Radiation Tolerant Optical Data Transmission Systems Development in the CERN/EP/ESE Group

Application/Development potential for ATS

EP-ESE Electronic Systems for Experiments

CERN

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(with input from many EP/ESE colleagues)

Introduction

EP-ESE
Electronic Systems for Experiments

- High data-rates coming out of particle physics experiments in the LHC era ➜ optical data transmission has become ubiquitous
  - Each large experiment has tens of thousands of optical links
  - Need to optimise fibre bandwidth utilisation led to need for development of aggregation/serialisation solutions
- Environmental conditions inside the detectors (radiation, (low) temperature, magnetic field) require:
  - some level of customisation of COTS parts (the optoelectronic components)
  - full customisation of the electronics, necessitating the design of custom ASICs for all link functions (de/serialiser, laser driver, receiving amplifier)
- Over-arching development strategy has been to follow telecom/datacom industry developments and minimally customise only as needed by the requirements
  - Projects matched to LHC experiments' upgrade schedules
    - LHC installation 2006-8 ➜ LS1 (2010) ➜ LS2 (2018) ➜ LS3 (2027) ➜ LS4 (2032)

Optical Link & Chipset Development History

EP-ESE
Electronic Systems for Experiments

CMS Tracker
Analogue Readout
Digital Control

CMS Pixel
Digital Readout
(Digital Control)

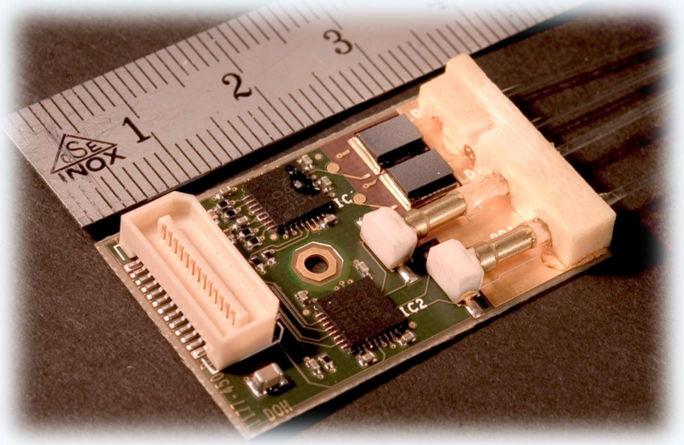
Common Project
Versatile Link / GBT
Digital Readout/Control

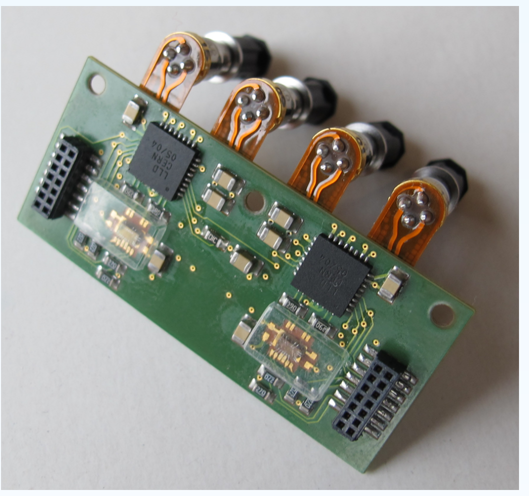
BI Project
CWDM Link
Digital Readout/Control

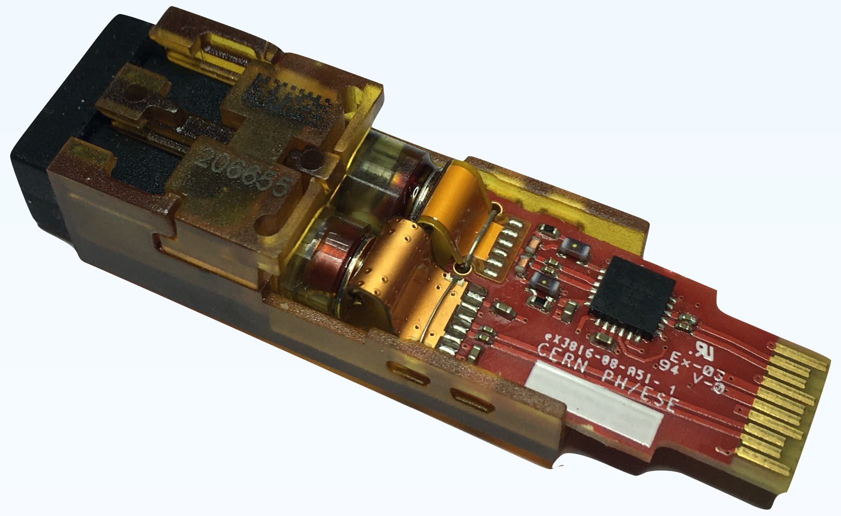
Common Project
lpGBT / Versatile Link+
Digital Readout & Control

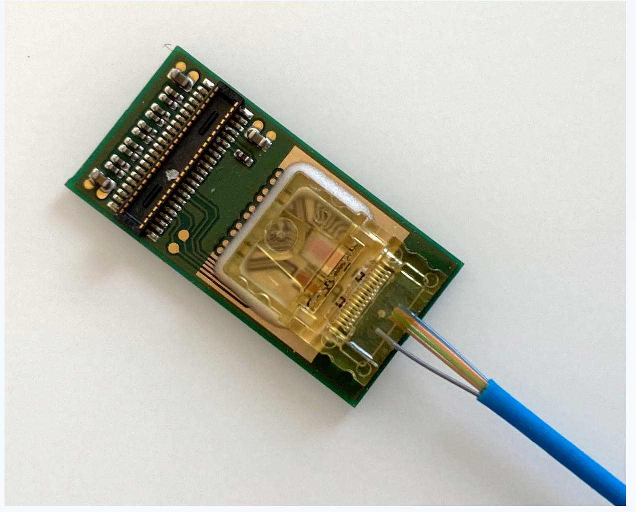
EP R&D
Silicon
Photonics

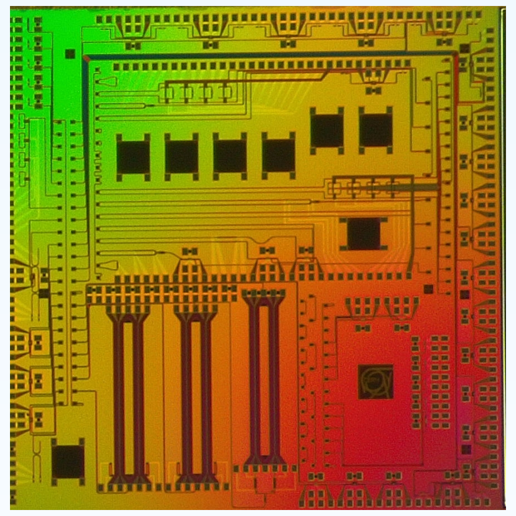
2005 | 2010 | 2015 | 2020 | 2025 | 2030

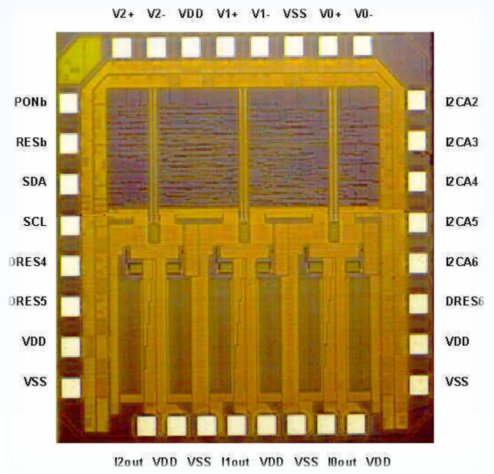


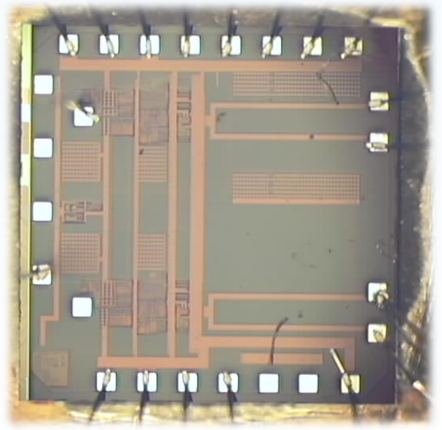


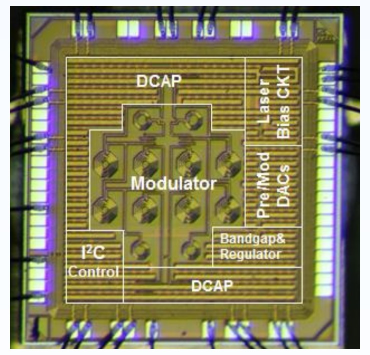


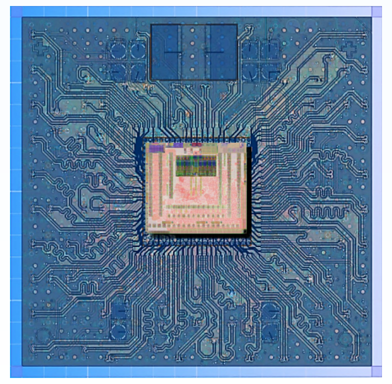


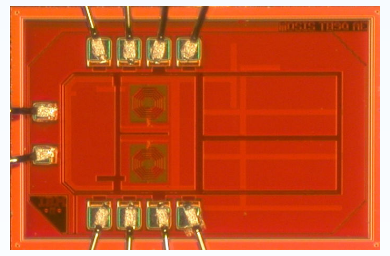


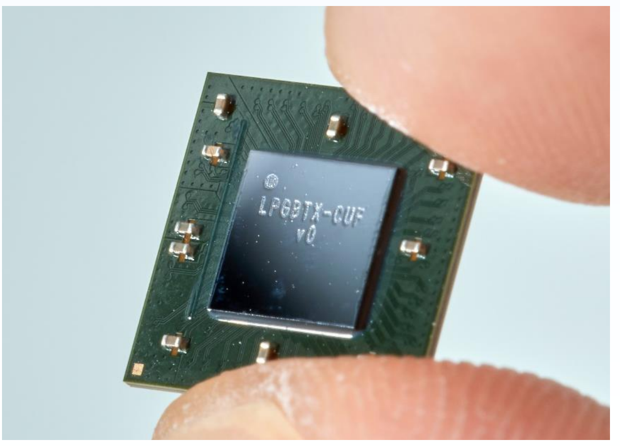






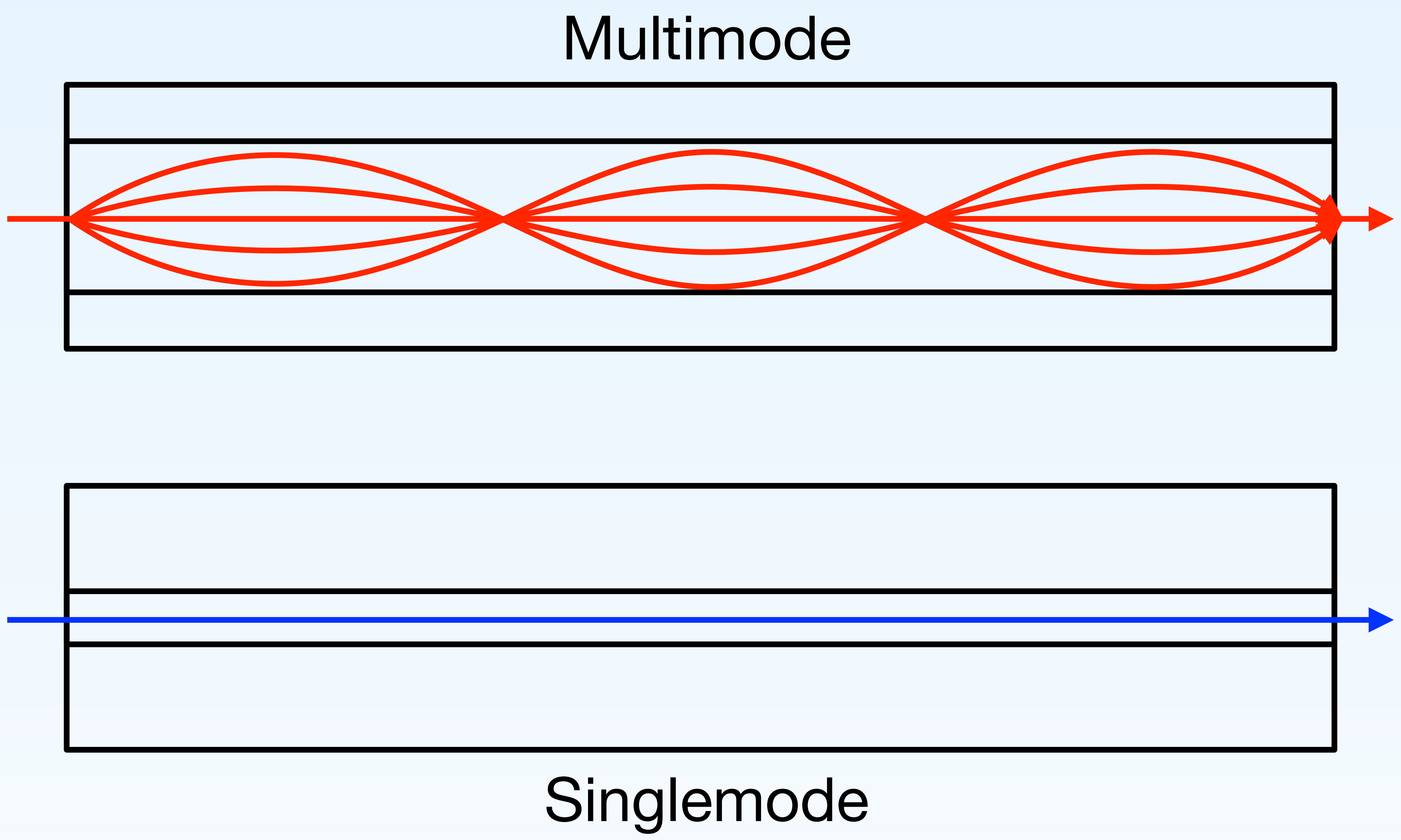






A quick word on Optical Fibre

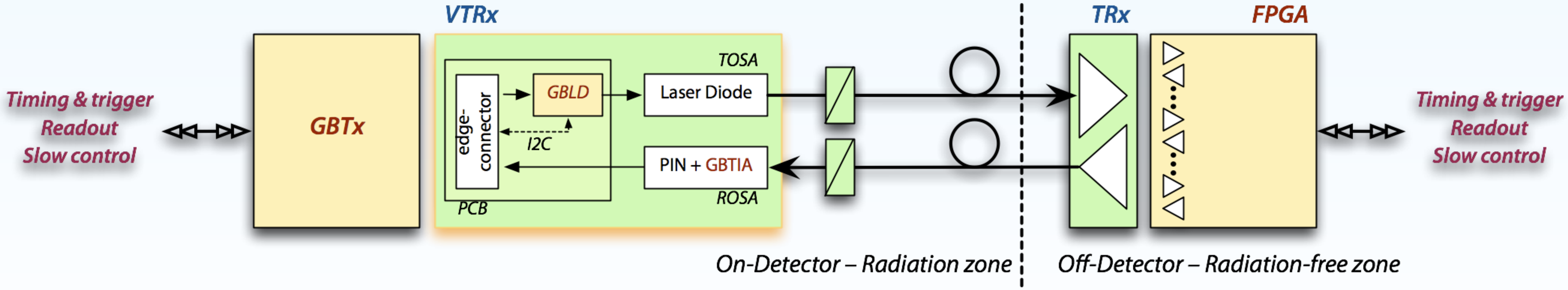
- Optical Fibres are divided into two main families
  - Single-mode & Multi-mode
- Different path lengths are possible through a multimode fibre, compared to only a single path in singlemode fibre
- Since the speed of light is constant in the glass, this leads to different parts of any light pulse we inject into the fibre taking varying amounts of time to exit the fibre
  - This broadening of light pulses is called “modal dispersion”
  - Modal dispersion in multimode fibres limits their so-called “Distance-BW product”



Systems based on multimode fibre at multi-Gb/s speeds are limited in max. transmission distance

Versatile Link & GBTx

- Radiation tolerant link designed for LS2 upgrades
  - Many constraints come from initial (incorrect, in hindsight) assumption that it would deployed in Inner Detectors with constrained material budgets
  - 5 Gb/s, bi-directional
  - Singlemode & multimode variants (MM max. distance 350-400m without radiation on fibre)
  - -30 to +60 °C
  - 10 kGy, 5×10^{14} 20 MeV n/cm^2
  - Project kick-off: 2008, production start: 2015, production end: 2019

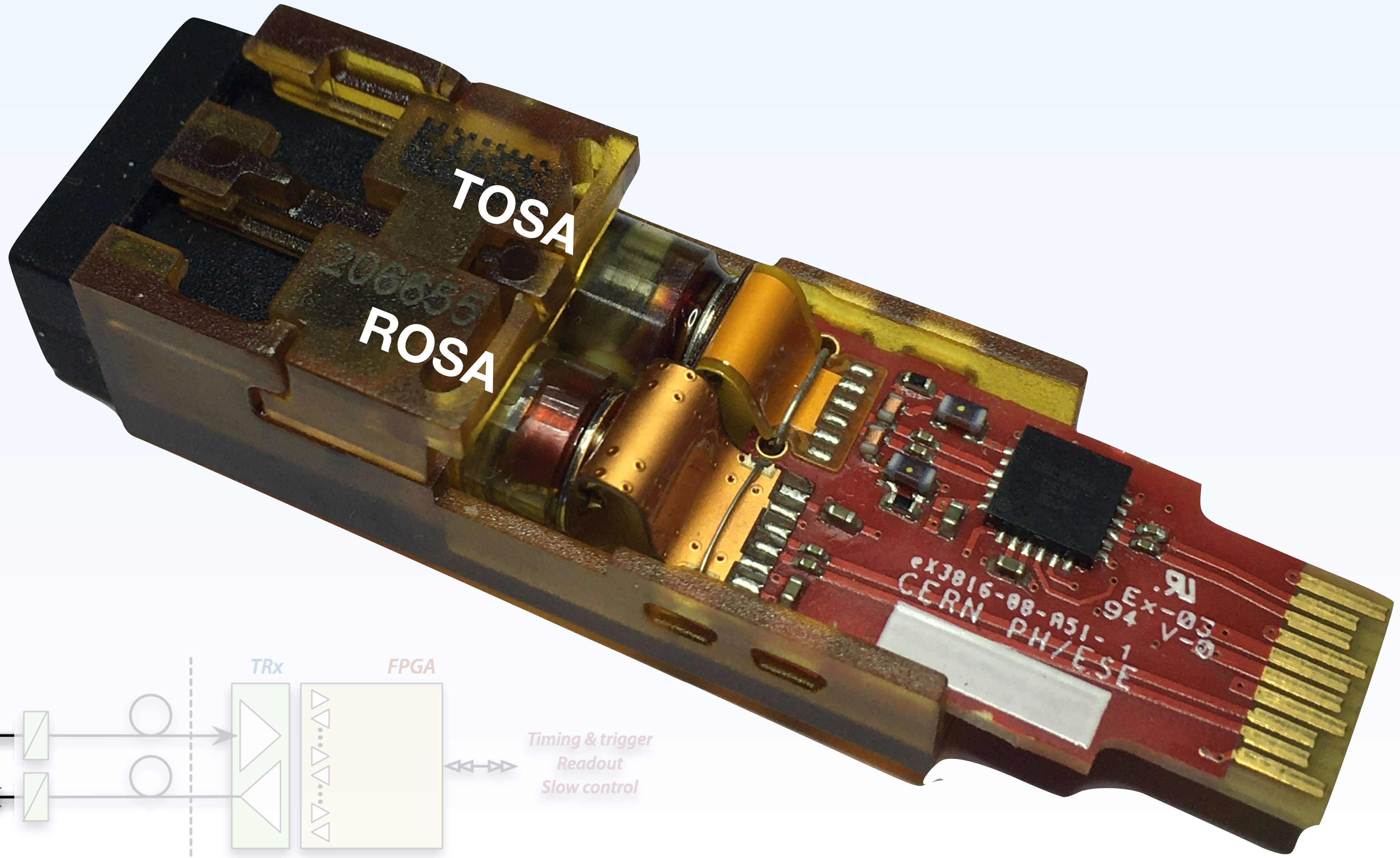


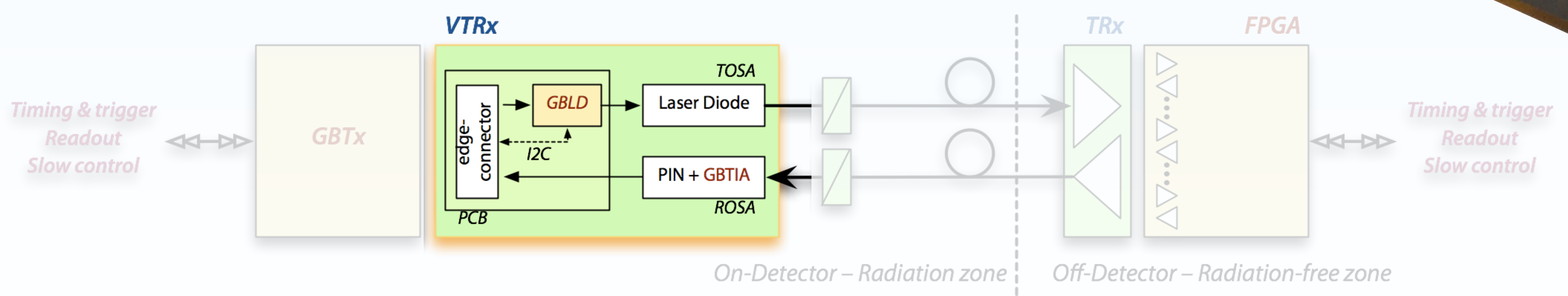
https://edms.cern.ch/project/CERN-0000076379

Versatile Transceiver (VTRx)

EP-ESE
Electronic Systems for Experiments

- Production of ~18k modules during 2016-2019
  - There is no remaining stock
- Delivered to all LHC experiments and some accelerator groups
  - Earliest deployment in CMS HCAL (YETS 2017/18)
  - Other deployments during LS2
- Non-LHC Users
  - CBM & Panda @ FAIR (GSI, D)
  - mu2e @ Fermilab
  - ITER



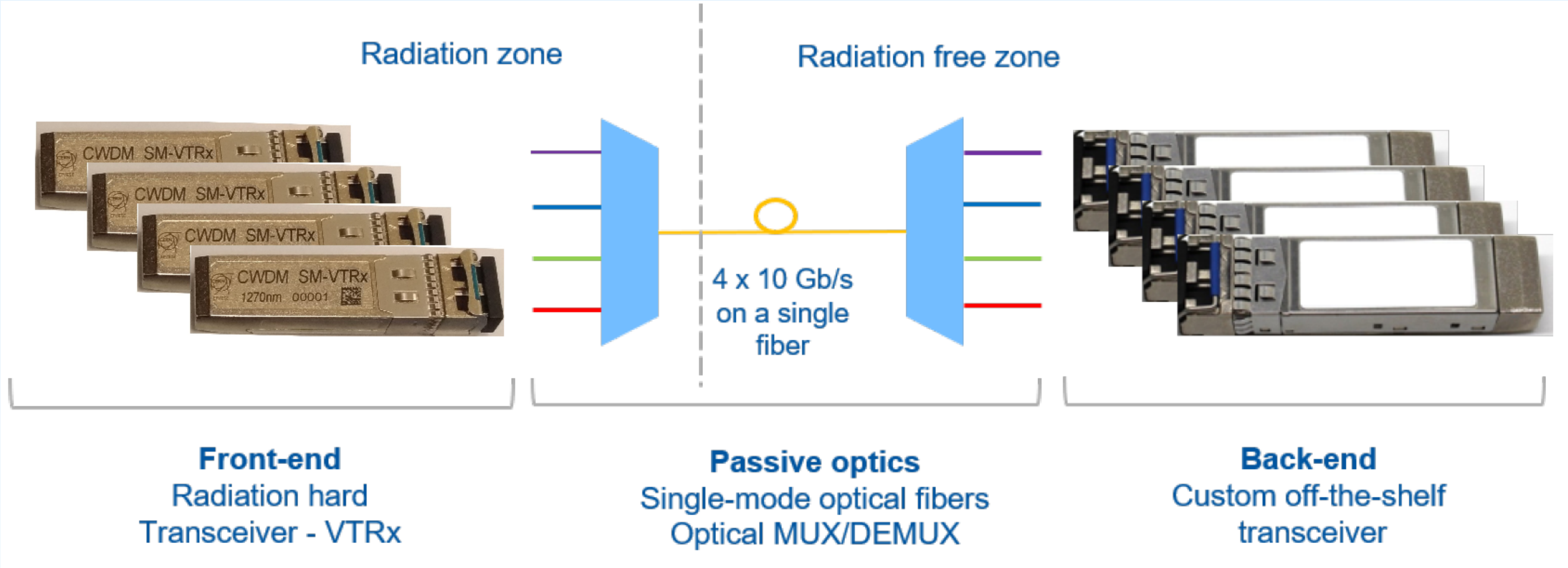


Versatile Link & GBT Radiation Qualification

EP-ESE
Electronic Systems for Experiments

- Custom ASICs (Laser Driver, TIA, GBTx)
  - SEE (Ions at LLN & Legnaro, Protons at CERN, PSI)
  - X-ray TID (at CERN)
- Optoelectronic components (VCSEL, PD)
  - SEE (Photodiodes: Protons at PSI)
  - Total Fluence (neutrons at LLN, pions at PSI)
- Full Assembly
  - Total Fluence at LLN
  - Gamma TID at Ionisos
- On-line data taking preferred for all tests
  - Dynamic effects, annealing important to extrapolate to final application
- CERN Facilities (PS Irrad, CHARM) have not been extensively used
  - Beams are not continuous, spill cycle leads to very high instantaneous flux
  - Mixing of TID and Displacement Damage makes analysis more complex
  - CHARM is not a good particle cocktail proxy for Inner Detectors of the LHC experiments

VL Spin-off: BI CWDM link



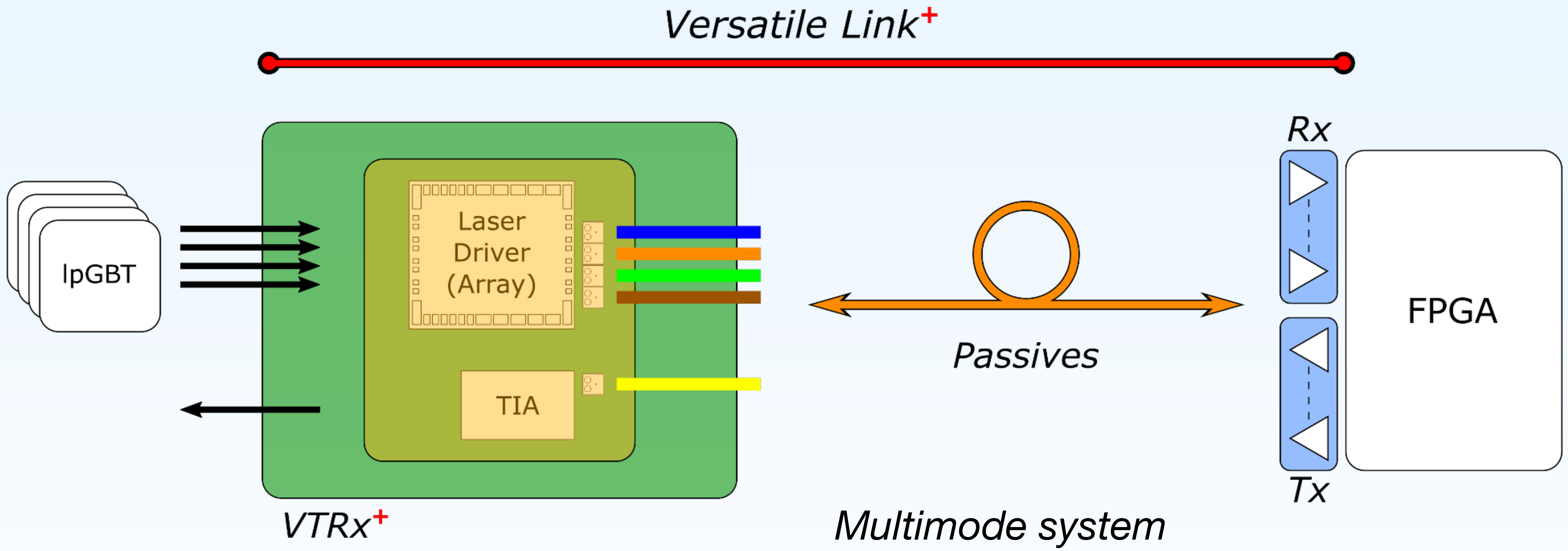
Singlemode system

Parameter	Value	Units
Uplink Bit Rate	5.12/10.24	Gb/s
Downlink Bit Rate	2.56/5.12	Gb/s
Wavelengths	1270/1290/1310/1330	nm
Total ionizing dose (TID)	10	kGy
Fluence	$5 \cdot 10^{14}$	20 MeV n/cm^2
Link Length	10	km

Project ongoing: target deployment by SY-BI in BPM and BLM systems in LS3/LS4

Versatile Link Plus & lpGBT

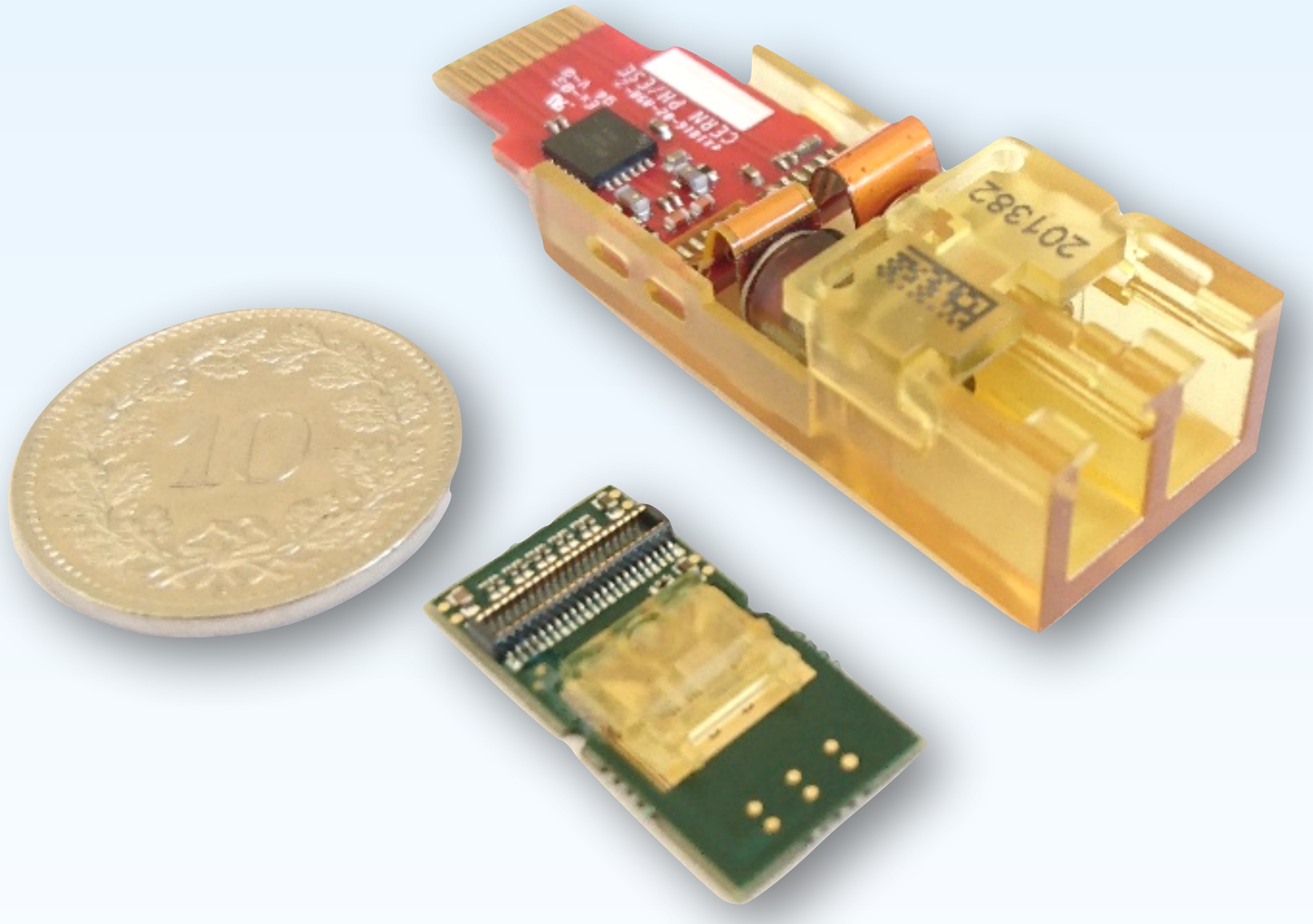
- The Versatile Link Plus (VL+) provides up to 40 Gb/s for the readout and 2.5 Gb/s for the control of High Luminosity LHC (HL-LHC) experiments (LS3 and beyond)
- This is a collaborative project, where in particular we have a strong collaboration with the EN-EL group responsible for CERN's optical fibre infrastructure



- Strong collaboration with lpGBT project: VL+ is protocol-agnostic, but it is designed to be fully compatible with lpGBT Serializer/Deserializer

VTRx+ Transceiver Module

- Miniaturized and pluggable
  - Electrical connector
  - Optical pigtail
- Up to 4Tx+1Rx configuration
  - configurable by channel masking
- Tx:
  - 1×4 850 nm VCSEL array
  - 5 and 10 Gb/s
- Rx:
  - 1x InGaAs photodiode
  - 2.5 Gb/s
- For harsh environment
  - Temperature: -35°C to +60°C
  - Total dose: 1 MGy
  - Total fluence up to 1×10^{15} n/cm^2 and 1×10^{15} hadrons/cm^2

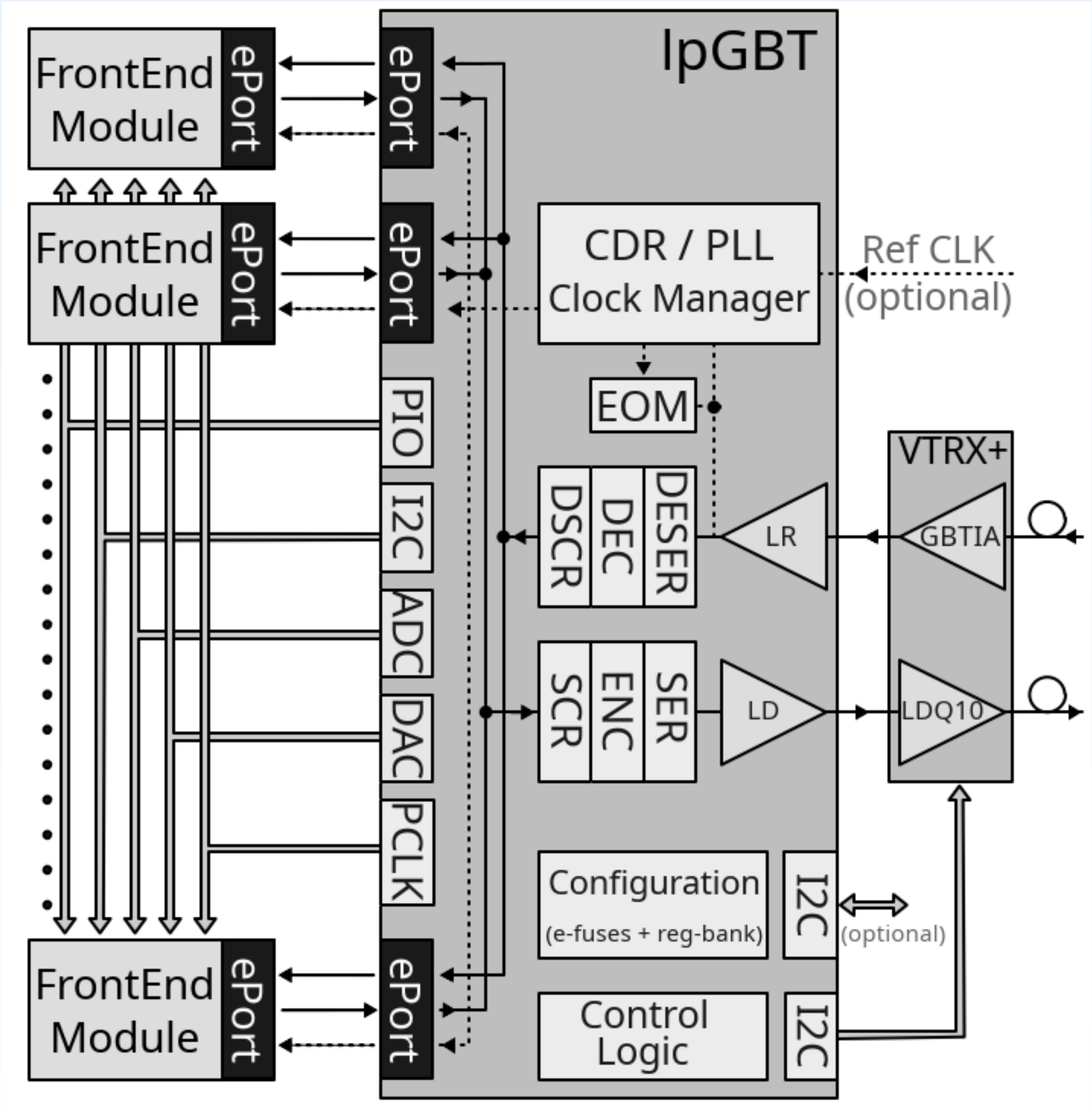


https://edms.cern.ch/project/CERN-0000149832

lpGBT Overview

EP-ESE
Electronic Systems for Experiments

- Down-stream data-rate: 2.56 Gb/s
  - High-precision clock recovery with stable phase
    - Fine phase shifting also available
  - Control path to attached peripherals via
    - bi-directional ePorts
    - GPIO (16 pins, either in or out)
    - I2C (3 Masters)
  - Internal peripherals (inc. 16-input analogue MUX)
    - ADC (10-bits)
    - Current DAC (8-bits)
    - Voltage DAC (12-bits)
    - Temperature Sensor
- Up-stream data-rate: 5 or 10 Gb/s
  - Two levels of FEC for data integrity
- Ability to operate in Transceiver or Transmitter-only modes



https://gbtproject.web.cern.ch/gbtproject/#lpgbt-ecosystem

Radiation Qualification

EP-ESE
Electronic Systems for Experiments

- lpGBT
  - TID: x-ray dose to 1 MGy
  - SEE: HI testing in LLN with 5 ion species covering LETs from 6 to 32.4 MeV•cm^2/mg
    - SEE cross-sections extracted for multiple error types
    - Being written up in TNS paper that is currently under review

- VTRx+
  - Chipset TID: x-ray dose to 1 MGy
  - Chipset SEE:
    - HI testing of Laser Driver in LLN
    - Proton testing at PSI of Rx TIA
  - VCSEL/PD Total fluence: LLN neutrons to 3x10^{15} /cm^2
    - Every production wafer of VCSELs and PDs is qualified
  - Module TID: 1MGy
  - Module Total Fluence: LLN neutrons to 3x10^{15} /cm^2
    - This includes neutron SEE for the chipset, which agrees with HI & Proton testing

Radiation Penalties documented in:
https://edms.cern.ch/document/1833735/1

VTRx+ Module & lpGBT Production status

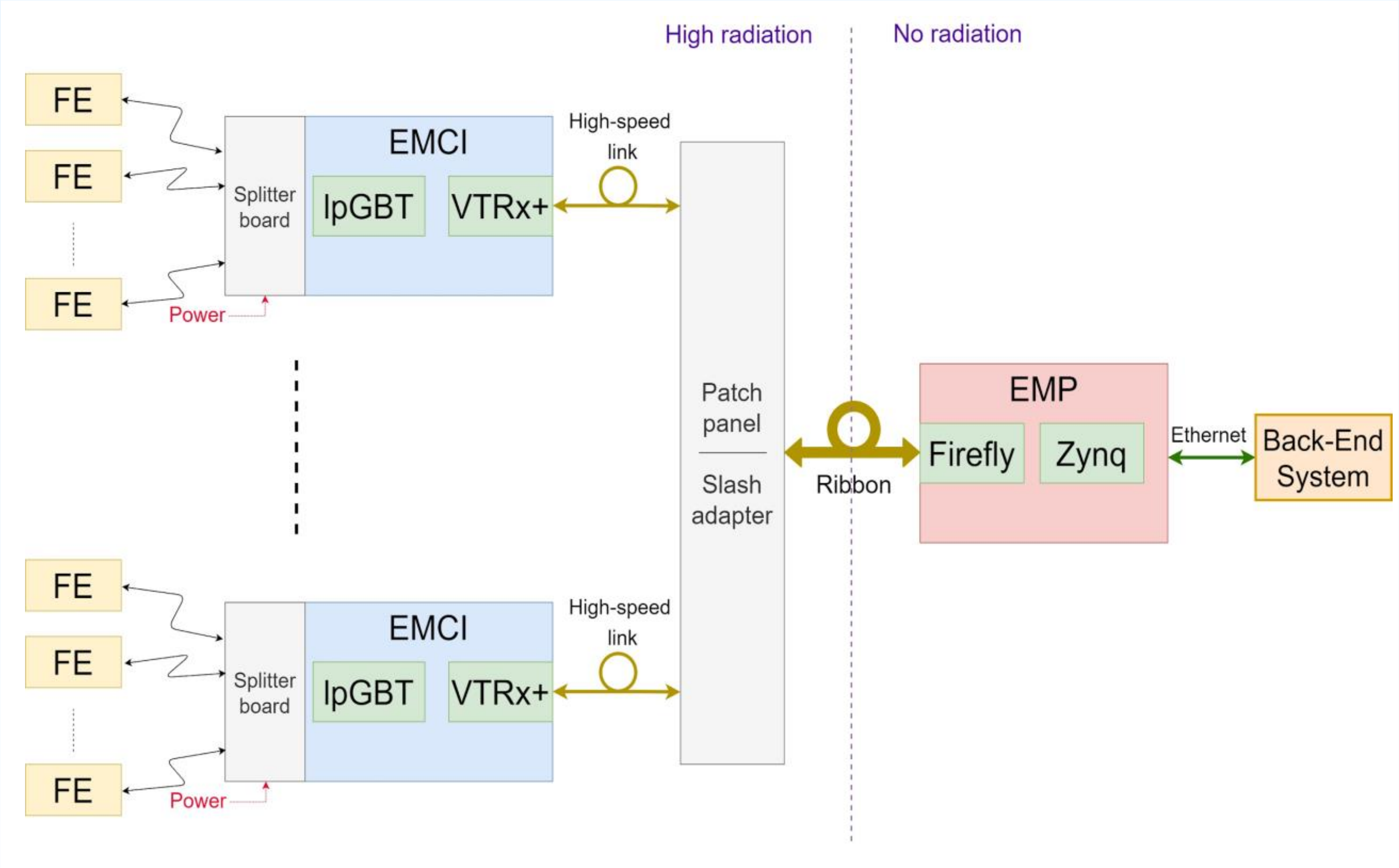
CERN EP-ESE Electronic Systems for Experiments

- VTRx+ is currently in production
  - The total production quantity will be approx. 100k modules
  - Production will run into 2026 at a rate of 2000 modules/month
  - There is component capacity to add more parts to the current production
- lpGBT production and chip testing is complete
  - The total production quantity is approx. 270k chips
  - Stock remains at the level of 20-30k after all LHC experiment needs are met

Example System Application: EMCI-EMP

- Intended for “slow” control in LHC experiments, will be deployed in ATLAS
- Collects and distributes monitoring data
  - via ADCs/DACs in lpGBT
  - e.g. supply voltages and currents, temperatures
- Provides configuration data to FE
  - Clocks
  - via I2C Masters in lpGBT
  - via lpGBT e-Ports
  - via GPIO in lpGBT
- EMP is based on a COTS SOM platform
- Star topology with up to 12 custom EMCI modules per EMP
- Each EMCI can receive data from up to 28 FE chips

Based on the VL+ Multimode system



Changing the transport layer to using Singlemode links would make this compatible with ATS Applications

The Common Project Model

- The optical link systems deployed in the LHC experiments at start-up were conceived and produced by many different groups
  - Using essentially the same set of base components
  - Necessitating individual component selection and qualification efforts
- Following a community-wide “Lessons learned” campaign after installation was complete, the groups re-focussed their efforts on a collaborative, common project model
  - Different groups took responsibility for different parts of the system and its development
    - SerDes ASICs, Laser Driver ASICs, Receiver ASICs, Optoelectronic components, Fibre, Back-End COTS
- This model has been very successful for now two optical link generations
  - Relies on ability of link developers to capture user requirements
    - Achieved in common projects by having collaborators from users in different experiments (applications)
  - Provides “standardisation” by another name
  - EP-ESE is ready to collaborate and extend this model that is already shared with SY-BI to others in the ATS sector

Component Supply vs Collaboration

EP-ESE
Electronic Systems for Experiments

- EP-ESE produces optical link components and ASICs on a cyclical basis, aligned with experiment upgrades (and thus naturally the LS)
  - This one-size fits most approach results in significant savings, particularly in testing costs associated with radiation-qualifying large numbers of different COTs components to multiple radiation levels
  - We are now in an R&D phase with Silicon Photonics (a Singlemode system) at the forefront
- For ATS to profit from these developments, one choice could be to purchase and store components during a production cycle, for future use
  - User support for the relatively complex lpGBT system is currently available, but this will not remain the case indefinitely. Depending on the length of storage for future use, this may become an issue
- Another possibility is to start a collaborative “common” project to develop a link system that might be appropriate for a large community of ATS users, as we are currently doing with SY-BI
  - Sharing the system requirements definition and the implementation according to the strengths of the various existing groups/teams.