Optical links

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Outline

- What can we do with fibres?
- Technology highlights
  - Why optics?
  - How optics?
  - Where optics?
- Applications of optical links (for HEP)
  - Data links
  - Timing and trigger
  - Pure Timing

Technology highlights

A communication channel at its bare minimum

transmitter

(laser, LED)

transmission media

(single or multimode fibres)

receiver

(photo or pin diodes)

- what can we speak about when we discuss “optical links”?
- type of connectors, cable harnesses, etc.
- speak about fibres (light propagation, polarization, dispersion modes, attenuation windows, etc.)
- transmitters or receivers: form-factors, opto-electrical features, etc.
- or even their ins and outs with photonics integration
- today: focus on **applications**

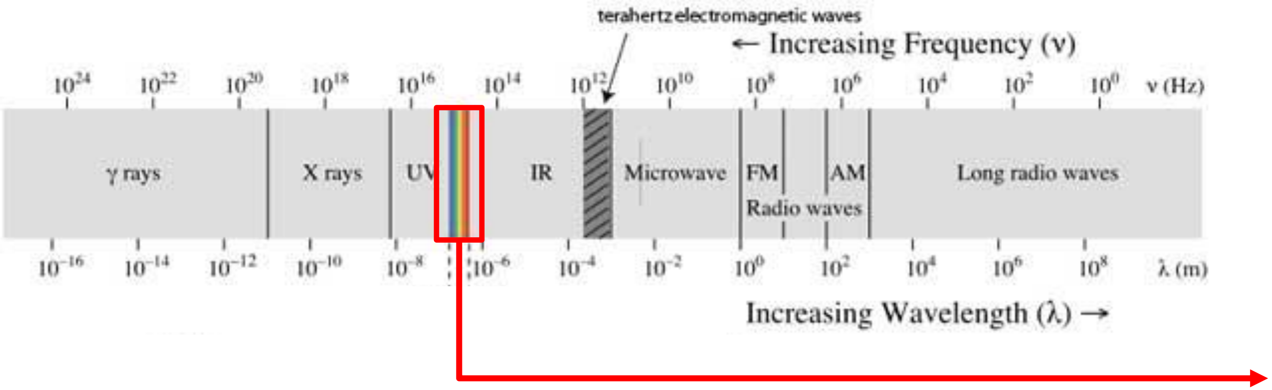
http://en.wikipedia.org/wiki/OSI_model

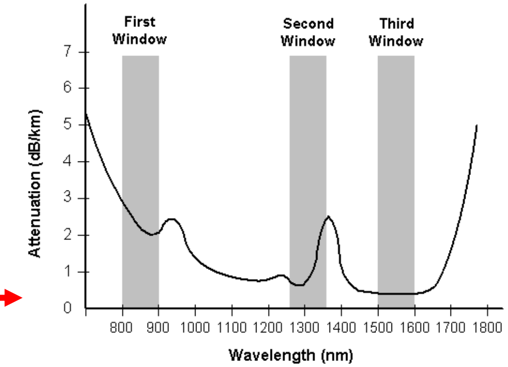
Why fibre optics?

- 🙂 Extreme high bandwidth per fibre (large "bandwidth × distance" product)
  One fibre can carry in the order of tens of Tbs (Tera bits)
- 🙂 If you have a wavelength in the THz domain… in time domain: order of Femto Seconds (fs)
- 🙂 Not sensitive to Crosstalk and EMI (Electro Magnetic Interference)
- 🙂 Low transmission loss
- 🙂 Galvanic separation in systems or system parts
- Highly reliable if mechanical aspects are well respected.
- Small dimension, low weight, low power consumption, well known standardization
- 😐 Mechanical fibre protection, manipulation and connection are delicate issues
- 😐 an Optical Network requires specialised and often more dedicated and expensive instruments
- Generally short distances using fibre are expensive (if bandwidth is not fully exploited)

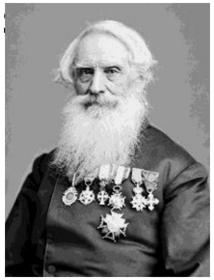
Shannon-Hartley theorem: $C = B \log(1 + S/N)$
Where C is the maximum theoretical channel capacity, with units [bits/second]; B is the channel bandwidth [Hz]; S is the signal power in watts [W] and N is the noise power also in Watts.

The old radio waves vs optical communication





- It's all about waves!
- What we are doing with optics today, follows more or less the path we went trough for the last couple of centuries with radio waves
- We use colors (wavelengths) as we use frequencies to create channels (multiplexing)
- We can slice channels in time (time division multiplexing)
- Optics still speaks "Morse code" (light on/off)
- Is the next real big challenge for optical links phase modulation?
- What will the future studies in optics bring to optical links?



1791 - 1872

Our friend… the ISO OSI model (again)

- International Organization for Standardization / Open System Interconnection: remember: if you are talking about engineering, can't do a talk without!☺
- It is a conceptual model that characterizes and standardizes the internal functions of a communication system by partitioning it into abstraction layers

OSI Model			
	Data unit	Layer	Function
Host layers	Data	7. Application	Network process to application
		6. Presentation	Data representation, encryption and decryption, convert machine dependent data to machine independent data
		5. Session	Interhost communication
	Segments	4. Transport	End-to-end connections, reliability and flow control
Media layers	Packet/Datagram	3. Network	Path determination and logical addressing
	Frame	2. Data link	Physical addressing
	Bit	1. Physical	Media, signal and binary transmission

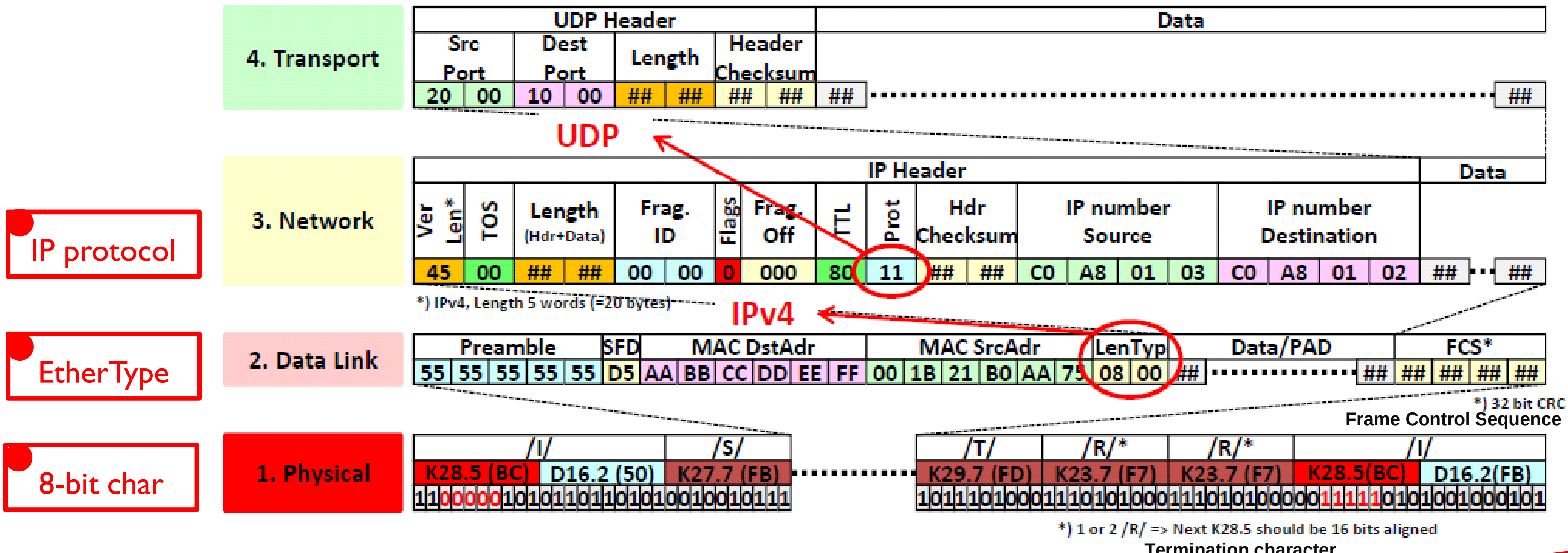
- On top of the physical layer, a "link" is setup
- You can exploit the physical layer alone
- Use a protocol (like in a speech)
  - Packet (phrases)
  - Character (words)
  - Ones and Zeroes (alphabet)
- Take advantage of the OSI model to define your protocol… or better stick to one!

http://en.wikipedia.org/wiki/OSI_model

Example: Gigabit Ethernet UDP-IP protocol

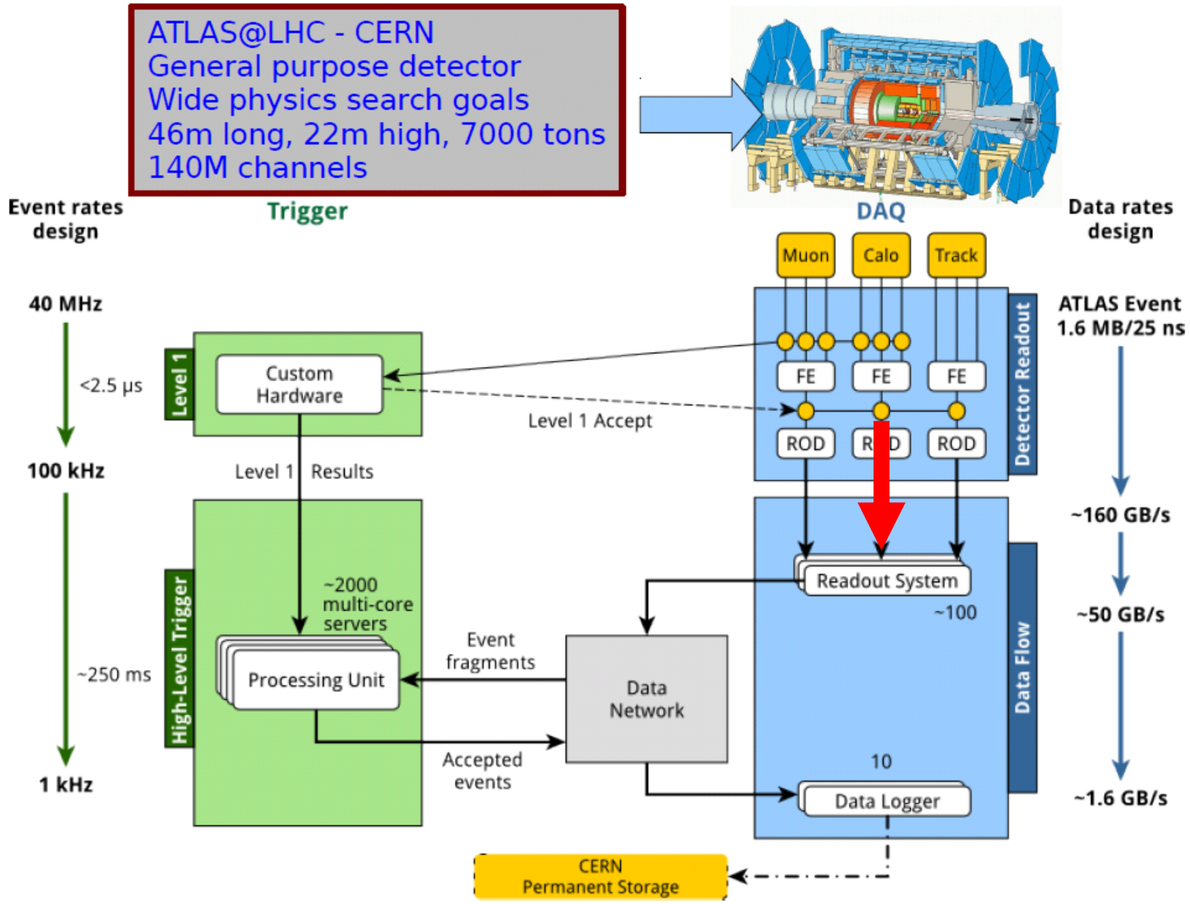
	Data Unit	Layer	Standard	
Host Layers	Data	7. Application		
		6. Presentation		
		5. Session		
	Segment	4. Transport	RFC-768	UDP
Media Layers	Packet	3. Network	RFC-791	IPv4
	Frame	2. Data Link	IEEE 802.3	MAC
	Bit	1. Physical		PHY

- The word "Ethernet" is one of the most abused terms in the "link world"…
- what is the "hardware engineer" definition?
- Eth0… NO! Simple: IEEE802.3
- Be careful with eating… "raw Ethernet"…☺



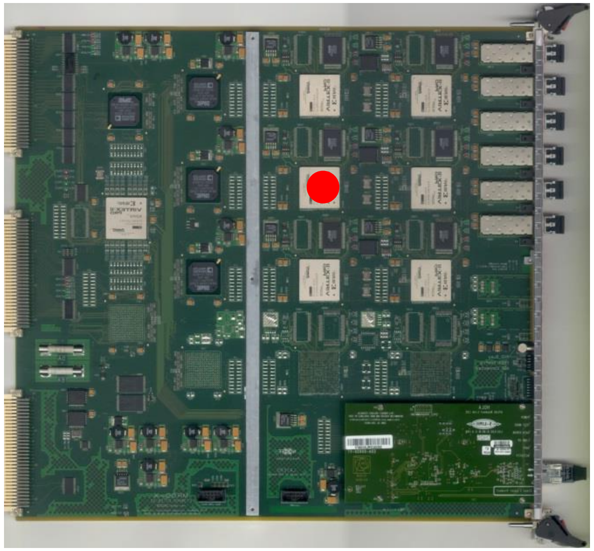
Data transmission on optical links

Optical links in ATLAS

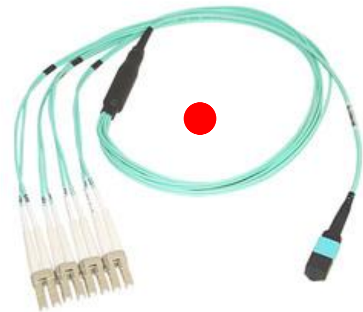


- There is an enormous amount of optical links throughout the whole detector DAQ
- Focus on links used to transfer data from the ReadOut Drivers (RODs, which in turn receive data from the on-detector electronics) to the ReadOut System (ROS)

Optical links in ATLAS: S-Link



Muon chamber ReadOut Driver (MROD)

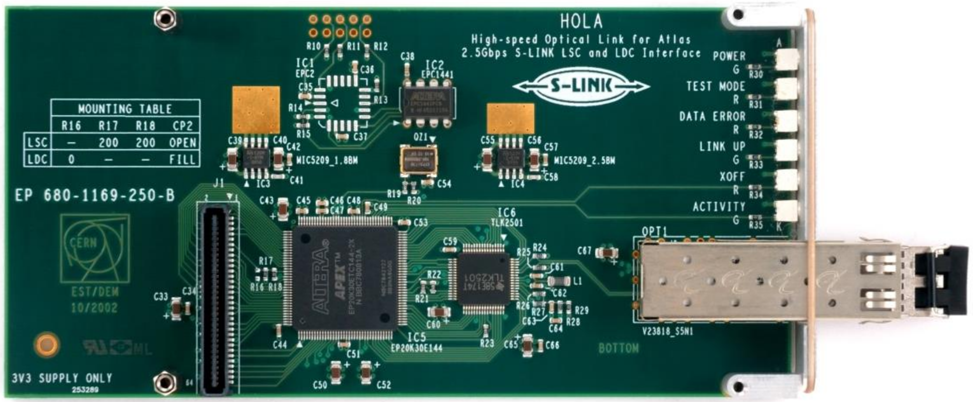


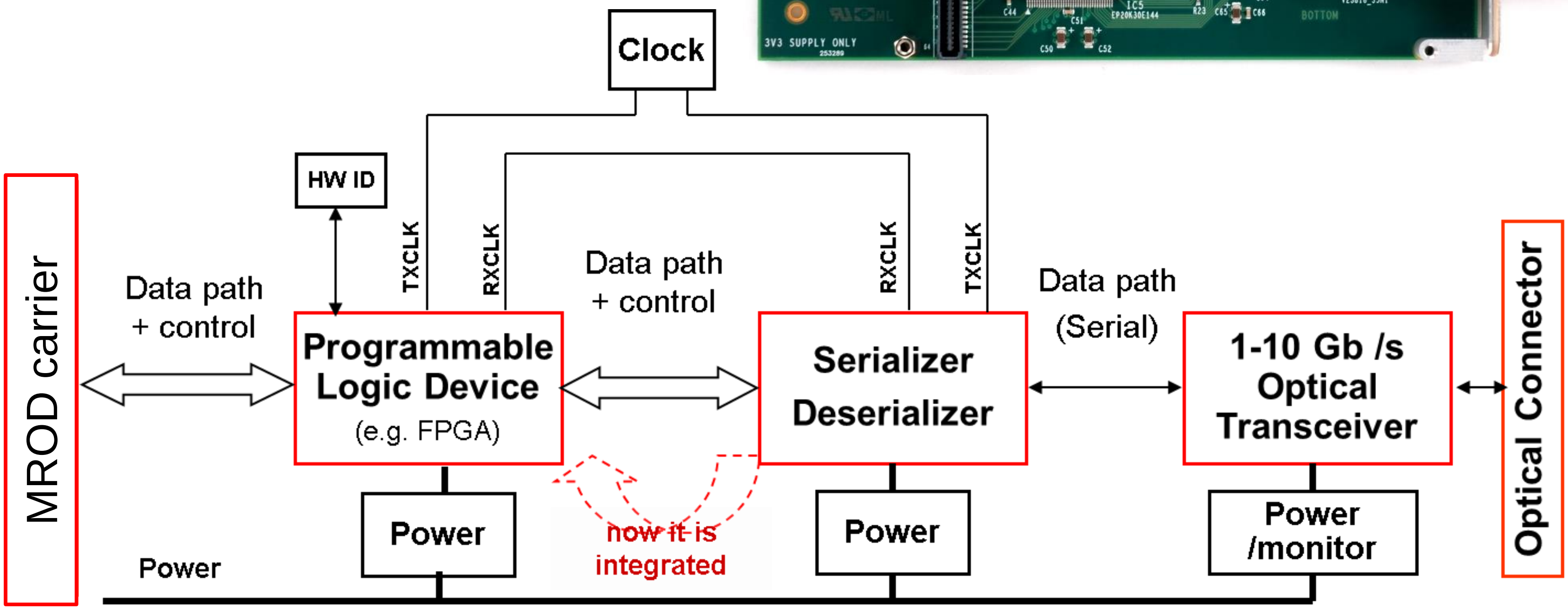
ROS - ReadOut Buffer INput (RobinNP)

- The S-Link (CERN, 1995) is a Simple Link Interface which can be used to connect any layer of front-end electronics to the next layer of read-out electronics. An S-Link is a link complying with this specification and can be thought of as a virtual ribbon cable, moving data (at 2.0 Gbps) or control words from one point to another
- In addition to simple data movement, S-Link includes the following features;
  - Error detection
  - Return channel for flow control ("XOFF")
  - Self-test function

Optical links in ATLAS: HOLA

- High-speed Optical Link for Atlas (HOLA) Link Source Card
- Nice example of the building blocks of a custom optical link interface card

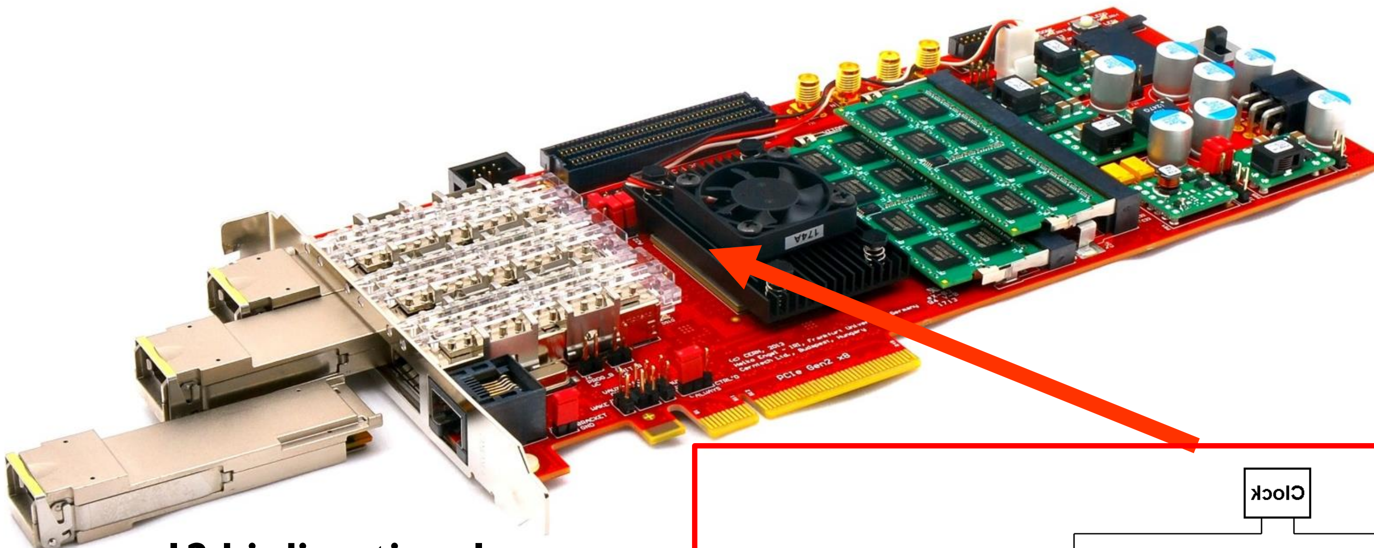




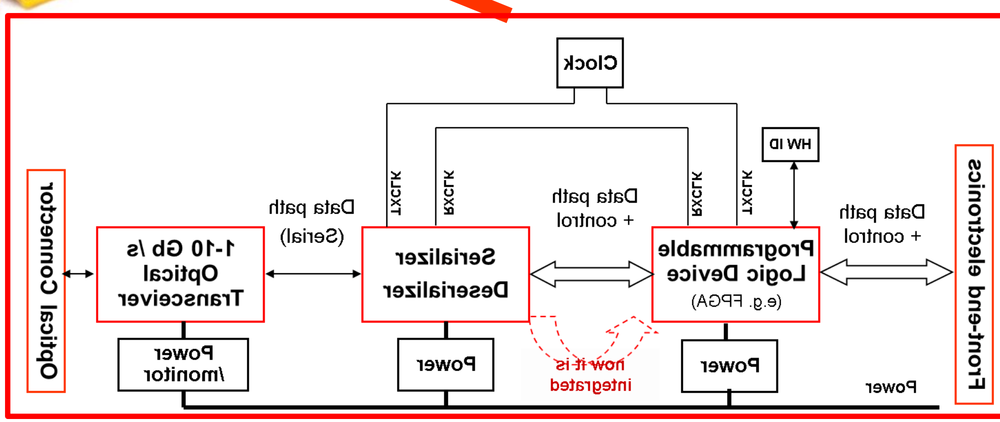
http://hsi.web.cern.ch/HSI/s-link/devices/hola/

Optical links in ATLAS: ROS RobinNP

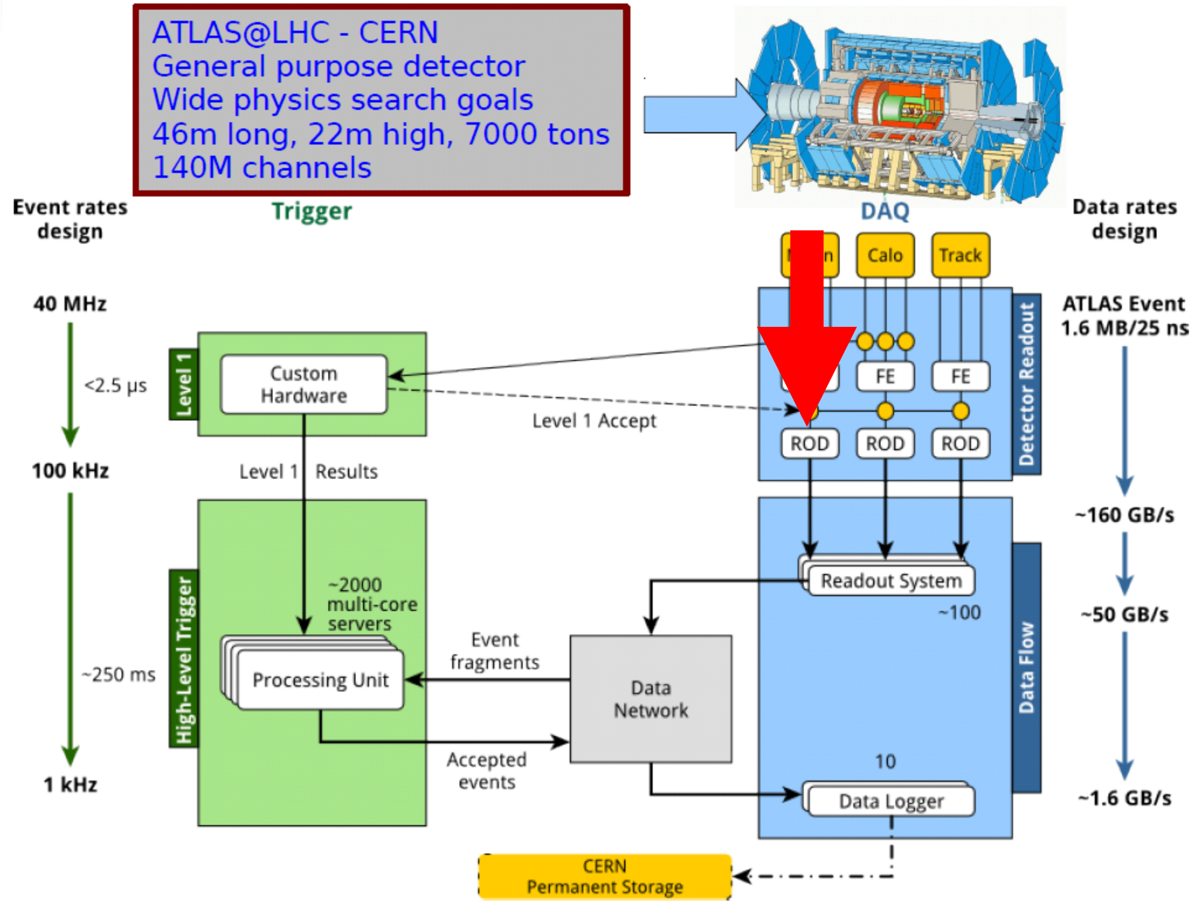
- Originally a „common" (C-) read-out card for the DAQ and HLT in ALICE
- It also became a common read-out card for ALICE and ATLAS…
- This is the HOLA Link Destination "Card" (FPGA core nowadays)



12 bi-directional optical links /card



Optical links in ATLAS: new detectors readout



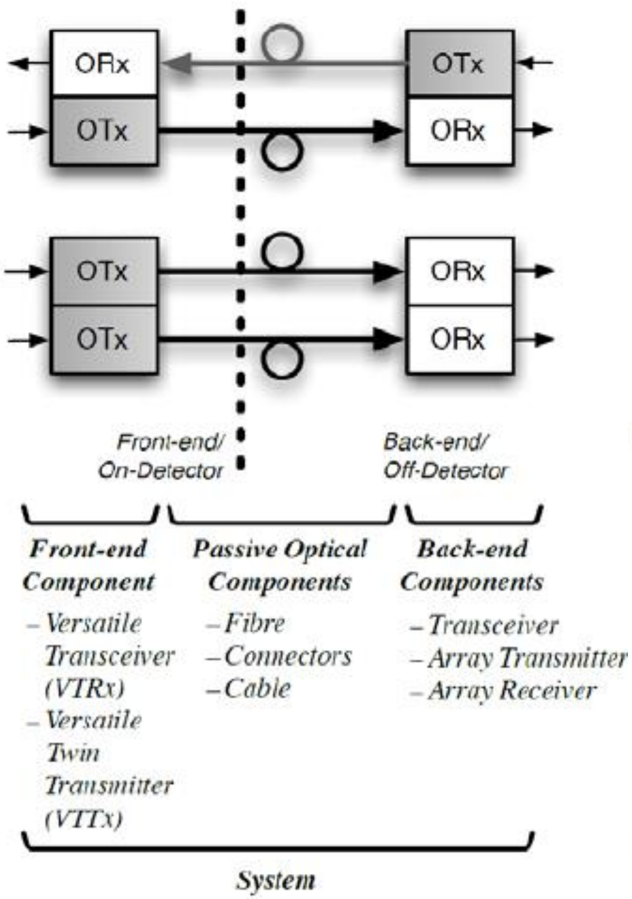
- There is new electronics being developed for the New Muon End-Cap (aka Small Wheel) that will require amongst others novel techniques for optical links
- One challenge is to tackle the **radiation hardness** problem

Radiation hardness problem

- CERN/LHC: serious need for a common, **radiation hard** high-speed digital link that can deliver data, control and trigger information on the same physical link to on-detector eletronics:
  - Radiation hardness
  - Error detection and correction
  - Constant latency
  - Light-weight (for transparency to particles)
  - Intense magnetic field resistant
- Common development efforts driven by CMS and ATLAS (and LHCb)
- Results: the **Versatile Link** and the **GBT protocol (**and ASICs)
- CERN provides: components, test boards, firmware and other support

https://espace.cern.ch/GBT-Project/default.aspx
https://espace.cern.ch/project-versatile-link/public/default.aspx

Optical links in the LHC future: Versatile link



VTRx and VTTx versions

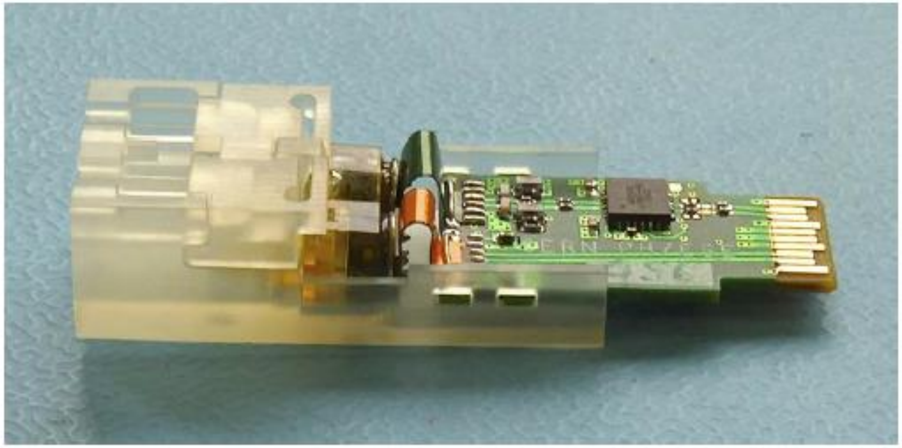


Figure 2: Photograph of a fully assembled VTRx

Lightweight custom transceiver

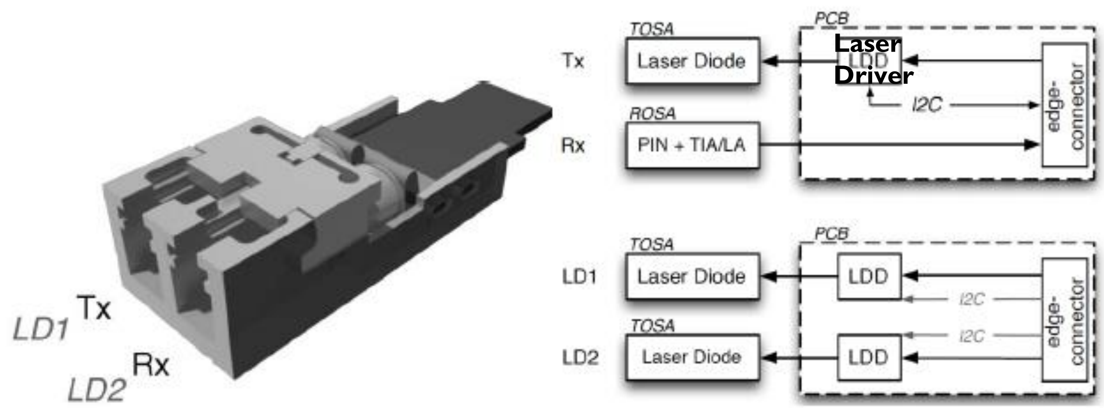
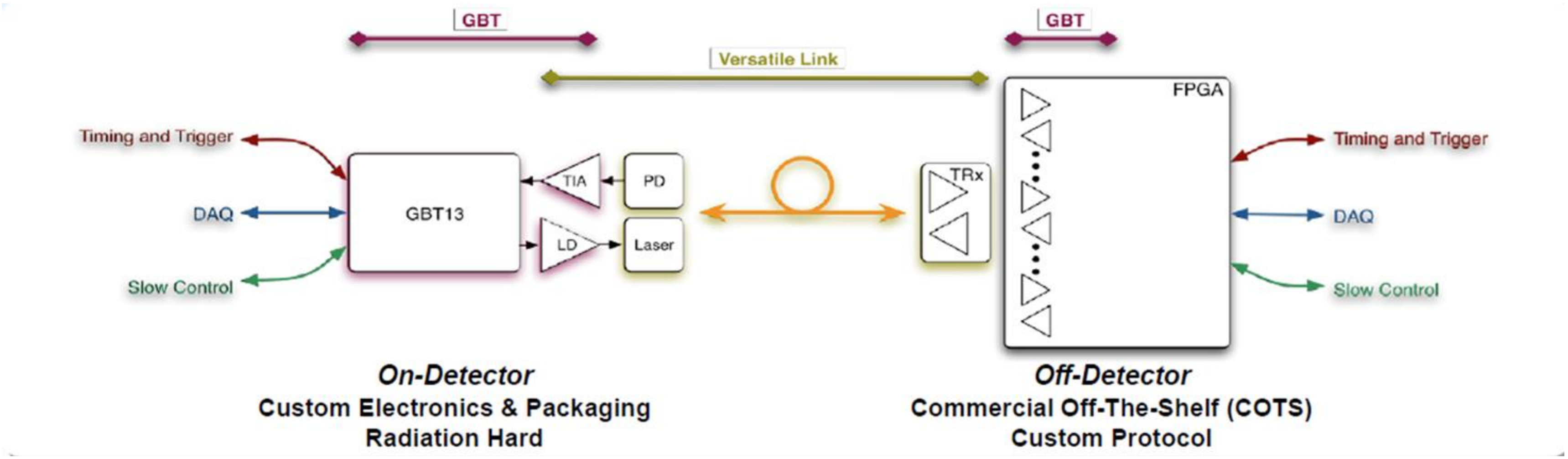


Figure 3: Sketch and blockdiagram of VTRx and VTTx modules

https://espace.cern.ch/project-versatile-link/public/default.aspx

Optical links in the LHC future : GBT link

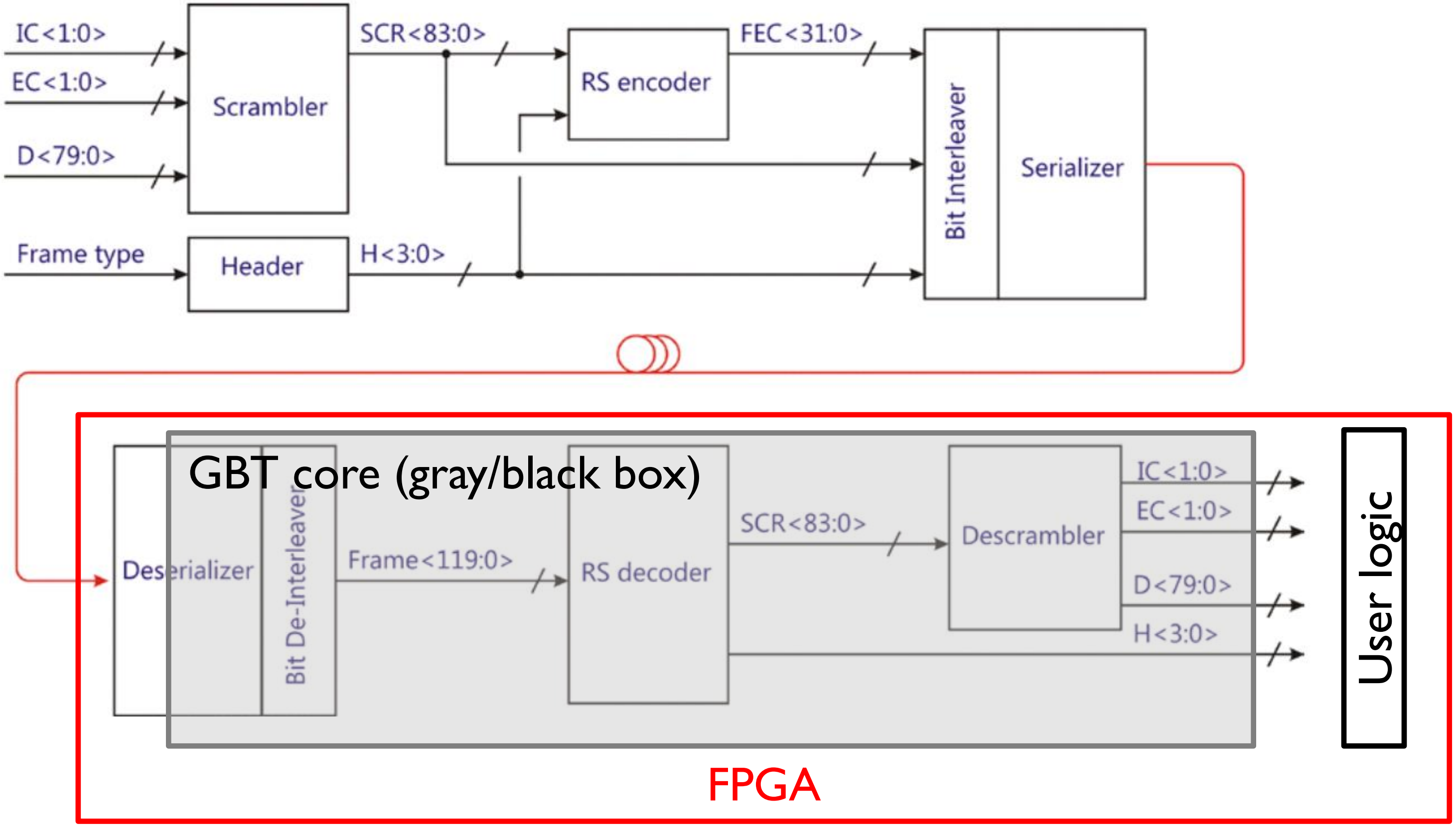


- On-detector components
  - Custom design components, ASICs (available only from CERN)
  - Radiation hard up to 10 kGray (1Mrad), 5×10^{14} n/cm^2
  - Magnetic field tolerant up to 4T
- Off-detector components
  - Commercially available components, i.e. optical transceivers, FPGAs (not radiation tolerant!)
  - Allow back-end specific implementations (power consumption, cooling, surface occupancy)

https://espace.cern.ch/GBT-Project/default.aspx

Optical links in the LHC future : GBT protocol

- GBT protocol inside the FPGA is a kit core provided by CERN

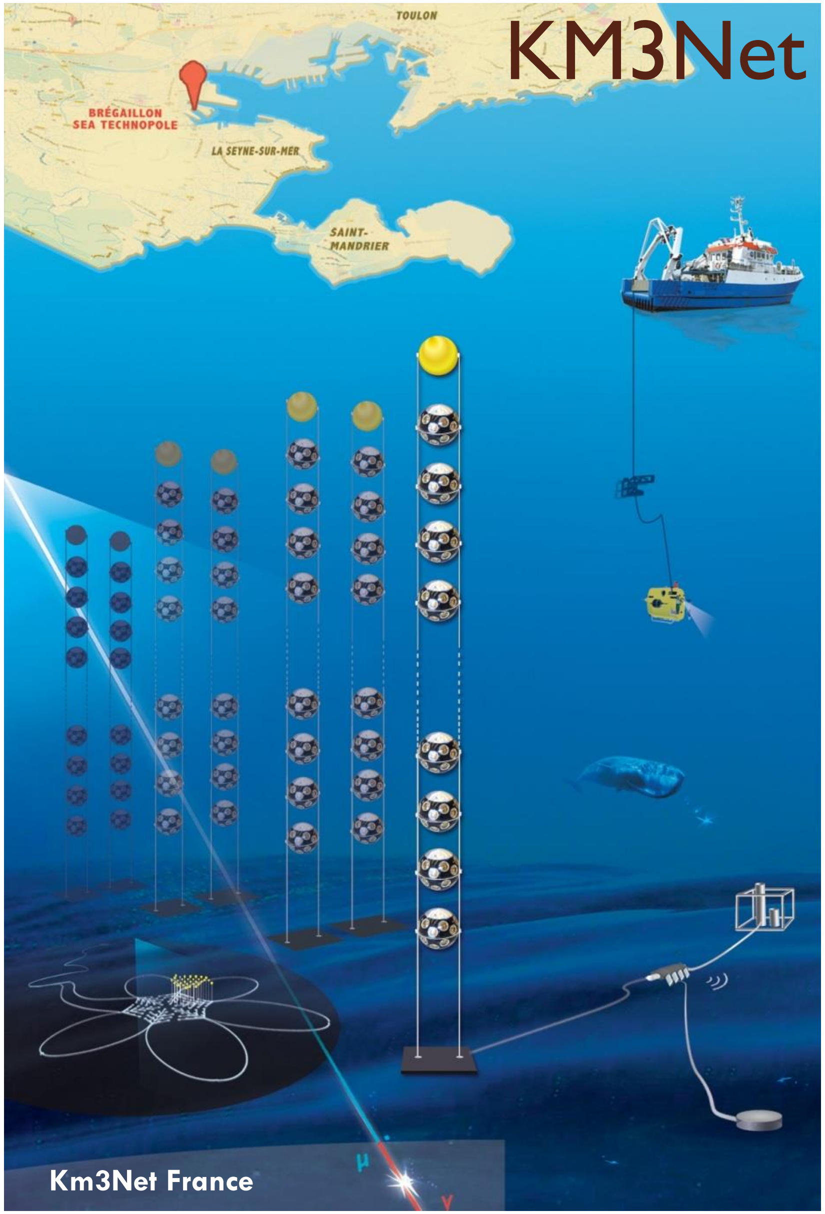


- There is a part to interface to the serializer, and another to the user logic
- The core *could* be used as a black box… but it might make your hair… gray!

https://espace.cern.ch/GBT-Project/default.aspx

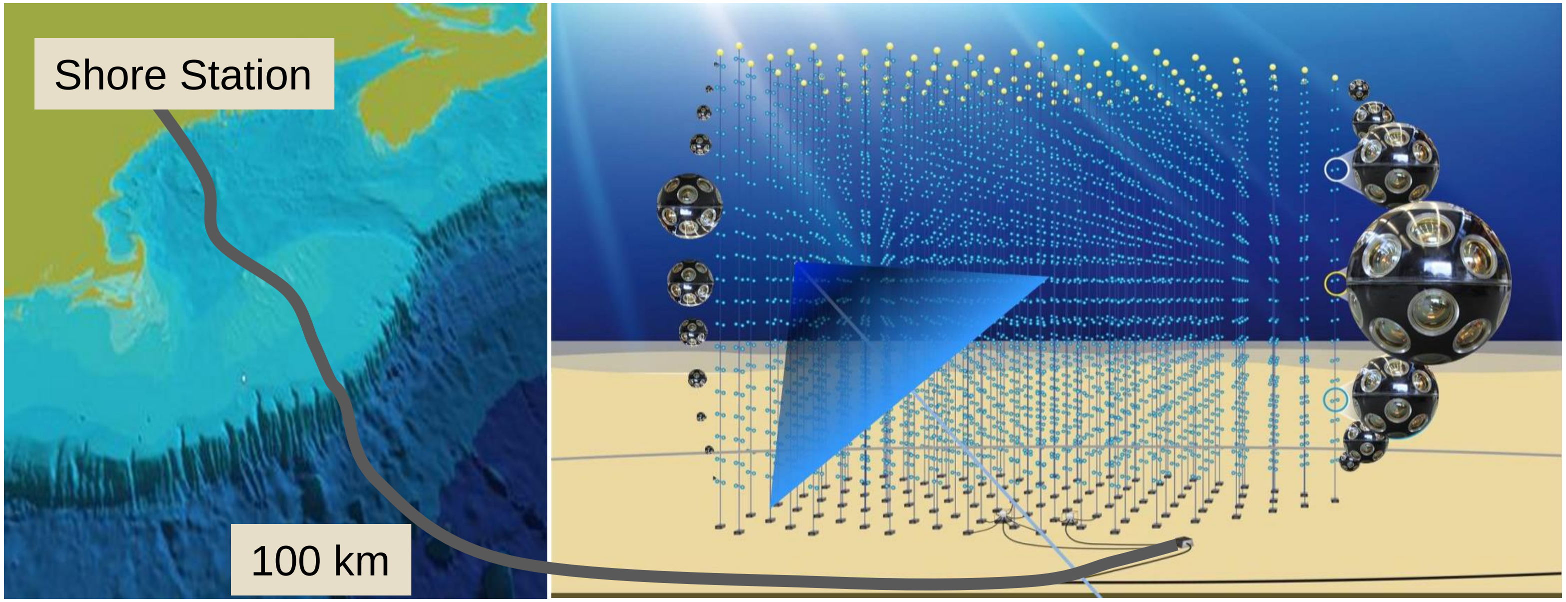
… it is not all about CERN

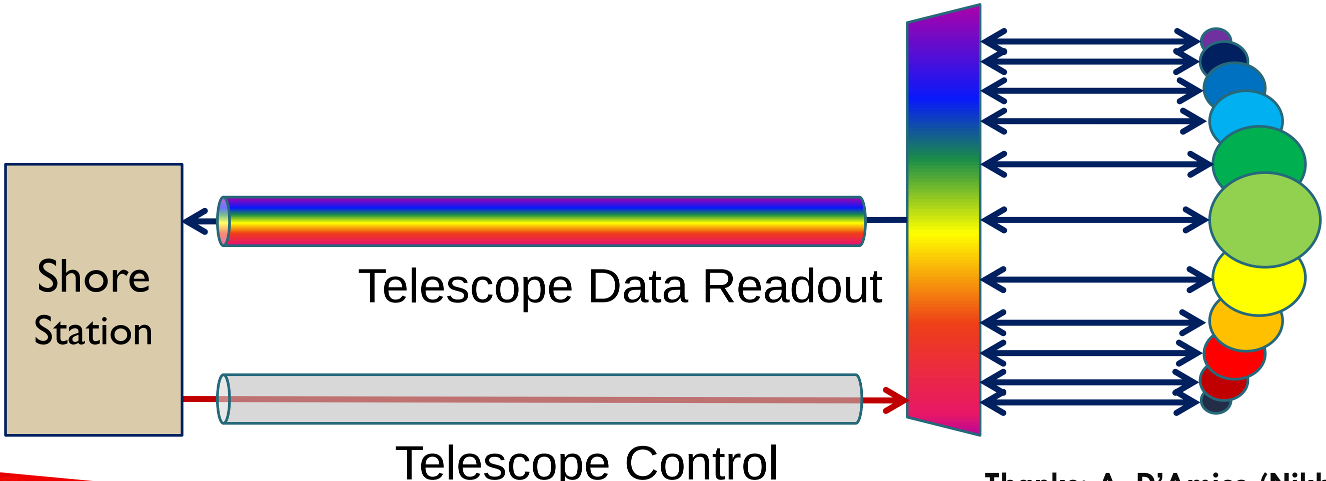
KM3Net Optical Network



- What is KM3Net?
- What are its technology highlight challenges?
- Equipment is sunk 2500-3500 m on the sea bed
- The focus for this presentation is on the special optical backbone to transfer data from the sub-sea stations and strings to the shore
- We are talking about a widely distributed (km^3) high-throughput network:
  - ~70ch spaced 50 GHz (colors!)
  - 90 Gb/s over 1 fibre
  - 20 – 36 fibres per backbone (“space multiplexing”)

KM3Net Optical Network



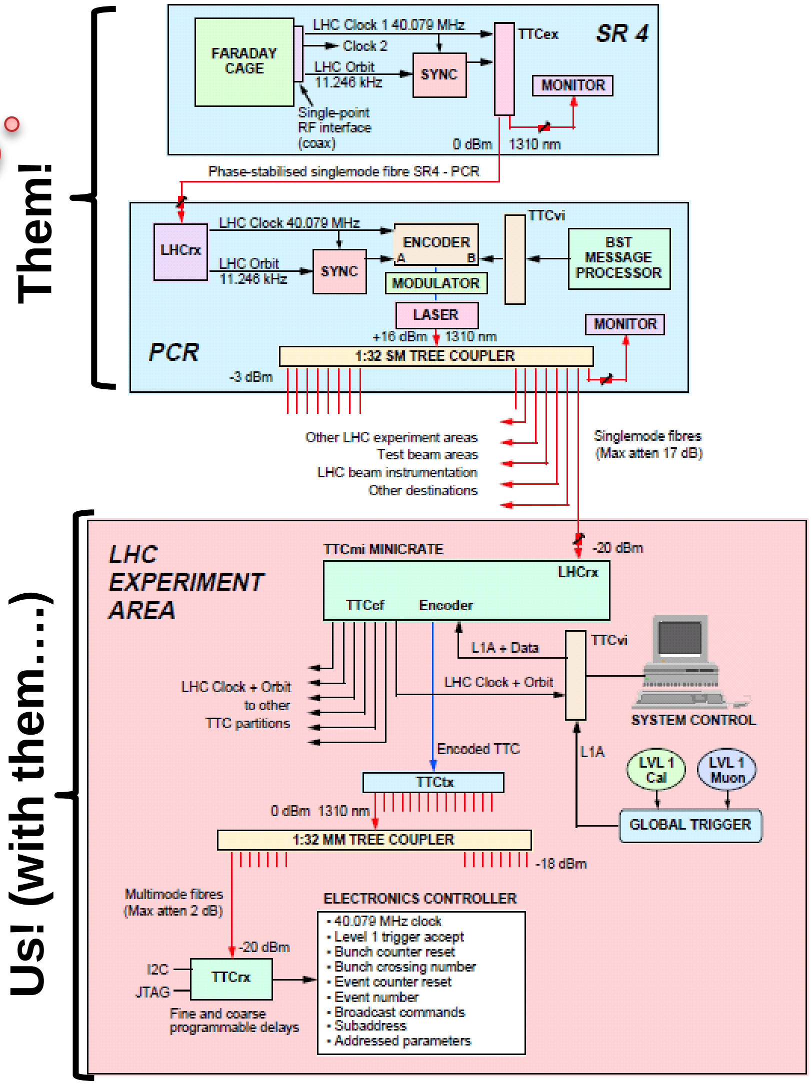


- We cannot **trigger** exploding stars…
- … but Ethernet (in “Morse code” mode) is used to distribute **timing**

Thanks: A. D’Amico (Nikhef)

Timing and Trigger on optical links

The (old) TTC system at CERN



- The overall Timing, Trigger and Control (TTC): guess what…
  It is a system architecture that provides the distribution of synchronous timing, (level-1) trigger, and broadcasts, as well as individually-addressed control signals
- appropriate **phase** relative to the LHC bunch structure is guaranteed
- account for the different **delays** due to particle time-of-flight and signal propagation.
- within each trigger distribution zone, the signals can be broadcast from a single laser source to several hundred destinations over a **passive optical network** composed of a hierarchy of optical tree couplers

http://ttc.web.cern.ch/TTC/intro.html

The TTC system: needs some refresh

Desired features of a new system

- Backward compatibility with legacy TTC system
- Bi-directionality
- Increased bandwidth
- Common system
- Scalability, partitioning flexibility
- Better performances than TTC for clock recovery (i.e. better clocks)
- Low and fixed latency (opens possibility to do time-stamping at the ROS)

- **Candidates: GBT Links and Passive Optical Networks (PONs)**

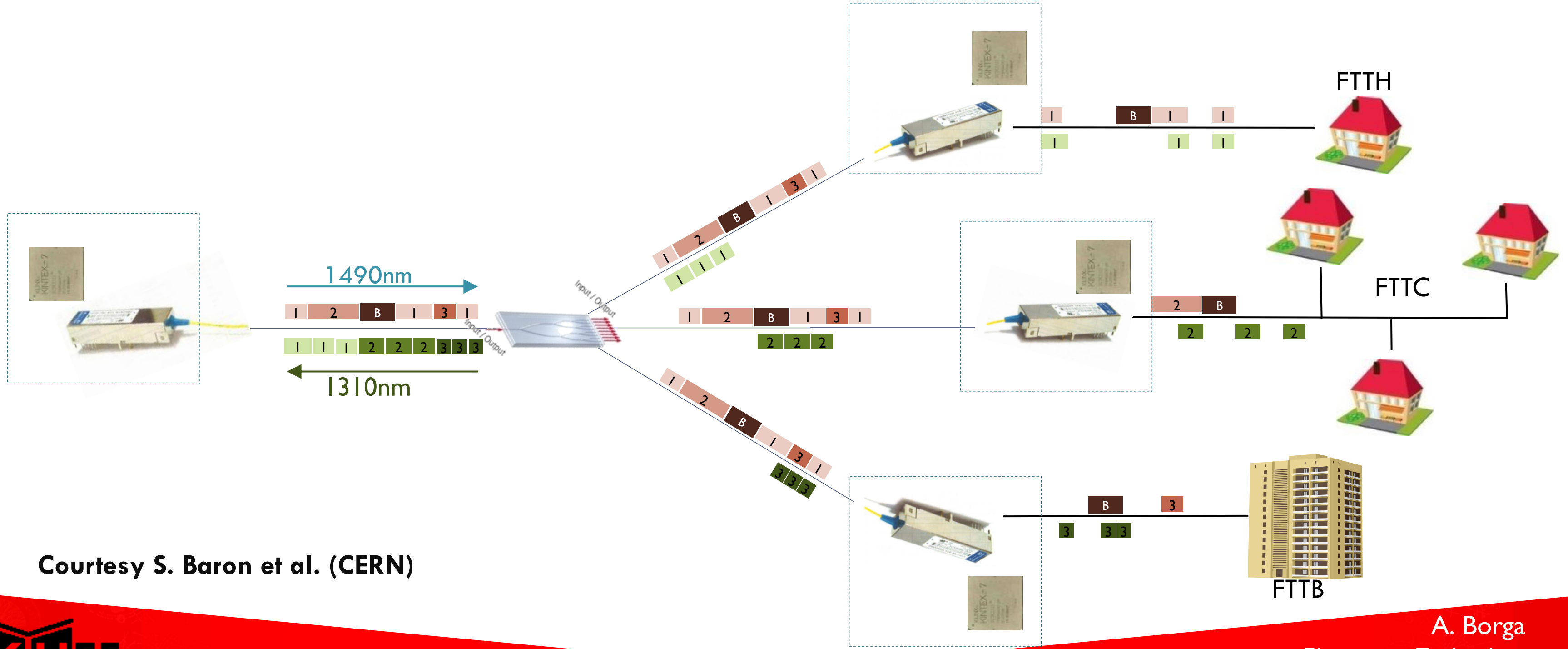
- **GBT: ideal for detectors environments, presently the only rad hard multi-gigabit optical link with deterministic latency**
- **Passive Optical Networks offer the ideal gear for backbone distribution**

http://ttc.web.cern.ch/TTC/intro.html

A. Borga
Electronics Technology Department

TTC Passive Optical Network (PON)

- Major topology of growing Access Network Market known as:
    - Fiber To The X (FTTx) (http://en.wikipedia.org/wiki/Fiber_to_the_x)
- Point-to-MultiPoint (P2M)
- One single fibre in charge of both downstream and upstream transmissions (using wavelength multiplexing technique)



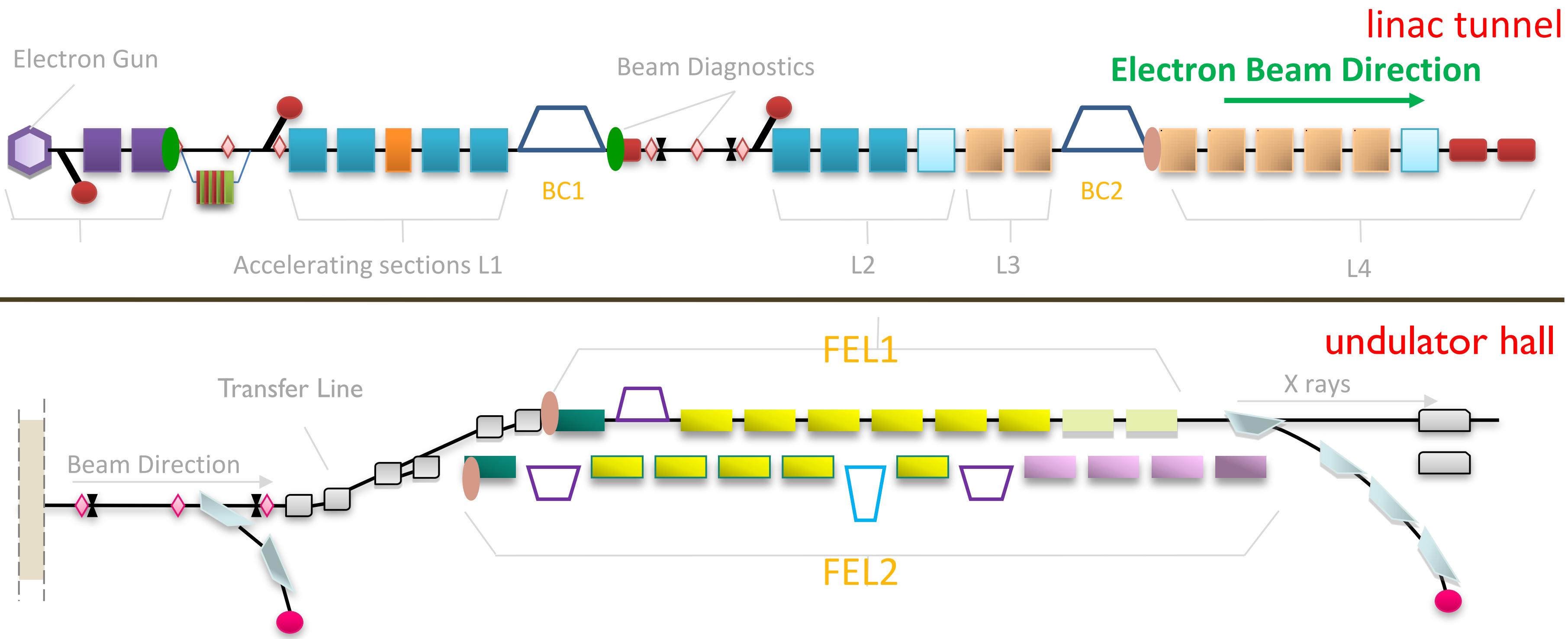
Courtesy S. Baron et al. (CERN)

Pure Timing on optical links

Optical timing for accelerators

lightsources.org

- This is a particle accelerator!
  (4th Generation Synchrotron light source aka Free Electron Laser)



- How to achieve correct driving of the magnets with respect to time?

http://www.elettra.trieste.it/FERMI/

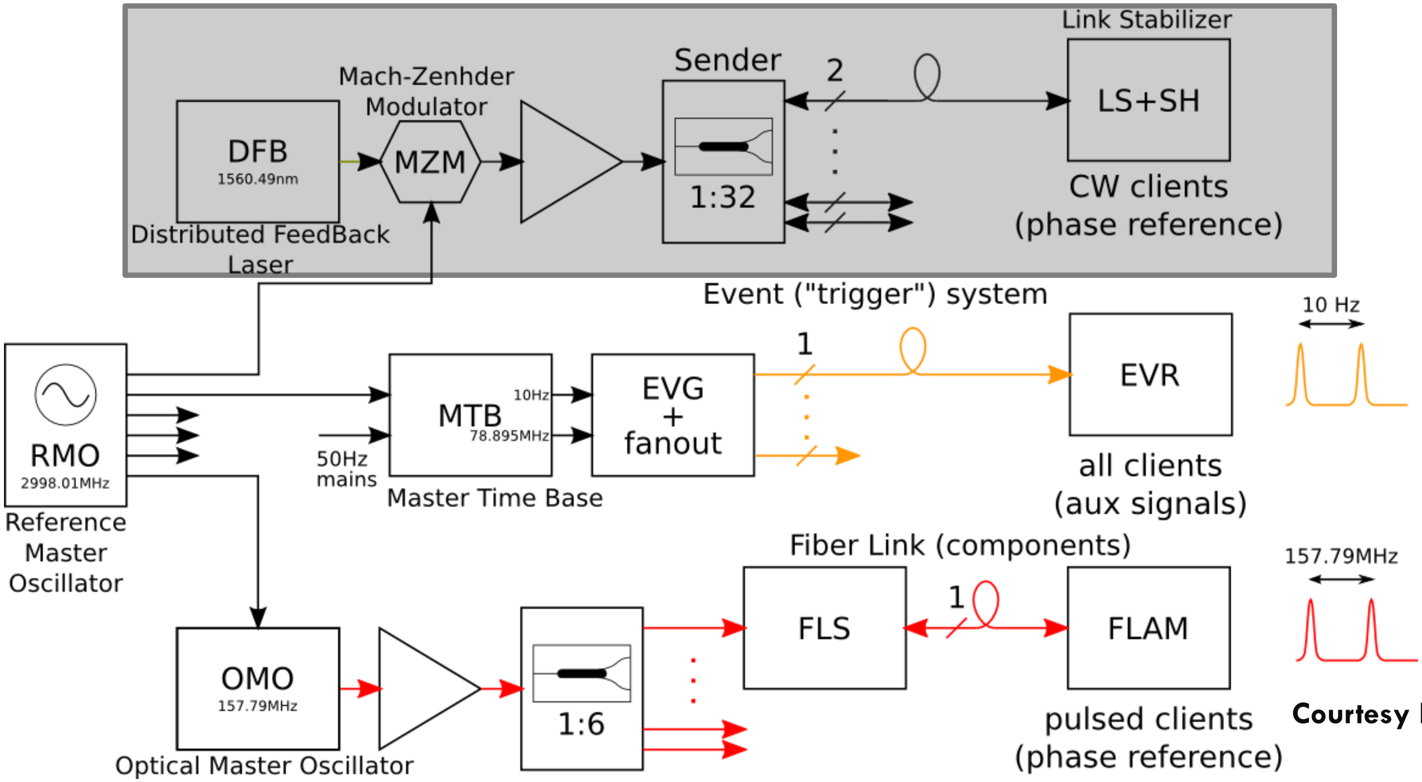
Optical timing for accelerators

Two class of signals are needed:

- aux signals (**triggers** and low-performance clock signals)
  - the machine is pulsed, hence the acquisition is not continuous but event based, therefore event-labelling for post-processing of data is required
- Ultra-stable phase reference signals (**"clocks"**)
  - used to synchronize key elements of the machine (klystrons, lasers, special diagnostics as the Bunch Arrival Monitor (BAM), etc.)

Why optical? large scale facilities (100s meters – a few km) with demanding requirements (10s femtosecond level stability). Optical techniques are available to achieve the result!

Optical timing for accelerators



This is our clock!

Courtesy F. Rossi (FERMI@Elettra)

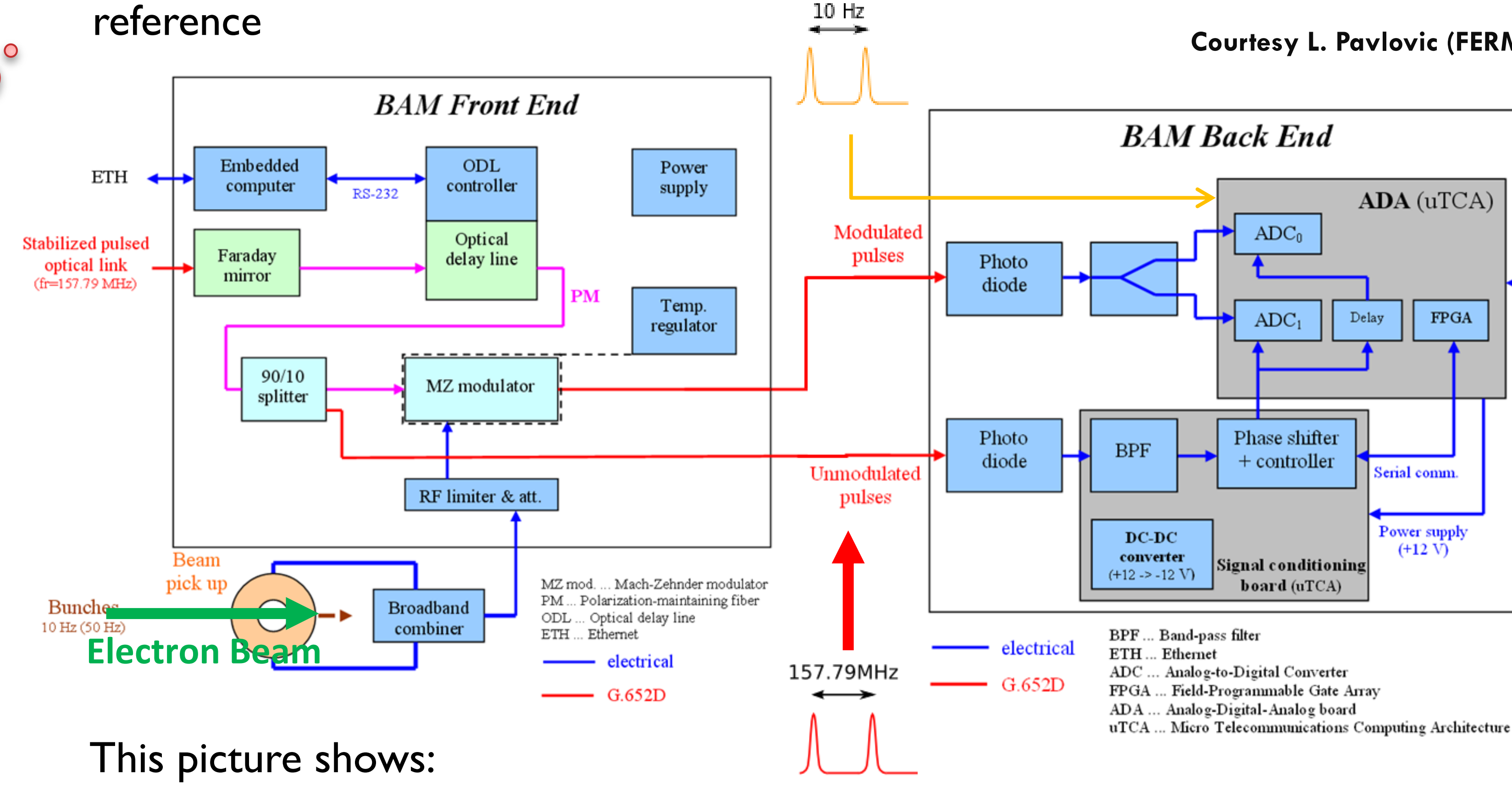
- A **pulsed system** exploits an Optical Master Oscillator (OMO) as reference signal which generates ~150 femtosecond (fs) wide pulses. The timing information is encoded in its repetition rate (157.79MHz). The fiber length variations are then measured with a cross-correlation technique to stabilize the time of flight along the link… easy! ☺
- **ContinousWave (CW)** is a RadioFrequency (RF) modulation technique where a Distributed FeedBack (DFB) laser gets amplitude modulated (by a Mach-Zehnder Modulator MZM) to transmit a RF reference (2998.01 MHz) to clients. An interferometric technique is then used to measure variation on that reference (phase delay)… even easier!☺

A. Borga
Electronics Technology Department

Optical timing example: Bunch Arrival Monitor

- Measure the relative arrival time of the electron bunches against an ultra-stable timing reference

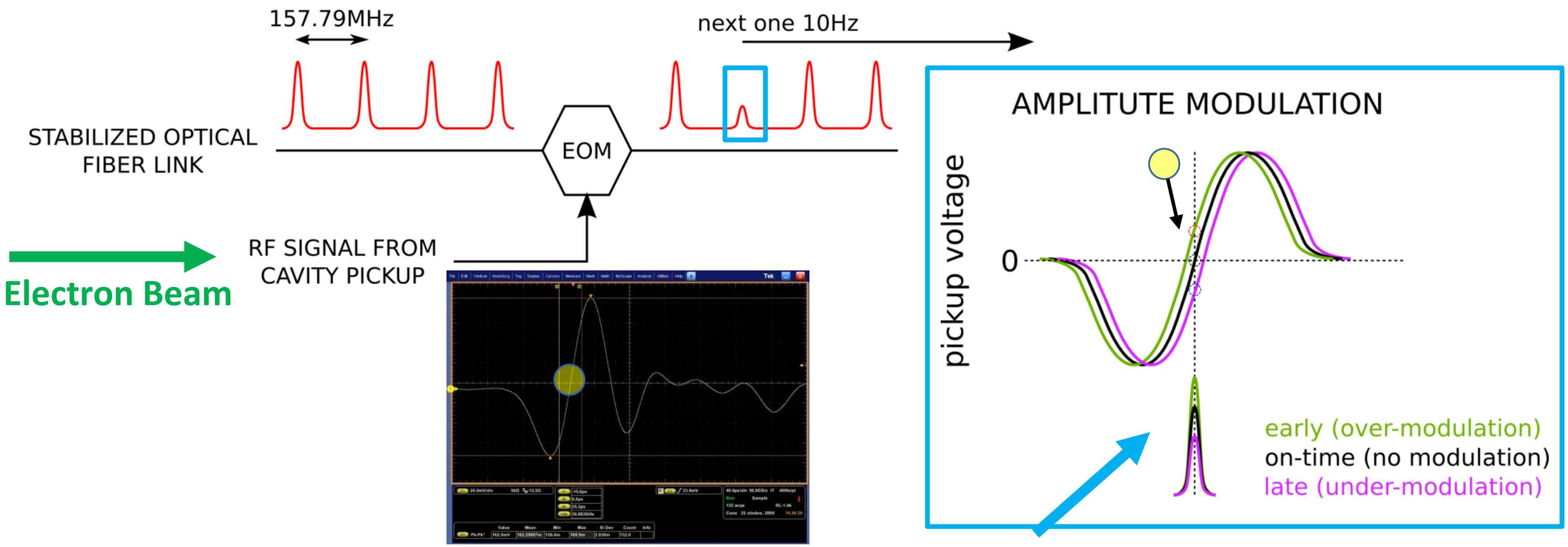
Courtesy L. Pavlovic (FERMI@Elettra)



This picture shows:

- Optical links
- An FPGA board that acts as a Trigger(ed) DAQ
- A set of ADCs

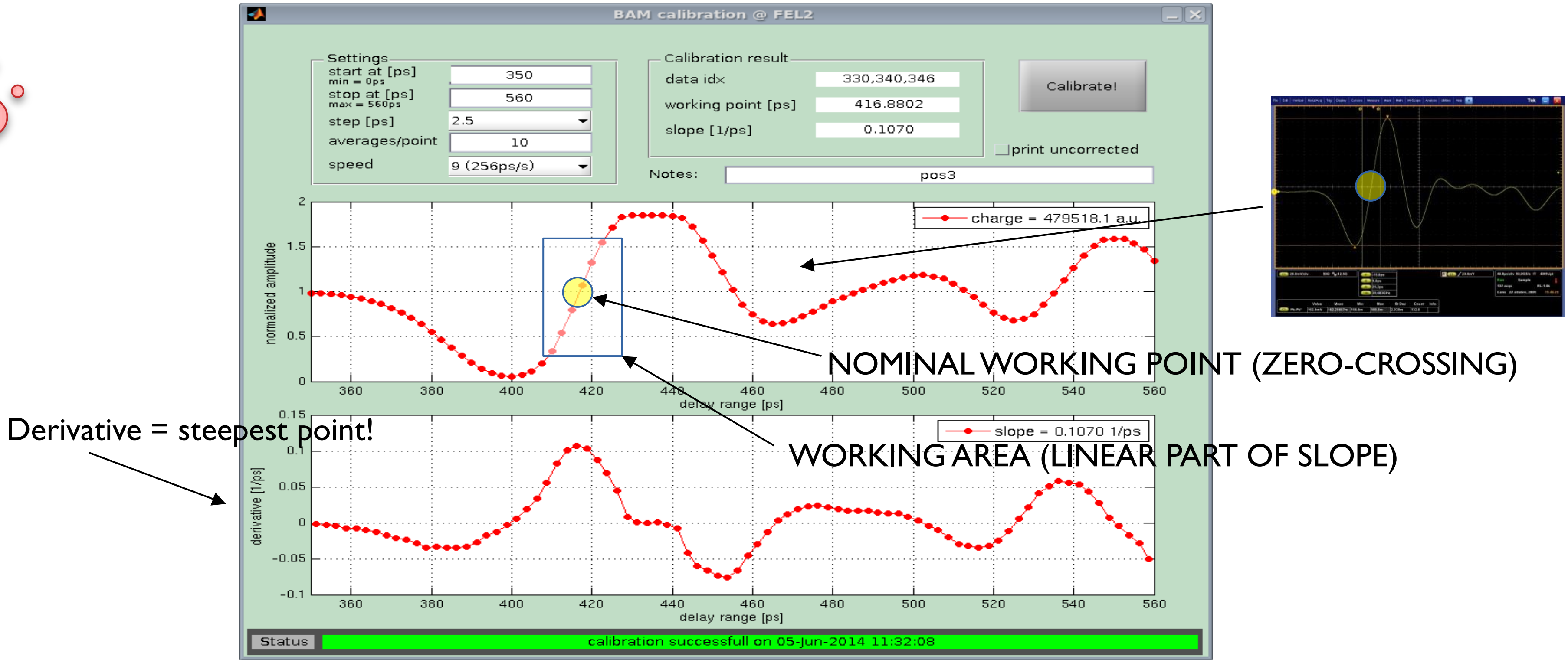
Optical timing example: Bunch Arrival Monitor



This is what we want to measure!

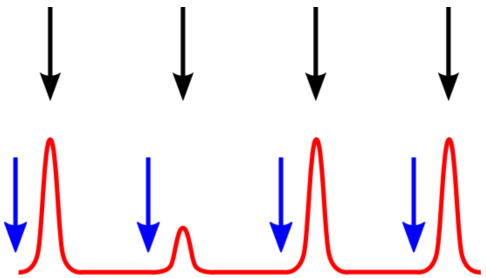
- The Electro Optical Modulator **converts timing changes into amplitude modulation** (read by 16bit fast ADCs)
- Calibration is required to find the optimum time2amplitude conversion factor
- A single impulse is modulated (the cavity signal fades out in a time shorter than the period of the optical pulses train)
- The more rapid the amplitude change the best the modulation it gets

Optical timing example: Bunch Arrival Monitor



- Calibration is required to find the time2amplitude conversion factor
- The electron beam is kept stable during calibration
- An optical delay line is used to sweep the optical pulses over the pickup signal
- The resolution depends on the amplitude noise (both sampling pulses and acquisition system) and on the RF signal slope (<10fs RMS)

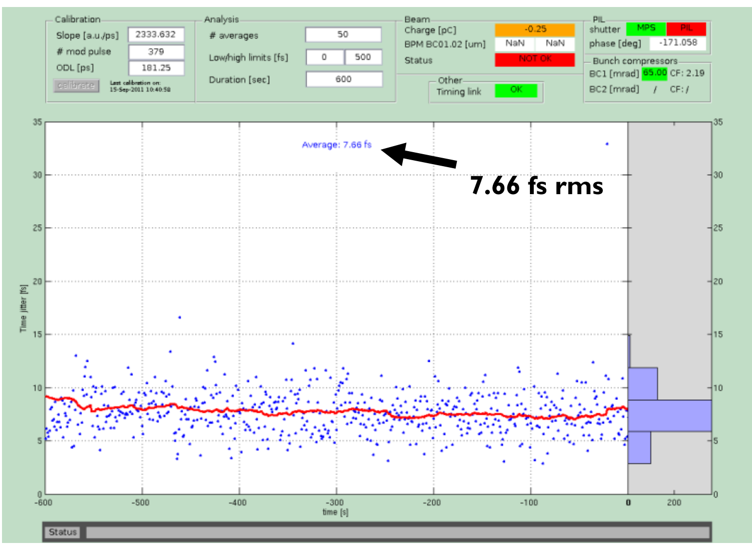
Optical timing example: Bunch Arrival Monitor



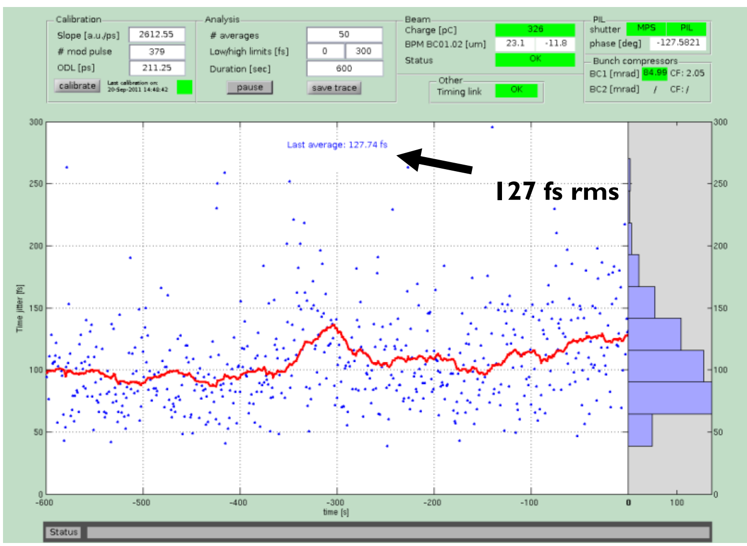
channel 1 - peak
channel 2 - baseline

- A synchronous sampling clock is extracted from the signal and split between two acquisition channels with a fixed delay between the two
- Two ADCs are employed to filter out noise and normalize the amplitude of the optical pulses

- …and this is a BAM measurement!



Noise floor



Beam stability

United Nations Educational, Scientific and Cultural Organization

International Year of Light 2015

Takeaway thoughts

- Light… has a bright side!
- Application of optical links are broad and varied
- It has a fundamental importance and interest in both the physics (of the phenomena) and engineering (of the equipment)
- There are lots of Nobel prize winners for optics related discoveries! OSA The Optical Society
- **Think hard!** 
- Acknowledgments:
Peter Jansweijer (Nikhef), Fabio Rossi (FERMI@Elettra)