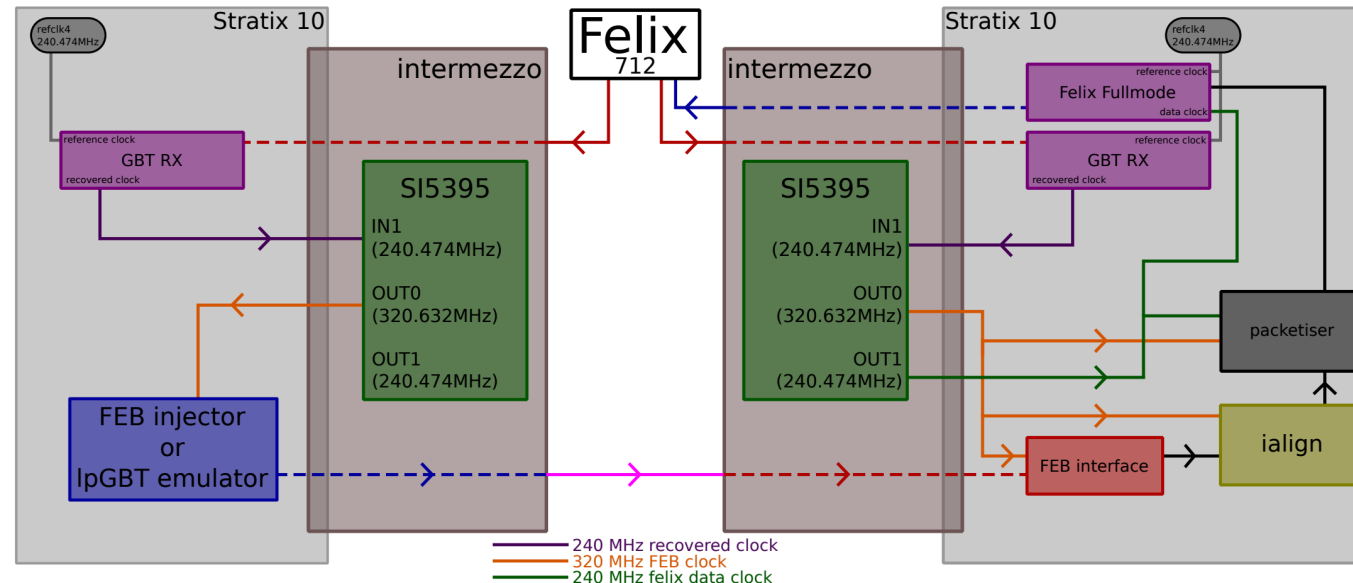
LASP and Machine Learning

- Given the up to 200 pile-up collisions at HL-LHC, overlapping pulses are expected to lead to degradation in energy, timing and trigger performance.

- The current Optimal Filter approach to energy reconstruction may be improved by machine learning algorithms in FPGA's Data Processing Core!

- Recurrent and convolutional neural networks, and long short-term memory algorithms are being explored.
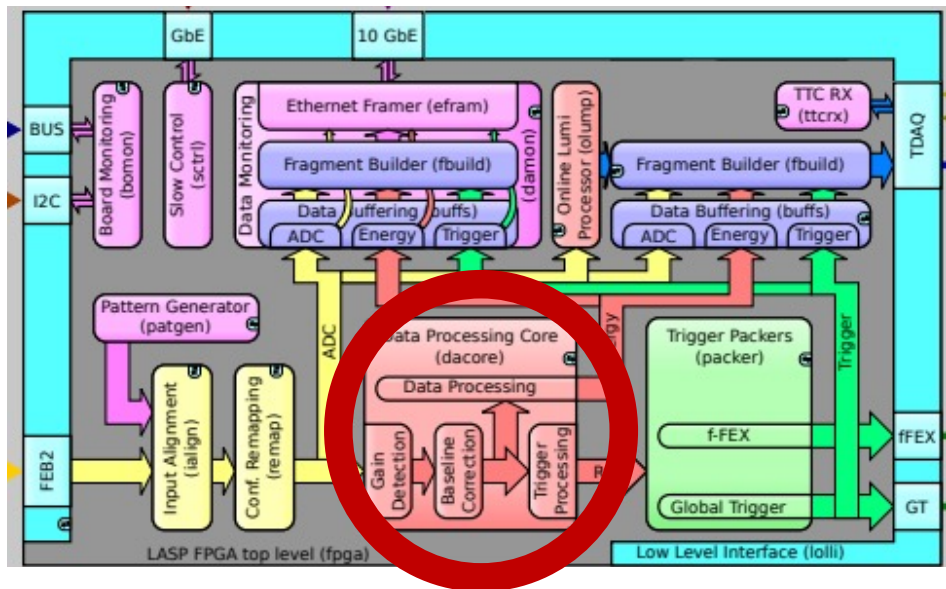
LASP FPGA Firmware Diagram
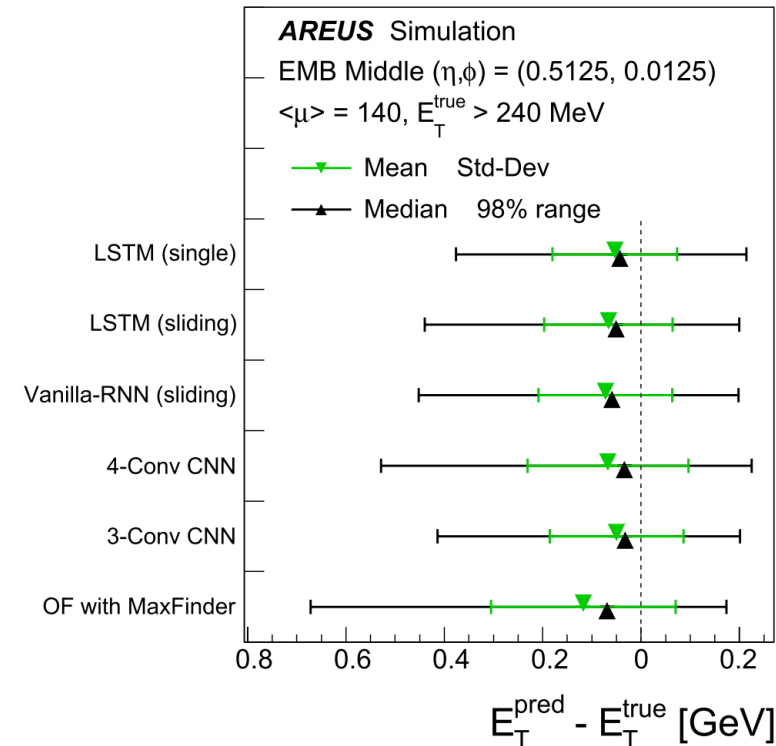
Summary/Overview

- The LAr Calorimeter is necessary for the success of the physics program of the ATLAS Collaboration.
  - Challenges: Much higher pileup, possible increased energy, increased granularity of information for trigger, higher radiation.
  - Solution: Complete replacement of on- and off-detector readout electronics by 2029.

- Development of the ATLAS Liquid Argon Calorimeter Readout Electronics for the HL-LHC continues at a good pace.
  - Full custom LAr-specific ASICs at or approaching last "prototype" stage before production.
  - Work ongoing toward full slice + systems test.
  - Off-detector firmware is continuing to develop.

- On track for ATLAS installation after Run-3!