Instrumentation of Particle Physics Experiments

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WHEPS – WEIHAI HIGH ENERGY PHYSICS SCHOOL 2015

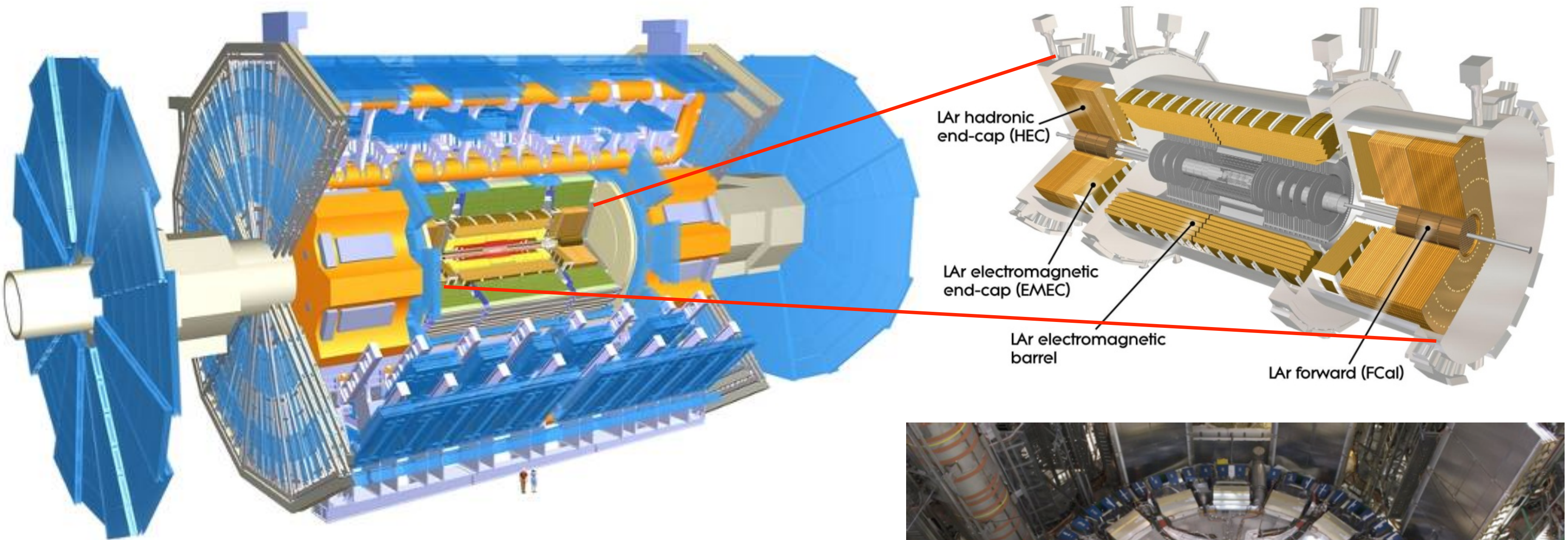
Lecture 2 – ATLAS LAr Readout Electronics

- ATLAS LAr Calorimeter
- LAr Readout Electronics
  - LAr Front End Electronics
  - LAr Back End Electronics
  - LAr Trigger Readout Electronics
- Grounding of ATLAS LAr Calorimeter

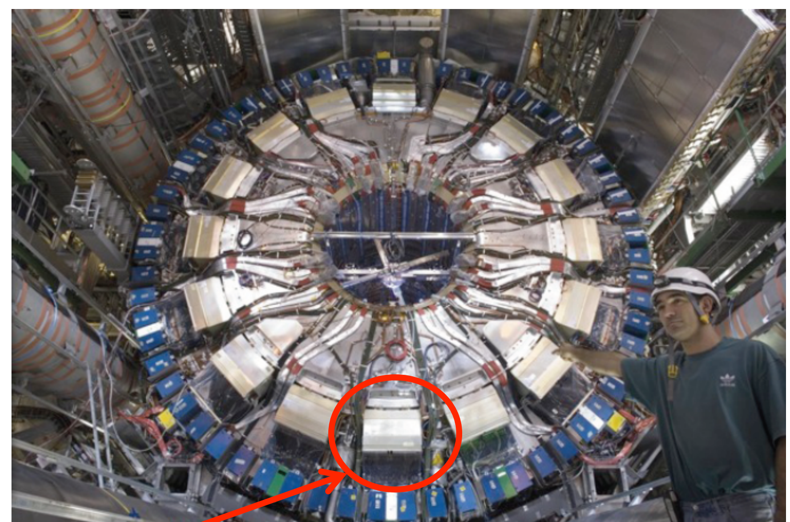
ATLAS LAr Calorimeter

- Physics goals dictate the calorimeter design
  - Higgs search in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow$ *4 leptons (lepton = e, μ)* requires precision measurement of photon and electron
  - SUSY search using missing E_T needs precision measurement of visible energy
  - Low event rate in searches for Higgs and other new physics ($W' \rightarrow e\nu$, $Z' \rightarrow ee$) require high efficiency, high resolutions (E and spatial)
  - High (35 MeV to 3 TeV) dynamic range to maximize discovery potential
- The ATLAS LAr calorimeters is almost hermetic with $|\eta| \leq 4.9$
  - High granularity: 182,468 cells
  - Excellent resolution with EM accordion ***sampling*** calorimeter design
    - e/γ: $\sigma(E)/E(\mathrm{GeV}) = 10\%/\sqrt{E} \oplus 0.4/E \oplus 0.7\%$

ATLAS LAr Calorimeter



- **Liquid Argon Calorimeter**
  - **Electromagnetic Barrel (EMB)**
    - **$|\eta|<1.475$ [Pb-LAr]**
  - **Electromagnetic End-cap (EMEC)**
    - **$1.375<|\eta|<3.2$ [Pb-LAr]**
  - **Hadronic End-cap (HEC)**
    - **$1.5<|\eta|<3.2$ [Cu-LAr]**
  - **Forward Calorimeter (FCAL)**
    - **$3.1<|\eta|<4.9$ [Cu,W-LAr]**

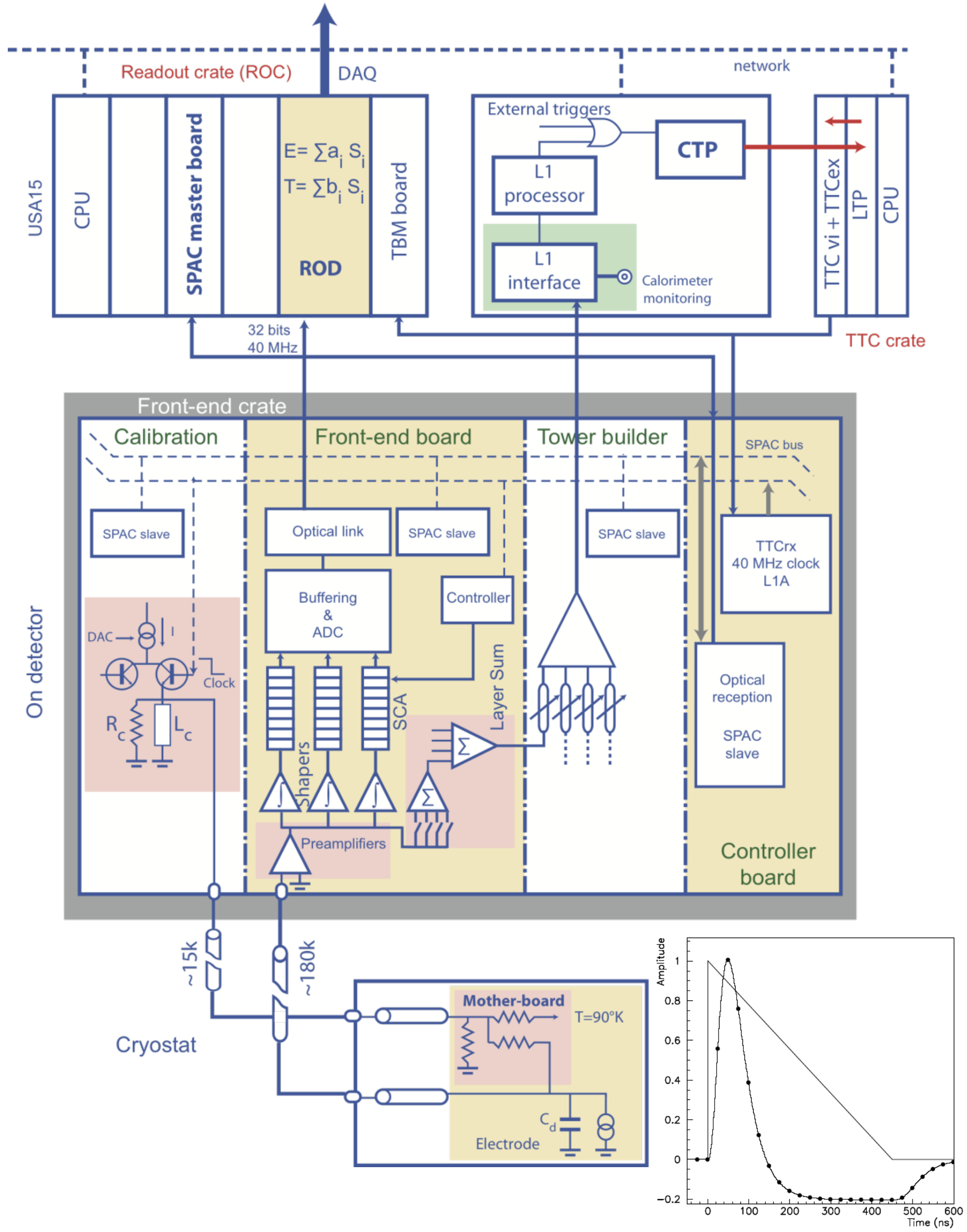


Front End Crate

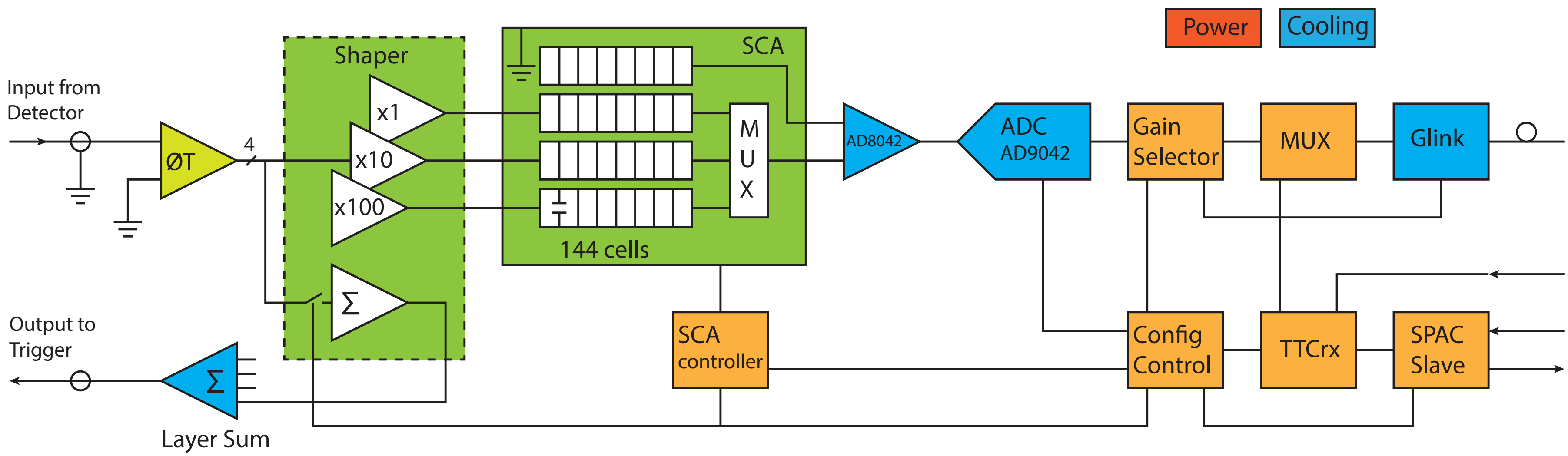
Barrel calorimeters in detector hall, surrounded by barrel toroids

LAr Readout Electronics

- 182,468 detector channels
  - EMB: 109,568 channels
  - EMEC: 63,744 channels
  - HEC: 5,632 channels
  - FCAL: 3,524 channels
- Front-end Electronics
  - 58 Front End Crates
  - 1524 Front End Boards
  - ~300 other boards (calibration, tower builder, controller, monitoring)
  - 58 LV Power Supplies
  - ~1600 fiber optic links between FE and BE
- Back-end Electronics
  - 16 Back End Crates
  - 192 Read Out Driver Boards
  - 68 ROS PCs
  - ~800 fiber optic links between ROD and ROS



LAr Front End Electronics



- Requirements
  - Readout channel: 182,468
  - Dynamic range: 16 bits (3 gains plus 12 bit ADC), signal shaped to prevent electronics pileups
  - Data rate: 40Msps sampling and analog pipeline (SCA); L1 trigger on board up to 100 kHz
  - Radiation tolerance

Test	Pre-Selection	Qualification
TID	1.2×10^3 Gy	5.8×10^2 Gy
NIEL	3.3×10^{13} cm^{-2}	1.7×10^{13} cm^{-2}
SEE	6.3×10^{12} cm^{-2}	3.2×10^{12} cm^{-2}

ASIC Criteria

Test	Pre-Selection		Qualification	
	unknown qualification batches	known qualification batches	unknown batches	known batches
TID	7.8×10^3 Gy	3.9×10^3 Gy	7.8×10^3 Gy	1.9×10^3 Gy
NIEL	6.6×10^{13} cm^{-2}	3.3×10^{13} cm^{-2}	6.6×10^{13} cm^{-2}	1.7×10^{13} cm^{-2}
SEE	1.3×10^{13} cm^{-2}	6.3×10^{12} cm^{-2}	1.3×10^{13} cm^{-2}	3.2×10^{12} cm^{-2}

COTS Criteria

Front End Electronics Design Challenges

- Large readout channels (~182k). High density frontend boards (128 channels per board)
- Low power (~ 0.7 W) per channel, but ~80 W per FEB → water cooling
- Large dynamic range (16 bits resolution achieved by 3 gains with a 12 bit ADC)
- Measure signals at LHC bunch crossing frequency of 40 MHz
- Store signals during L1 trigger latency of up to 100 bunch crossings or 2.5us latency
- Digitize on board and read out 5 samples/channel at L1 rate up to 100 kHz
- Event sample organization and data serialization on board. Send 1.6 Gbps data through optical data link to backend
- Mixed sensitive analog signals and MHz to GHz digital signals on the same board
- Very low jitter clock (<20 ps) for high speed serial data transmission
- High reliability over expected lifetime of > 10 years
- Components and subsystems must tolerate expected radiation levels of 10 yrs LHC operation ➔ large number of rad-hard ASICs development and extensive rad-hard evaluations on both ASICs and COTS

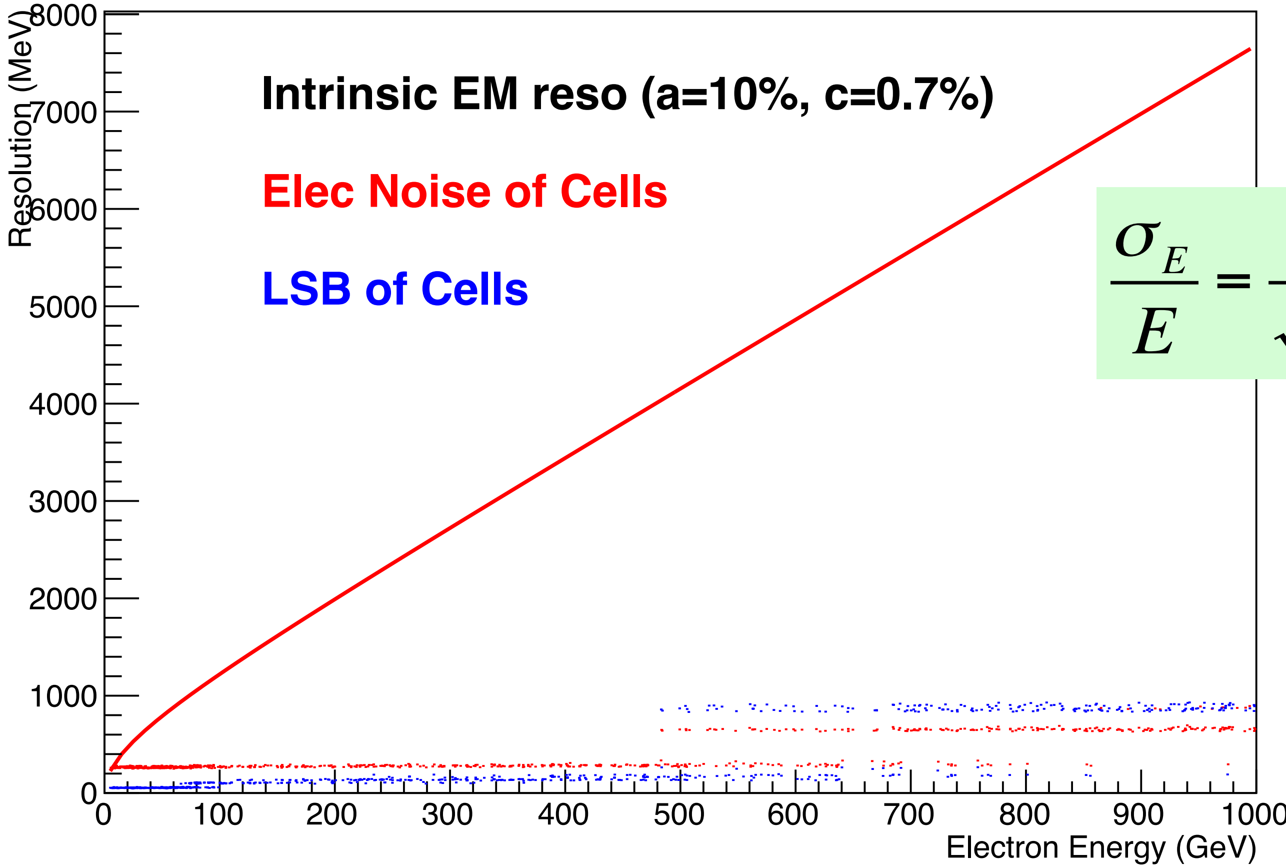
3-Gain Configuration

- LAr Central EM Barrel ($|\eta| < 0.8$) Middle Layer

Range	Current [uA]	Noise Current [nA]	Energy [GeV]	Noise Energy [MeV]	S/N
1	67.5	102.6	25	38	657
2	675	189	250	70	3571
3	6750	1601.1	2500	593	4215

- 3 gain x 12-bit resolution to cover 16-bit dynamic range
  - S/N in high gain is relatively low ($657 < 2^{10}$), can't make efficient use of 12-bit ADC
    - 12-bit ADC will not provide full 12-bit resolution
  - The noise level after digitization is set relatively high, approximately 6 ADC counts
  - This makes noise far away from ADC quantization noise LSB/$\sqrt{12}$

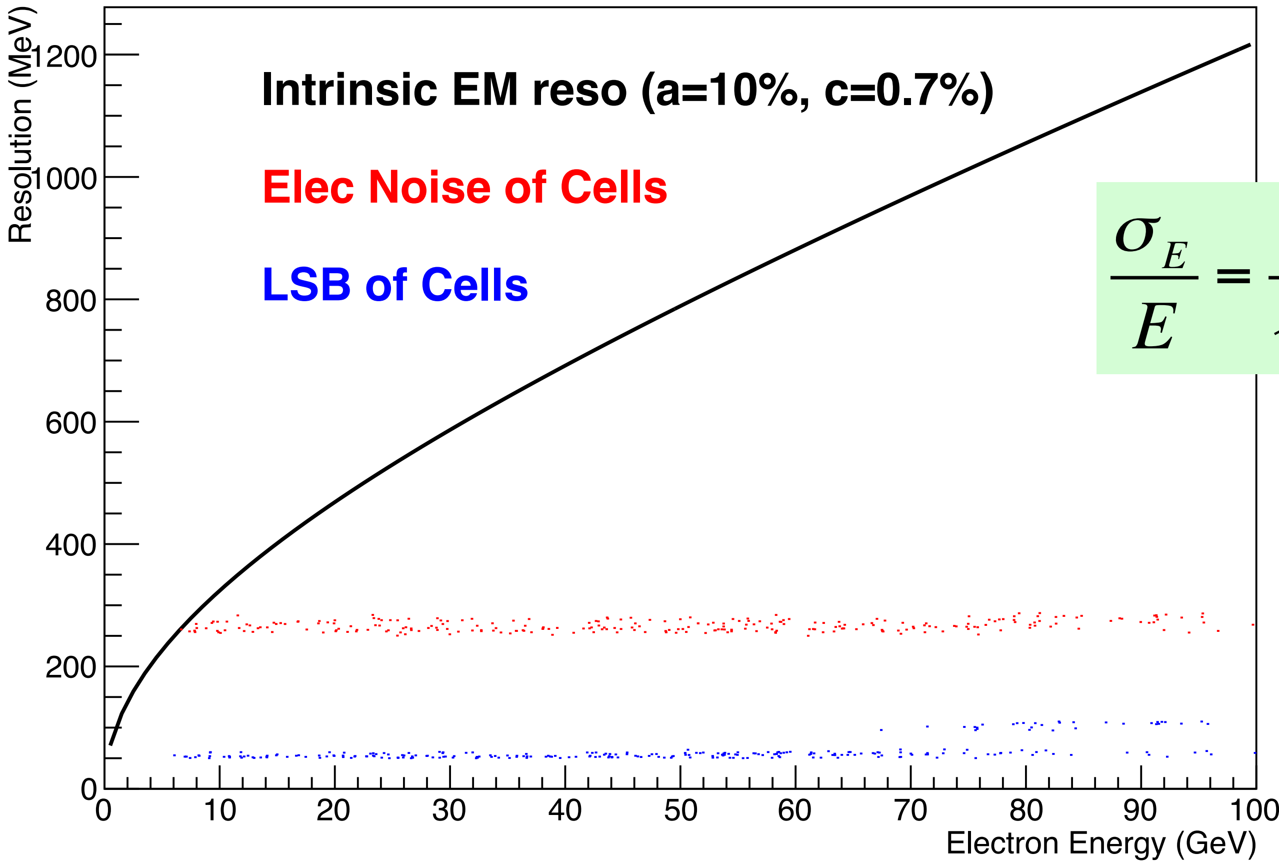
3-Gain Configuration



$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Comparison of electronics noise to the calorimeter resolution

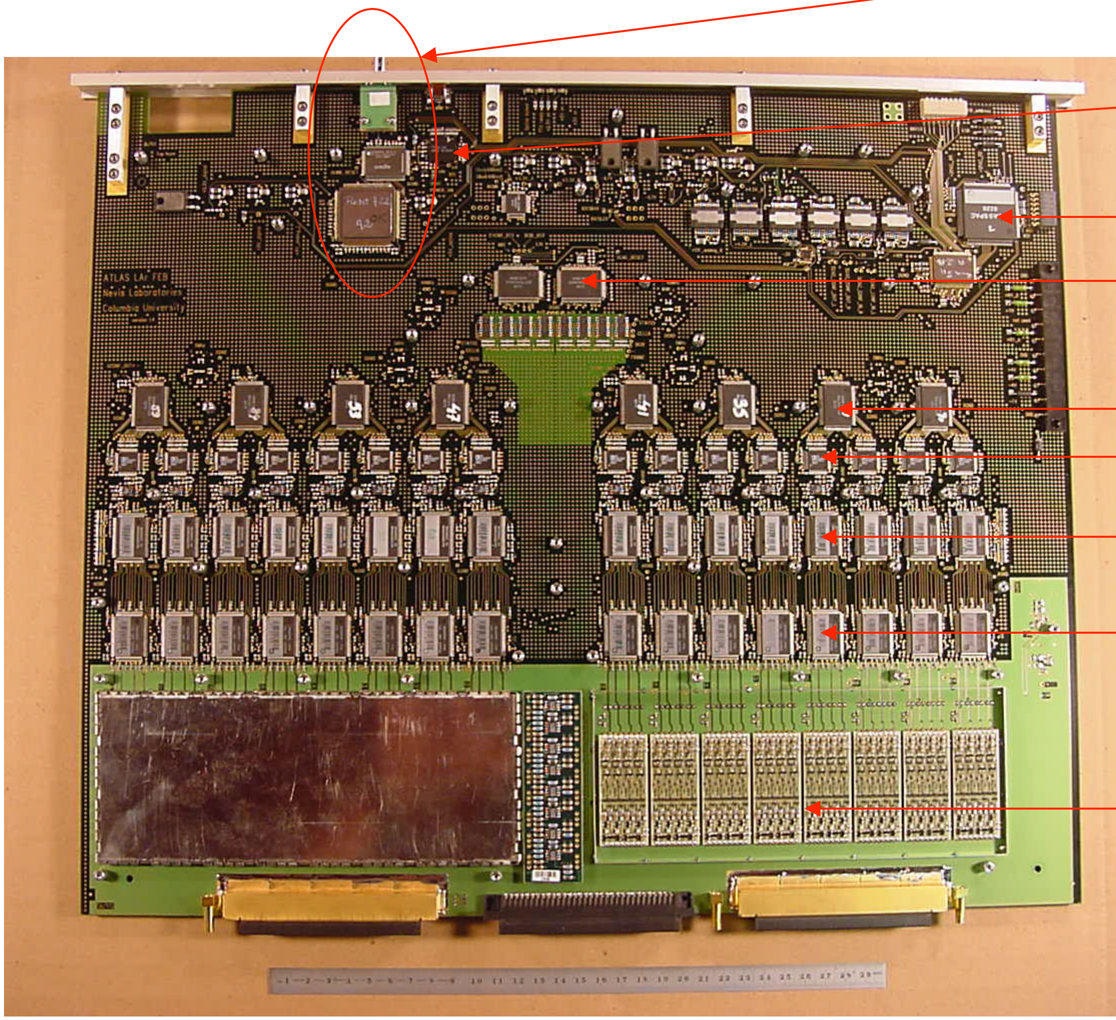
3-Gain Configuration



$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Comparison of electronics noise to the calorimeter resolution
  - Minimize the noise contribution to the degradation of calorimeter performance

ATLAS LAr Front End Board



Optical link TX (Sub. System, DMILL, COTS)

TTCRx (DMILL)

SPAC (DMILL)

SCA Controllers (DSM)

GainSel (DSM)

ADCs (COTS)

SCAs (DMILL)

Shapers (AMS)

Preamps (Sub. System)

Mix of severial rad-hard technologies,
19 pos. + neg. Vreg

ASICs in LAr Front End Electronics

- Front End Board

Technology	Components
AMS BiCMOS	Shaper (32)
DMILL	SCA(32), SMUX, TTCrx, CFGCTRL, SPAC_slave,
DSM (0.25μm)	GainSele(8), QPLL, CLKFO, SCAC(2), DCU2(2)
RHBip 1	VREG (19)

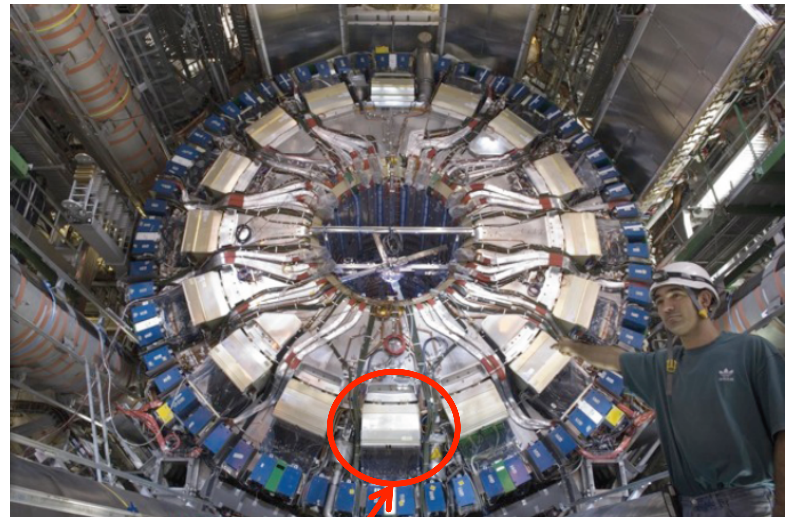
- Calibration Board

Technology	Components
AMS BiCMOS	HF Switch (128)
DMILL	Opamp (128), DAC, CALogic(6), SPAC_slave, TTCrx, delay(2).
RHBip 1	VREG (5)

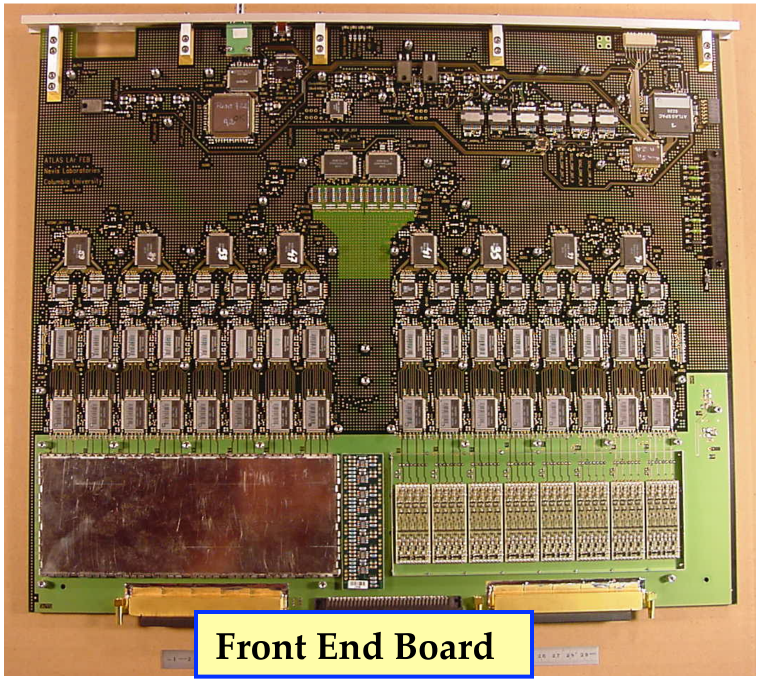
Test station of SCA – a 144 cells of analog pipeline ASIC based on radiation hard DMILL technology

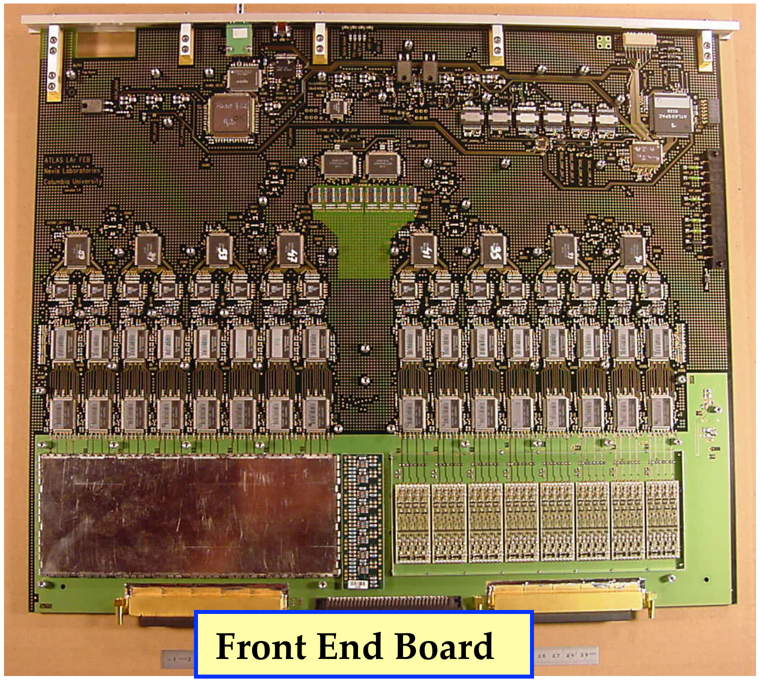
LAr Front End Electronics System

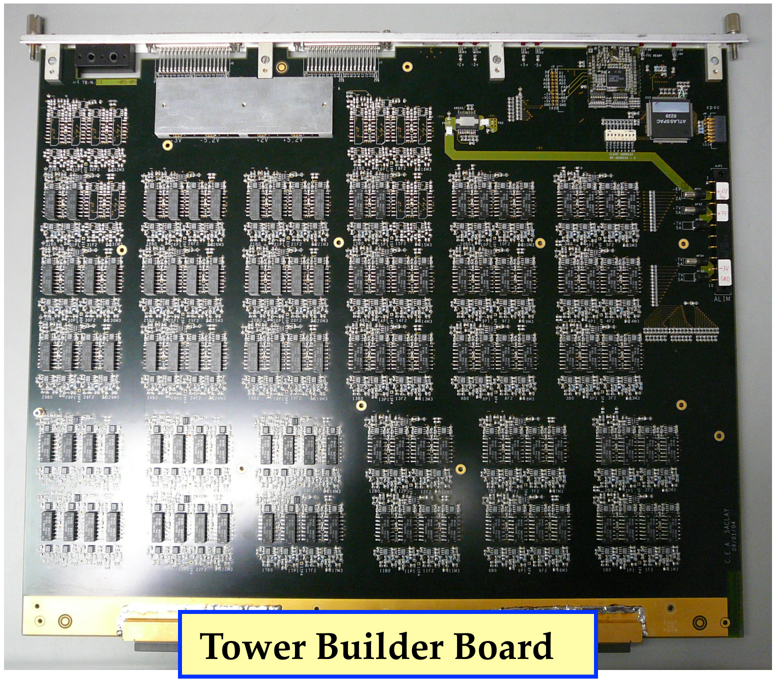
- 58 Front End Crates
- 1524 Front End Boards
- ~300 other boards
  - Calibration Board
  - Tower Builder Board
  - Tower Driver Board
  - Controller Board
  - Crate Monitoring Board
  - Purity Monitoring Board
- 58 LV Power Supplies
  - ~3.5kW high power density
  - Radiation tolerant
- ~1600 fiber optic links between FE and BE

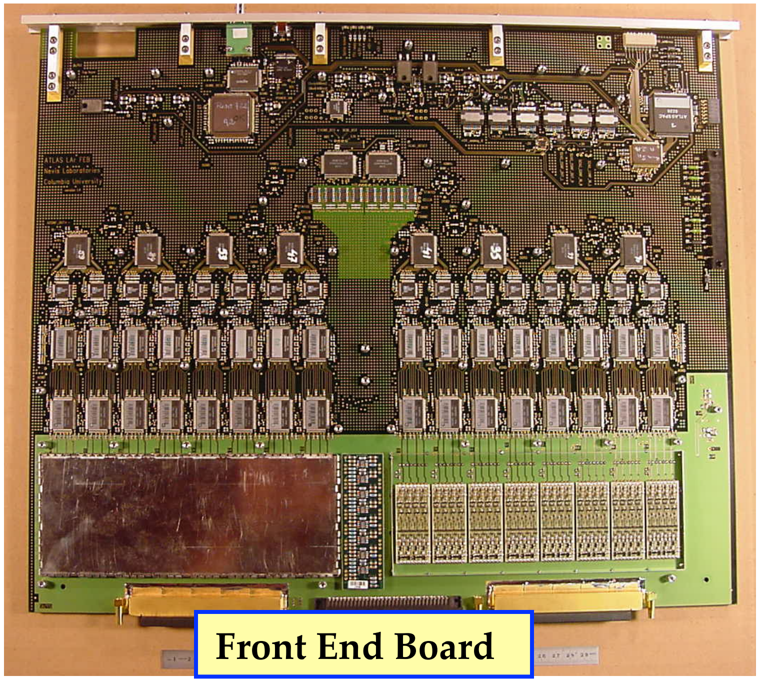


About 30 front end electronics boards installed in one Front End Crate with water cooling, powered by a ~3.5kW LVPS

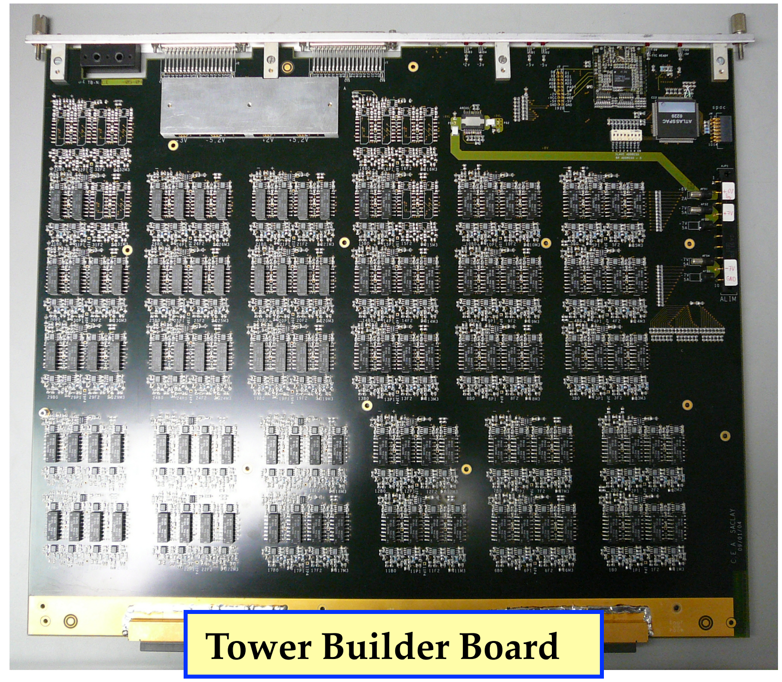

Front End Board


Front End Board

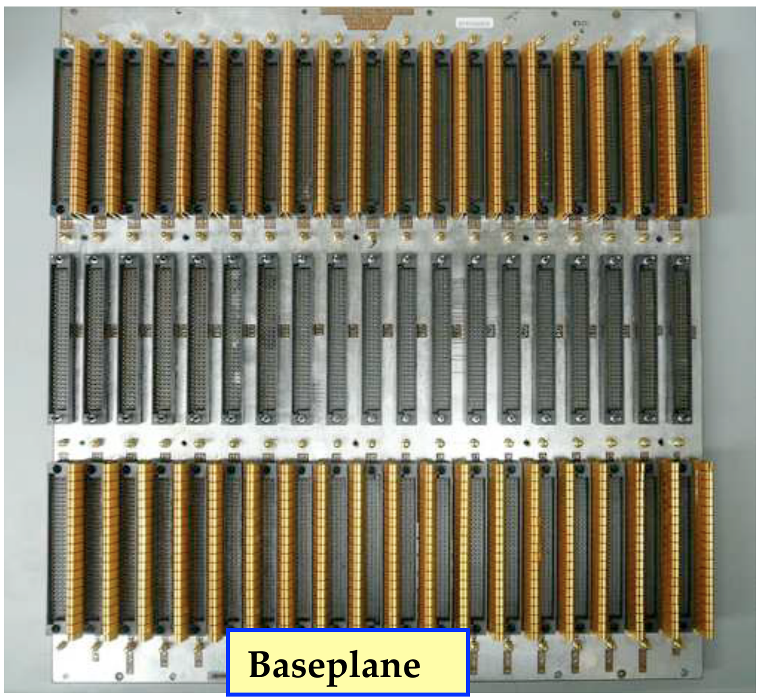

Tower Builder Board



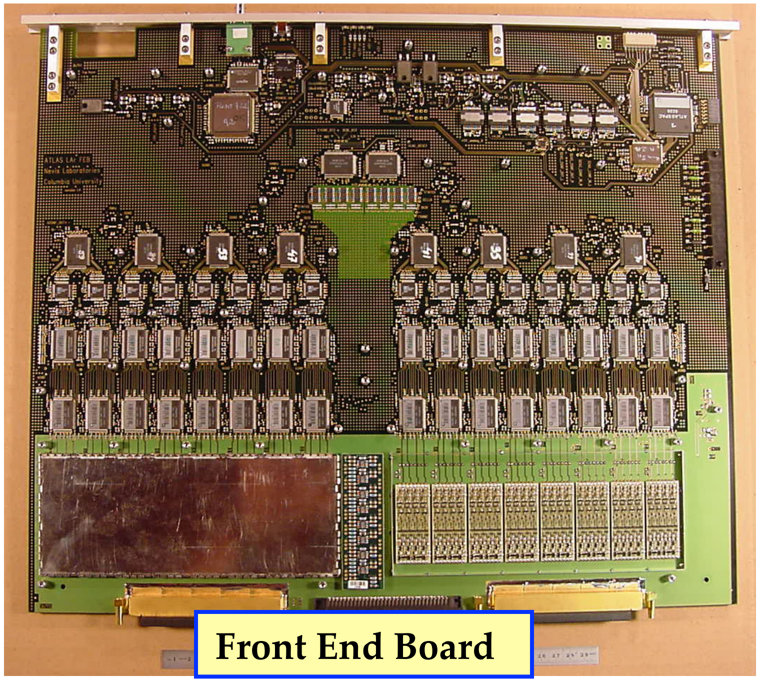
Front End Board

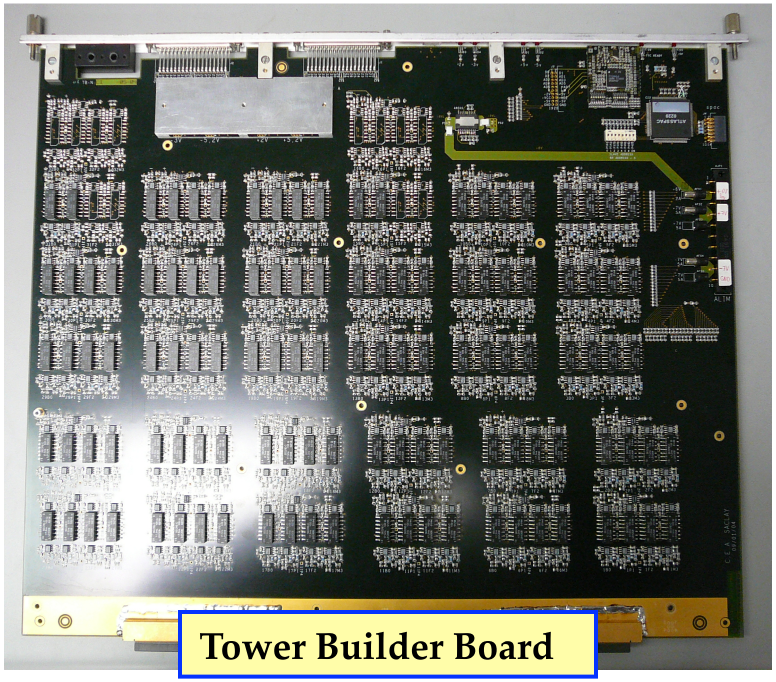


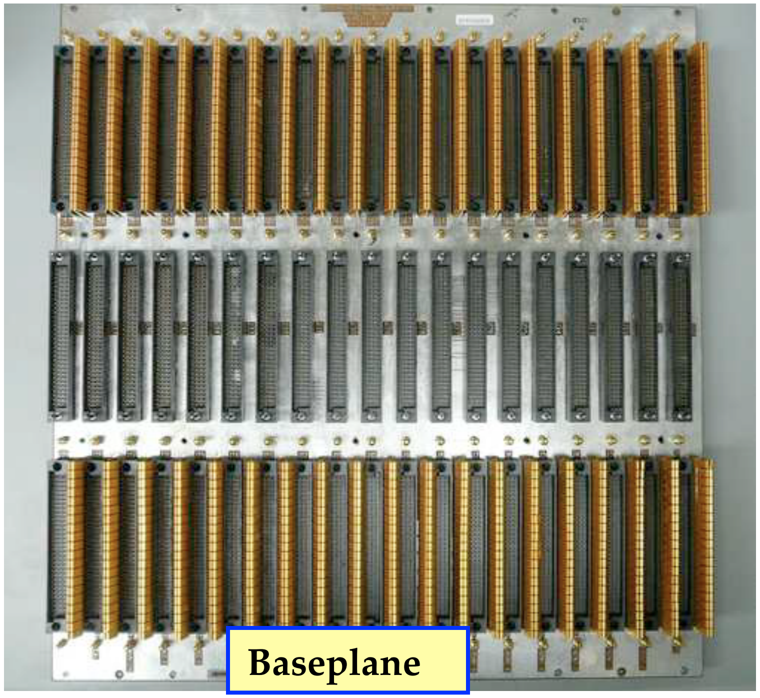
Tower Builder Board

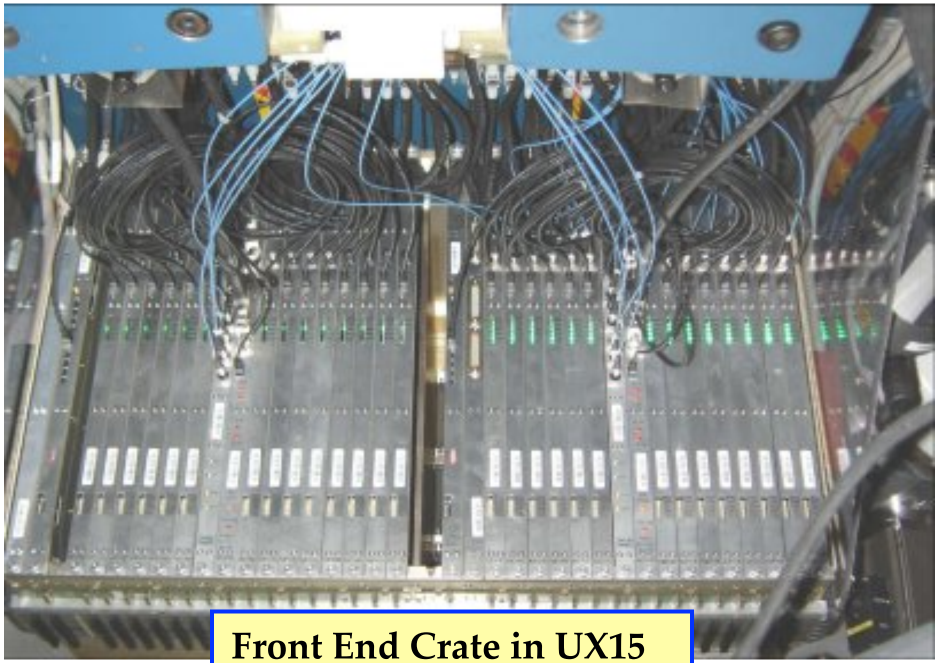


Baseplane

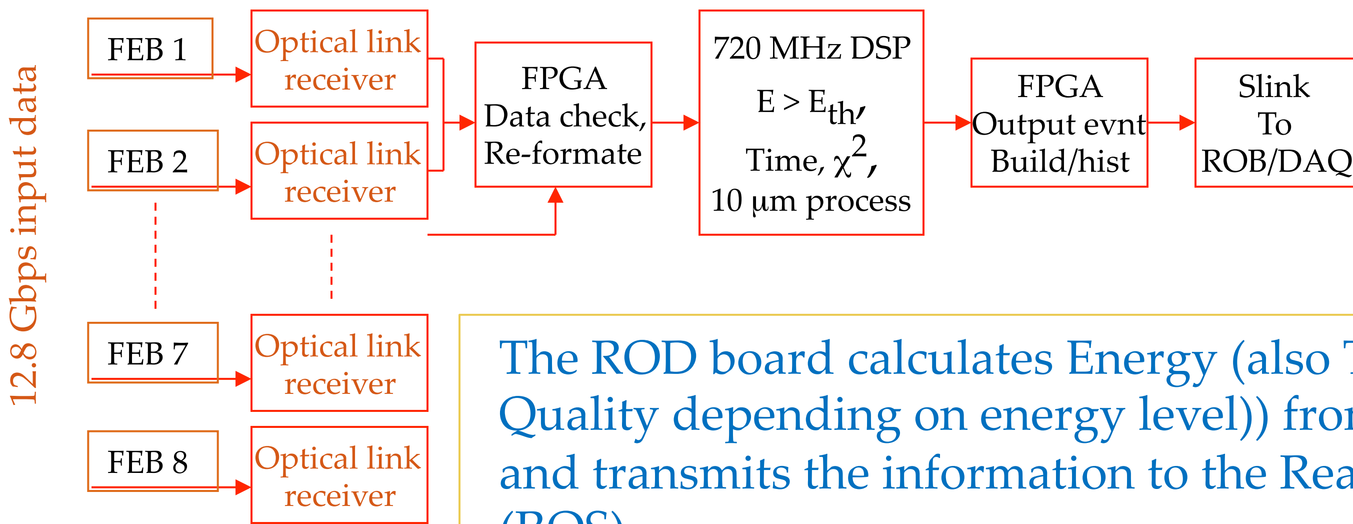

Front End Board


Tower Builder Board


Baseplane


Front End Crate in UX15

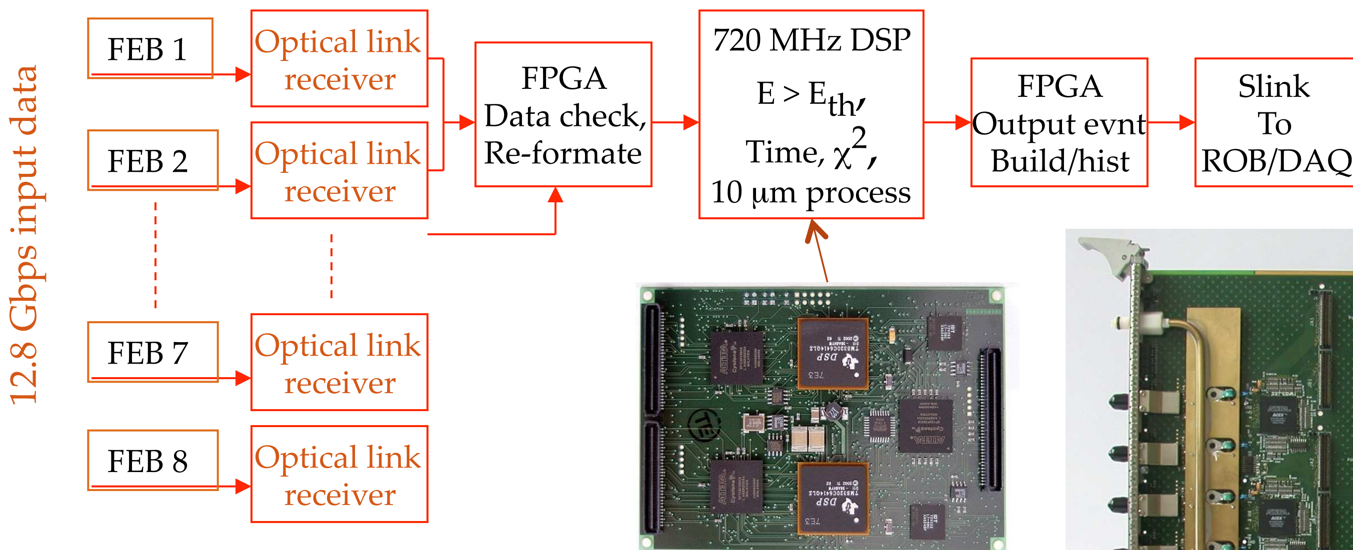
LAr Back End Electronics



The ROD board calculates Energy (also Time and Quality depending on energy level)) from FEB samples and transmits the information to the Read Out System (ROS)

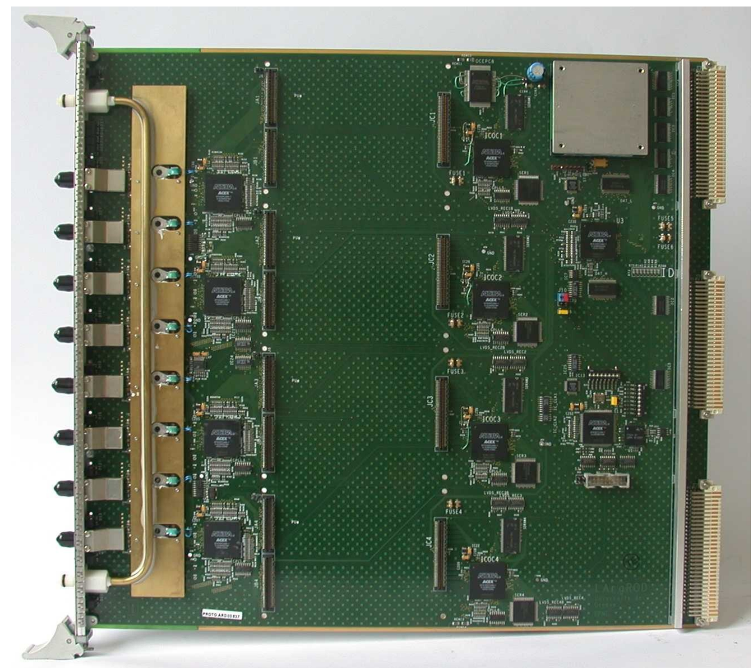
- Requirements
  - Input data rate at 12.8 Gbps from 8 FEBs
  - Data processing speed meets 100 kHz L1 trigger requirement
  - On-line monitoring, histogramming and control signal generation

LAr Read-Out Driver



PU Mezzanine

- Two or four processing units (PU) on ROD mother board
- Processing speed meets 100 kHz L1 requirement
- TTC interface for running on LHC clock
- VME64X interface



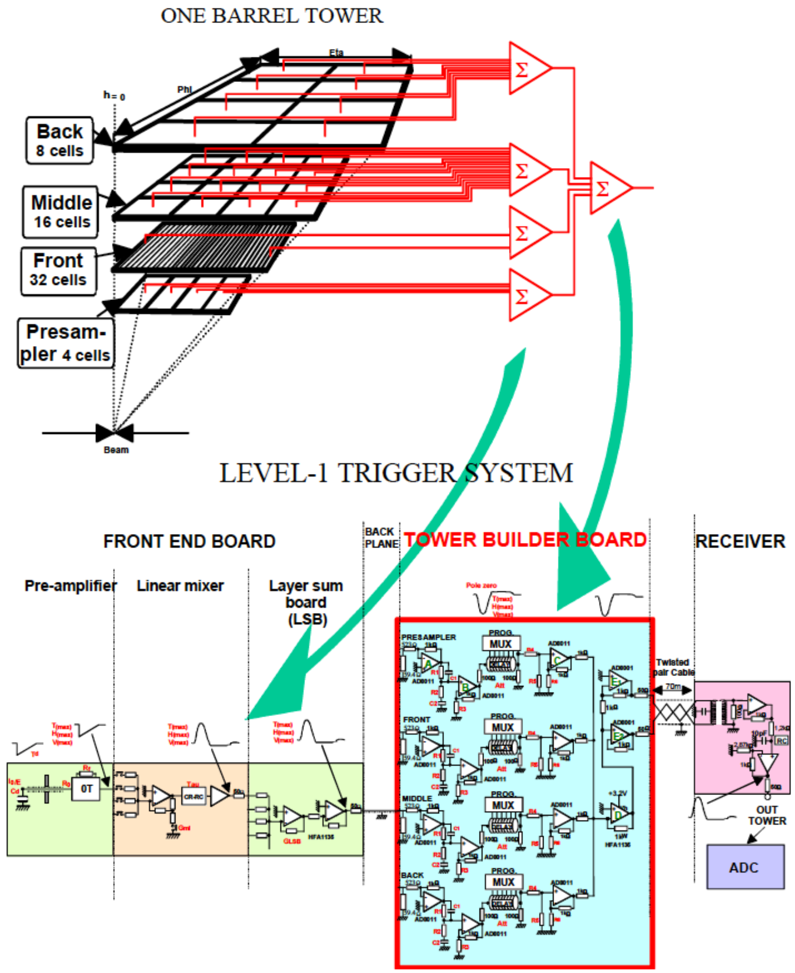
ROD motherboard

LAr Back End Electronics System

- 16 Back End VME Crates
- 192 Read Out Driver (ROD) Boards
  - Each ROD is a VME64x 9U module
- 68 ROS PCs
  - To receive data from 192 ROD boards
- ~800 fiber optic links between ROD and ROS
- TTC distribution system in USA15
  - 4 TTC crates
    - 6 partitions in 3 crates and one controller crate
    - 36 modules of 7 different types
    - 8 optical couplers
    - Over 200 fibers to FE and BE

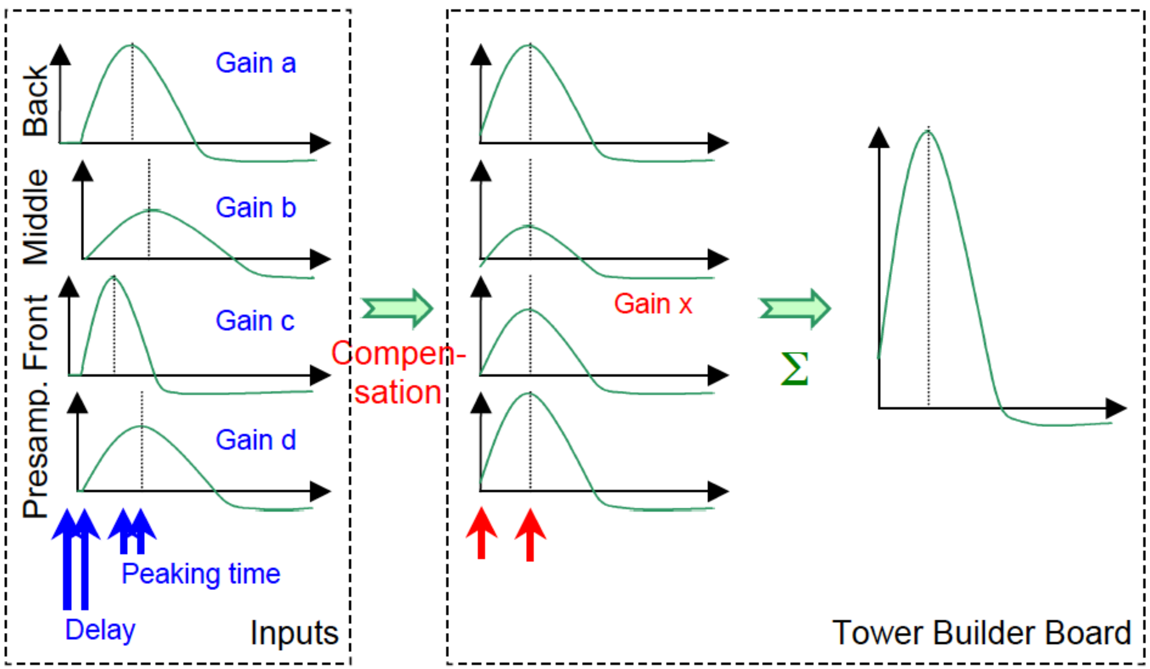
LAr Trigger Readout Electronics

- LAr trigger readout goes through Tower Builder Board, Trigger Cable and arrives at Receiver Board in USA15



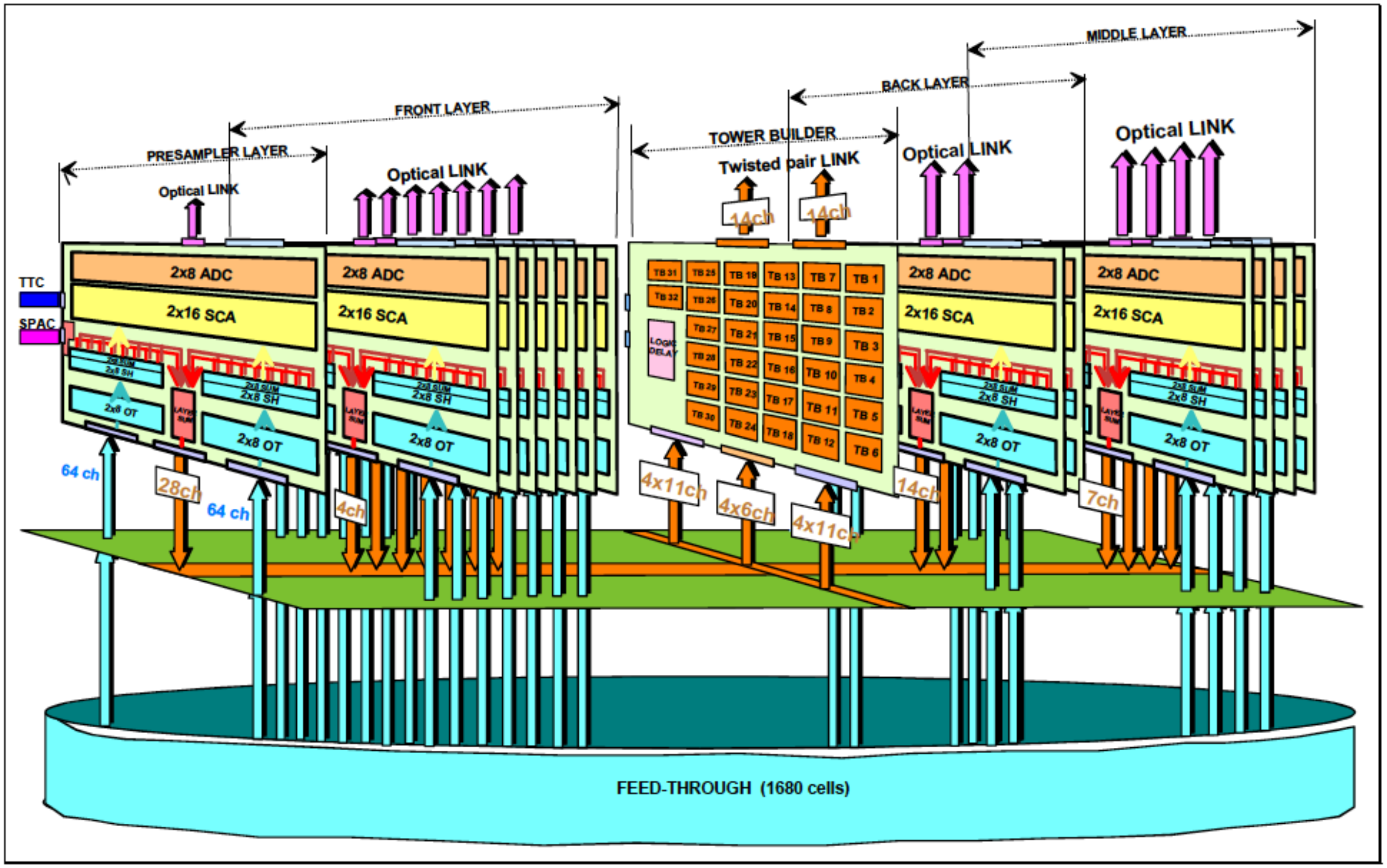
LAr Trigger Readout Electronics

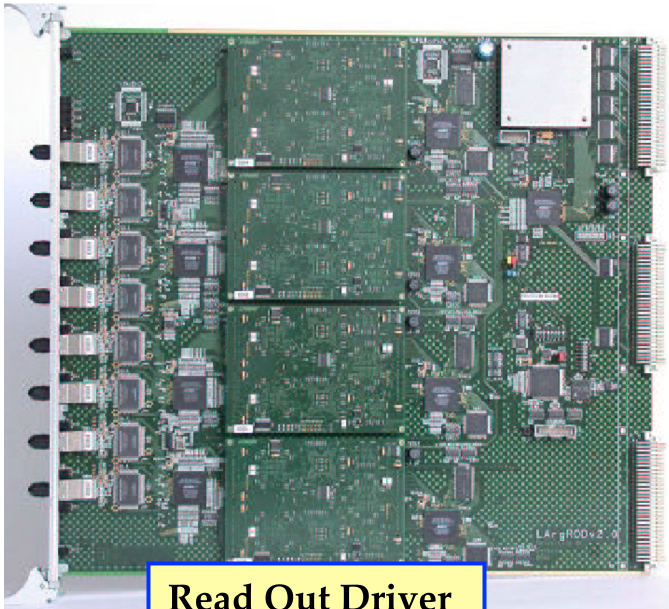
- Analog trigger sum signals are going through proper compensation before summing together to form a trigger tower
- TBB has the following functionalities
  - Adjust the input signals shape, gain and delay
  - Add these signals tower by tower
  - Drive the resulting output signals to the trigger chain Receiver in the Level-1 cavern, through a 70 m ***copper*** cable



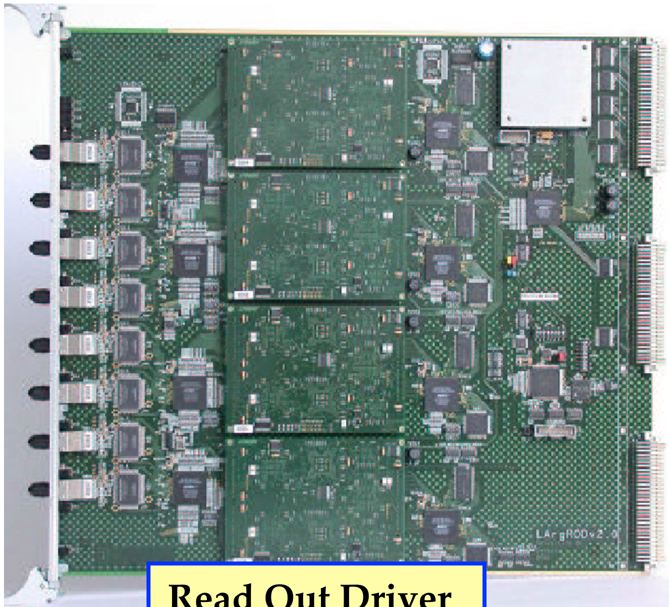
LAr Trigger Readout Electronics

- Implantation of the FEB and the TBB in the Barrel Front End Crate (FEC), just on a Feedthrough, and data buses linking them

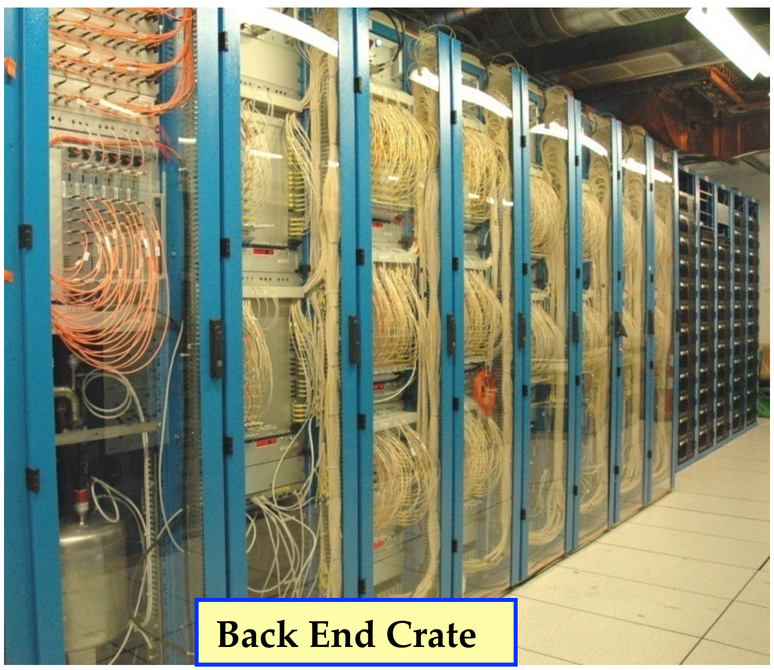




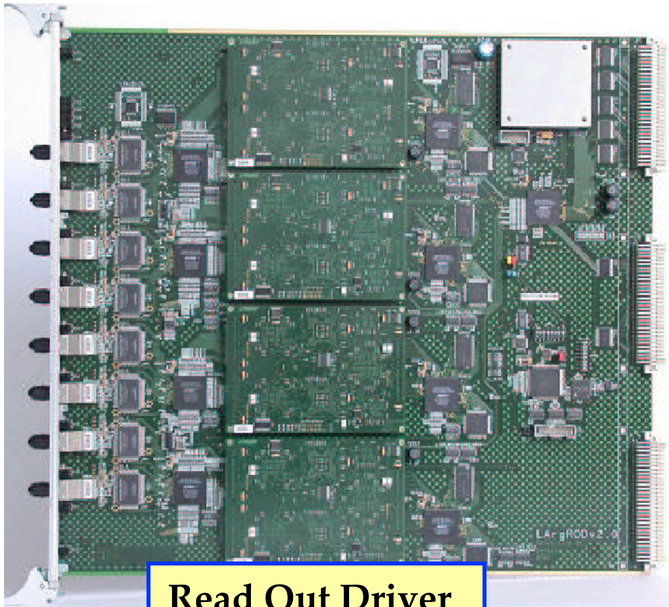
Read Out Driver



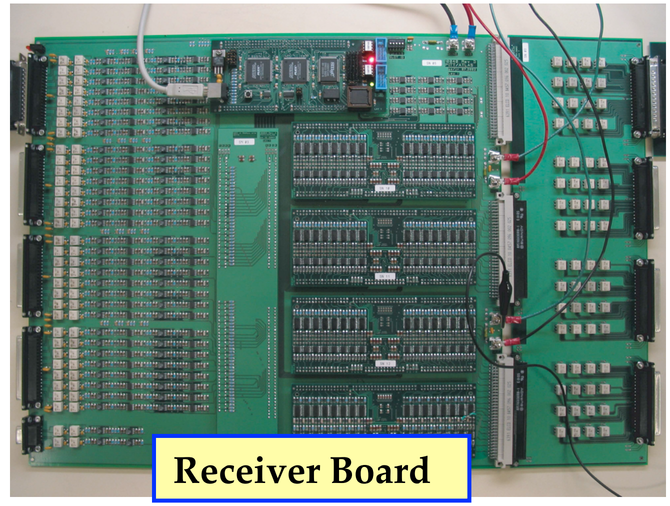
Read Out Driver



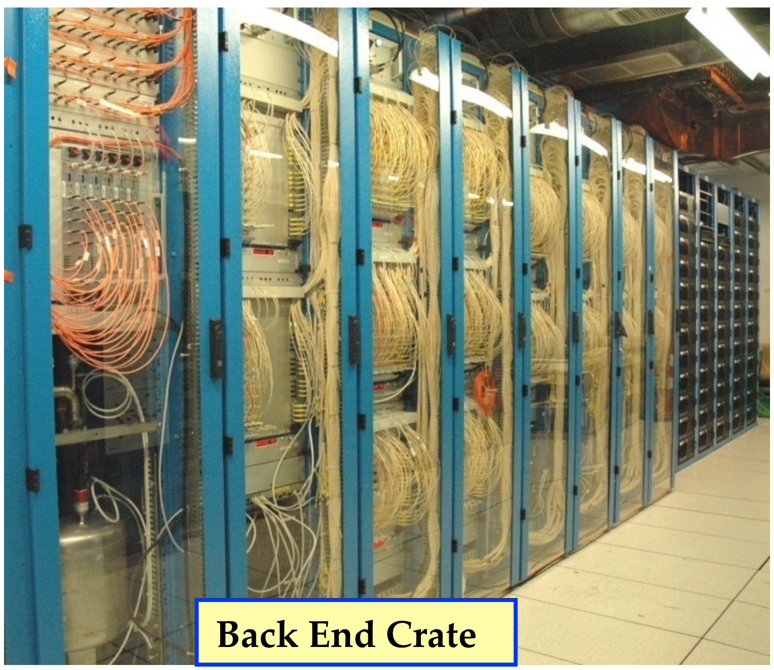
Back End Crate



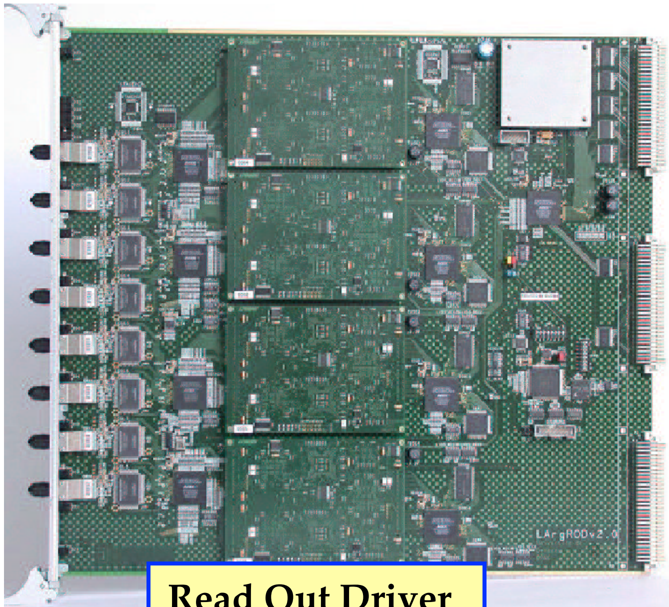
Read Out Driver



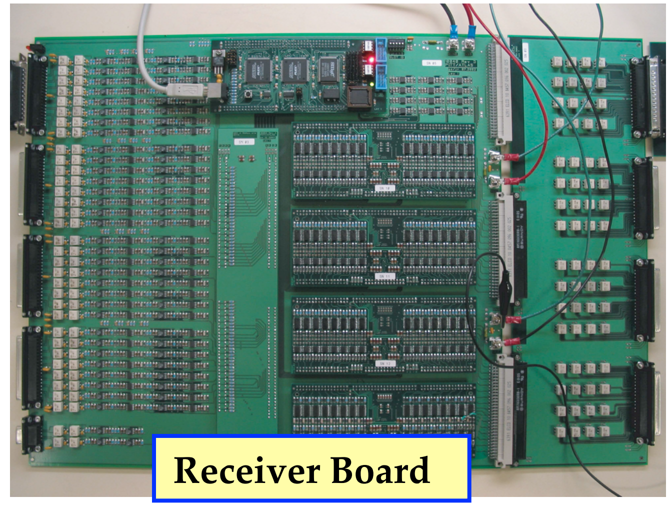
Receiver Board



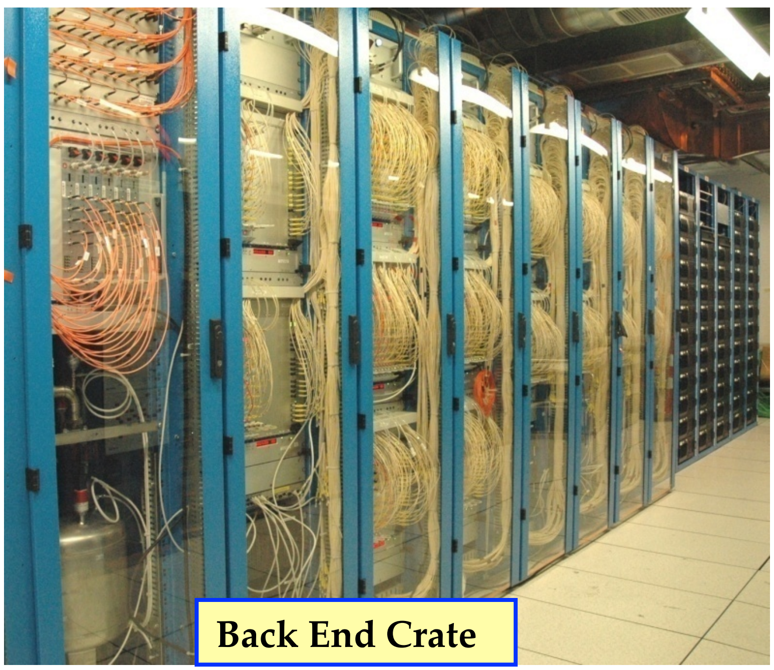
Back End Crate



Read Out Driver



Receiver Board



Back End Crate

Cabling from Receiver to L1Calo

Grounding of ATLAS LAr Calorimeter

- Grounding is an very important topic in the readout electronics system design of a large experiment
- The ground scheme of the ATLAS LAr calorimeter has gone through serious studies

Shielding Effectiveness Against EM Radiation

- Thick shields ($t \geq \delta$)
  - Reflection attenuation $$A_r = 20\log\frac{|Z_w|}{4|Z_s|}$$
  - Characteristic impedance of the shield material
    $$|Z_s| = (\omega\mu/\sigma)^{1/2} = 3.7\times10^{-7} f^{1/2}$$
  - Skin depth $$\delta = 2/(\omega\mu\sigma)^{1/2} \qquad |Z_s| = \frac{\sqrt{2}}{\delta\sigma}$$
  - Wave impedance Z_W: ratio of the electric field and the magnetic field
    - Far field ($r > \lambda/2\pi$): 377Ω impedance of the free space (and air)
    - Near field ($r < \lambda/2\pi$)
      - Electric antenna: ~1/r
      - Magenetic antenna: ~r
  - Absorption attenuation $$A_a = 6.2t(\omega\mu\sigma)^{1/2} = 8.7t/\delta[dB]$$
  - A copper shield 0.5 mm thick provides a far field attenuation at 100 kHz of only about 21 dB by absorption, and nearly 120 dB by reflection. In this case, absorption becomes dominant only above ~ 5 MHz.

Shielding Effectiveness Against EM Radiation

- Very thin shields (t << δ)
  - Total attenuation

$$A = 20\log\frac{|Z_w|}{4|Z_s|} + 20\log(2\sinh\frac{t}{\delta})$$

  - Since sinh(t/δ)~t/δ

$$A_r \approx 20\log\frac{|Z_w|\sigma t}{2\sqrt{2}} = 20\log\frac{|Z_w|}{2\sqrt{2}\rho}$$

  - For very thin shields, attenuation due to reflection is determined simply by the ratio of the wave impedance and the sheet resistivity of the shield
  - Low mass shields, such as aluminized Mylar windows on gas proportional chambers, can still provide very useful shielding. For example, 0.1 μm of aluminum, which is about 1/800th of the skin depth at 1 MHz, gives ϱ ≈ 0.25 Ω/square and $A_r \approx 533 = 55$ dB.

The Role of Apertures (Gaps) in the Shield

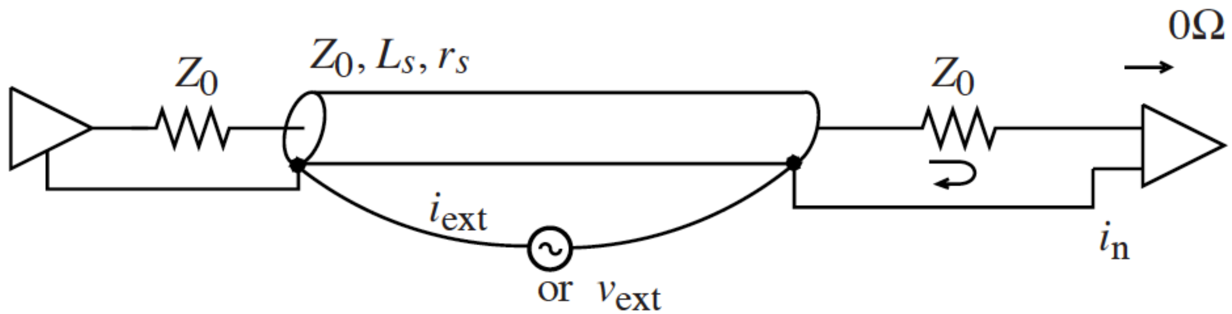
- Aperture attenuation
  - λ: wavelenth
  - L: the longest dimension of the aperture, regardless of its shape

$$A_{ap} = 20 \log \frac{\lambda}{2L} [dB]$$

- The attenuation reduces to zero dB at the wave guide cutoff frequency $\lambda/2L = 1$
- At lower frequencies (1 kHz–1 MHz), it is possible to achieve very high shielding attenuation
- At high frequencies (>10 MHz) shielding effectiveness will be aperture-limited
- The importance of electrical continuity of any shield cannot be overemphasized.

Noise Induced in Shielded Conductors by Ground Loop Currents

a) Single ended PA



* Δv in the shield $= i_{ext}(j\omega L_s + r_s)$ for $r_s \ll Z_0$

* Δv in center lead $= i_{ext} \cdot j\omega L_s$

* emf in the receiver $= i_{ext} \cdot r_s$

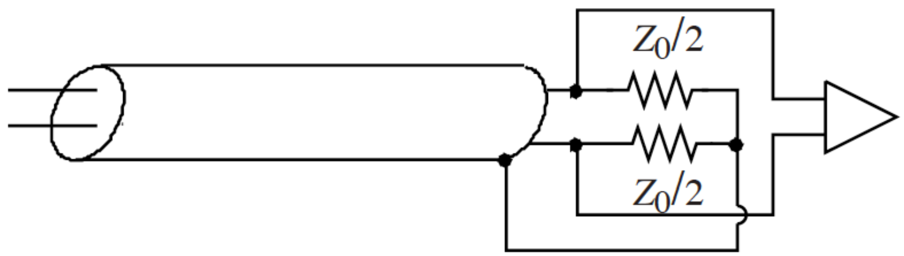
* noise current $= \dfrac{i_n}{i_{ext}} = \dfrac{r_s}{2Z_0}$ for current in the shield

* noise current $i_n = \dfrac{v_{ext}}{2Z_0} \cdot \dfrac{r_s}{r_s + j\omega L_s}$ for voltage in the loop

- The ratio of the shield resistance to the shield inductance is then a determining parameter for the receiver noise current

Noise Induced in Shielded Conductors by Ground Loop Currents

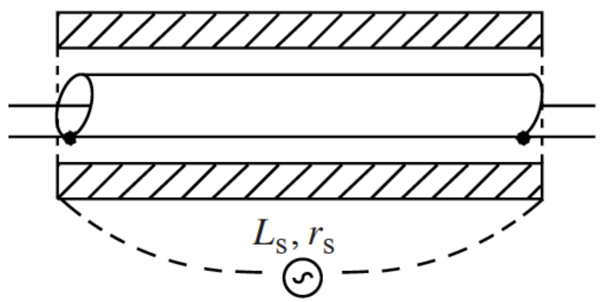
b) "Common Mode"



cmr ~ 10 – 10^3 common mode rejection

Noise currents reduced by $\frac{\text{cmr}}{4}$ compared to a)

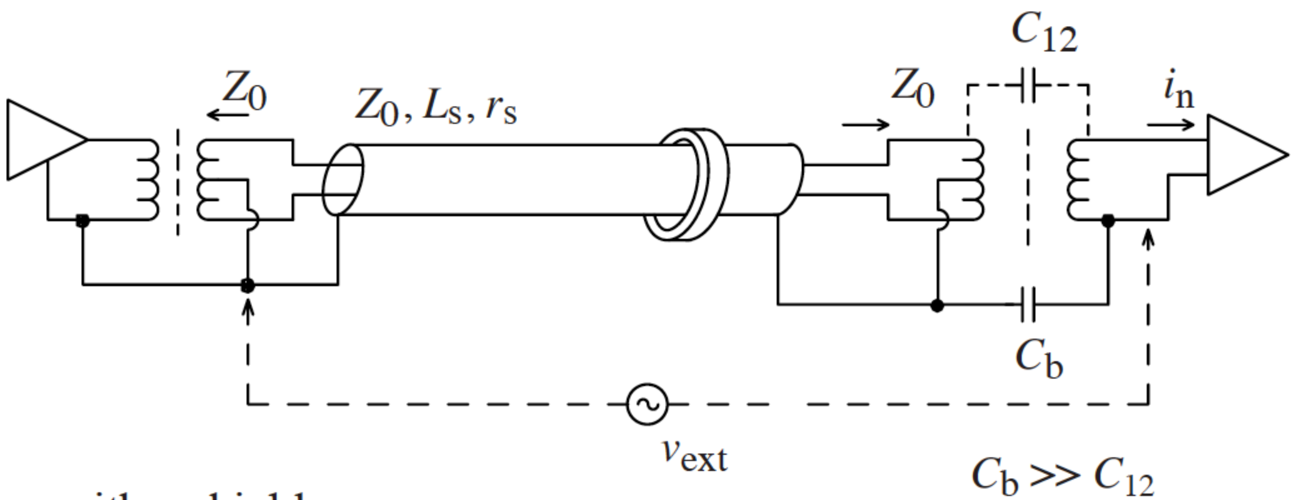
c) Double Shield



r_s may be much smaller

- For shielded, balanced transmission lines, noise rejection is improved by the common mode rejection of the receiver (i.e., cmr/4)
- A principal role of double shielding for terminated transmission lines is to reduce further the shield resistance, r_S

Noise Induced in Shielded Conductors by Ground Loop Currents



with a shield

$$i_n = \frac{v_{ext}}{Z_0/2} \cdot \frac{r_s}{r_s + j\omega L_s} \cdot \frac{1}{cmr}$$

← common mode rejection ratio

- A transmission line connection for analog signals with a very high dynamic range (~ 5×10^4)
- Inductance of the shield can be artificially increased by several turns on a ferrite core
- Differential amplifiers are also commonly used instead of transformers, with somewhat lower rejection of the noise and crosstalk.

Grounding of ATLAS LAr Calorimeter

- Primary guidelines from the ATLAS Policy on grounding
  - All detector subsystems will be electrically isolated
  - There will be no connection to ground other than "Safety Networks"
  - There will be no connection between different detector subsystems
- Detailed guidelines
  - Isolation of power supplies
  - Signal communications by ***electro-optical*** or ***differential transmission lines***
  - Detectors in Faraday cages

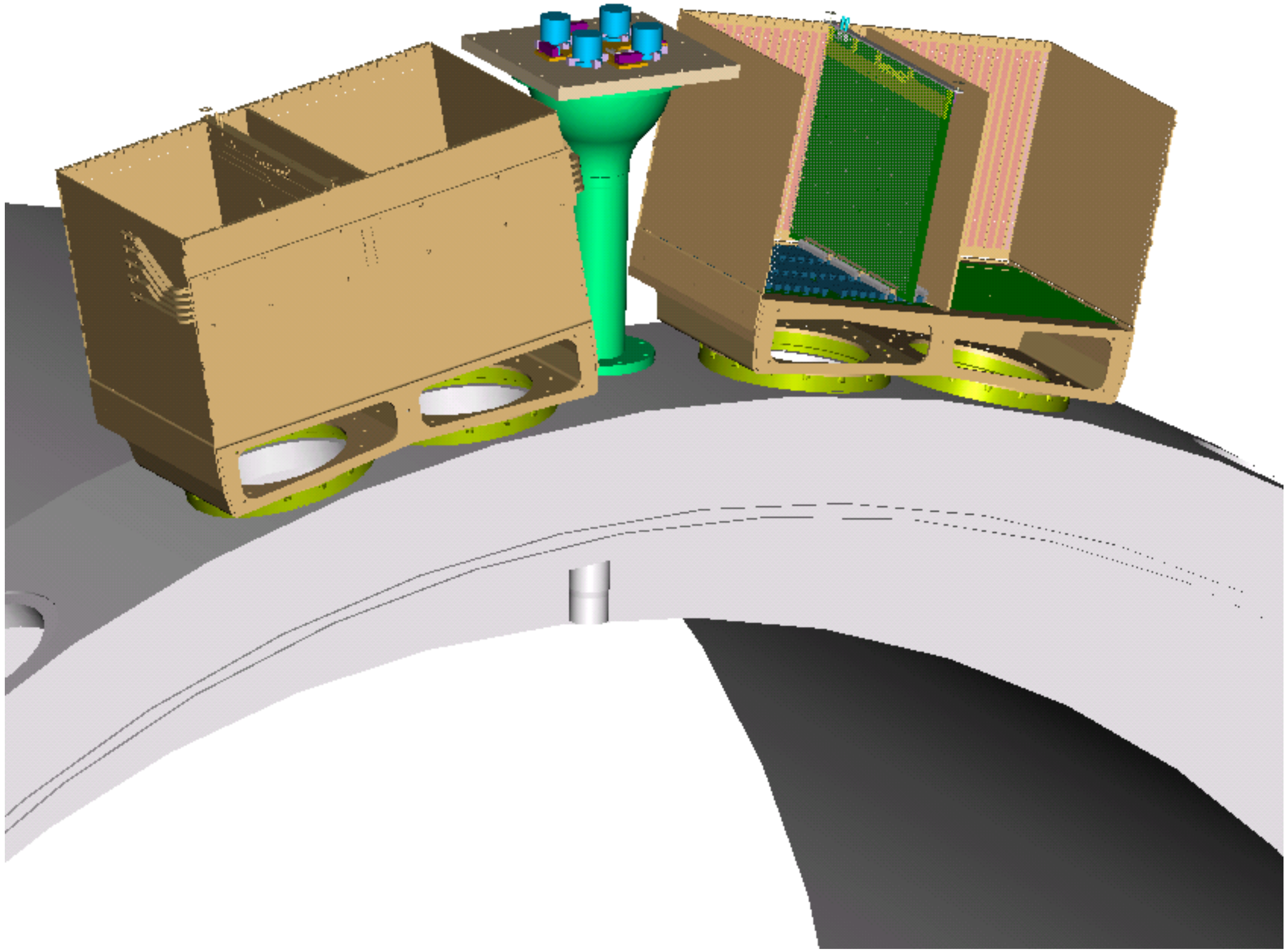
Grounding of ATLAS LAr Calorimeter

- Key points in the implementation of electrical isolation within the subsystem and with respect to other subsystems
  - Carefully designed faraday cage
  - Clock, trigger, data through optical fibers
  - LVL1 sums – differential transformer Coupled
  - Separate power return for every voltage in each crate
  - LV, HV supplies floating (with safety connections)
  - Mechanical support insulating
  - LAr cryogenics and cooling lines floating
  - Solenoid lines insulated, power supplies floating
  - Slow controls – Optical or transformer coupled
  - Sensors – isolated
  - General checking for "inadvertent" connections to various grounds

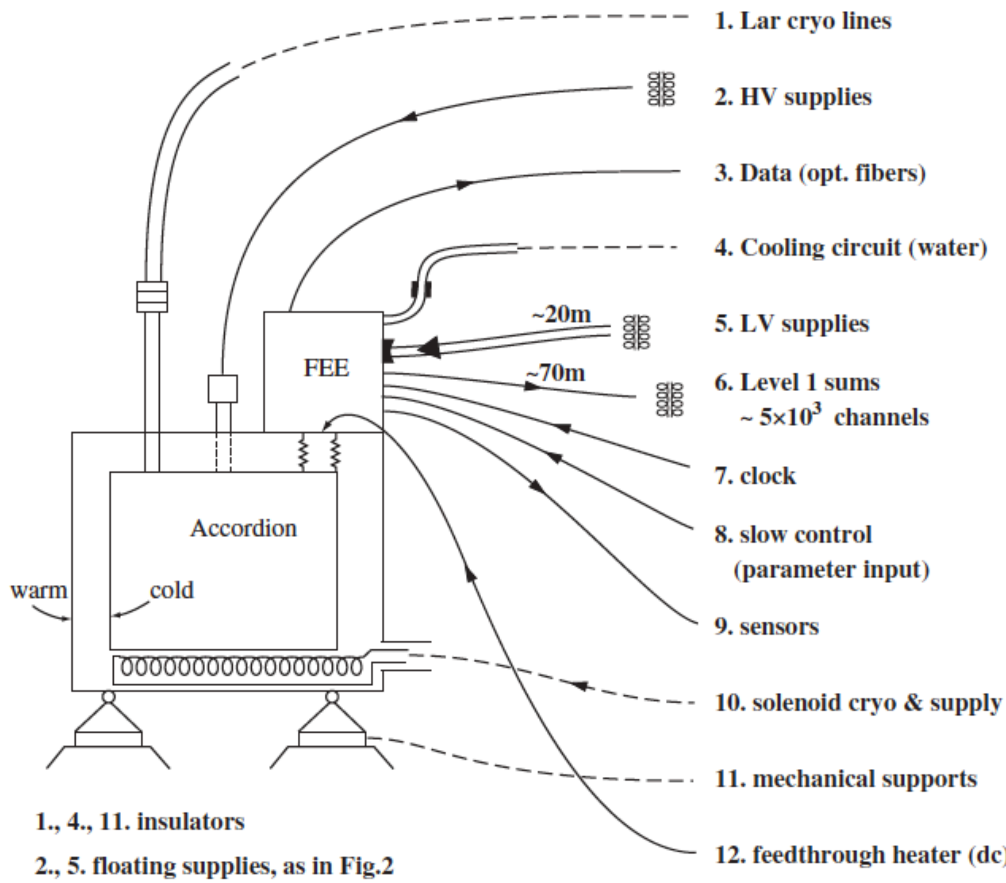
Grounding of ATLAS LAr Calorimeter

- To avoid coherent signals in group of read-out channels
  - Noise from digital circuits generated locally on a single read-out board in the crate
    - Cured by careful design of layout, filtering on the board, shielding of preamplifiers, minimization of digital operation on the board
  - EM radiation surrounding the electronics and noise induced by penetration into cryostat/crates
    - Cured by well designed Faraday cage comprised of the cryostat, the feedthrough and the crates
    - No electrical penetration in the cryostat except for signal and high voltage feedthrough
    - All services (pressure and temperature) filtered in the crates and fed into the cryostat on shielded cables

Grounding of ATLAS LAr Calorimeter



LAr Cal. Vital lines (i.e., Potential ground loops)



1., 4., 11. insulators

2., 5. floating supplies, as in Fig.2

6. differential transmission transformers (balun or signal)

7., 8. opto-couplers (or transformers)

9. insulate sensors; different techniques at various receivers

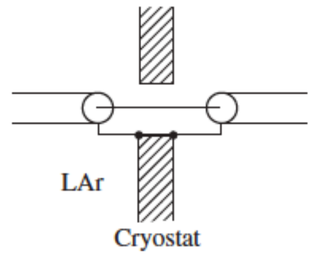
10. solenoid line to be insulated, power supply floating

12. heater insulated, capacitors to pedestal, floating supply

Fig. 1

Rules for Entering the Cryostat

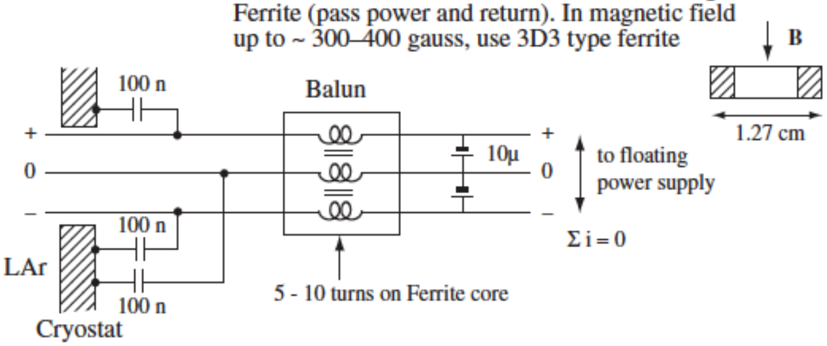
1. Coaxial Cables



- Shield connected to cryostat before penetrating Faraday cage
- Short connection, low inductance
- Performed on standard feedthroughs

2. Power Supplies

- Capacitors with short leads, close to cryostat low inductance connection
- No net DC Current in Balun to avoid saturating Ferrite (pass power and return). In magnetic field up to ~ 300–400 gauss, use 3D3 type ferrite



3. Probes, HV

- Capacitors with short leads, close to cryostat, low inductance connection
- R > 1 kΩ can be replaced by L > 1mH when no current flows

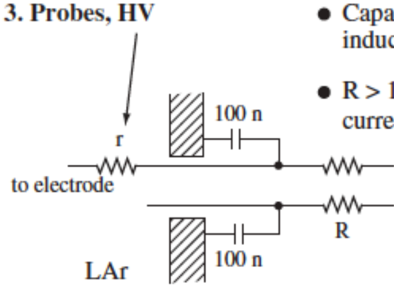


Fig. 3

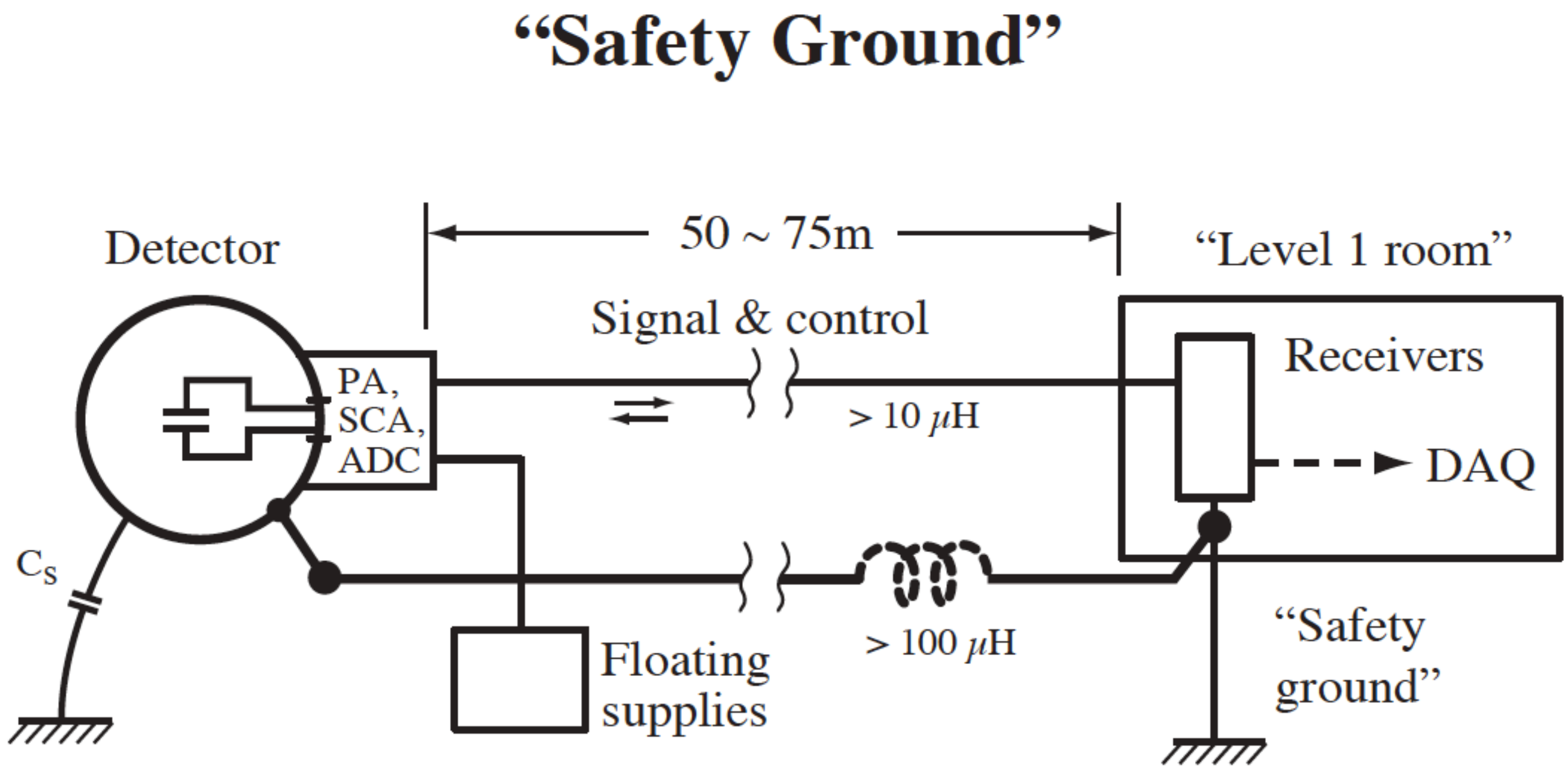
Grounding of ATLAS LAr Calorimeter

- Well defined safety ground
- The ground should be at USA15
  - To preserve from EMI the Level 1 trigger sum signals
  - The grounding scheme should extend the faraday cage of the calorimeter to include the twisted pair cables coming from the trigger sum board
  - The common braid of Level 1 cables from each crate needs to be connected to the safety ground (through a ~ 2 cm braided Cu cable)

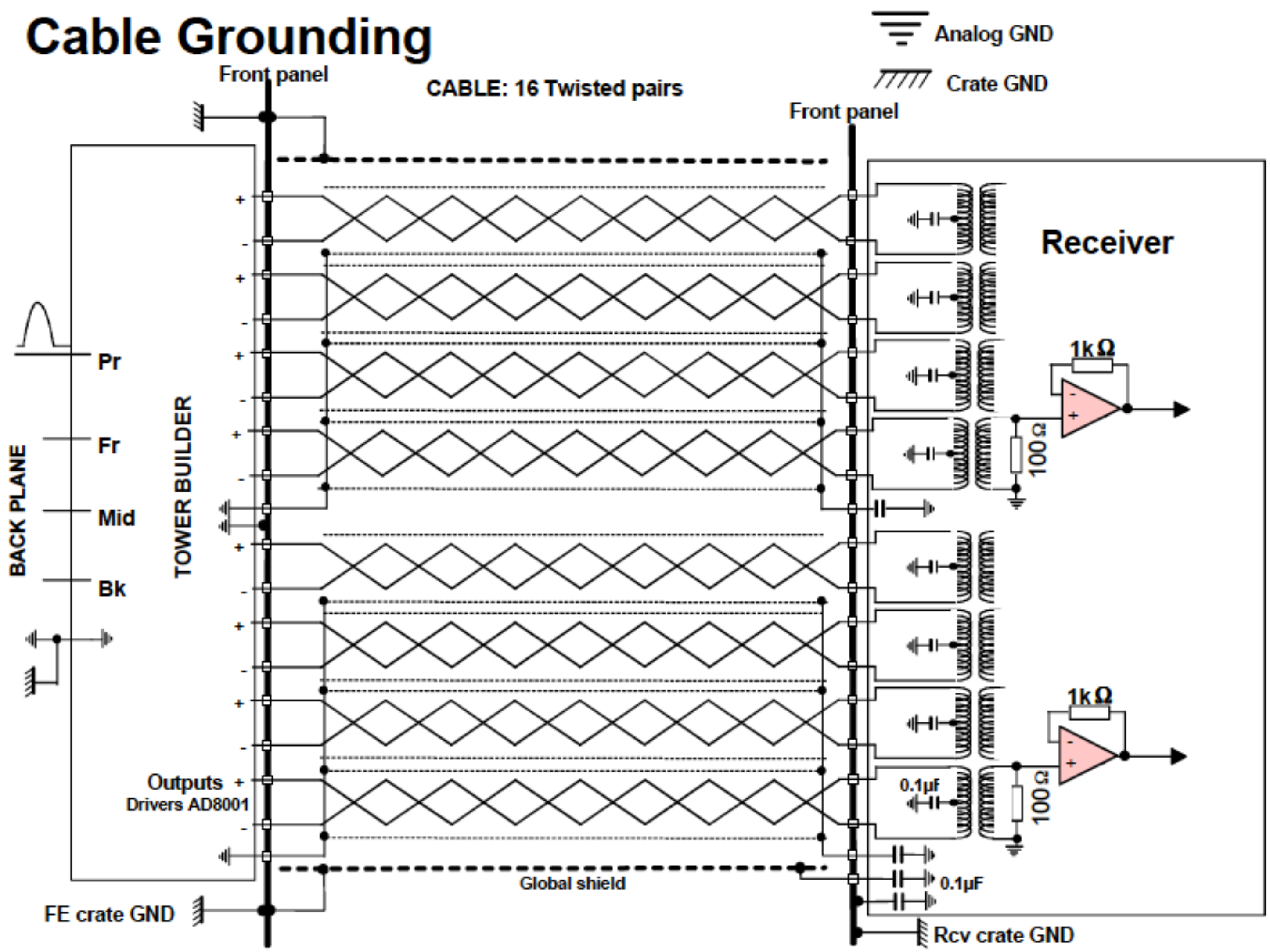
Grounding of ATLAS LAr Calorimeter

- Currents coming through ground loops
  - It is the most demanding issue since it involves potential connections to equipments at various distance from the cryostat
- Basic design approach: isolate each cryostat with its read-out from everything else
  - Only one location where a connection to "ground" will be allowed for DC and low frequencies
  - Cryostats must be insulated at their supports and in all cryogenics lines and services
  - Each read-out crate has to be connected to his own floating power supply
  - The two halves of the accordion stack will be insulated from each other and from their supports and connected to the cryostat at their feedthroughs via signal cables
  - EM end-caps will be treated in the same way

Grounding of ATLAS LAr Calorimeter



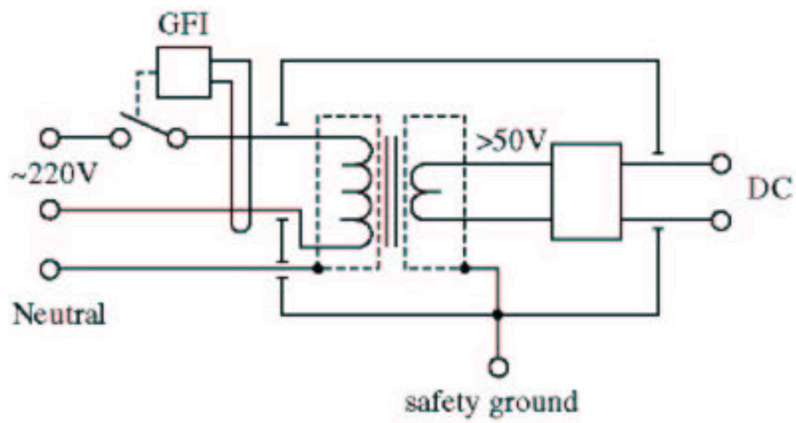
Grounding of ATLAS LAr Calorimeter



Grounding of ATLAS LAr Calorimeter

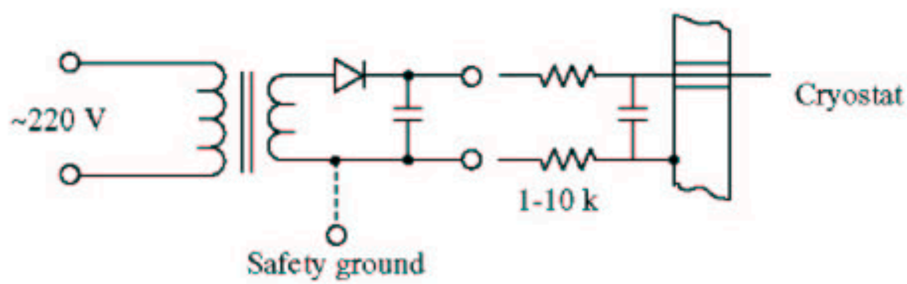
Floating Supplies

1. LV Supplies <50V



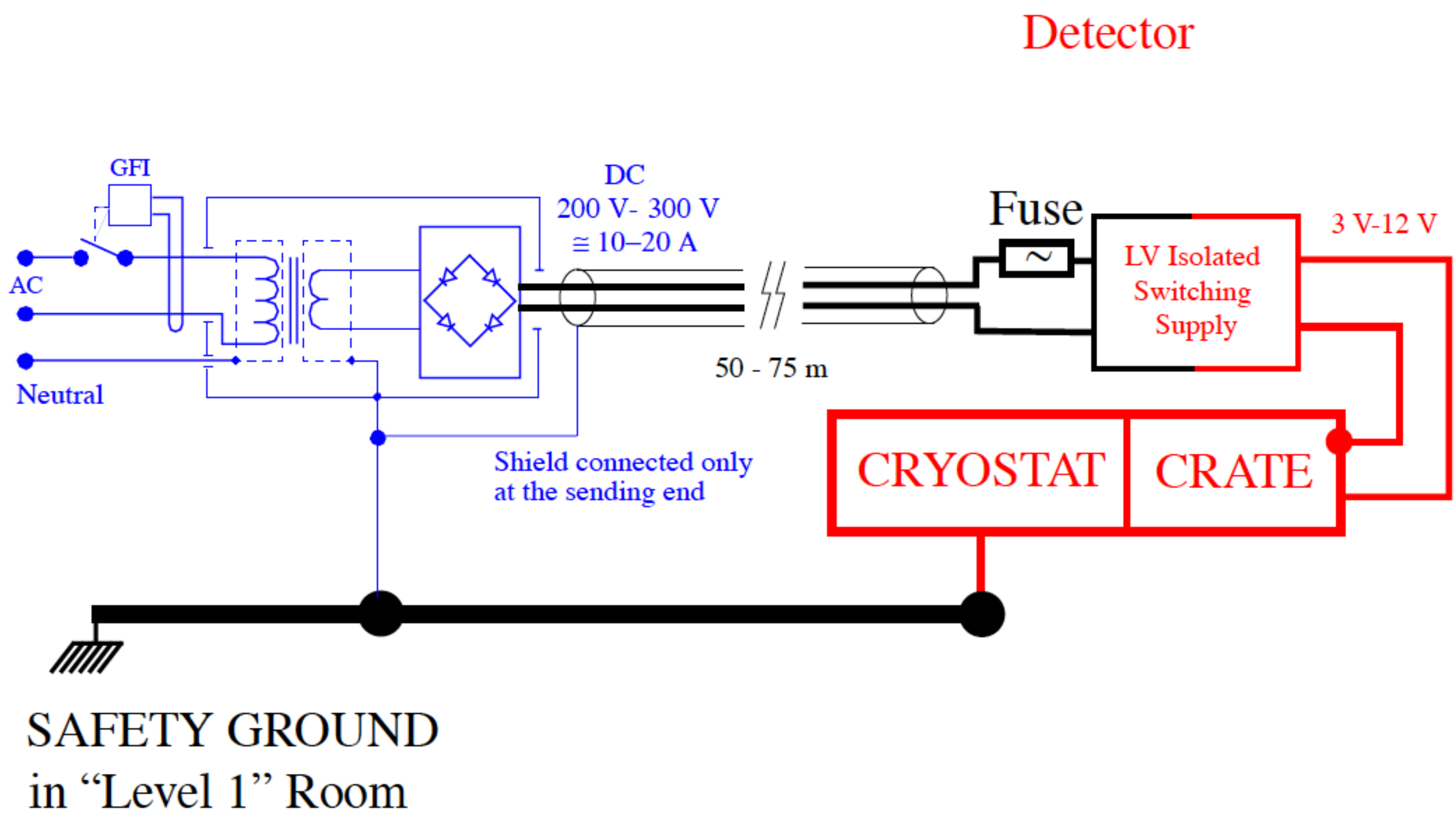
<50V secondary is allowed to float

2. HV Supplies > 50V ⟶ ~kV Supplies, low current



Grounding of ATLAS LAr Calorimeter

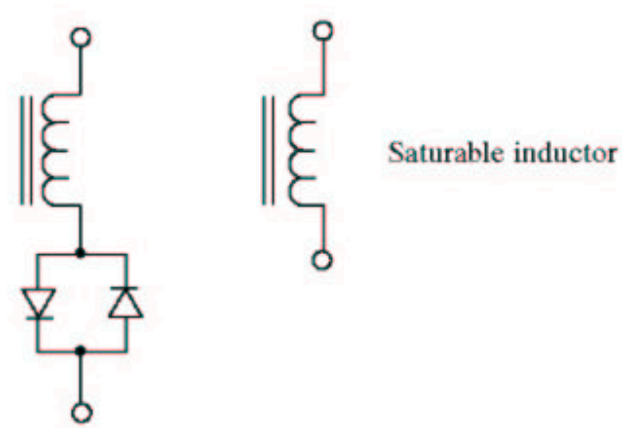
Low Voltage Switching Supplies and Rectifier



Grounding of ATLAS LAr Calorimeter

- Supplementary safety grounds
  - If the analysis of the whole subsystem identifies a "component" which if accidentally disconnected could present hazard, then the "component" must have a supplementary ground connection
  - Such a connection should be through a nonlinear element.

3. Supplementary safety grounding: high impedance at low voltage



ATLAS Ground Isolation Monitor

- The control of the isolation of the cryostat can only be done in DC
- To carry on this control while keeping the connection to earth, a current source in USA15 injects a reference current (up to 500 mA) onto the cryostat under test using a dedicated test cable
- If the cryostat is fully isolated (as designed) from the earth in UX15, the injected current returns entirely through the ground cables of the cryostat, back to USA15
- A high precision DC current probe (part number IPCT, manufactured by Bergoz) is used to measure the differential current between the injected and the returned currents
- http://www.bergoz.com
- The output of the current probe is coupled to a voltage comparator that triggers an alarm in the experimental cavern UX15 when a current leak is detected, providing instantaneous warning to the operators during installation and maintenance
- The accuracy of the monitor allows for a detection of current leaks as low as one milliampere, which turns out to be sufficient to detect weak or accidental indirect contacts between a grounded device and the cryostat
- The readings of the current monitor can be viewed on-line through by means of a web enabled data logger (WebIO)
- Whenever an alarm is triggered, the WebIO device sends an SMS and an email notification tovthe person in charge of controlling the grounding

ATLAS Ground Isolation Monitor

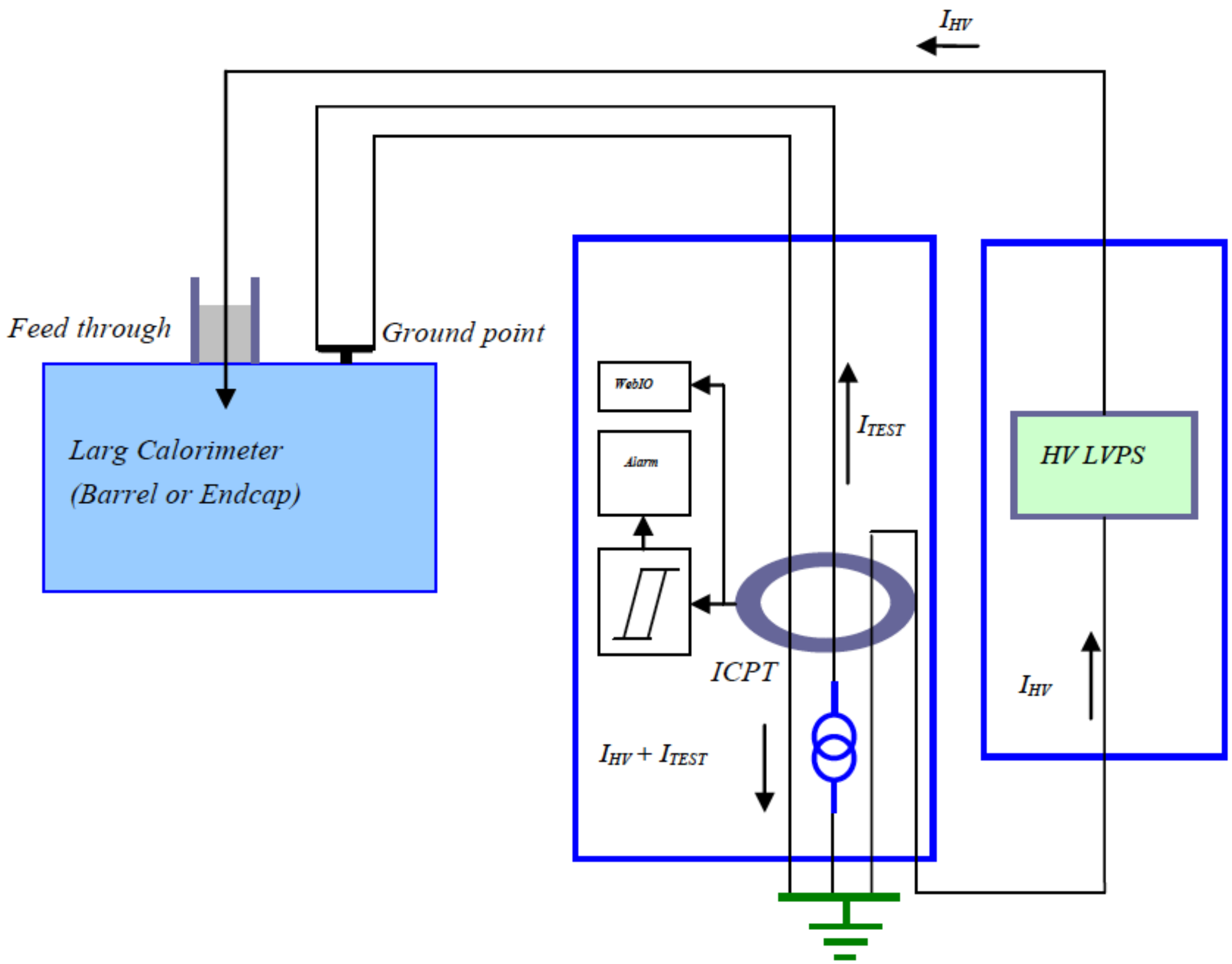
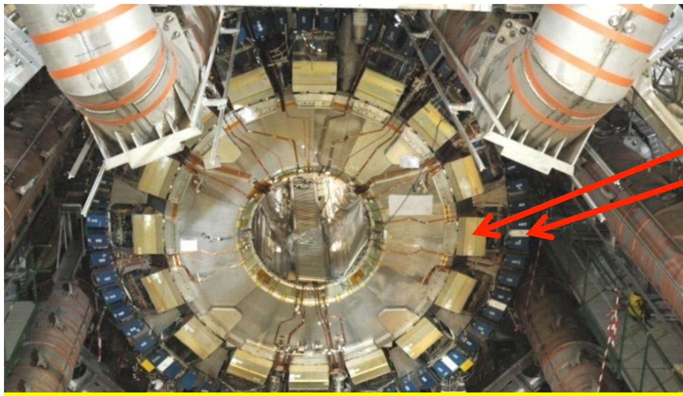


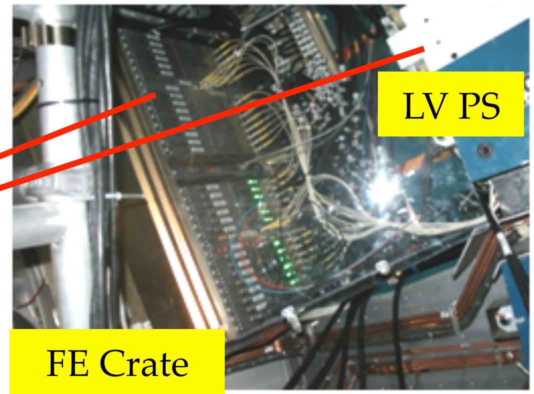
Figure 21: isolation monitor for the liquid argon cryostats. The current monitor ICPT from Bergoz has a full scale dynamic range of ± 10 mA and the readings are available through a web enabled data logger (WebIO).

LAr Calorimeter Installation and Commissioning

- October 2004: Barrel cryostat in the cavern
- July 2005: First BE RODs installed in USA15
- July 2005: First FE electronics installed on the Barrel
- April 2006: All 3 cryostats in the cavern
- August 2006: First cosmic signal recorded, Barrel (1 FE crate) with Tile calorimeter
- May 2007: Back End electronics completed
- Summer 2007: FE Low voltage power supplies fully available after refurbishment
- April 2008: FE electronics refurbishment completed
  - Sept 2007: Endcap C
  - Dec 2007: Endcap A
- May 2008: Readout of the full calorimeter, closure of the apparatus

LAr Readout Electronics


Barrel side view with FE Crates & PS

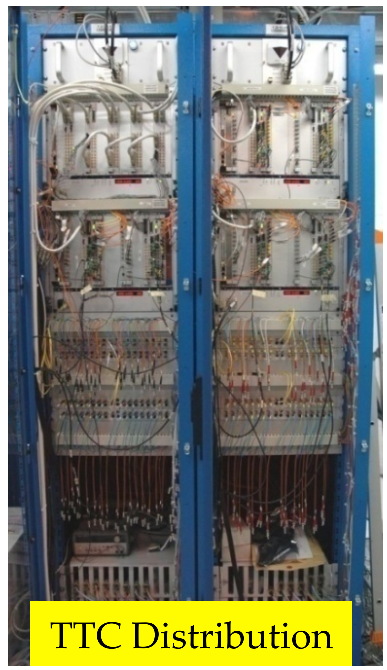

LV PS

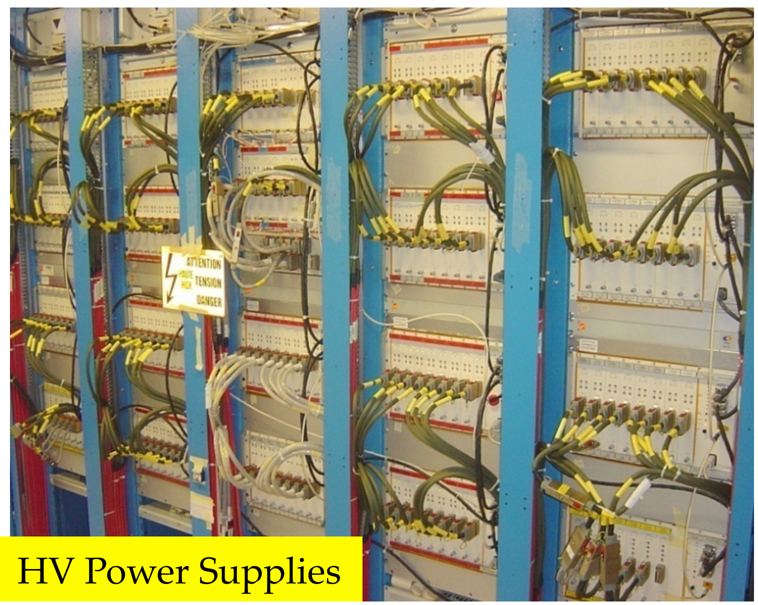
FE Crate

USA15

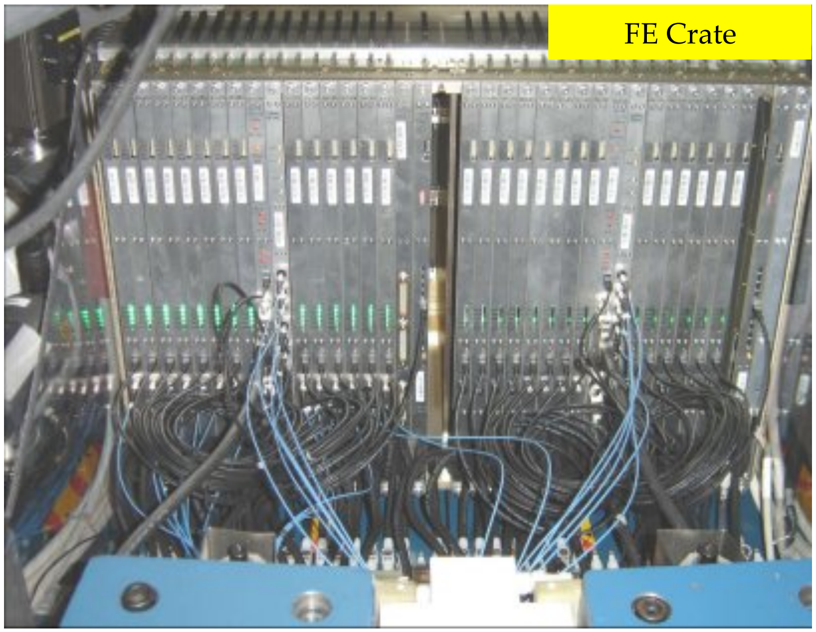

LV 280V Power Supplies

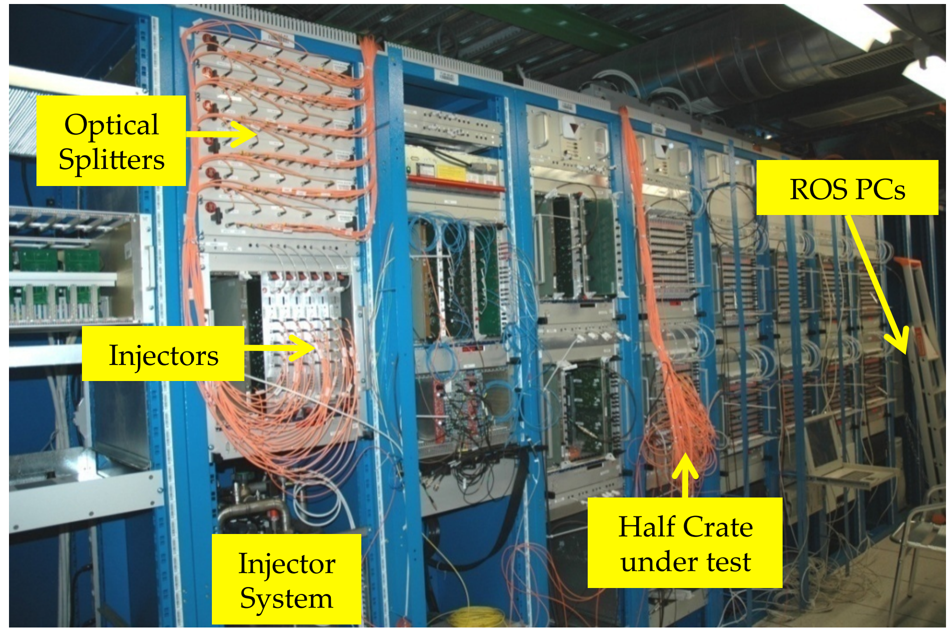

BE ReadOut Electronics


TTC Distribution


HV Power Supplies

LAr Readout Electronics





LAr Readout Electronics

- The ATLAS Liquid Argon calorimeter readout electronics system has been running since 2008
- This readout system is designed to fulfill the requirements from physics goals set for the ATLAS experiments
- In order for the front end electronics to work on the detector, in radiation environment, large number of ASICs have been developed using various rad-hard technologies
- This system has reached its design goals from the excellent results in LHC Run 1 – ***Discovery of Higgs Boson***