Front-end electronics and optical links

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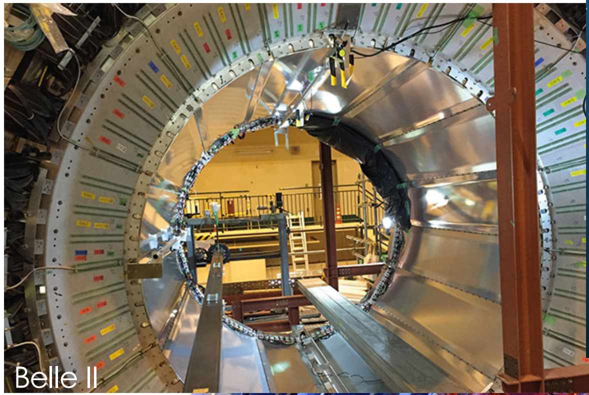
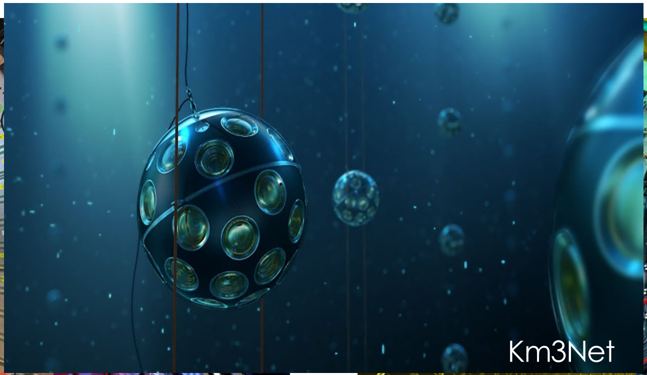
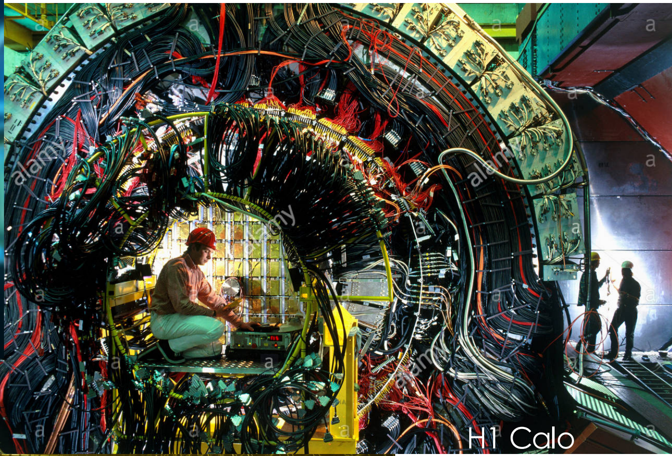
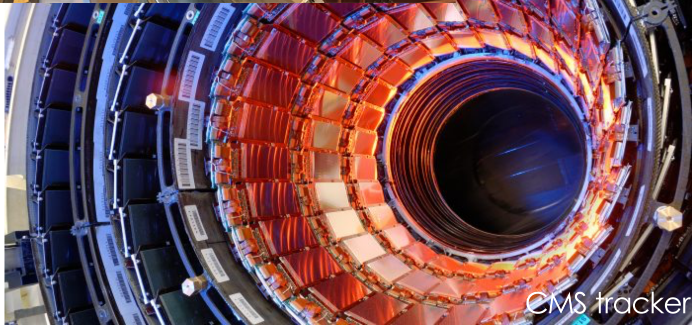
Outline

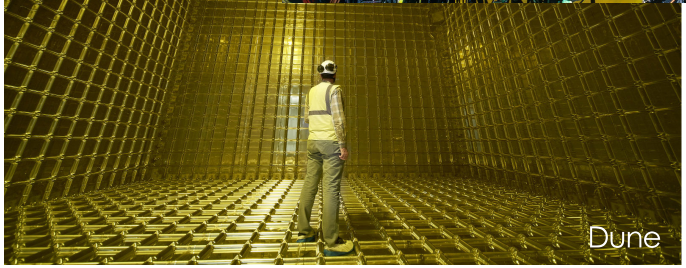
- Sensors. Signal formation and characterization
- Front-end electronics
  - Building blocks for energy and time measurement
  - Readout system architectures
  - Front-end system implementation examples
- Optical links
  - Fibers and connectors
  - Assemblies: types and future trends
  - Impact in readout systems


Belle II


Km3Net

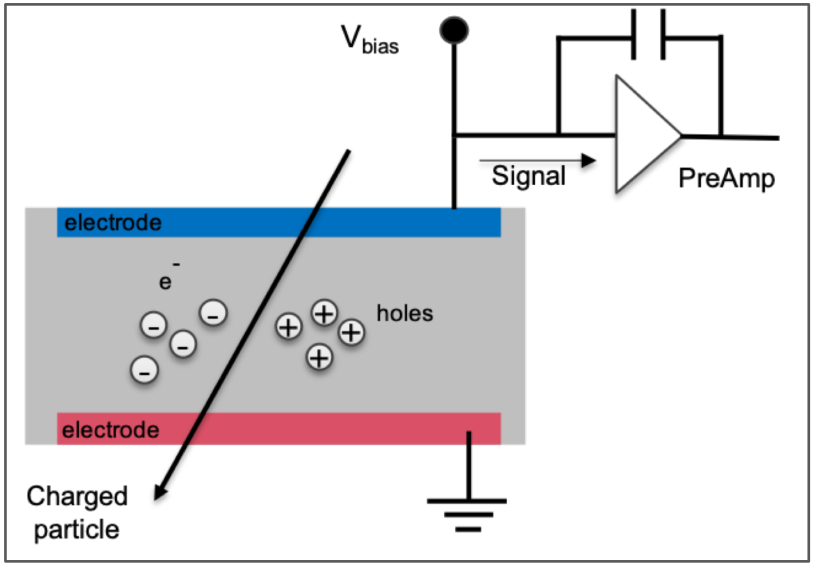

H1 Calo

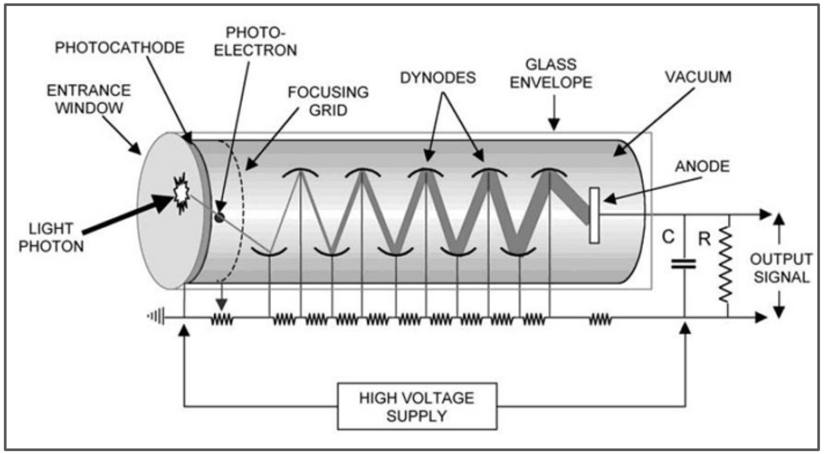

CMS tracker


Dune

Signal formation in detectors

- Silicon: Charged particle creates e$^-$ - holes pairs
  - The motion of the charges induces a current in electrodes
  - Signal ends when charges reach electrodes- Slew rate ∝ dV/dt
- Similar principle in gas detectors



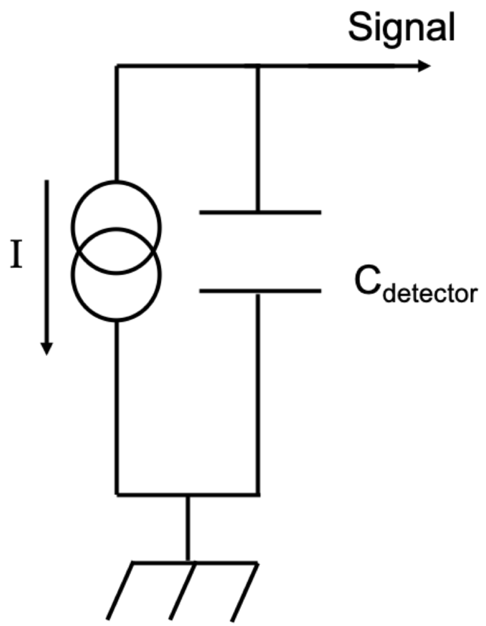


- Photomultipliers
  - Photoelectric effect: γ → e$^-$
  - Cascade multiplication in dynodes
  - Gain up to $10^4 - 10^7$ depends on HV value

Sensor model

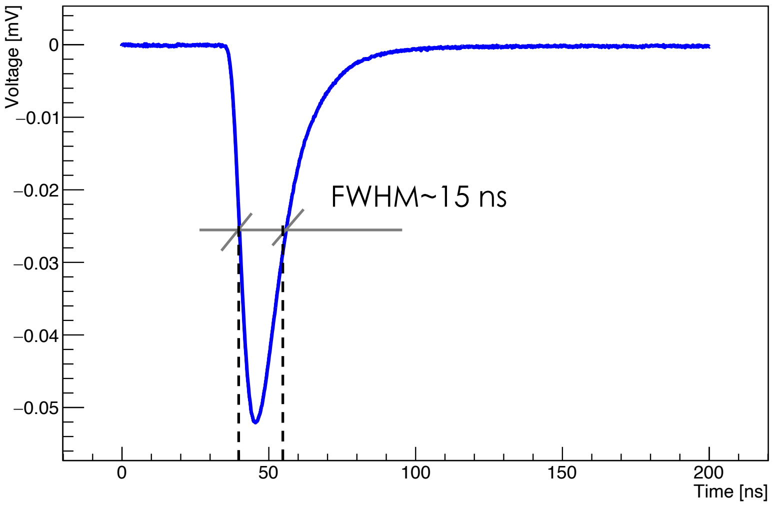
- Detector can be modelled as a Capacitance
  - Readout electronics specific for each case
    - Pixels : 0.1-10 pF
    - PMs : 3-30 pF
    - Ionization chambers: 10-1000 pF
  - R or RLC may be more accurate but still an ideal case
    - Connectors and cabling
    - Grounding
    - Crosstalk
    - HV, bias –> Calibration
- Signal : current source
  - Pixels : ~100 e-/µm (MIP: ~10^4 e^-)
  - Gas detector: primary e^-: ~10-40 cm^{-1} (gain 10^5-10^7 with anode voltage)
  - PMs : 1 photoelectron : 10^5-10^7 e^- (MIP ~10-20 photoelectrons)
- Modeled as an impulse (Dirac)

$$i(t)=Q_0\delta(t)$$



Sensor signals

- Usually short current pulses
  - Thin silicon detector (10 –300 um): 100 ps–30 ns
  - Thick (~cm) Si or Ge detector: 1-10us
  - Proportional chamber: 10 ns – 10 us
  - Microstrip Gas Chamber: 10 – 50 ns
  - Scintillator+ PMT/APD: 100 ps -10 us



Photomultiplier signal

What can we measure from these signals?

- Integral of current = charge → proportional to Energy
- Time of signal above a threshold -> Energy ToT
- Signal above a threshold → Digital (tracks)
- Time of leading edge – pulse peak → time of arrival (ToF)

$$E \propto Q = \int i(t)dt$$

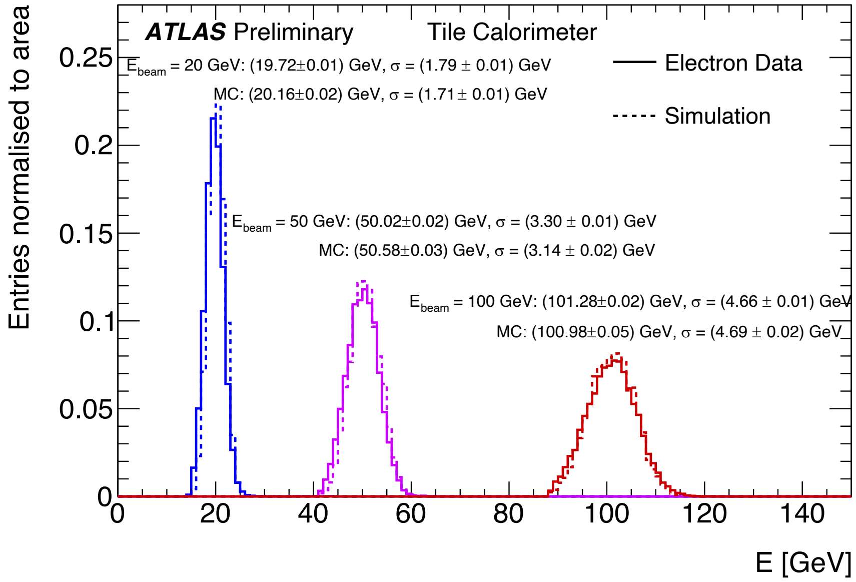
...and how do we measure?

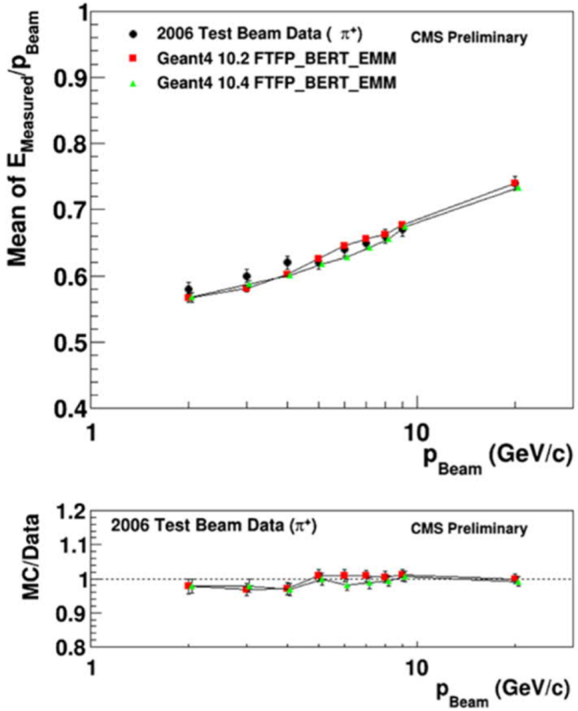
Front-end electronics for Energy measurement

- Energy deposited in the detector: integrate sensor signal current
  - Charge integrator circuit
  - Preamplifier with pulse shaping and ADC
  - Amplify current pulse and use dual slope integrating ADC

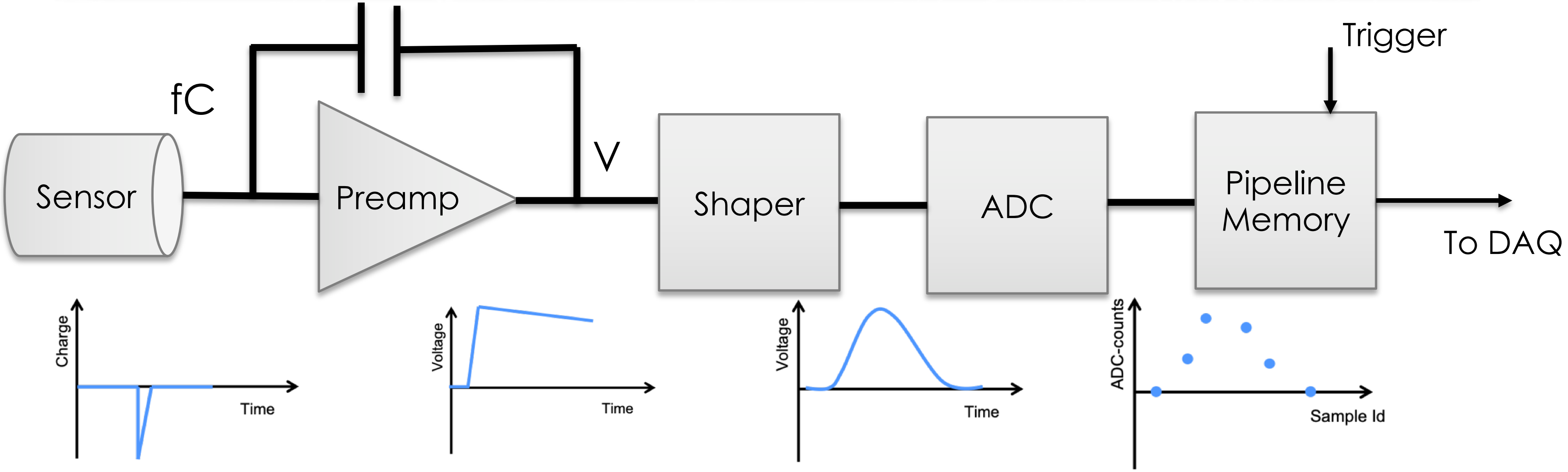
$$E \propto \boldsymbol{Q} = \int i(t)dt$$

- Then convert the charge into Energy → Calibration
  - Detector response – charge collection parameters - electronics





Front-end electronics for Energy measurement



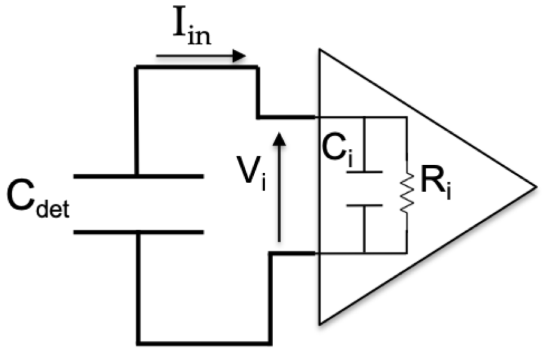
- Sensor : fC signal
- Preamplifier : amplification
- Shaper : improve S/N ratio
- ADC : sample the signal
- Memory : delay for trigger decision
- Signal processing : charge reconstruction
- More functionalities: Calibration, offset shifting

Preamplification

- Amplification of small signals from detector keeping high signal to noise
  - Keep output gain constant→ high input capacitance in parallel with detector capacitance (not constant)

$$V_i = \frac{Q}{C_{det}+C_i}$$

  - Located close to the sensor
    - Reduce looses
    - Reduce the pickup of noise

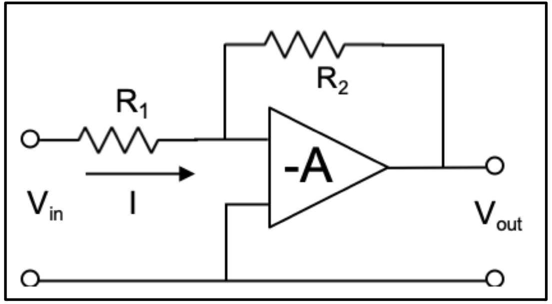


- Types of preamplifiers
  - **Current sensitive** : not apply to detectors because the low amp impedance
  - **Voltage sensitive**

$$V_i = \frac{Q}{C_{det}+C_i} \rightarrow G = \frac{V_{out}}{V_{in}};$$ sensible to impedance variations (semiconductors!)

$$V_{out} = -\frac{R_2}{R_1}V_{in}$$

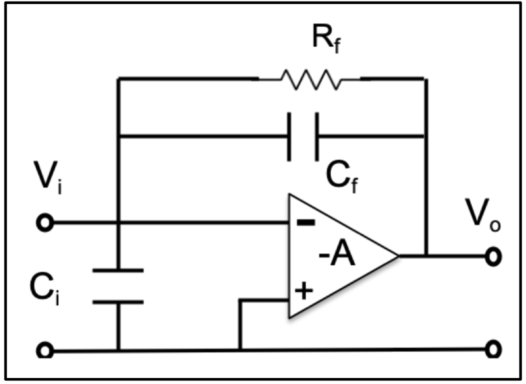
Voltage Sensitive



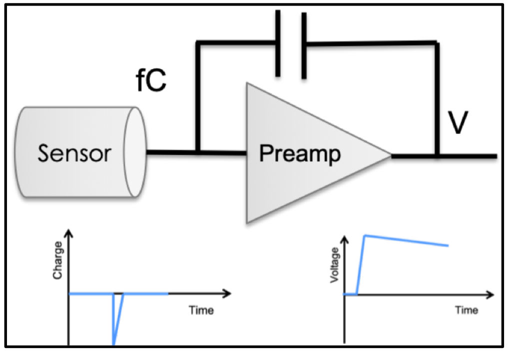
  - **Charge sensitive**
    - Not sensitive to impedance variations : $C_i = C_{det} + C_{cable} + C_{preamp}$
    - R_f and C_f determines the output decay constant of the signal produced

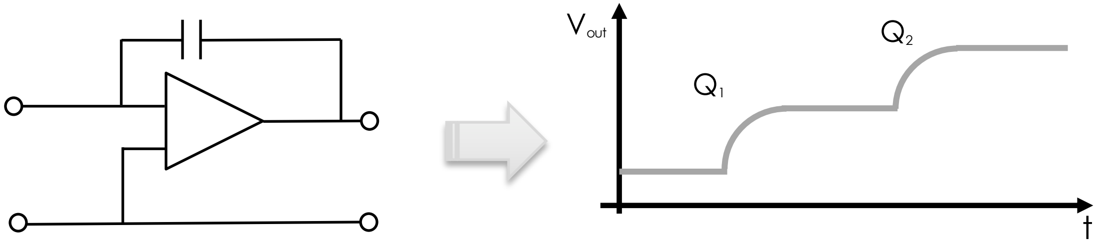
$$V_{out} = -\frac{Q}{C_f}$$

Charge Sensitive

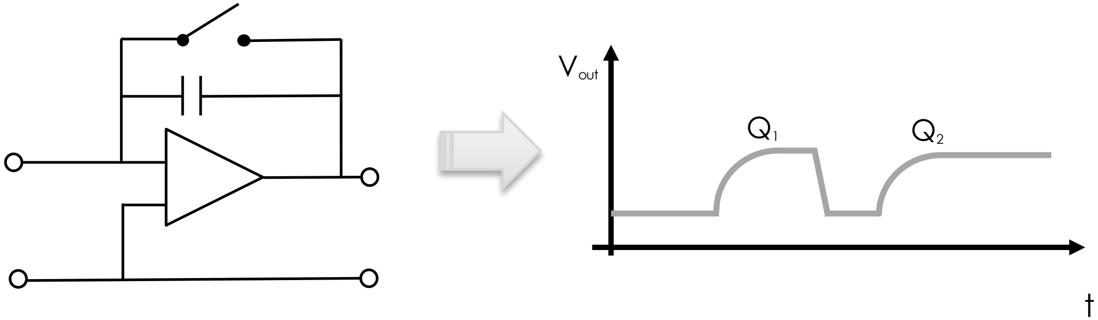


Charge Sensitive PreAmplifier

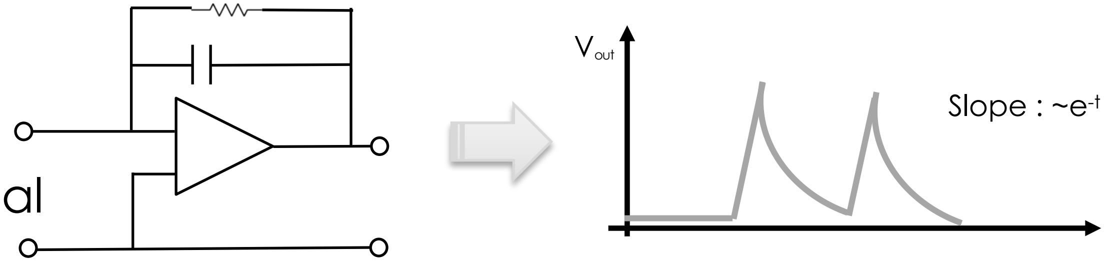




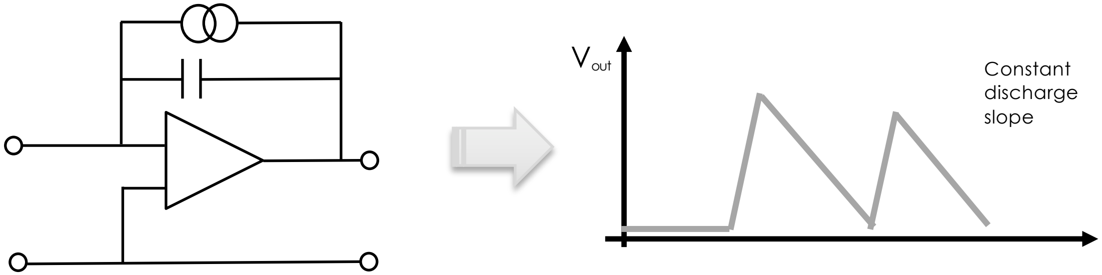
Integration



Reset



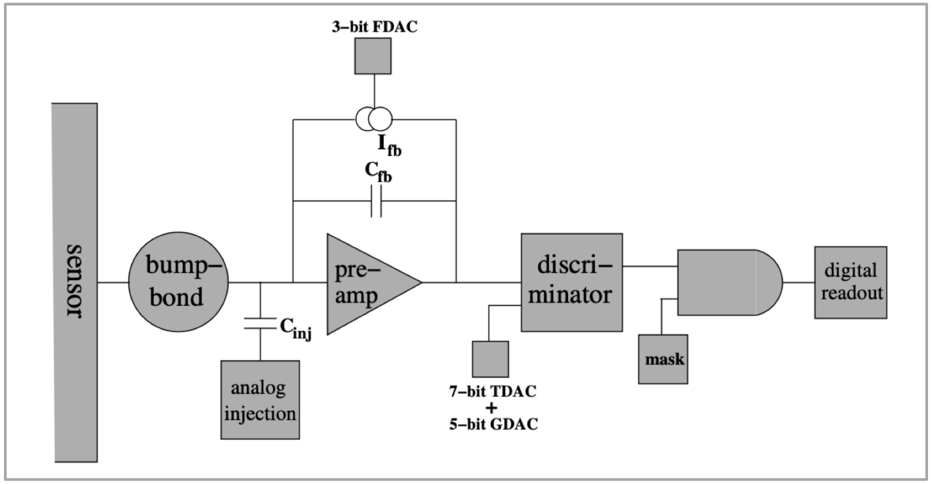
Exponential



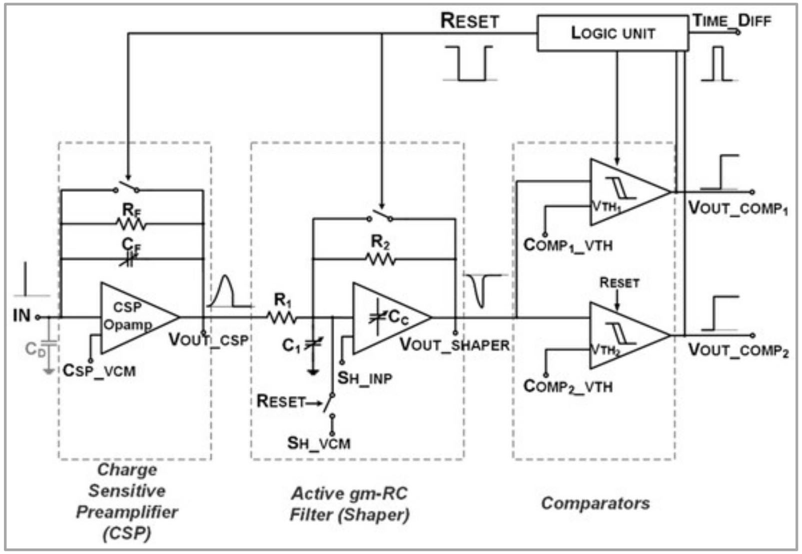
Constant slope

Examples

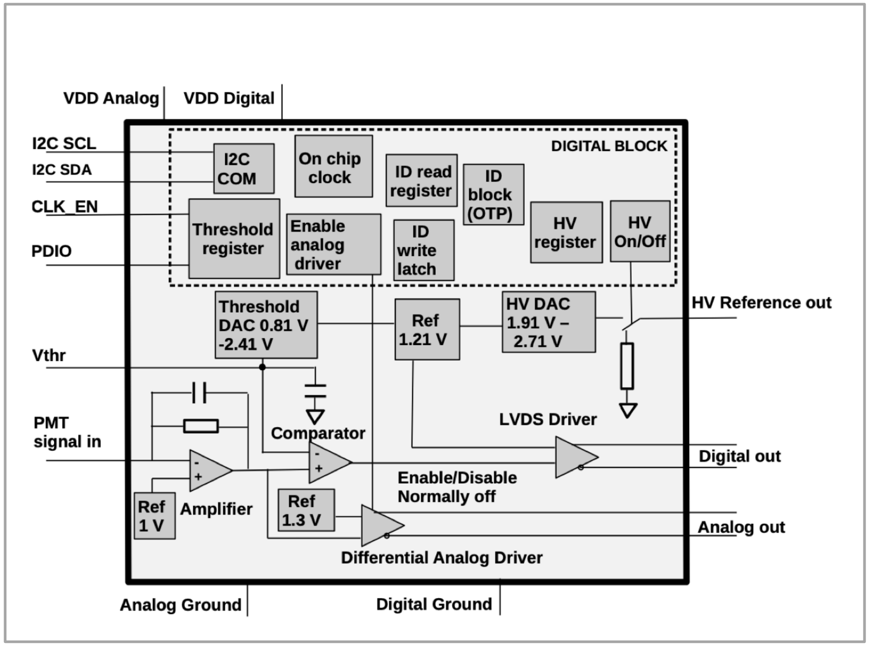
ATLAS Pixel FE-I4A



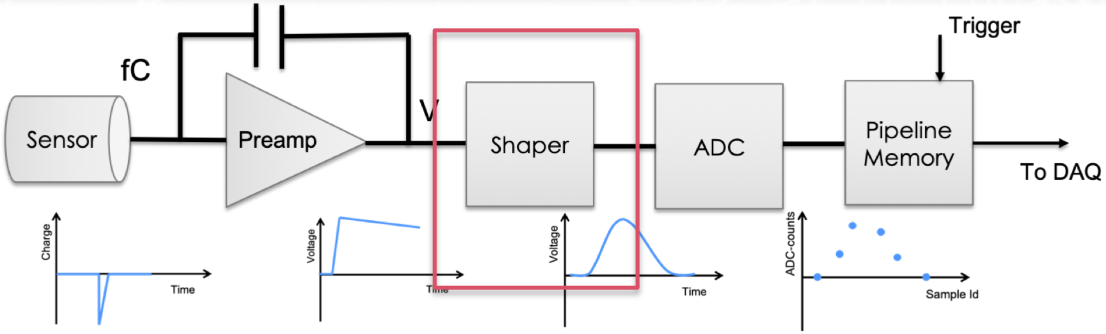
Upgrade ATLAS Muon Drift-Tube Detectors



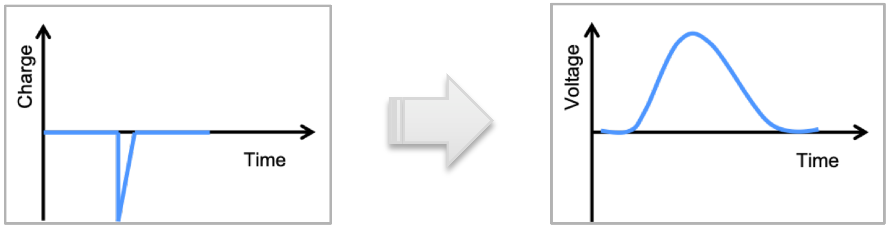
Km3Net



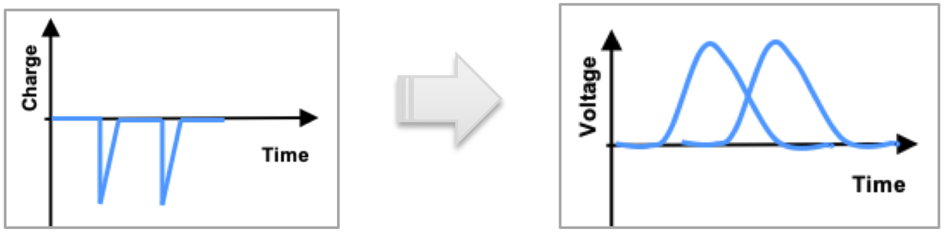
Pulse shaping



- Improve signal to noise ratio : compromise
  - Limit the bandwidth to decrease the noise but keeping information
  - Remove high frequencies before the ADC (Nyquist theorem)



  - In colliders with reduced bunch spacing pulses can overlap: pileup



Concatenation of filters

CR : differentiator circuit - high pass filter

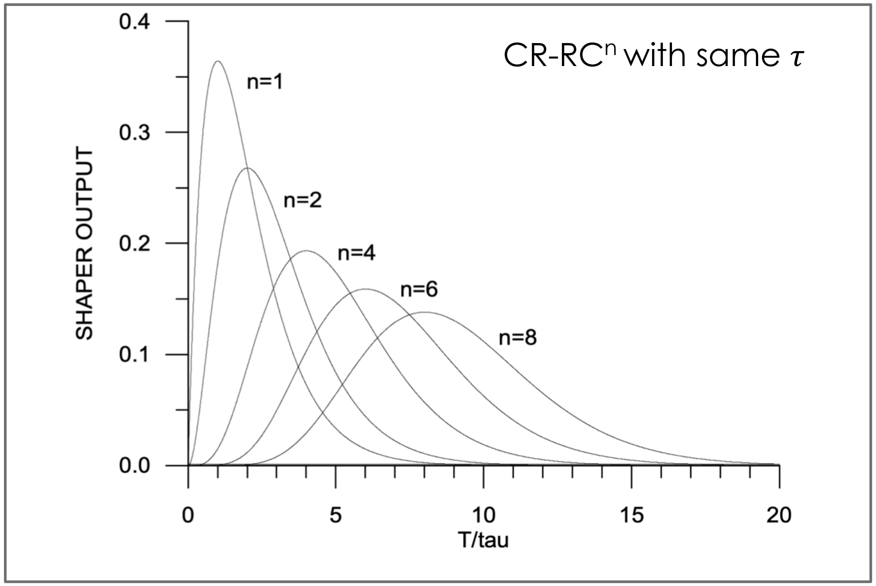
RC : Integrator circuit - low pass filter

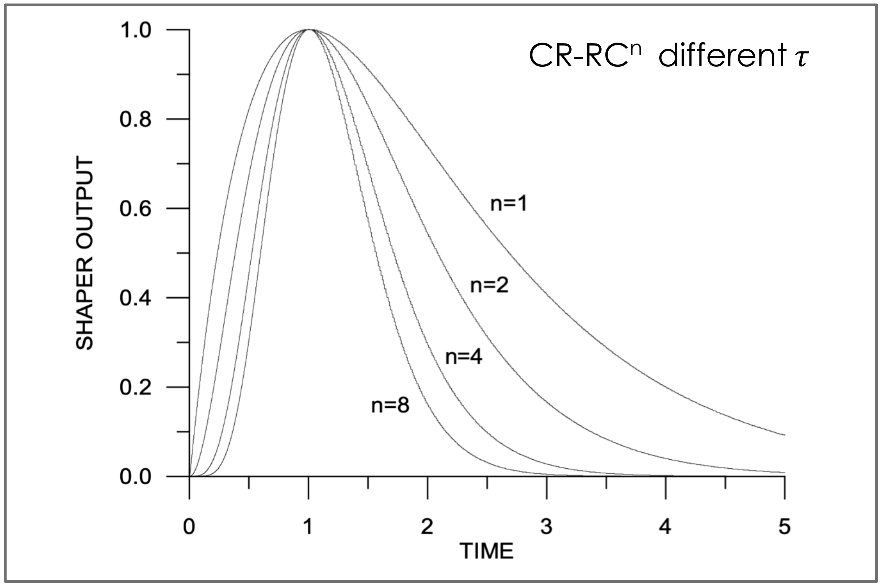
Pulse Shaping

- Circuit CR-RC-RC-RC….
  - A differentiator circuit CR followed by n integrator RC **with the same time constant** → the pulse forms approximately a gaussian shape

$$V_{out} = V_0 \left(\frac{t}{\tau}\right)^n e^{-t/\tau}$$

  - The peaking time is defined by (n x τ) so wider shapes are obtained with more poles
    - Increased pileup with respect to a simple CR-RC but the S/N ratio can improve up to 20%
  - If the time constant is changed $\tau_n = \tau_1/n$ → preserves the peaking time

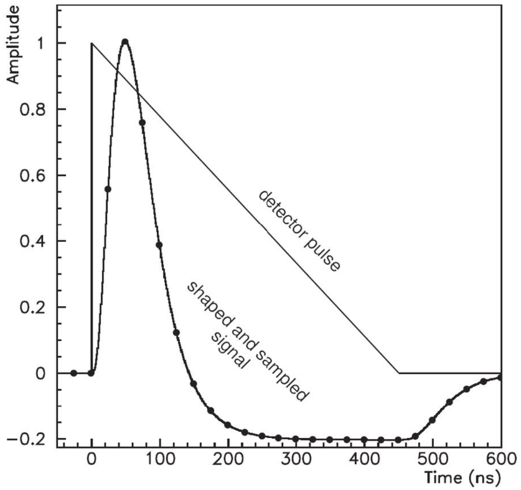




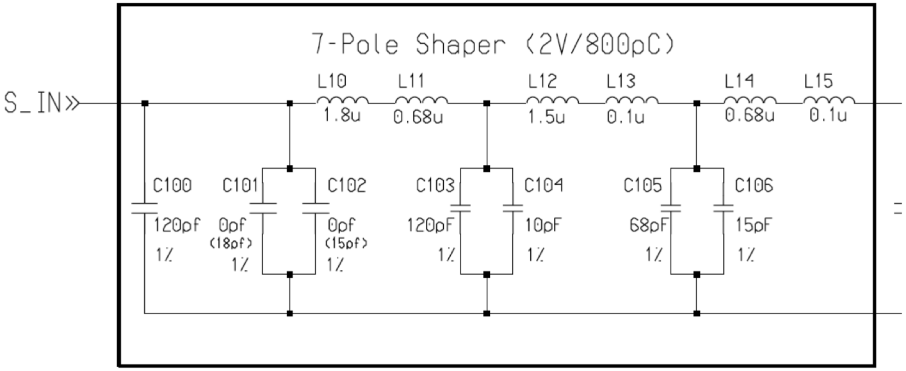
Pulse Shaping

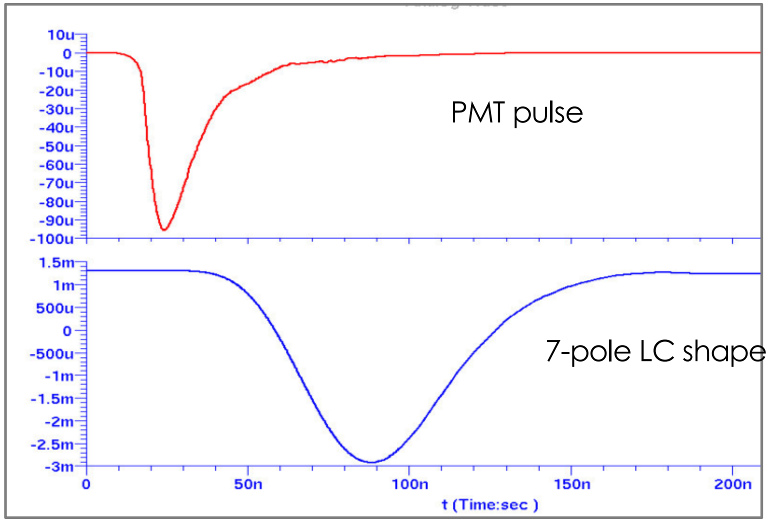
- Circuits with 8 stages or more are common
- Other passive networks provide similar results: LC
- Output frequencies in accordance with ADC sampling clock (Nyquist)

CR – RC^2 – ATLAS EM Calorimeter



ATLAS HAD Calorimeter





ADC

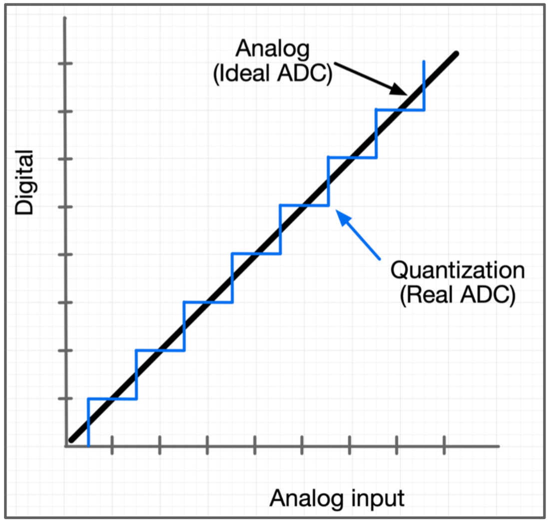
- Analog to Digital Conversion : quantization
  - Pulse amplitude or current integration digitization
  - Sampling clock synchronization is crucial
- Dynamic range
  - Is defined by the smallest and largest (range) voltage (energy) signal of interest
  - This can be achieved with one or multiple ranges

Example: Range [0.12, 800] pC

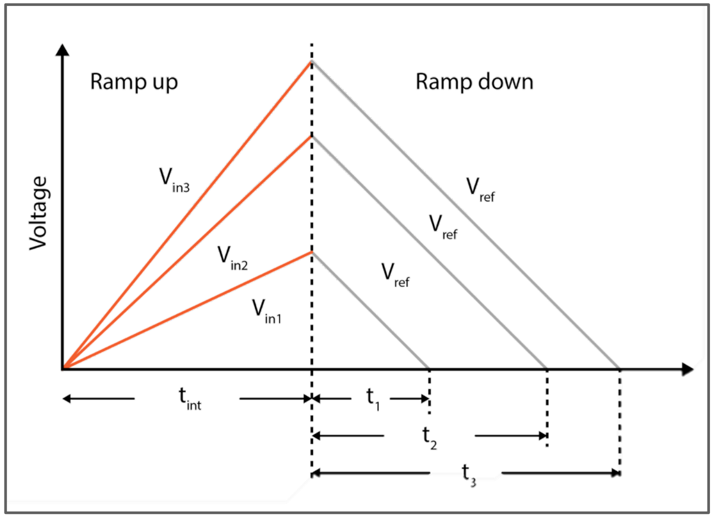
16-bit ADC (resolution $800/2^{16}=0.01$pC) → Two ranges of 10-bit each

Gain1 (x1): resolution $800/2^{10} = 0.78$ pC

Gain2 (x64): resolution $(800\text{pC}/64)=12.5\text{pC}/ 2^{10} = 0.01$ pC

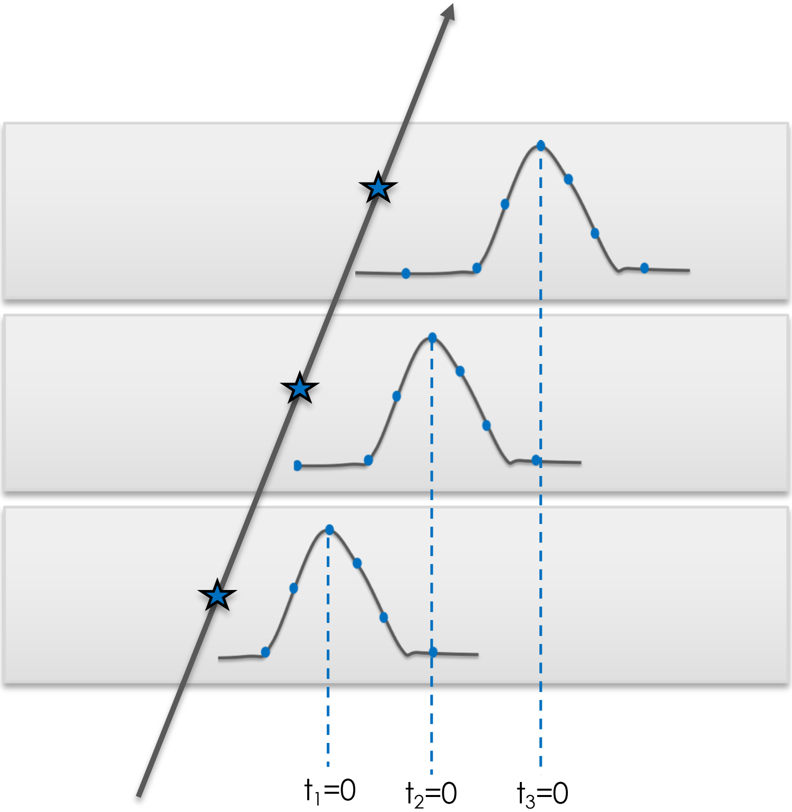


- Types
  - Successive approximation register (SAR) (most popular)
    - Compares with a reference voltage which must be stable
    - Latency (~4-6 cycles) in pipeline mode
  - Delta-sigma ADCs
    - Oversampling and DSP filter
    - High resolution (20 bits) but slow < Mbps
  - Dual slope
    - Integrator discharged with known slop
  - Flash ADC
    - Fast and no latency
    - Low resolution (usual < 8 bits)



ADC digitizing clock

- In particle colliders the clock is synchronous with the beam crossing
  - Ideally a sample in the peak
  - Channel-to-channel configuration to adjust the phase
  - Good quality clock distributed with possibility to shift the phase
  - Phase must be fixed and deterministic – not trivial!
  - Small event by event variations can be measured



Memory – event selection latency

- Pipeline memories keep the data saved until a decision/trigger is received
  - Reduces the amount of data transferred → as data volumes and trigger rates increases new architectures must be adopted
- The memory can be analog
  - Switch Capacitors Array : analog delay
  - Signals are digitized if event selected by trigger: slower ADC needed
- Depth of pipeline memory?
  - Defined by the trigger latency (~3-10 μs)
  - Must be synchronous : event identification
- Gain selection. Before or after?
- Trigger veto? Buffers? – Data flow control

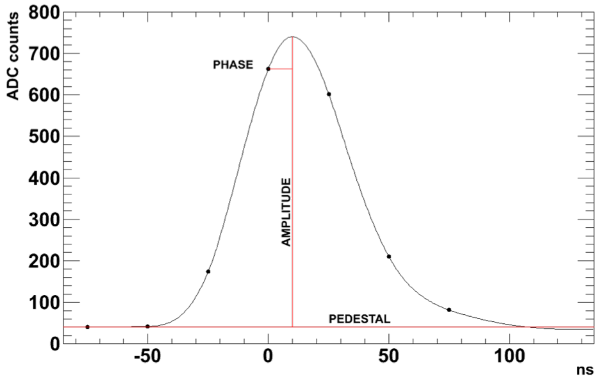
Energy measurement methods

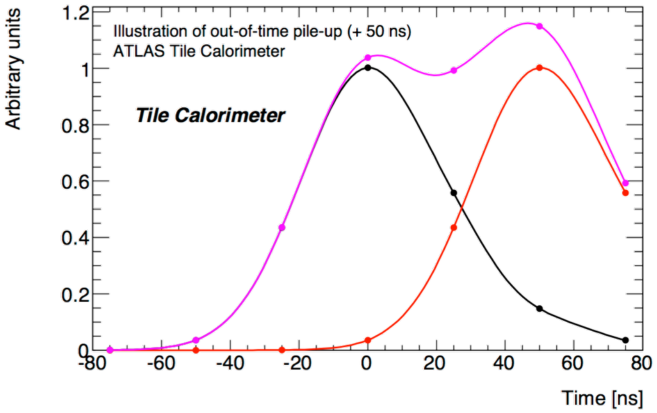
- Signal reconstruction – digital filter
  - Relatively simple but requires DSP functions
  - Extraction of information after quantization and deformation

$$A = \sum_{i=1}^{7} S_i a_i$$

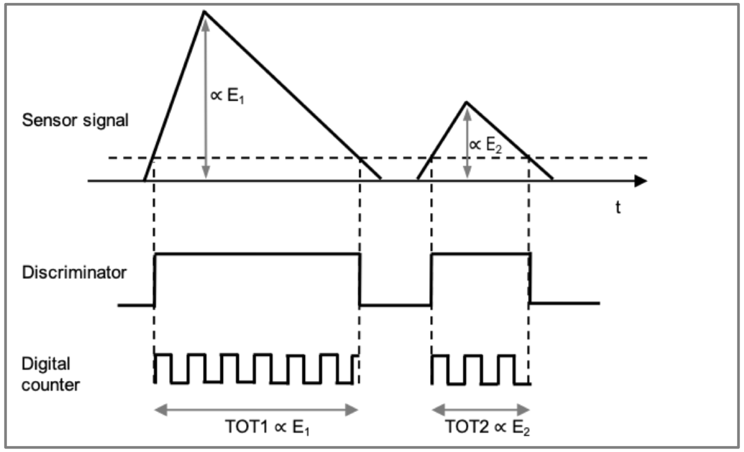
$$\tau = \frac{1}{A} \sum_{i=1}^{7} S_i b_i$$

$$Q_F = \sqrt{\sum_{i=1}^{n} \left(S_i - (A g_i + A\tau g'_i + p)\right)^2}$$





- Time Over Threshold : simple, front-end electronics
  - Example: ATLAS Pixel detector, Km3Net

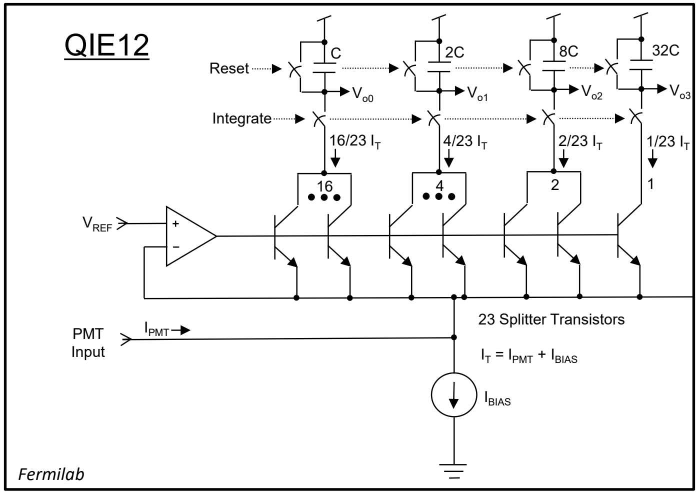


Energy measurements methods

Charge integration for a PMT

- Followed by an ADC
- No timing information for peak → TDC
- Example: QIE ASIC
  - Several versions tailored for specific detectors
    - KTeV (QIE5), CDF (QIE6), MINOS (QIE7), CMS (QIE8, QIE10, and QIE11)

- In all the cases the digital value must be converted to Energy → Calibration



Fermilab

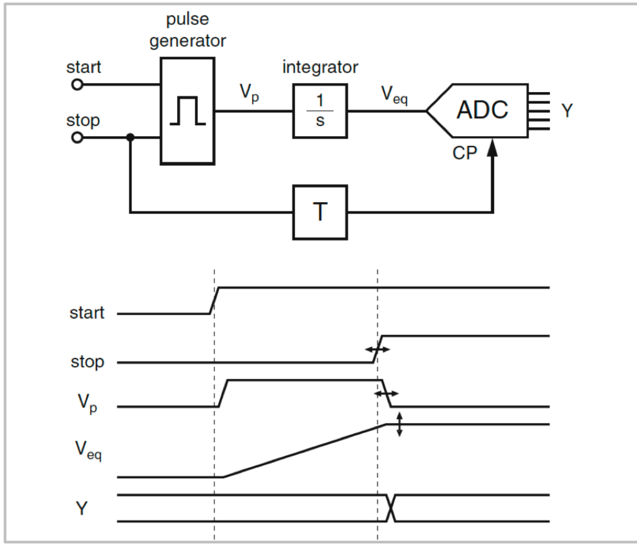
$$E(\mathrm{GeV}) = A(\mathrm{ADC}) \cdot C_{\mathrm{ADC}\to\mathrm{pC}} \cdot C_{\mathrm{pC}\to\mathrm{GeV}} \cdot C_{\mathrm{Cesium}} \cdot C_{\mathrm{Laser}}$$

Electronics Testbeam Scintillator PMT

Front-end electronics for time measurement

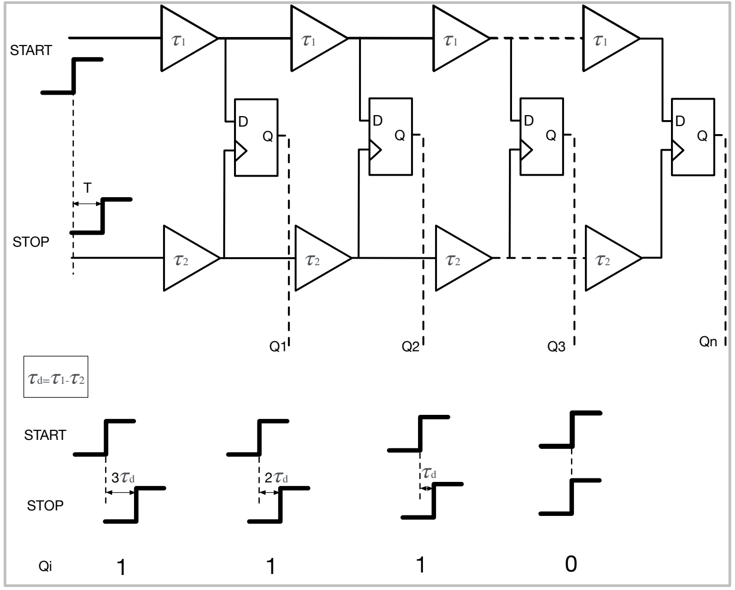
Discriminator followed by a TDC

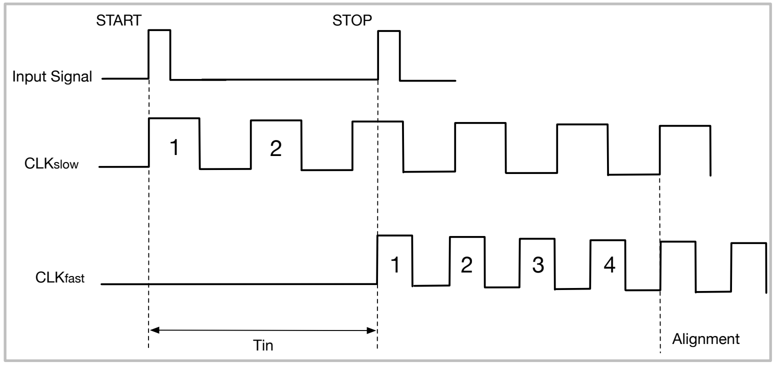
- Same principle as the ToT
- Implemented in front-end and the result transmitted
  - Different implementation techniques
    - Analog TDC
    - Dual slope (same approach as for ADC)
    - Fully digital :
      - » Vernier: Classic- Delay-Line Based
      - » Can be implemented in FPGA



Analog TDC

Delay-Line Based TD

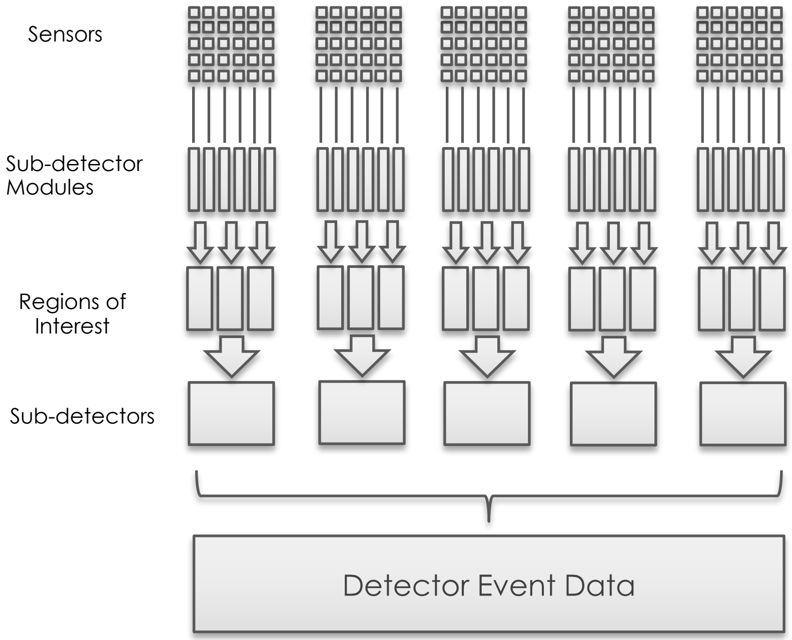


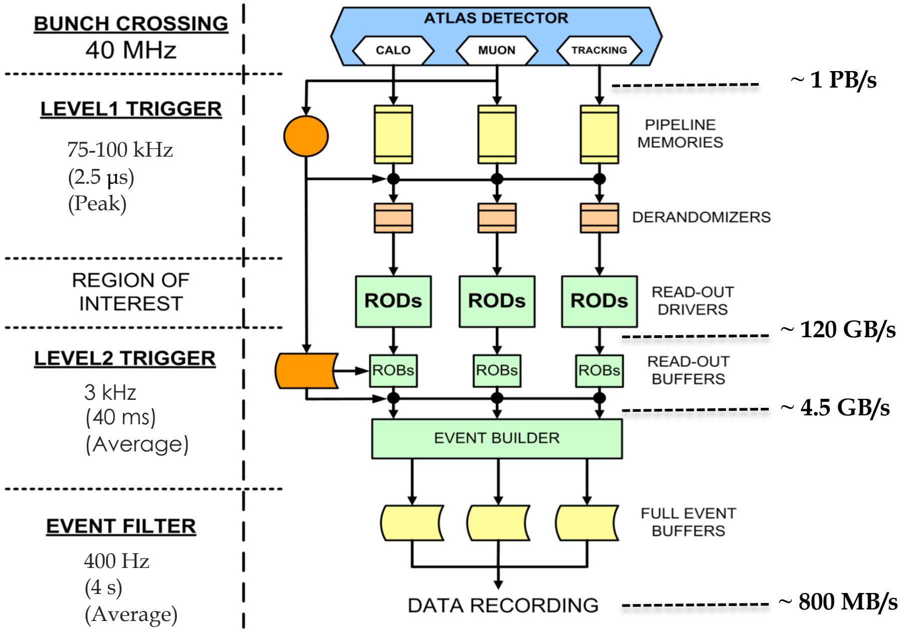


Classic Vernier TDC

Signal processing → back-end electronics

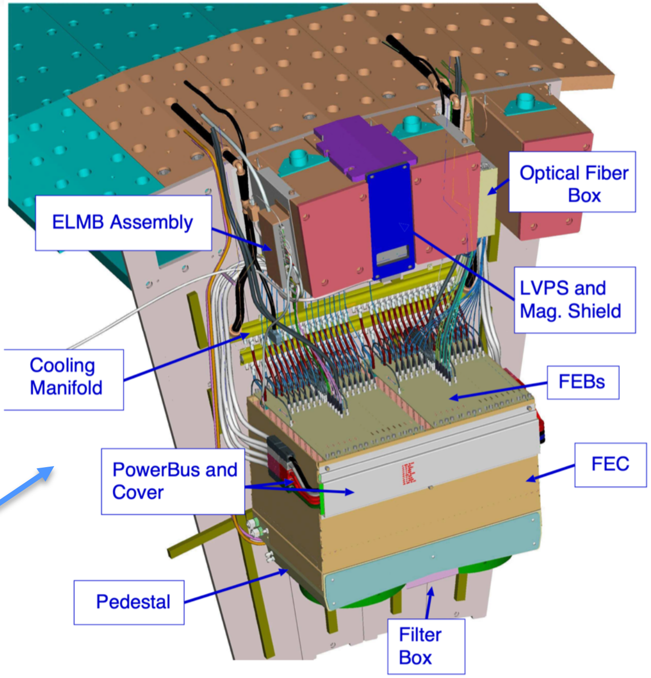
- The data readout follows a modular aggregation schema to gather information from bigger detector parts
  - Final goal is to obtain an event data packet for the entire detector
  - Each step in data acquisition chain: select and pack

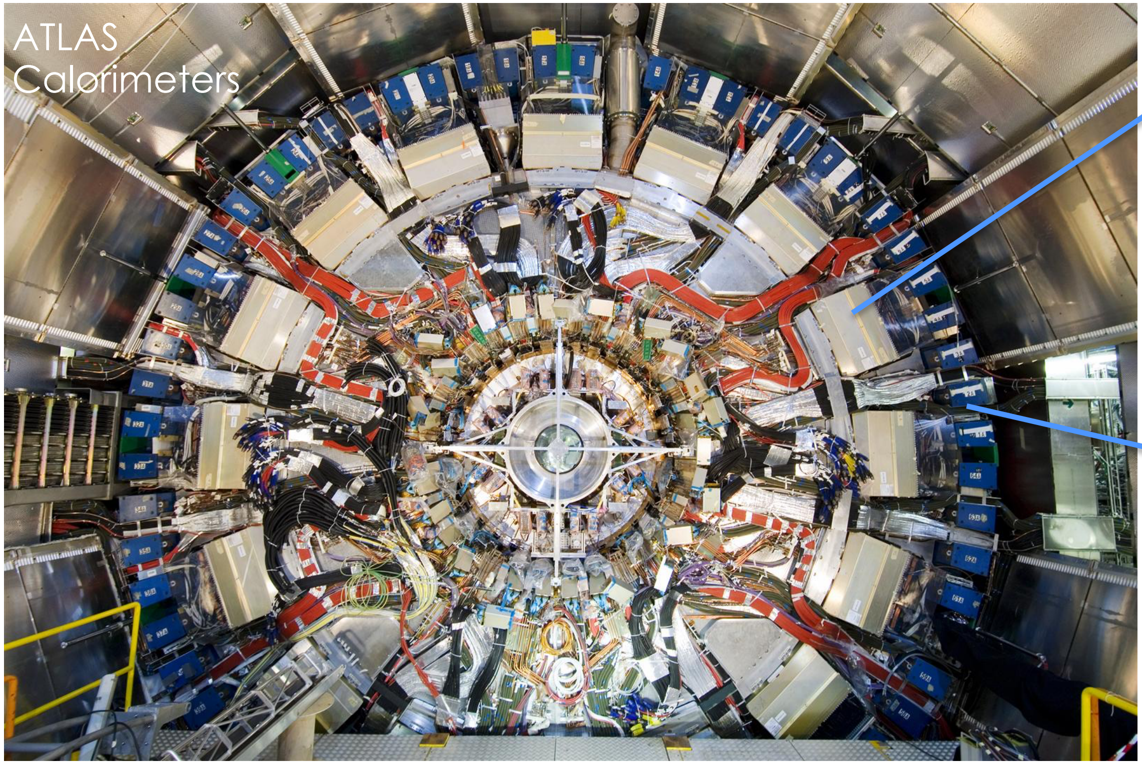


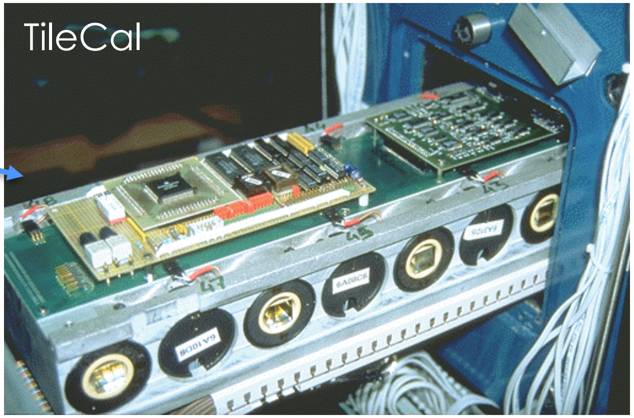


Front-end Implementation

- Very-FEE → Data collection, packing and interface with Back-end
  - Very-FEE as close as possible to the sensor
  - Back-end interface: data collection and basic packing/compression (zero suppression)
    - Custom backplanes
    - Mechanical structures with cabling
    - Accessibility

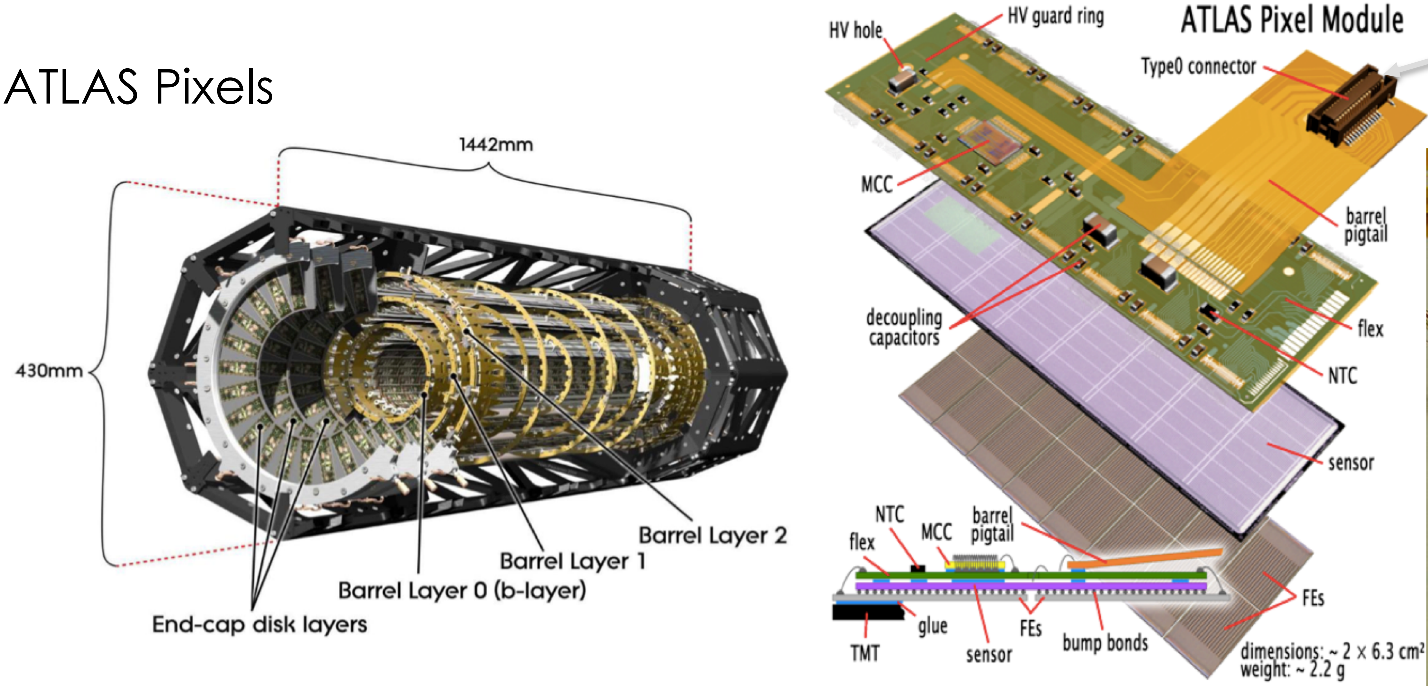






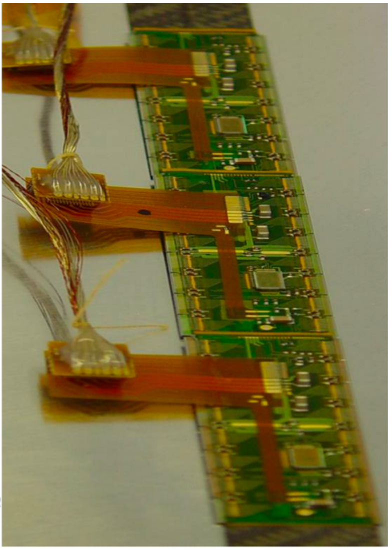
Front-end Implementation

ATLAS Pixels



(a) (b)

Services and data collection

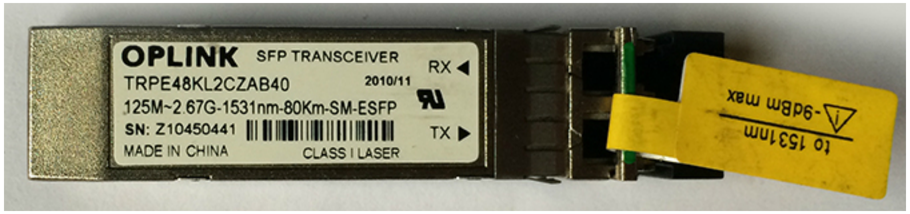


Other front-end electronics functionalities and considerations

- Radiation tolerant – ASICs (Mrad) vs COTS (Krad)
- Power regulation and distribution
  - Low and high voltage: stability, granularity, control and monitoring
  - Front-end vs Back-end: access, cabling, redundancy
- Cooling
- System slow control
  - Decouple from data path. 24/7 functioning
- System health monitoring
- Clock distribution
- Calibration systems
  - Configuration and control: dedicated runs or during datataking
  - Same or different readout path
- Connections to the backend
  - Serialization/Deserialization
  - Optical fibers : large aggregated data volumes

Optical links

- Class 1, 1M • Safe if not magnified (Laser printers, CD/DVD Players) - TYPICAL OPTICAL TX
- Class 2, 2M • Safe if you blink, short periods! (bar code scan, pointers)
- Class 3R • Low risk, be careful
- • Class 3B • Do not look directly (CD, DVD) • Class 4
- • Permanent eye damage (cutter)



Copper vs Fibers

- PROs
  - High rates (Tb/s)
  - Low weight
  - Long range (1000s Km)
  - No interference / noise
  - Evolving technology
  - Good integration with FPGAs
- CONs
  - Expensive technology
  - System complexity
  - Mechanical fragility
  - Installation complexity
  - Terminations (connectors delicate)

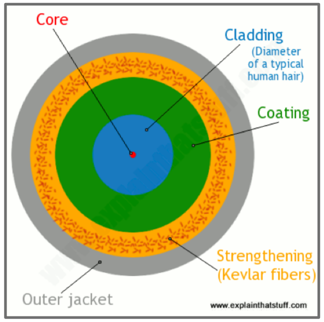
Optical fiber transmission

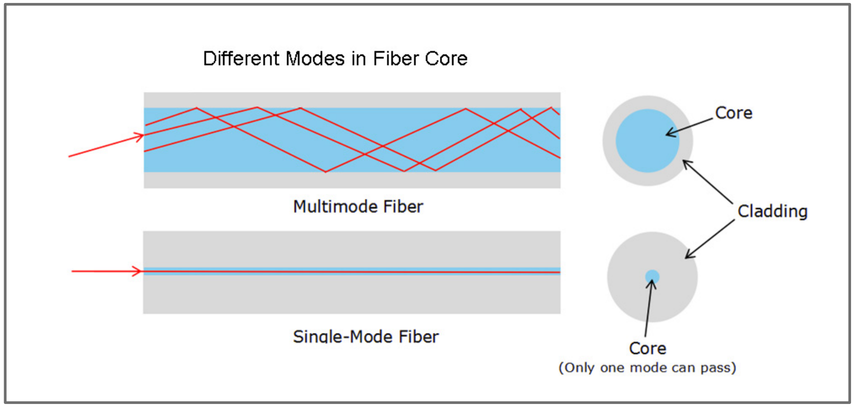
- Basically is a light guide. Core: low refraction index. Cladding: high refraction index
- SINGLE MODE
  - Smaller core diameter (8-10 µm)
  - Higher bandwidth and longer range
  - No "modal dispersion"
  - ~80 Km unamplified : 1000s of Km amplified
  - Very expensive and precise laser transmitters
- MULTIMODE
  - Much wider core (~50 µm)
  - Much more forgiving wrt light quality & alignment
  - Attenuation influenced by "modal dispersion"
  - Multiple propagation modes allowed in the light guide
  - Range limited to hundreds of meter
  - Light sources are considerably cheaper

Type	Fiber Diameter(µm)	Fiber Type	Fast Ethernet 100BASE-FX	1 Gigabit Ethernet 1000BASE-SX	1 Gigabit Ethernet 1000BASE-LX	10Gbps Ethernet 10GBASE	40Gbps Ethernet 40GBASE SR4	100Gbps Ethernet 100GBASE SR4
OM1	62.5/125	MMF	2000m	275m	550m	33m	Not supported	Not supported
OM2	50/125	MMF	2000m	550m	550m	82m	Not supported	Not supported
OM3(laser optimization)	50/125	MMF	2000m	550m	550m	300m	100m(SR4)	100m(SR4)
OM4(laser optimization)	50/125	MMF	2000m	550m	550m	400m	150m(SR4)	150m(SR4)
SMF	9/125	SMF	2000m	5km at 1310nm	5km at 1310nm	10km at 1310nm	N/A	N/A

Datasheet

- Link Lengths at 1.25 GBd:
  - 0.5 to 550 m - 50 µm MMF
  - 0.5 to 550 m - 62.5 µm MMF
  - 0.5 m to 10 km - SMF





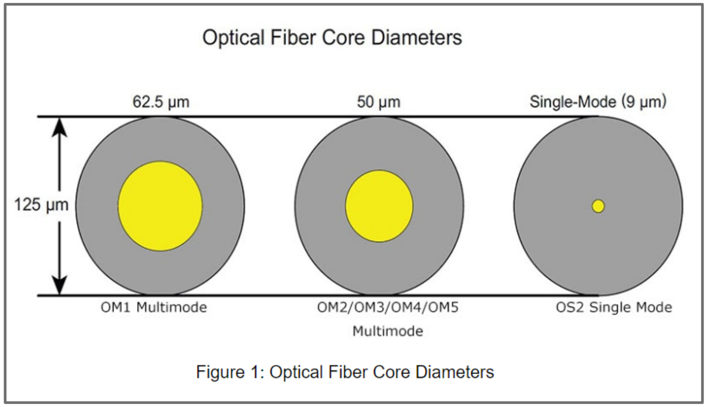
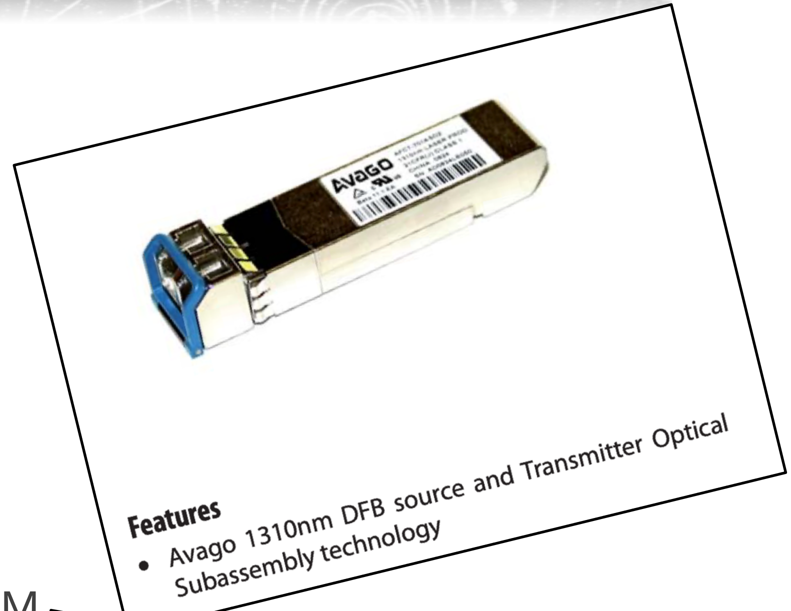


Figure 1: Optical Fiber Core Diameters

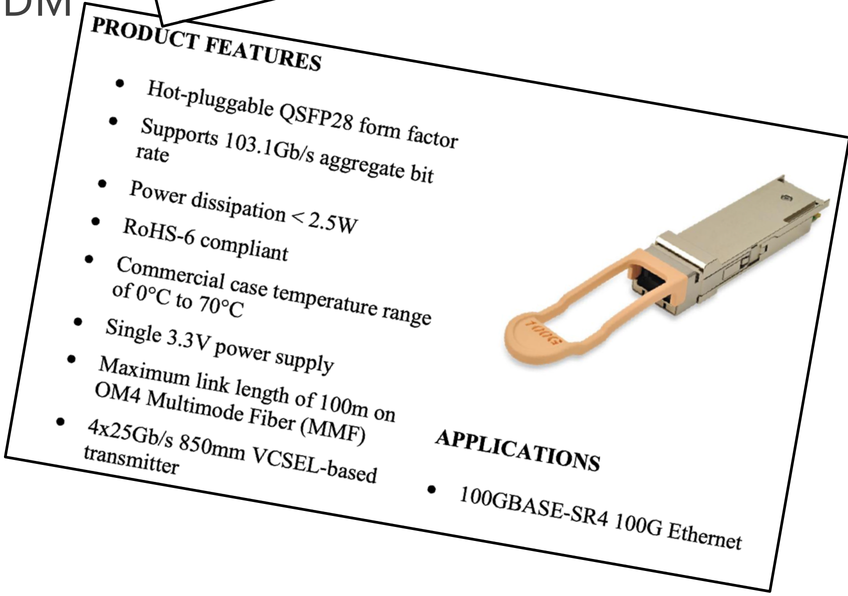
Transmission bands

- "First Window" – 850 nm
  - **Highest attenuation, "short range" (~100 m)**
- "Second Window" – 1310 nm
  - **"O-band", kilometer range**
- "Third Window" – 1550 nm
  - "C-band", "Conventional band", long-reach DWDM
- "Fourth Window" – 1590 nm
  - "L-band", "Long band"



Features

- Avago 1310nm DFB source and Transmitter Optical Subassembly technology



PRODUCT FEATURES

- Hot-pluggable QSFP28 form factor
- Supports 103.1Gb/s aggregate bit rate
- Power dissipation < 2.5W
- RoHS-6 compliant
- Commercial case temperature range of 0°C to 70°C
- Single 3.3V power supply
- Maximum link length of 100m on OM4 Multimode Fiber (MMF)
- 4x25Gb/s 850mm VCSEL-based transmitter

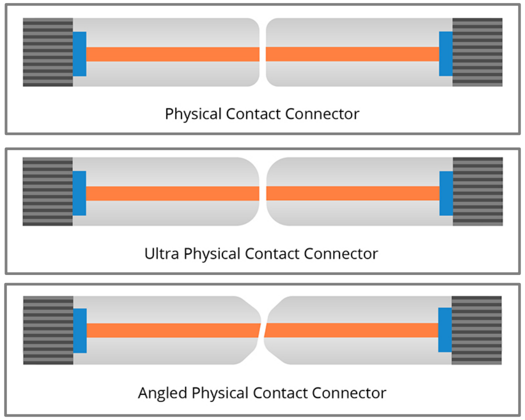
APPLICATIONS

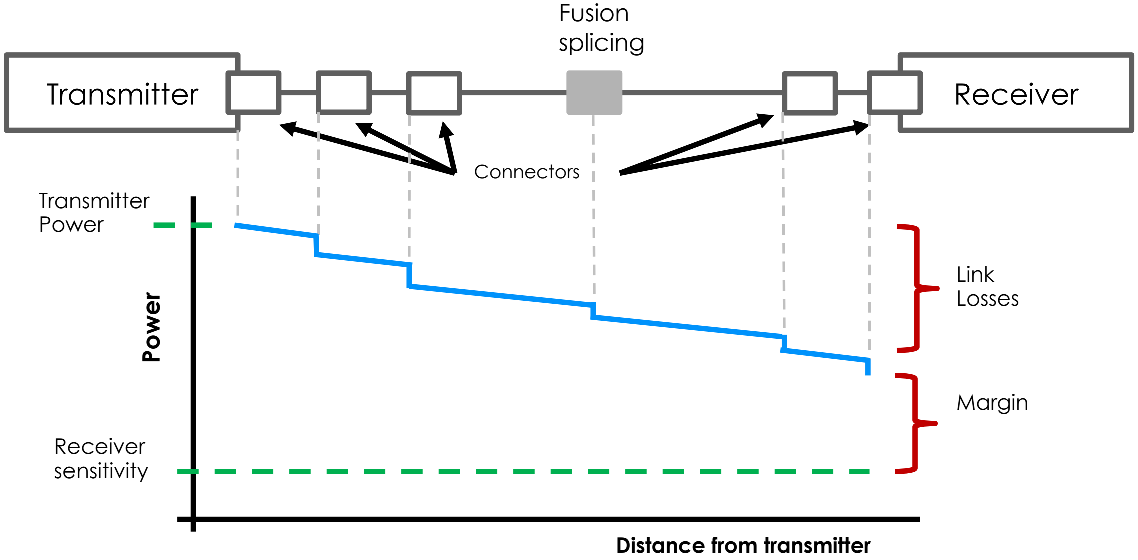
- 100GBASE-SR4 100G Ethernet

Attenuation

- As light propagates in a fiber, its intensity decreases – fiber losses
  - Scattered by defects in the glass
  - Absorbed by impurities and converted to heat
- Attenuation is measured in “Decibels” (logarithmic)
  - 1/10 = -10 dB
  - 1/100 = -20 dB
- Combining losses/gains expressed in dB = addition
- Other causes
  - Insertion loss (connectors) and splicing
  - Optical splitting (1:2 → 3 dB)
  - Return loss (PC, UPC, APC)
  - Bending loss
  - Dirt
  - Radiation induced “darkening”

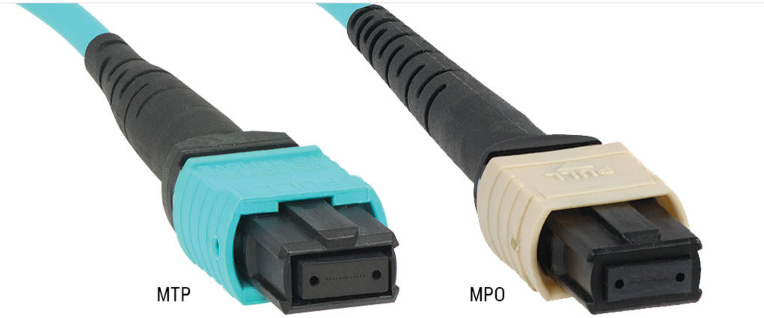
Fiber optic connector endfaces

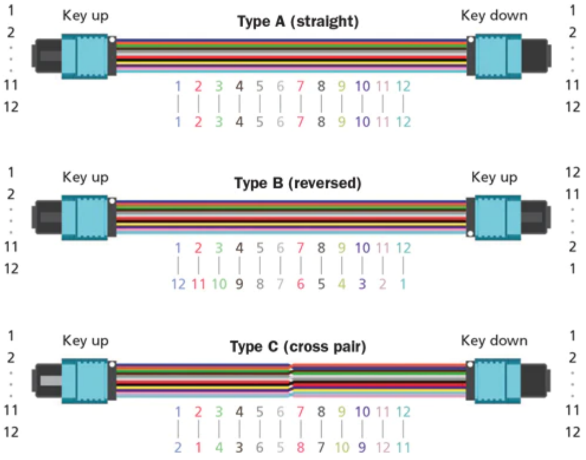


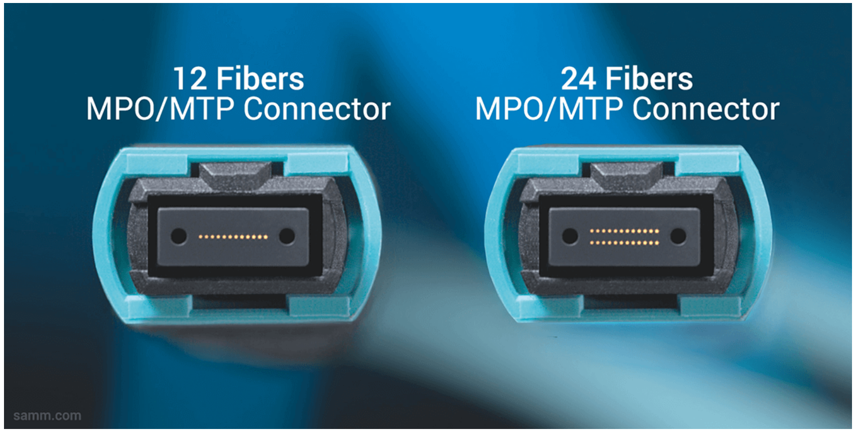


Assemblies

- Single core fibers: SC, ST, FC, LC
- MPO (Multi-Fiber Push On) cables
- 8, 12, 16, and 24. 32, 48, and 72 fiber counts
- MTP® connector is a trademark by US Conect for a version of the MPO connector with improved specifications
  - **More robust metal**
  - **Pin Clamp (vs plastic)**
  - **Floating ferrule**
  - **Improved guide pins**
  - **Removable housing**
  - **Lower insertion loss and higher reliability**





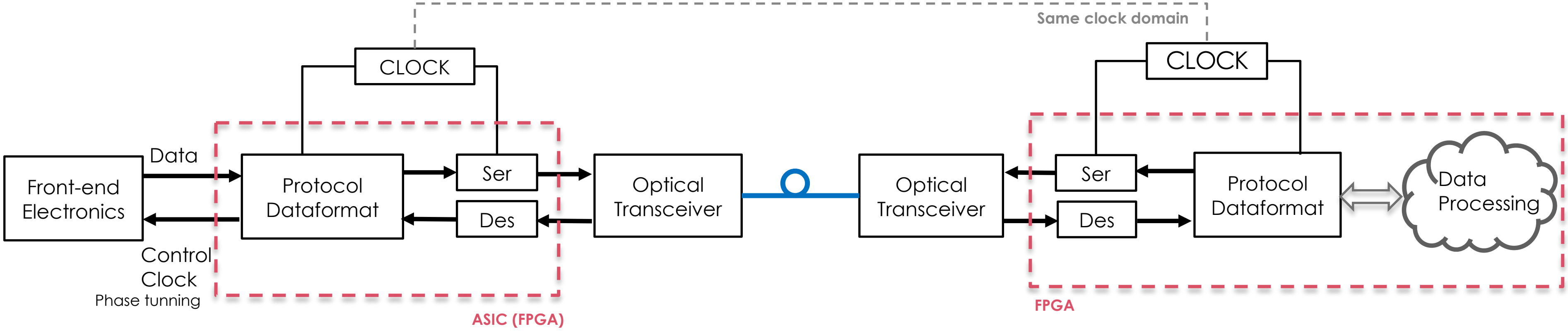


Form factors

- SFP/SFP+/SFP28 : Single Full Duplex lines: 4 / 10 / 25 Gbps (Compatible)
- QSFP (QSFP28) : 4 RX / 4 TX up to 10 Gbps/ 28 Gbps
  - QSFP-DD: Double Density (8 RX/ 8 TX): Extend QSFP capacity with backward compatibility → Up to 8 lines @ 25 Gbps (**400 Gbps**)
  - QSFP-DD800: Individual lines speed up to 112 Gbps
  - They support breakout cables QSFP → SFP
- POD (miniPOD, microPOD): 12 lines TX or RX. More than 10 Gbps each
  - Large density. Not mounted on PCB edge. Can be grouped in higher density patch cords: MTP12-MTP24-MTP72
- Firefly (SAMTEC) : High bandwidth density : 12 lines. 28 Gbps per line
- Versatile Link PLUS : Custom Rad-hard CERN project
  - SFP-like form factor. Compatible with commercial connectors
  - Deterministic latency in both directions

System integration

- Front-end to back-end communication can be asymmetrical
  - Fixed latency path for event identification
  - One single clock domain across the optical link with phase tuning in the front-end
- Data packing
  - Dataformat is detector specific should permit flexibility
  - Protocol for data encoding: DC balancing, error detection and correction (FEC) , comma words (alignment)
    - Overhead
    - Standard IP cores (8b/10b) or custom (GBT)
- Serialization/Deserialization
  - Now included in the same device (ASIC or FPGA)
- Optical Transceivers
  - Radiation tolerant in the front-end
  - Same or different assembly: breakout cables: 12 x LC → 1 MTP

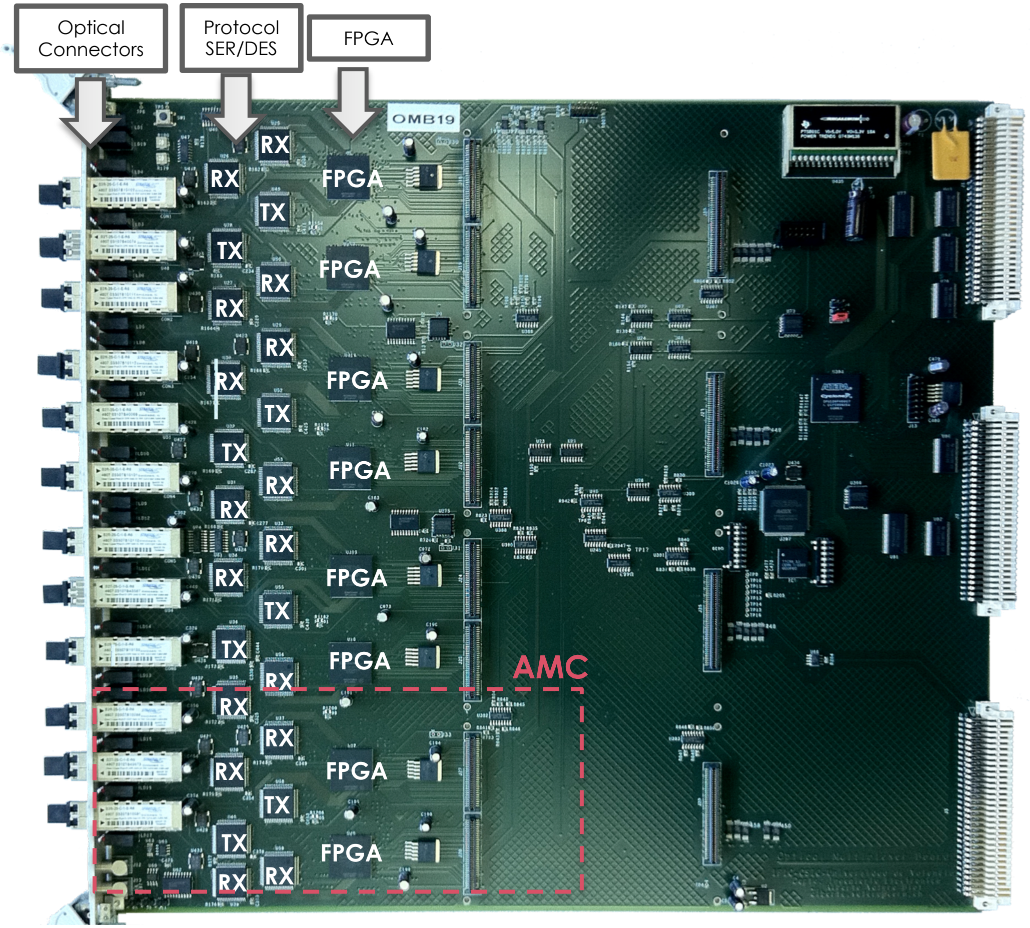


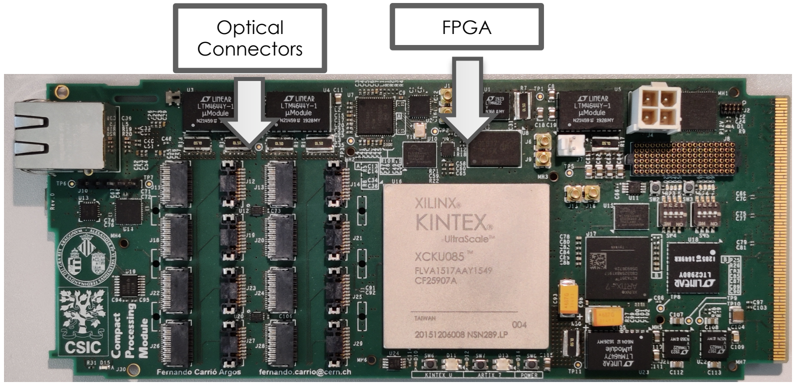
Evolution of data acquisition systems

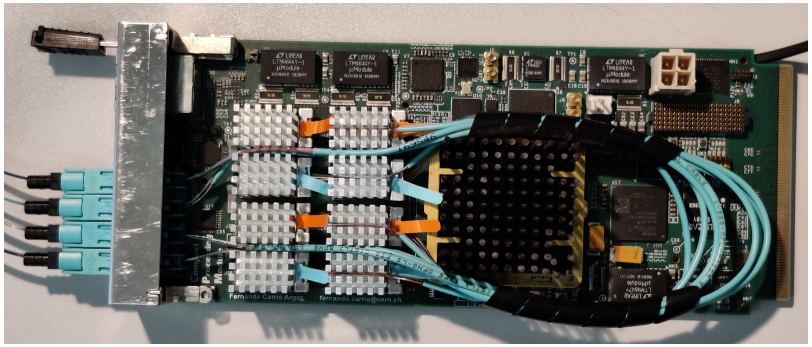
Huge increase in aggregated data rates not only due to individual line speeds

OMB (2005): VME9U ~ 34 x 36 cm
Throughput (max 1Gb/s x line): TX: 8 Gb/s ; RX: 16 Gb/s
12 SFP optical transceivers, 24 G-Link ser/des, 8 FPGAs

CPM (2020): AMC ~ 7.4 x 18 cm (x4 OMB)
Throughput (16 Gb/s line): TX: 512 Gb/s ; RX: 512 Gb/s
8 Firefly , 1 FPGA







Evolution of DAQ systems

- The high data rates provided by optical links permit "simpler" readout architectures
  - Triggerless readouts : (LHCb, ALICE, DUNE) : Aggregated data rate O(10 Tb/s)
- Higher channel density allow system upgrades without expanding counting rooms
  - Re-structure the readout blocks → move front-end functions to "back-end"
    - Lower radiation levels
    - Improve operability and accessibility
  - FRONT-END does not mean INSIDE the detector anymore
    - Continuous digitization and readout with data processing, data flow control and buffers "off-detector"


KIP HD
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Thank you