Optical Links
for on-detector electronics

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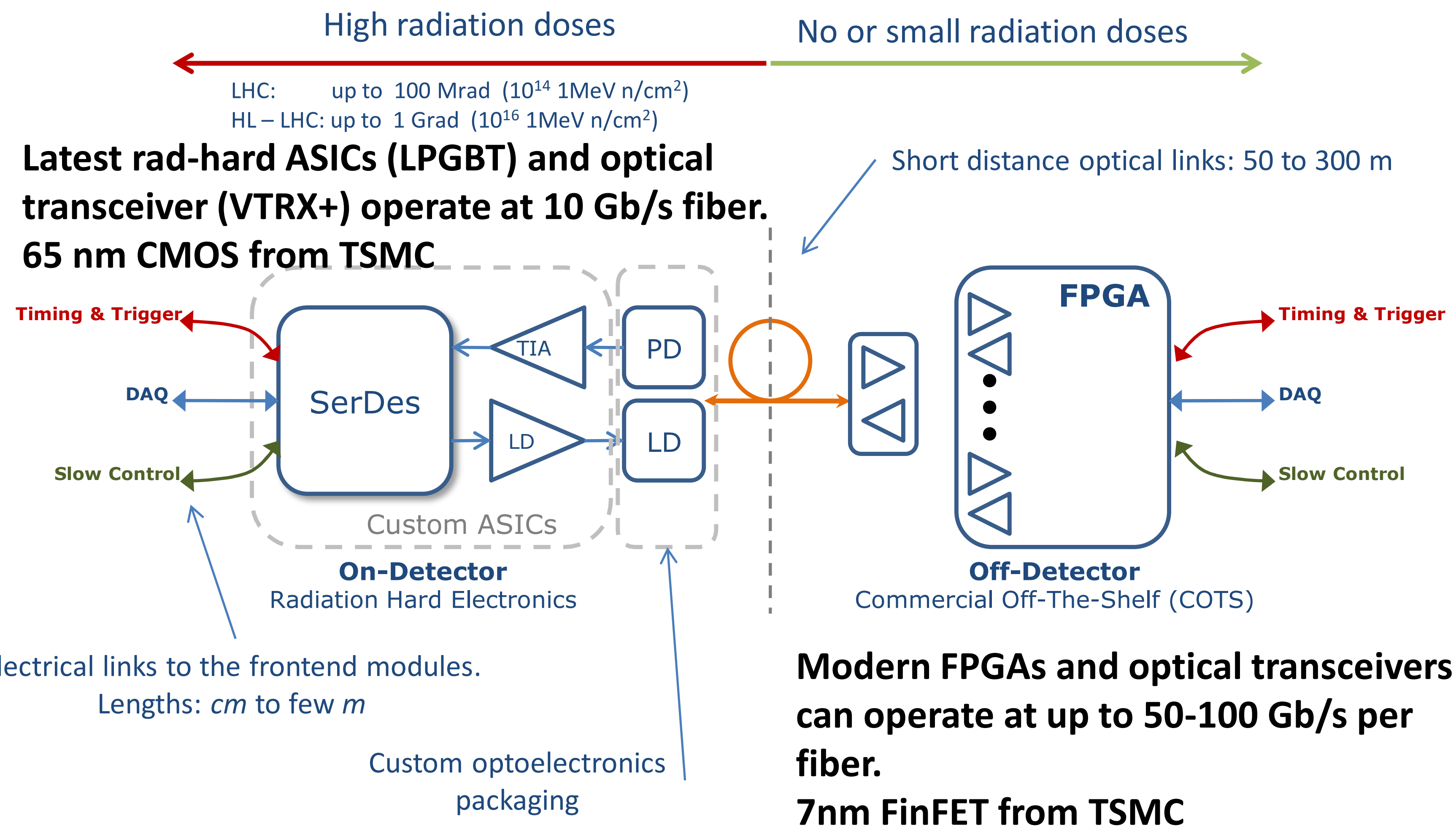
Introduction

Today's typical HEP Link Architecture

Challenges:

- Radiation (TID, SEE), in both pp and ee machines
- Reliability, especially the link to detector, and the radiation induced degradation in photo diode.
- Low power, low mass and small footprint
- There is also interest in cryo-capable fiber-optical links. Most COTSs don't work in LAr.
- **Future experiments at FCC-hh will require links operating at 100 Gb/s.**



Latest rad-hard ASICs (LPGBT) and optical transceiver (VTRX+) operate at 10 Gb/s fiber. 65 nm CMOS from TSMC

Modern FPGAs and optical transceivers can operate at up to 50-100 Gb/s per fiber. 7nm FinFET from TSMC

Slide from Paulo Moreira, CERN EP workshop on R&D, 2019/10/24

Current status*, trend

	Generation/Speeds		(AS)ICs	OMs (Optical Modules)
Current LHC detectors	1*,	1.6 Gbps	G-Link (the only COTS, bipolar) GOL (0.25 um CMOS)	OTx, ORx (COTS based custom modules) SC or ST type of COTS transceiver
Phase-I upgrades	2,	4.8 Gbps	GBTx, GBLD, GBTIA, LOCx2-130 (130 nm CMOS)	VTRx (LC connectors, CERN common project)
		5.12 Gbps	LOCx2, LOCld (0.25 um SOS)	MTx, MTRx (specially for LAr, 6 mm height)
Phase-II upgrades + R&D**	3,	5.12 /10.24 Gbps 20.48 Gbps	lpGBT, LDQ DLAS10, cpVLAD, QLDD, QTIA, GBS20 (65 nm CMOS)	VTRx+ (4 Tx + 1 Rx array) MTx+, MRx+, MTRx+, QTRx

*, the list is not complete. For example, it does not include link through electric cable. Also not listed are the custom modules in tens of Mbps developed for inner trackers.

**, these are some of the R&Ds, not including links for applications in LAr.

Trends:

- ASIC technology, 130, <u>65</u> and 28 nm CMOS, technology identified by CERN.
- Optical module, custom, and from single channel LC TOSA/ROSA to array optics.
- R&D organization, common projects in ASIC and module developments, led by CERN.
- For ultra high rad-tol Electric connection for inner tracker (pre-emphasis and signal equalization) because of the long twin-ax cables

Current status*, trend

- ASIC technology, 130, 65 and 28 nm CMOS, technology identified by CERN.
- Optical module, custom, and from single channel LC TOSA/ROSA to array optics.
- R&D organization, common projects in ASIC and module developments, led by CERN.
  - Custom electronic components (aggregation ASIC, VCSEL driver, etc)
  - COTS VCSELs and photo-diodes are selected for radiation tolerance.
- For very specific applications:
  - With ultra high rad-tolerance and reliability requirements (ex, inner tracker): copper cables with pre-emphasis and signal equalization. Radiation tolerance of the optical transceivers (VTRX+) is limited by VCSELs and photo-diodes.
  - In liquid argon (ex, DUNE): digital and analog links, and at 89K.

Proposed R&D

- CERN has R&D on experimental technologies: https://ep-dep.web.cern.ch/rd-experimental-technologies. The most recent "EP R&D Day 2022-1" can be found at: https://indico.cern.ch/event/1156197/
- ASIC:
  - Technology identification: 130, 65 and 28 nm CMOS, for the HEP community.
  - Data rate:
    - for 65 nm, 10 Gbps is the limit if NRZ (non-return-to-zero) due to rad-tol requirement (lpGBT). PAM4 has been explored to reach 20 Gbps (GBS20).
    - For 28 nm, the limits are about 25 Gbps NRZ and 50 PAM4 (CERN R&D).
  - Serializer and laser driver for detector side, FPGA for the off-detector electronics, but ASIC in some cases?
    - Serializer: after lpGBT, what will be use case for a new design?
    - Laser driver: direct modulation? PAM4? SI-photonics?
    - Combine serializer and driver in PAM4 (GBS20)? and ASIC PAM4 receiver needed?
  - Equalizer for electric cable (GBCR), currently at about 1 Gbps per lane level. Any use case for higher speeds?
- Optical module:
  - LC based (VTRx) and array based (VTRx+). Will other developments (MTx+, QTRx) needed?
  - Modularizing the link detector side transmitter: serializer + PAM4 (GBS20) with LC based transmitter (GBT20)?

Proposed R&D

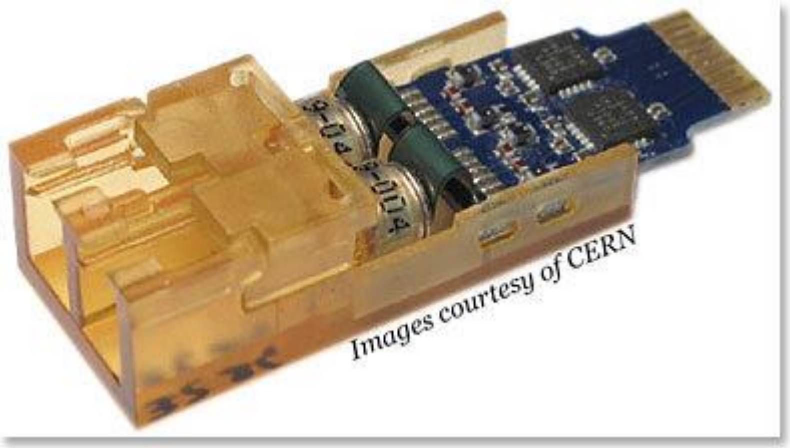
- ASIC:
  - Technology identification: 130, 65 and 28 nm CMOS with one fab, for the HEP community. Special models for applications in radiation (CERN leads) and in liquid argon (US leads)
  - Data rate:
    - for 65 nm, 10 Gbps is the limit of NRZ (non-return-to-zero) due to rad-tol requirement (ex, lpGBT). PAM4 has been explored to reach 20 Gbps (GBS20).
    - for 28 nm, the limits are about 25 Gbps NRZ and 50 PAM4 (CERN R&D).

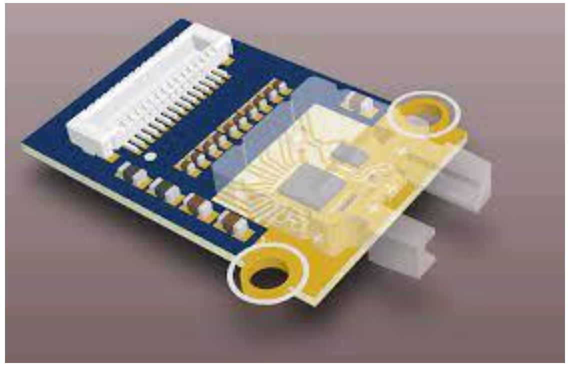
Proposed R&D

- ASIC (cnt'ed):
  - Serializer and laser driver for on-detector electronics, FPGA for off-detector electronics, but also ASIC when we cannot find work in the industrial standard (ex, PAM4 at 28 and 56 Gbps).
    - Serializer: after lpGBT, what will be use case for a new design?
    - Laser driver and optics: direct modulation? PAM4? SI-photonics?
    - Combine serializer and driver in PAM4 (ex GBS20)? and ASIC PAM4 receiver needed?
  - Equalizer for electric cable (ex GBCR), currently at about 1 Gbps per lane level, matching the input of lpGBT (1.28 Gbps). Any use case for higher speeds?

Proposed R&D

- Optical module and passives (fiber, connector):
  - LC based (VTRx) and array based (VTRx+). Will other developments (MTx+, QTRx) needed? or we rely on the CERN common projects also for future experiments?
  - Modularizing the link detector side transmitter: serializer + PAM4 (GBS20) with LC based transmitter (GBT20)?
  - Identifying rad-tol fibers (OM3, OM4) and connectors. Coupling (laser to fiber or fiber to fiber) efficiency in radiation or in LAr.



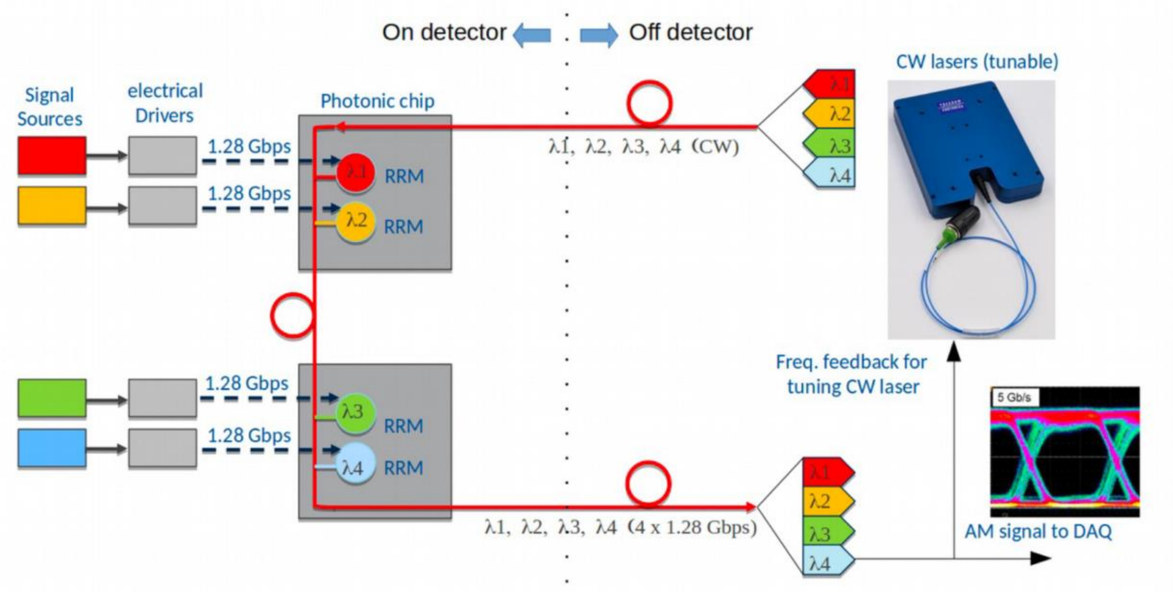


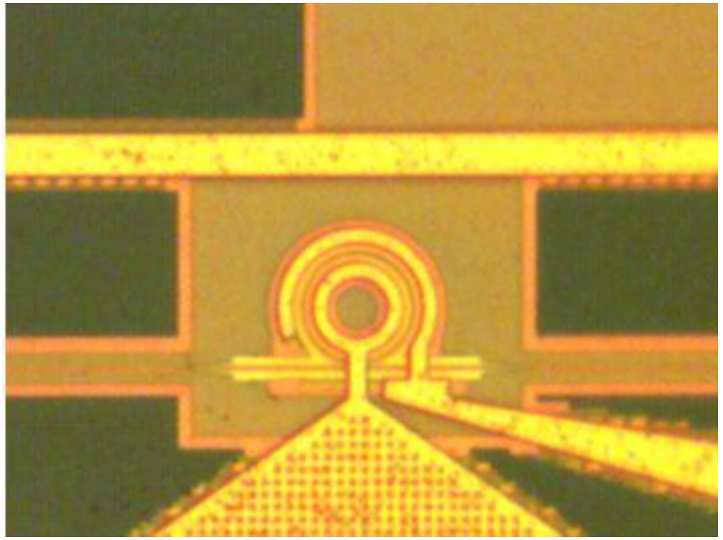
Proposed R&D

- Other technologies:
  - Silicon-photonics.
  - WDM (wavelength-division multiplexing).
- Link system level considerations. This has been well studied in the Versatile Link common project (CERN, with US participation). It needs to be looked at for future links (ex, those for DUNE).
- Organization:
  - Work with CERN.
  - US R&D, led by national labs.
  - Leverage from SBIR programs.

R&D for Si-photonics

- Si-pho enables us to place fiber-optical transmitter directly inside tracker.
- It uses CMOS process to fabricate waveguides and other optical components in the same Si wafer as the electronic circuits.
- R&D on Si-pho is ongoing at CERN and the US.
- The domestic effort is mostly limited to SBIRs. Partnership wish industry is key to cost-effective R&D. However, the US-based ASIC developers can benefit from getting access to the libraries of the optical components.





https://ep-news.web.cern.ch/content/silicon-photonics-high-energy-physics-experiments

Conclusion

- Over the past two decades, and mostly with applications in the LHC, HEP detector data transmission is dominated by optical link, and has seen an increase from 1 Gbps/lane to 10 Gbps/lane, with optical module from single channel (ST, LC) to array lasers.
- Design of the aggregator ASIC and optical transceivers for FCC-hh experiments is a monumental challenge.
- R&D for ASIC and optical link technologies is needed to meet the radiation and LAr/cryo requirements. VCSELs are the mainstream and the development needs to continue. Si-photonics enables event more rad-tolerant links but extra R&D is needed.
- Collaboration is essential for success.