Prospects on new link technologies

ECFA DRD7 Workshop

CERN

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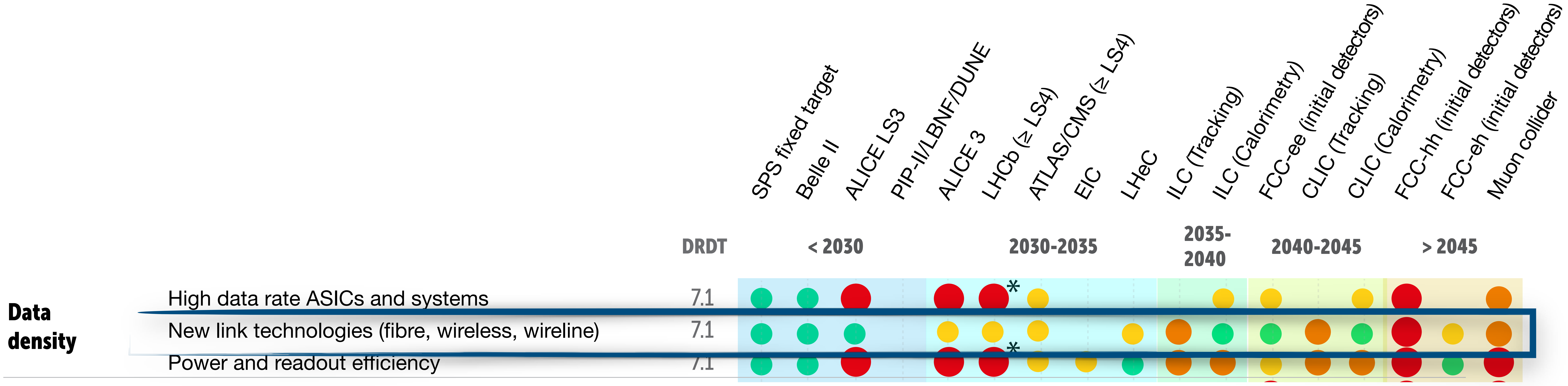
Many thanks to (among others):
N. Berger, R. Brenner, S. Cammarata, E. Ciaramella, D. Dancila, S. Faralli, M. Garcia-Sciveres, G. Magazzù, E. Locci, C. Scarcella, M. Schneider, J. Troska, F. Vasey

Future experimental challenges



Must happen or main physics goals cannot be met | Important to meet several physics goals | Desirable to enhance physics reach | R&D needs being met

Future experimental challenges

A few examples

Requirement	LHCb (LS ≥4)	ATLAS/CMS (LS ≥ 4)	HIKE (NA62++)	FCC-hh
Hit rate (GHz/cm^2)	12	6	10	10 (vertex) - 100 (EMCAL)
NIEL (10^{16} n_{eq}/cm^2)	6	1	1	10
TID (MGy)	10	10	10	250
Data rate (100 Gbs/cm^2)	1	1	0.2	1 - 10

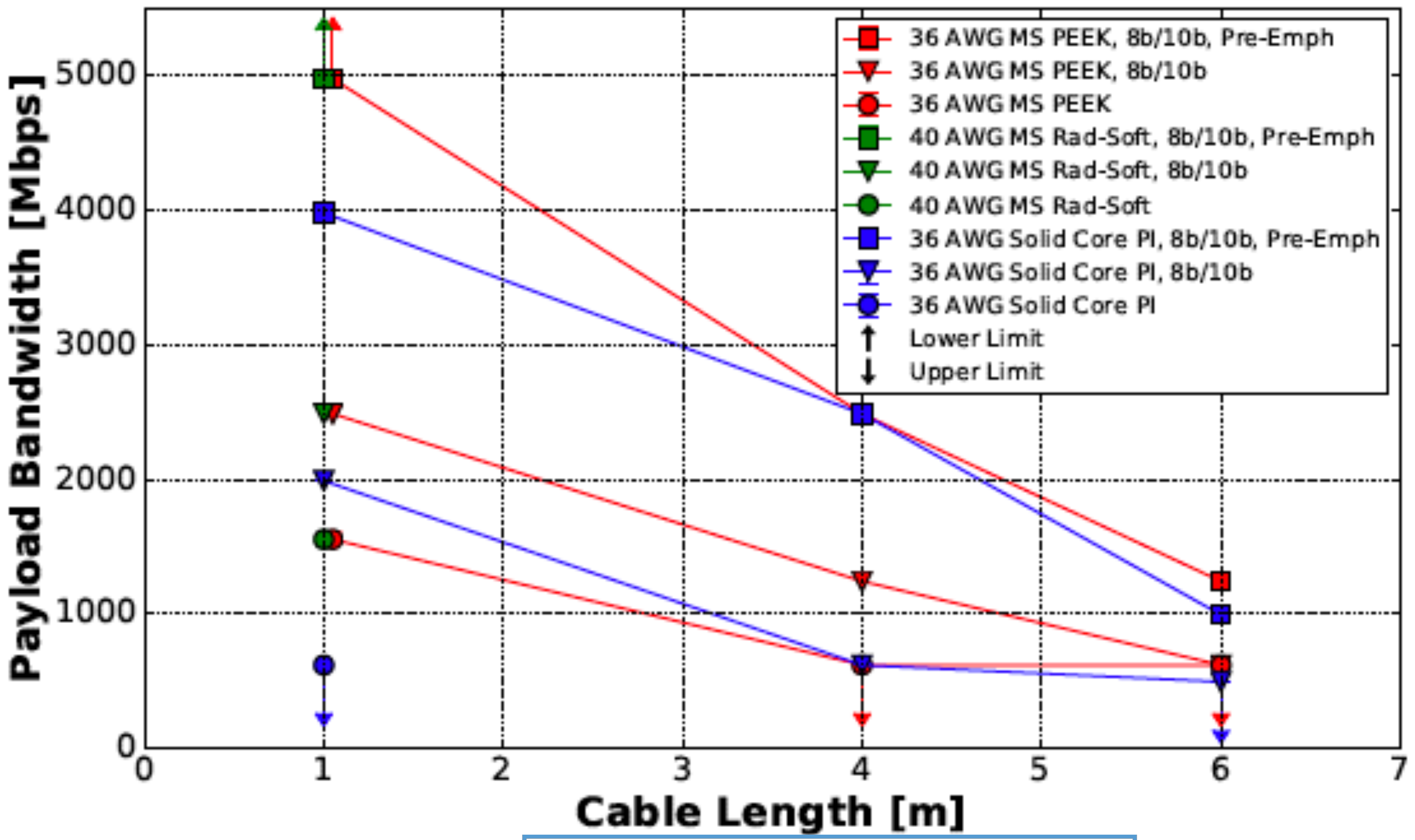
State of the art

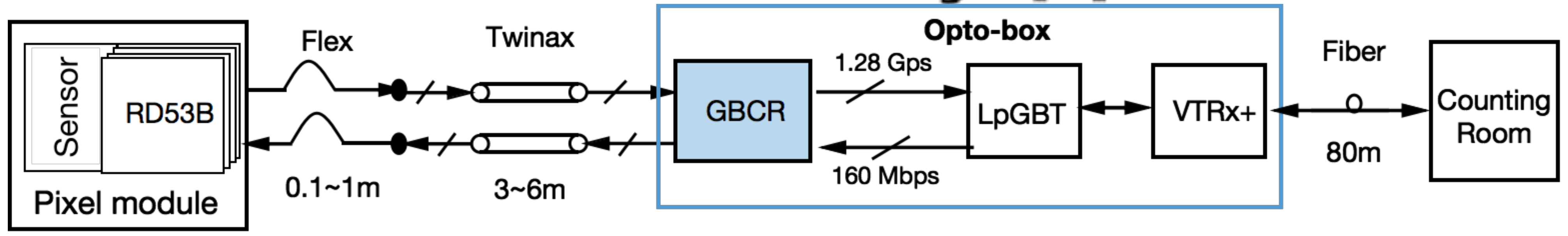
- **Current high-speed links are based on opto-electronics (VCSEL based) technology**
- **Radiation hardness is the major problem**
    - Currently used high-speed circuits (LpGBT, 10.5 Gb/s) are not qualified for TID exceeding 0.5 Grad and few 10^{15} n/cm^2.
  - Alternatives are being explored using
    - New optoelectronic devices, with laser sources placed outside the high-radiation zone
    - New physical layers
- **Electrical low-mass cables do not provide high-enough data rate and are limited to relatively small distances.**

Electrical low mass cables

How far and how light can we go?

- **ATLAS/CMS R& Phase-II upgrade**
  - ATLAS (6m) needs an additional ASIC to match input specs for LpGBT





- MU3E lightweight HDI
  - 0.05 % X/X0
  - Readout using LVDS

- *Advanced modulations schemes (PAM-4, QAM etc) must be deployed to reach faster speed*
  - The first CMS pixel detector readout used an analog scheme with address levels coded into six levels.

https://doi.org/10.1016/j.nima.2006.05.038.

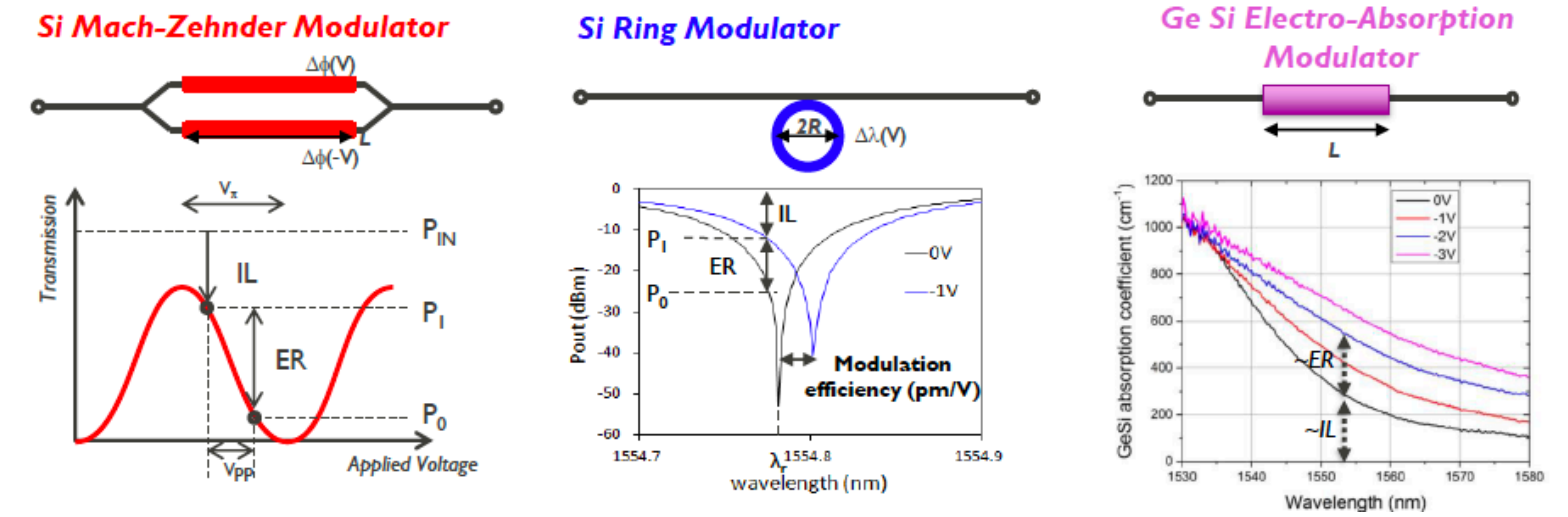
Silicon Photonics based links for HEP

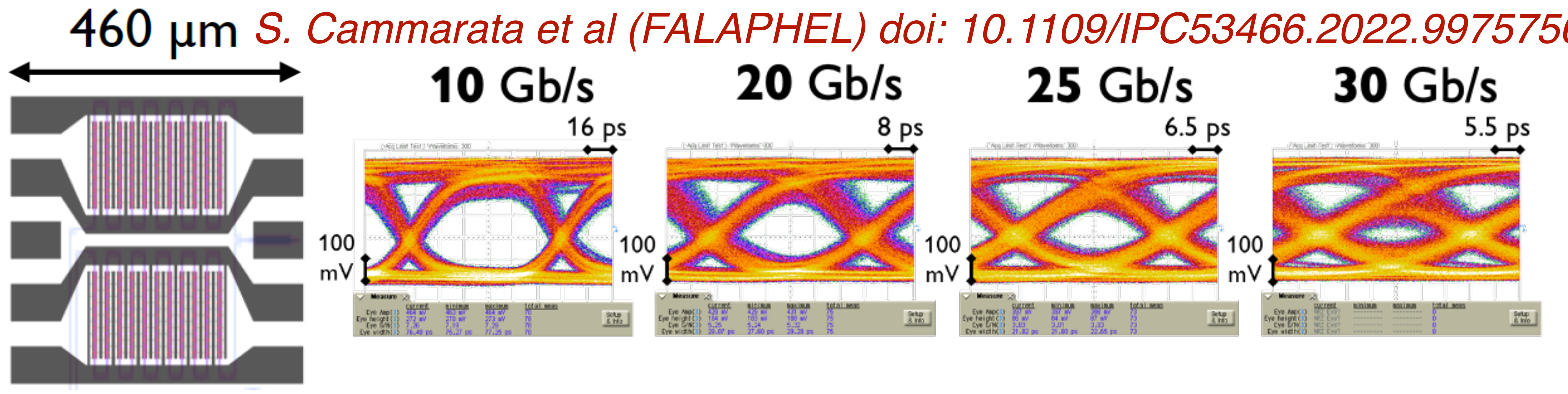
Telecommunication networks standard

- Allow very high speed performances (100G are the standard for data centres)
- Several technologies allow high-speed modulation of light from an electrical source
- Several modulation schemes (NRZ, PAM4, QAM) and multiplexing schemes (WDM, SDM, PDM) - although more or less difficult to implement - can be used to increase overall bandwidth while keeping “manageable” (up to 25G) the single lane speed
  - Intra-Data centres connections use highly parallel systems where a large system of fibres (or more generally optical cores or optical modes) must be deployed in a constrained space.
    - Applicable for FCC-hh ?
- In the past few years extensive R&D (particularly at CERN) has understood the mechanisms to increase radiation hardness of the devices

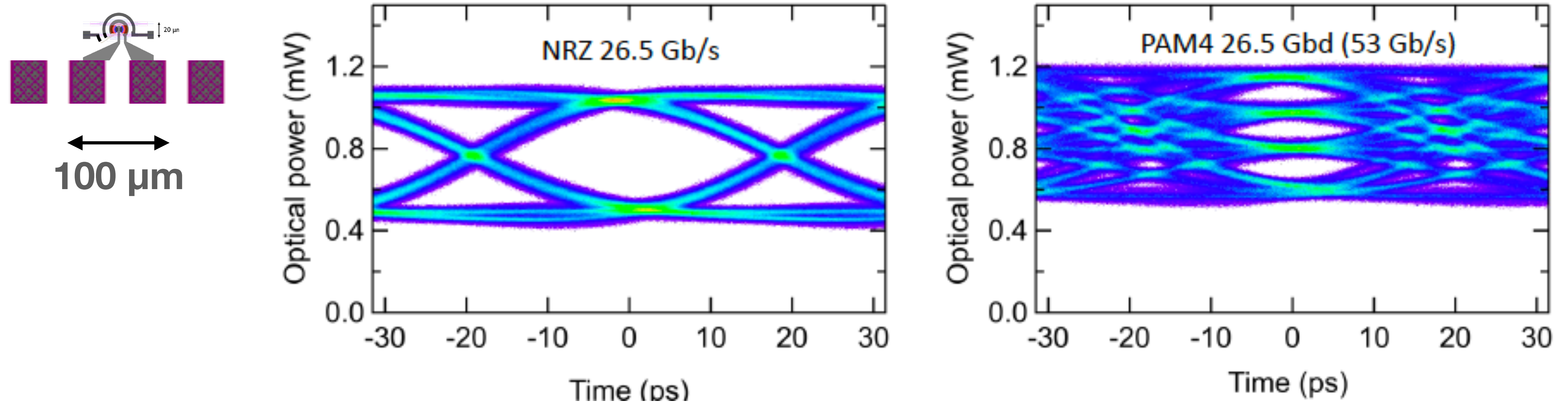
Silicon Photonics modulators

- **Mach-Zehnder Modulator (MZM)**
  - Temperature insensitive
  - Typically big footprints (~1 mm) and high V_{π} (2V)
  - Folded MZM have smaller footprint (0.5 mm)
- **Ring Modulators (RM)**
  - Much smaller intrinsically, but pads at 100 µm
  - Low power consumption
  - Temperature sensitive
- **Ge Si Electro-absorption (EA)**
  - More suitable for 1550 nm wavelengths
- **Thin-film LiNb on SOI waveguide**
  - 2 mm long devices driven with 1.4 V reach 40 Gb/s per lane
  - Still in R&D phase but appealing for FCC-hh





S. Cammarata et al (FALAPHEL) doi: 10.1109/IPC53466.2022.9975756.



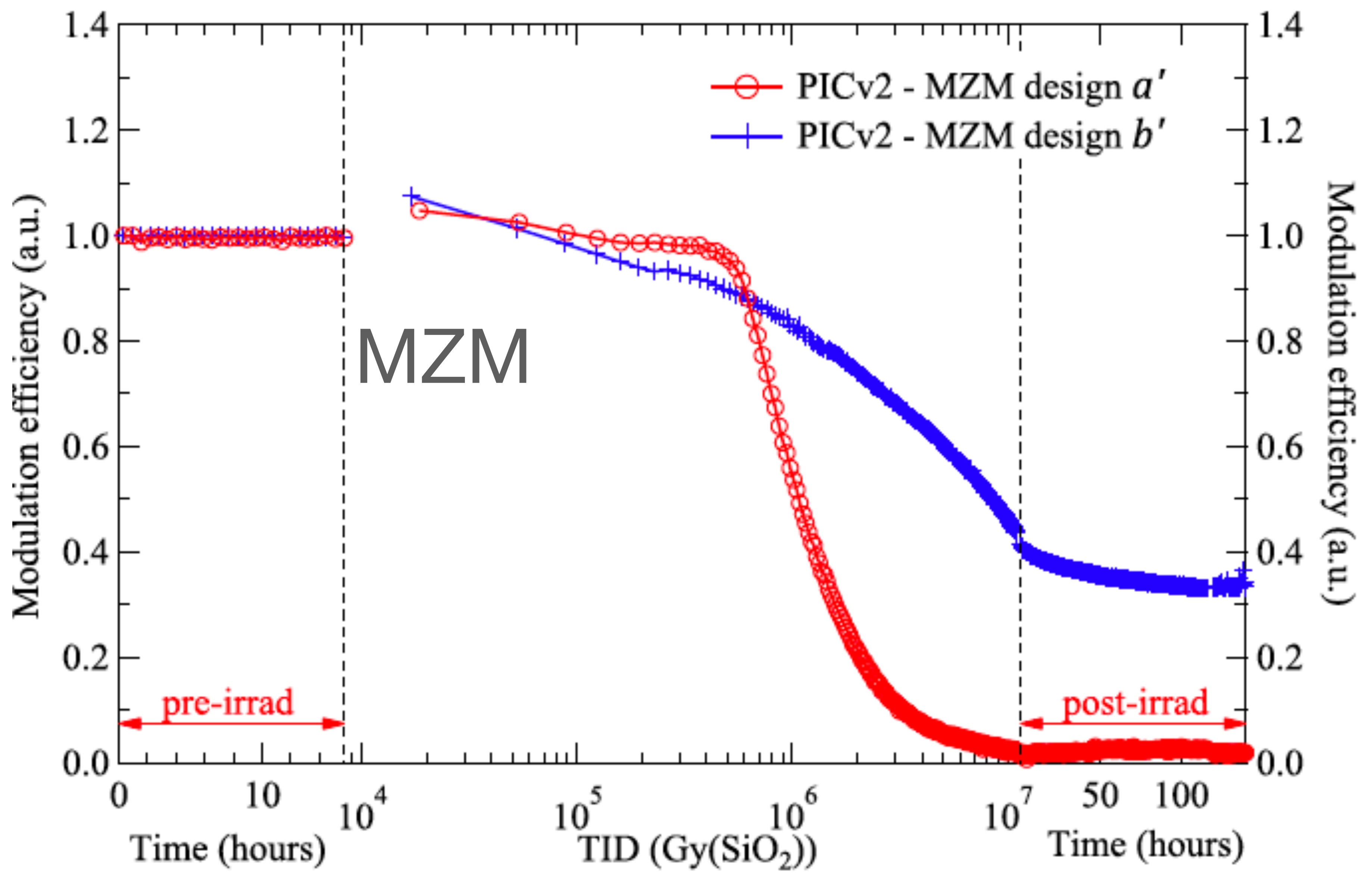
C. Scarcella et al. (CERN) TWEPP2022

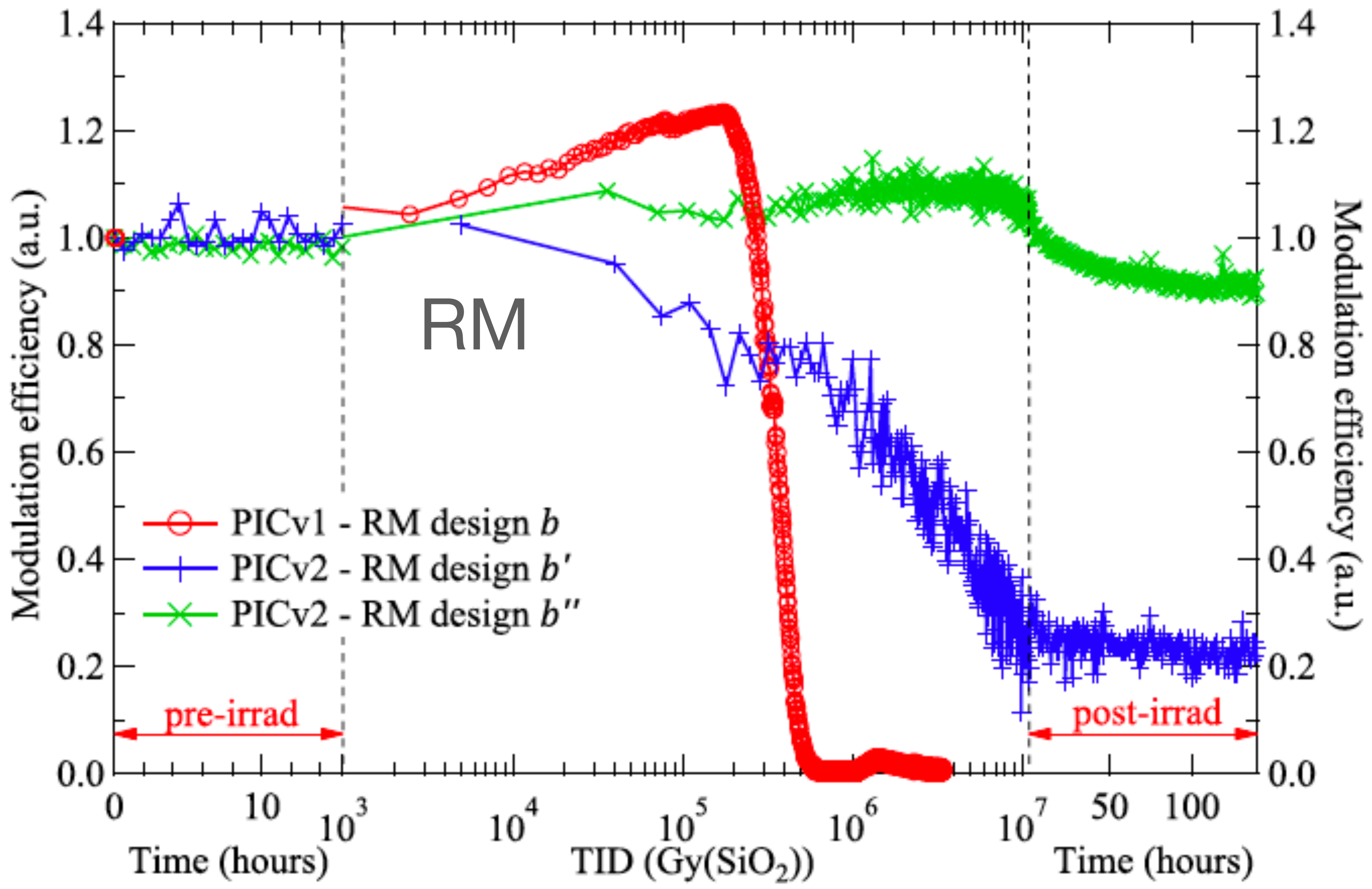
M. Lalović et al., doi: 10.1109/TNS.2022.3148579.

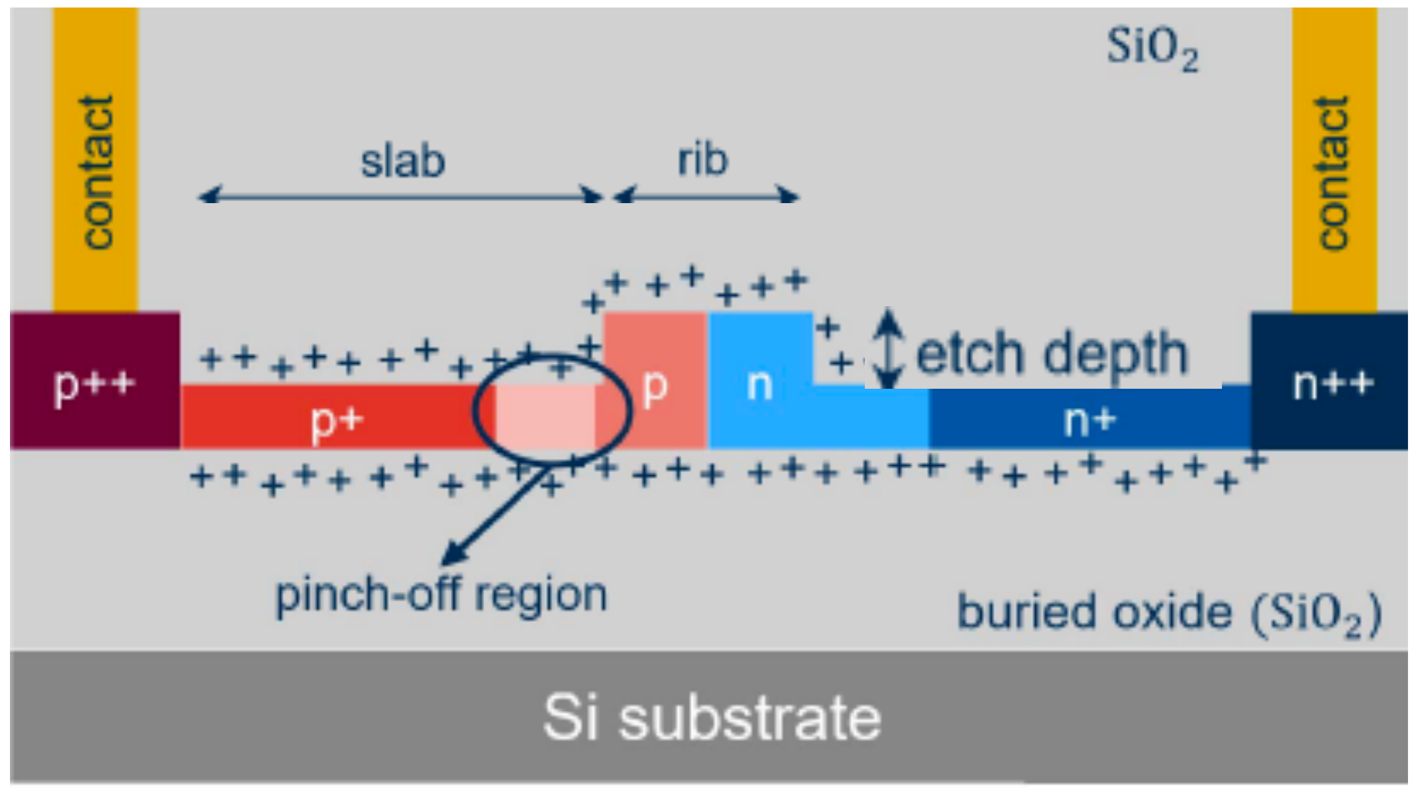
Silicon Photonics

Radiation tolerance

- Process and design dependence:
  - Loss of modulation caused by pinch-off effects of holes in the p-doped region
  - Higher doping concentrations or thicker etch depth allow more radiation resistance
  - Similar behaviour for RM and MZM
- Single-Event Effects devices started to be detected





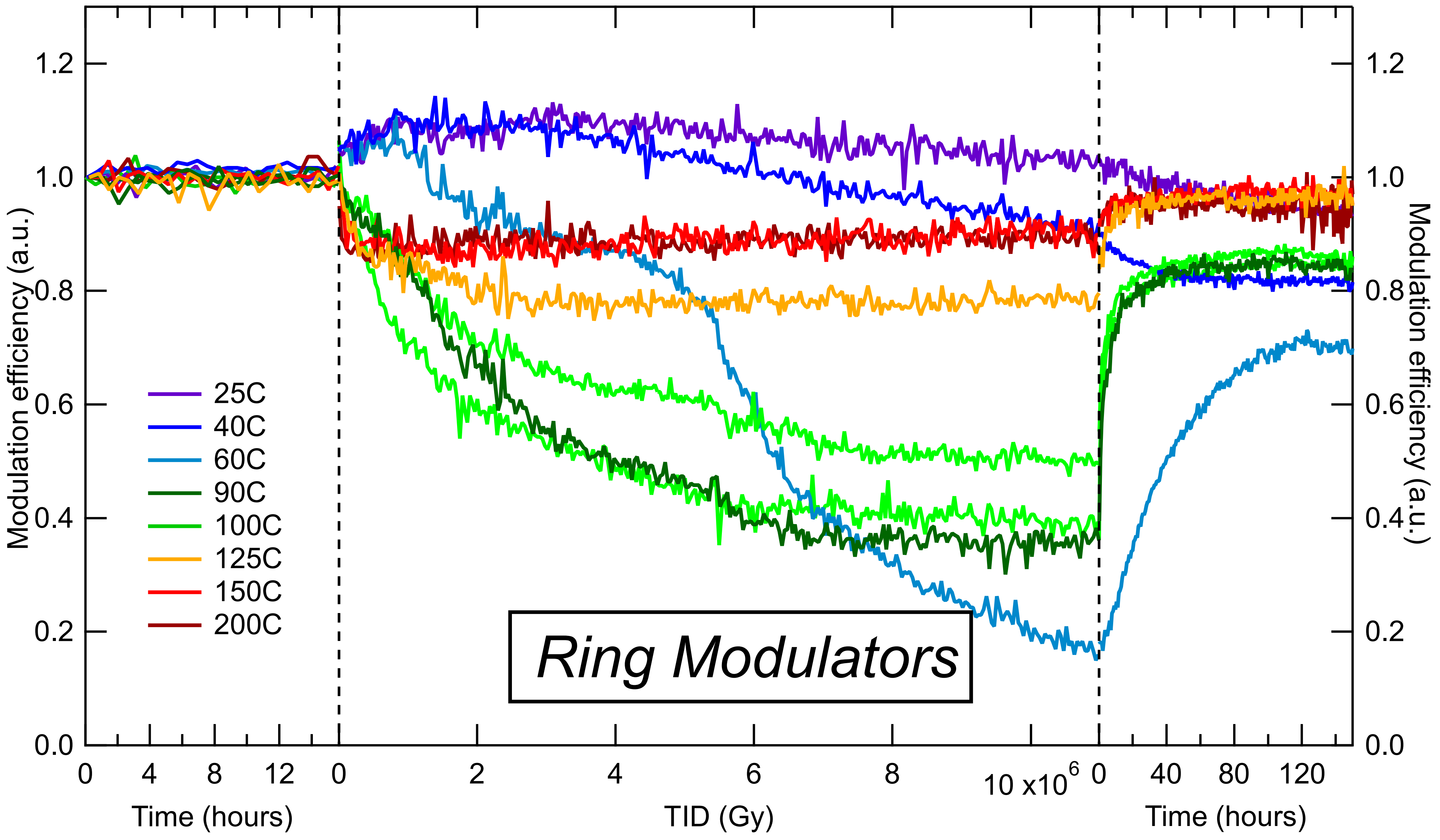


Silicon Photonics

Radiation tolerance

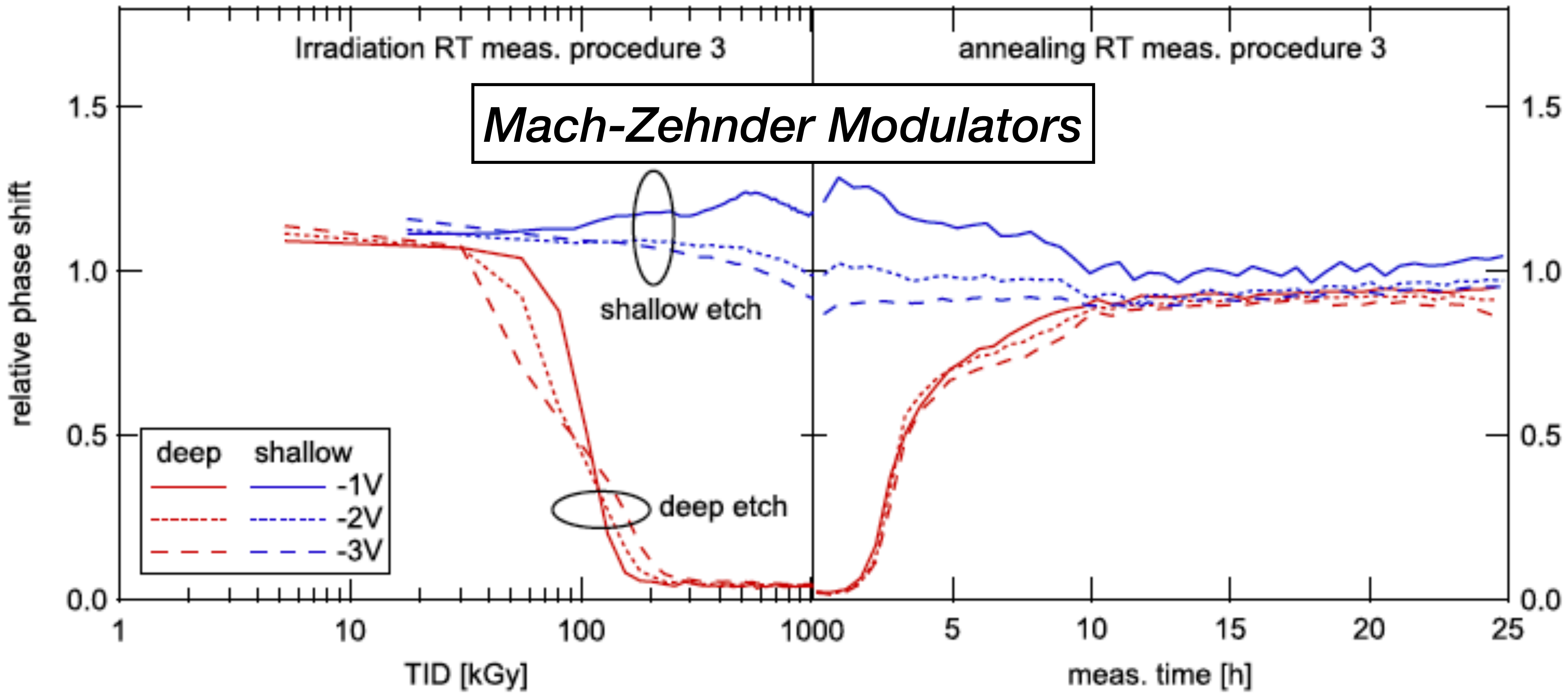
- CERN carried out X-ray & neutron irradiation tests
  - Neutron irradiation less damaging, independent of temperature
  - TID potentially more damaging, can be fully annealed with elevated temperature using on-chip heaters or reverse bias. Some effects due to temperature to be considered

M. Lalović et al., doi: 10.1109/TNS.2022.3148579.



> 10 MGy

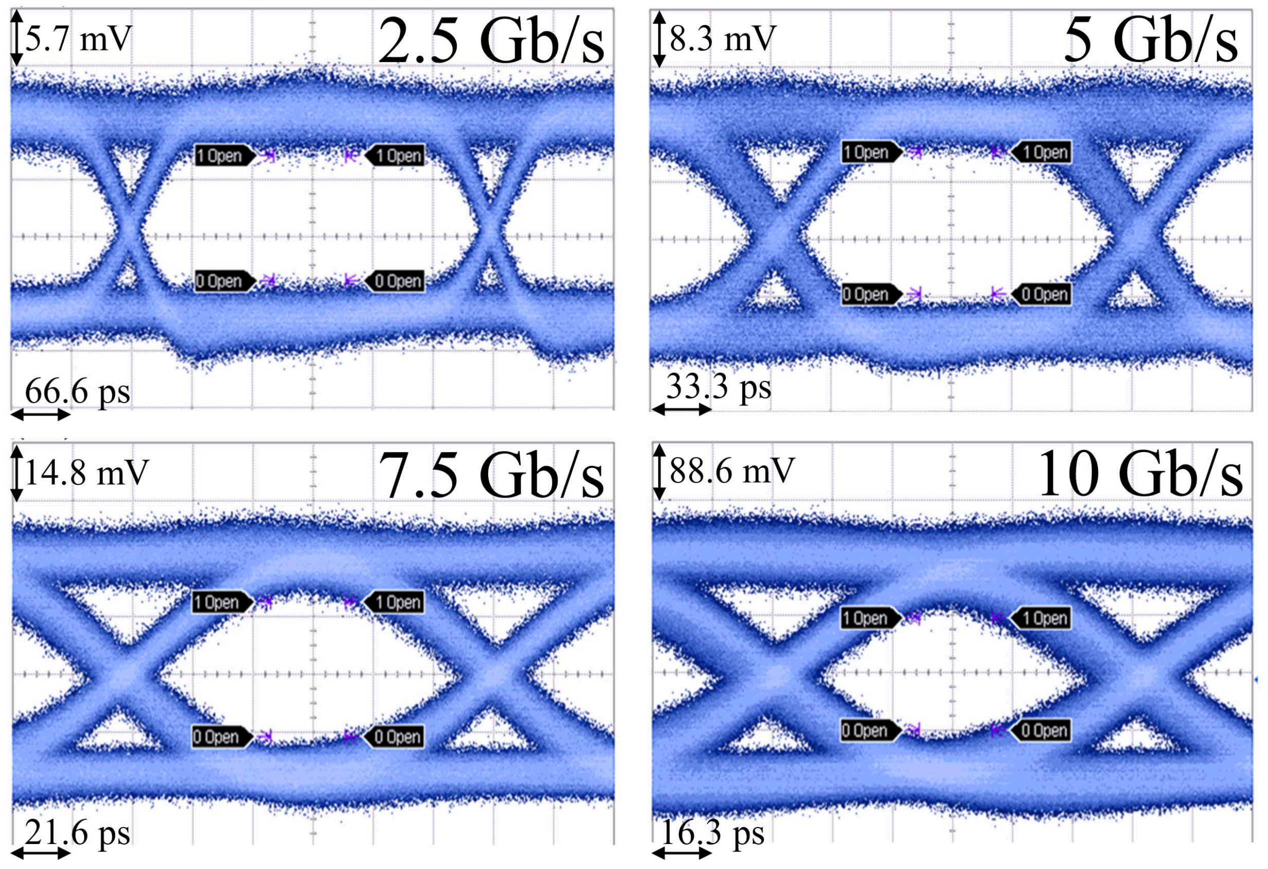
A. Kraxner et al., doi: 10.1109/TNS.2018.2823863.

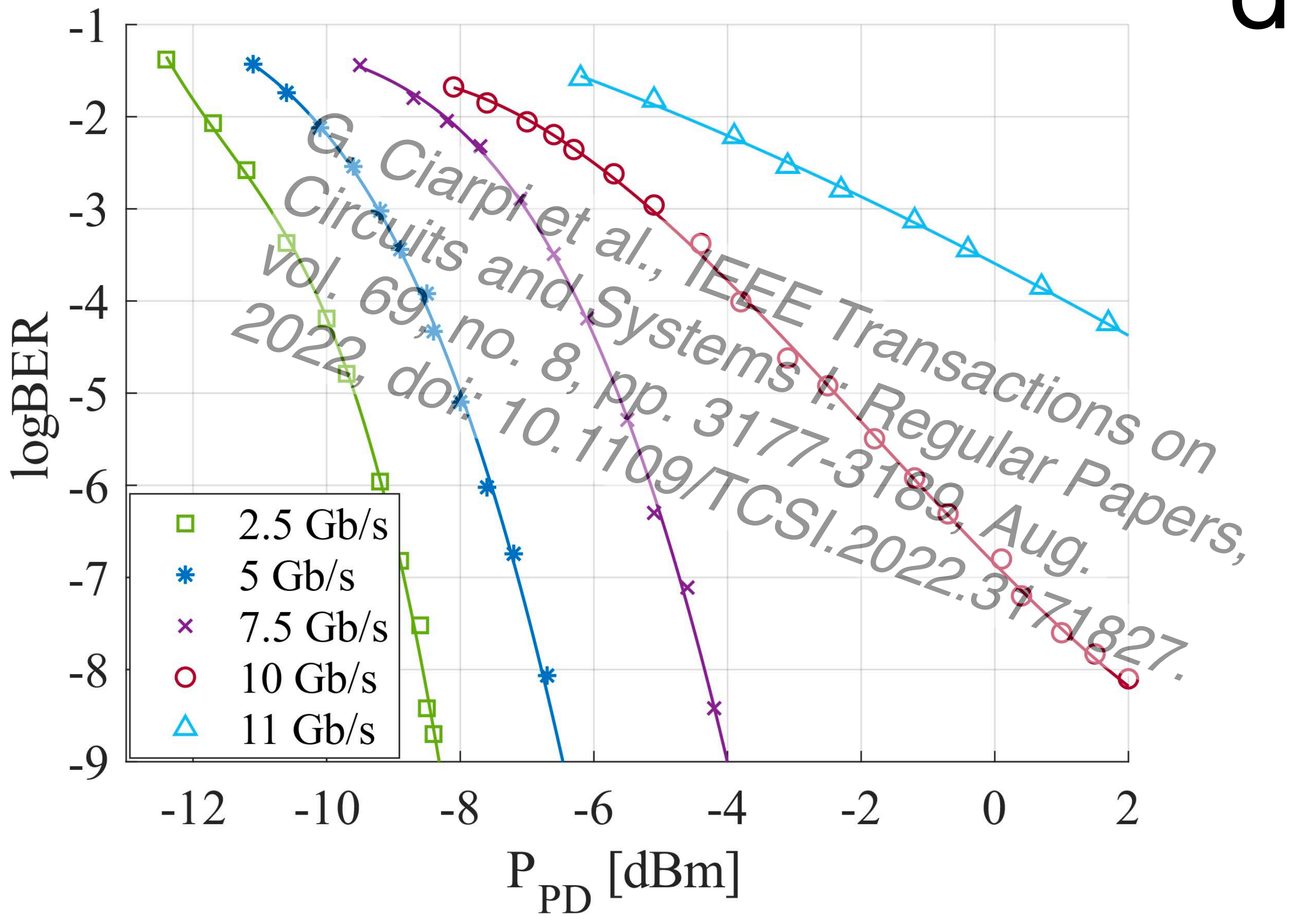


Silicon Photonics: integration with electric drivers

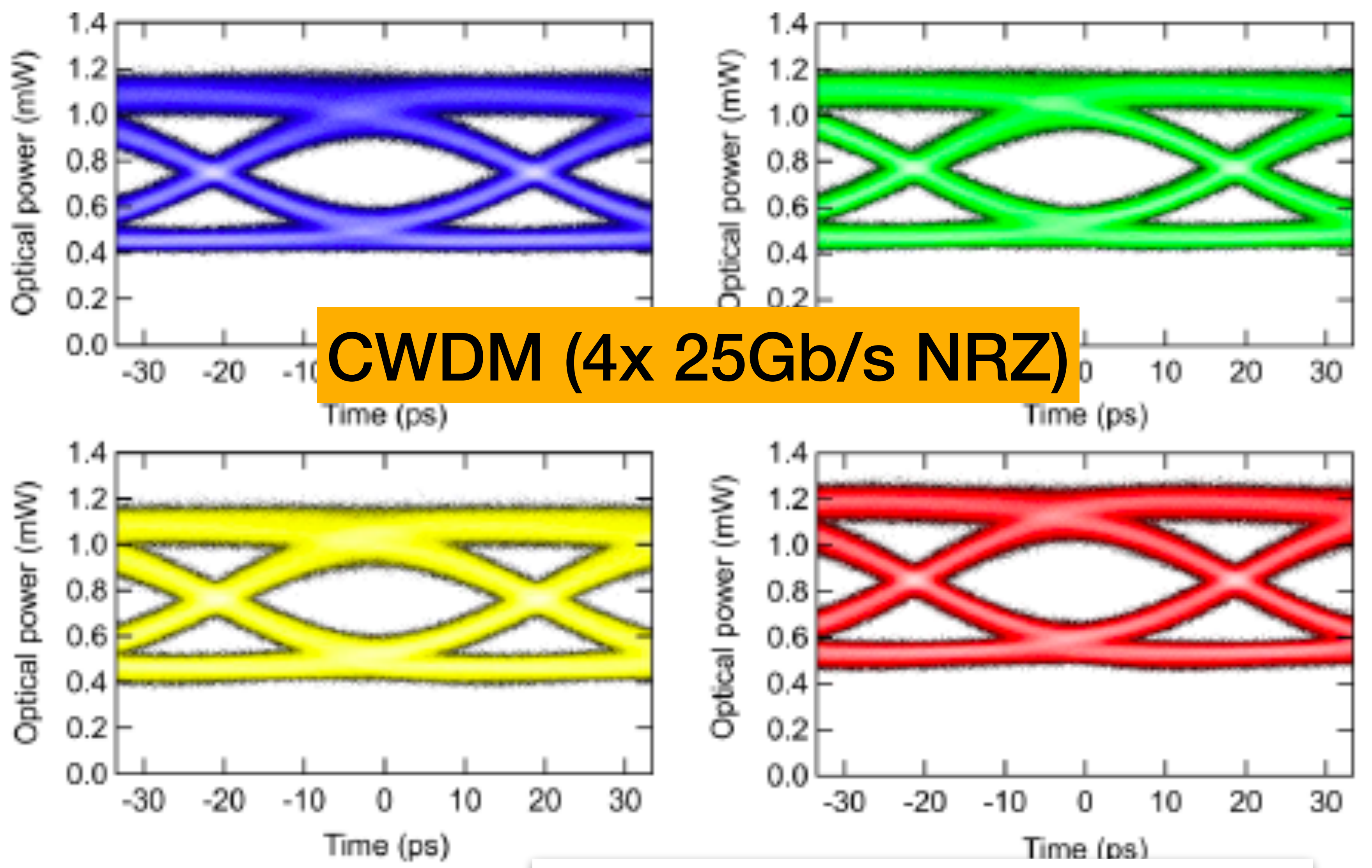
HEP state of the art

- CERN PIC (MZM - IMEC iSIPP25G) wire bonded to INFN rad-hard driver (65 nm)



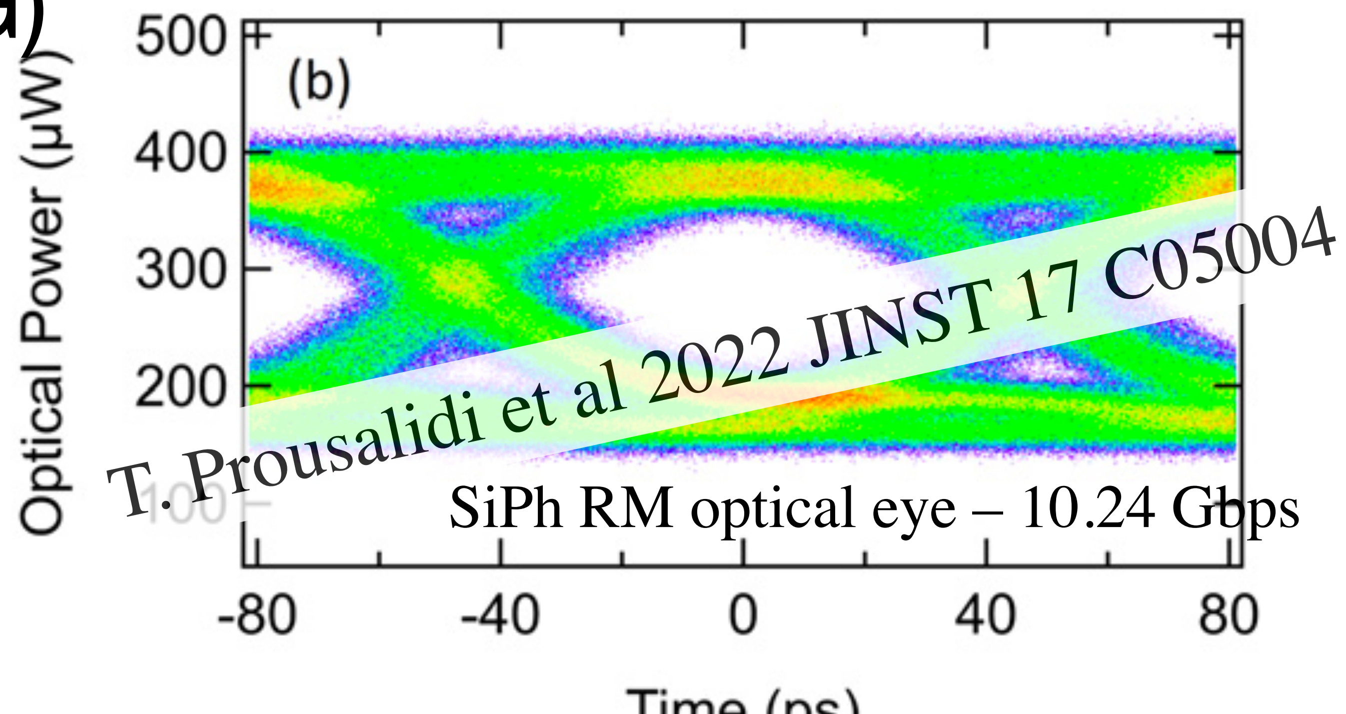


- CERN PIC (RM - IMEC iSIPP50G) wirebonded to commercial driver (CWDM demo)



C. Scarcella et al - TWEPP 2022

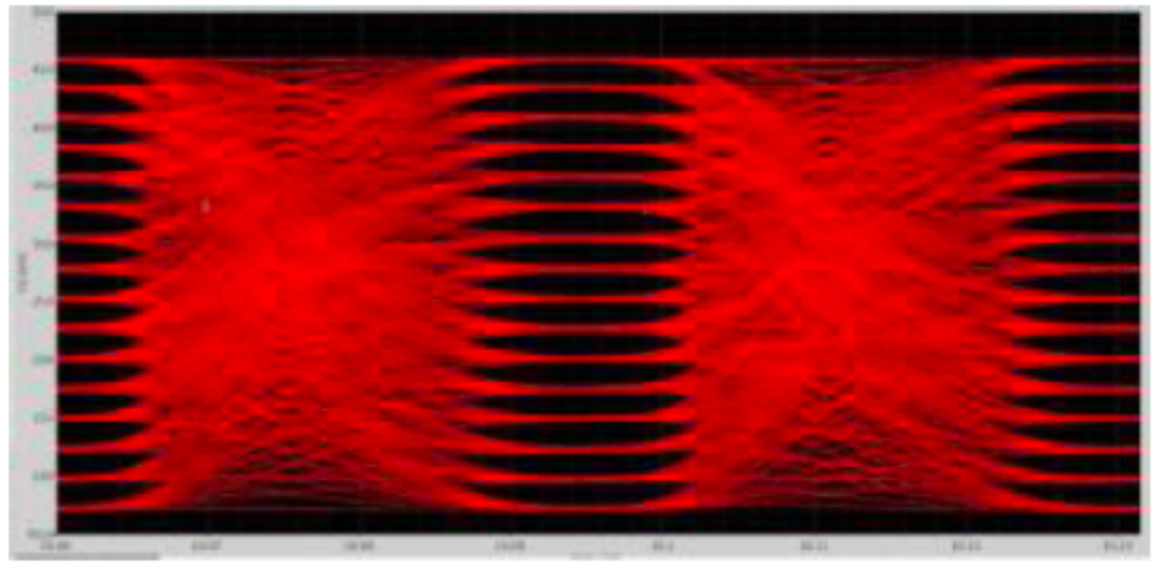
- CERN PIC (RM - IMEC iSIPP50G) wirebonded to LpGBT (65 nm)



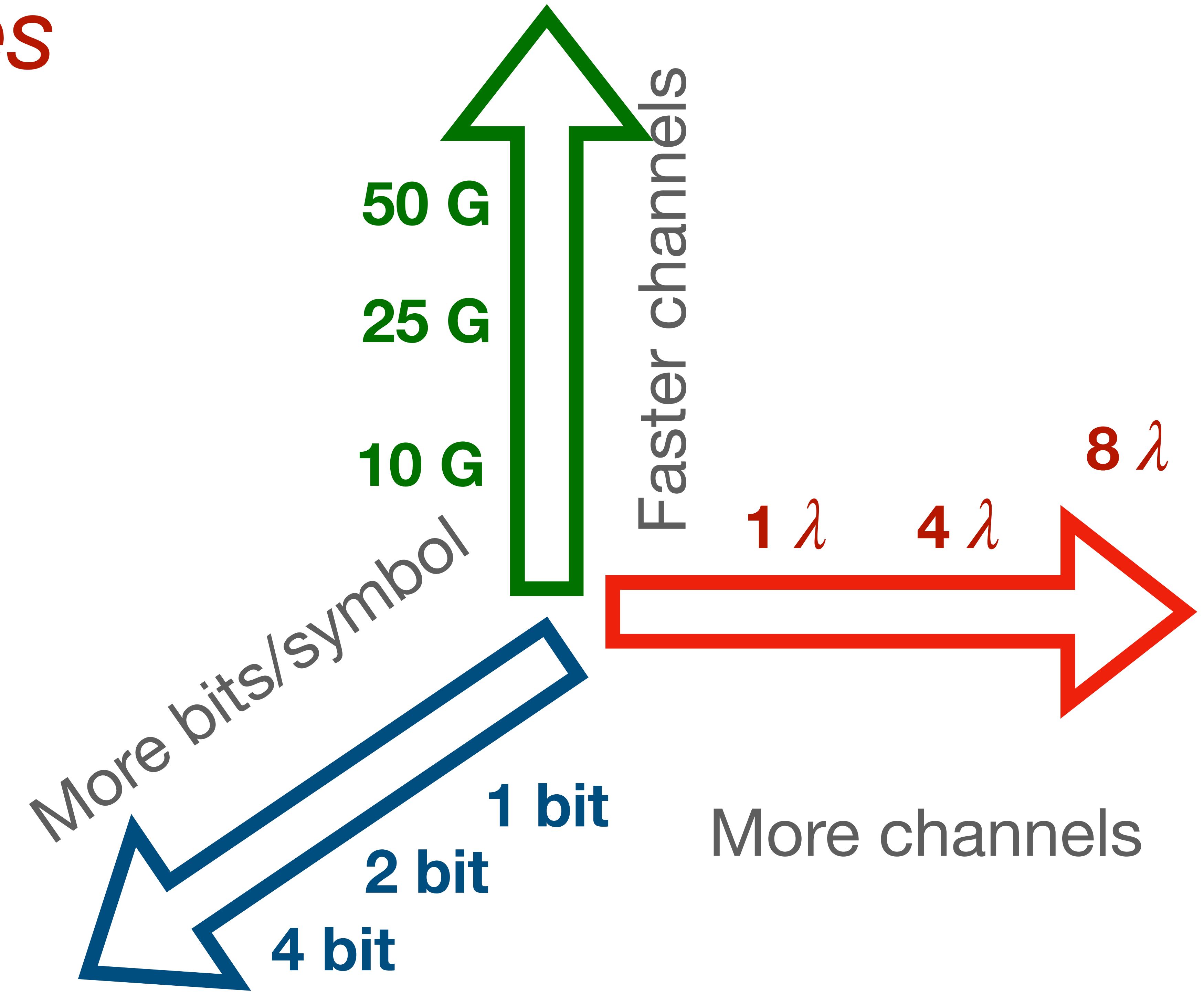
T. Prousalidi et al 2022 JINST 17 C05004

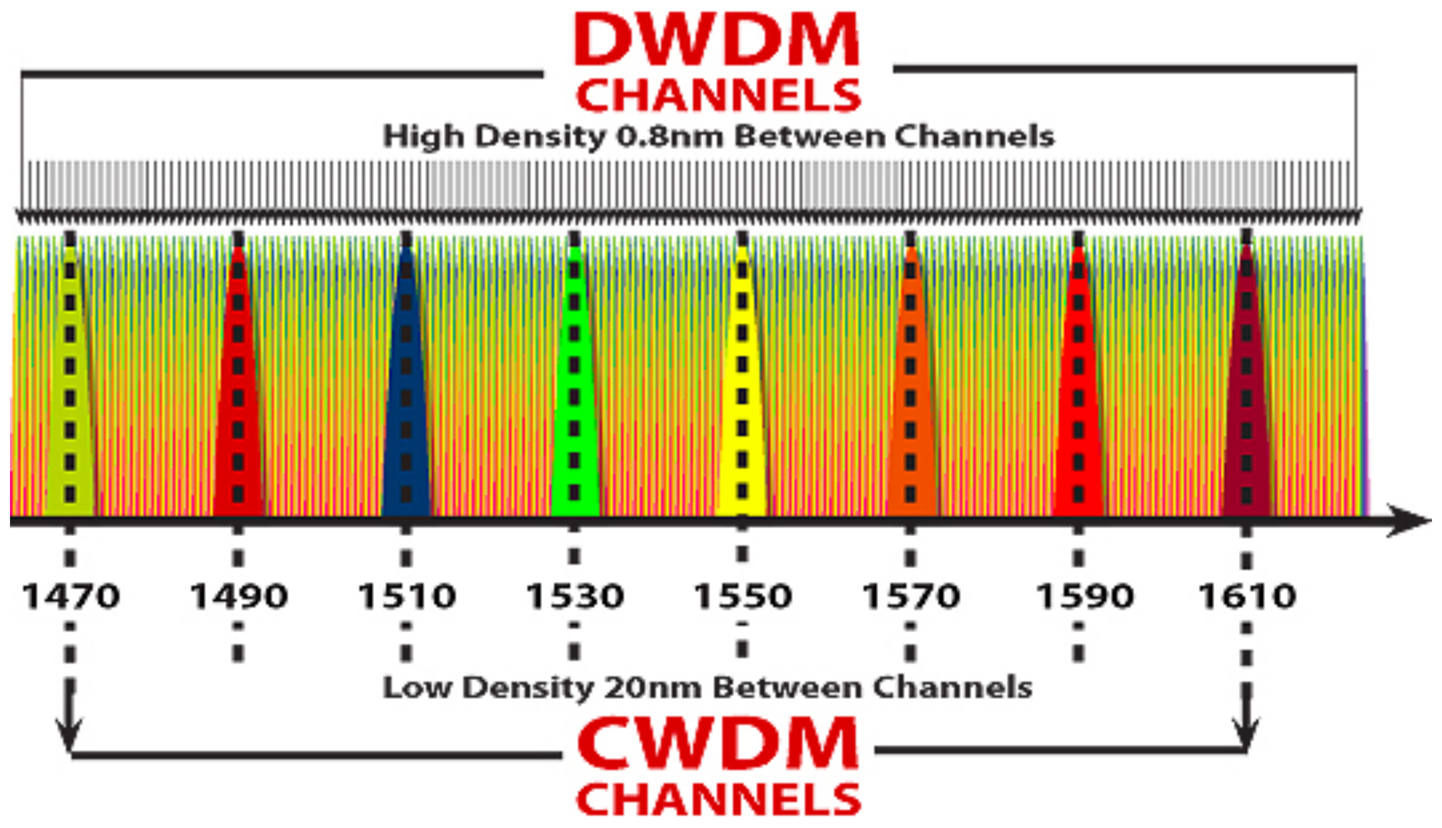
Optical transceiver scaling

Increasing data rates



PAM-16 (LightWire/Luxtera)





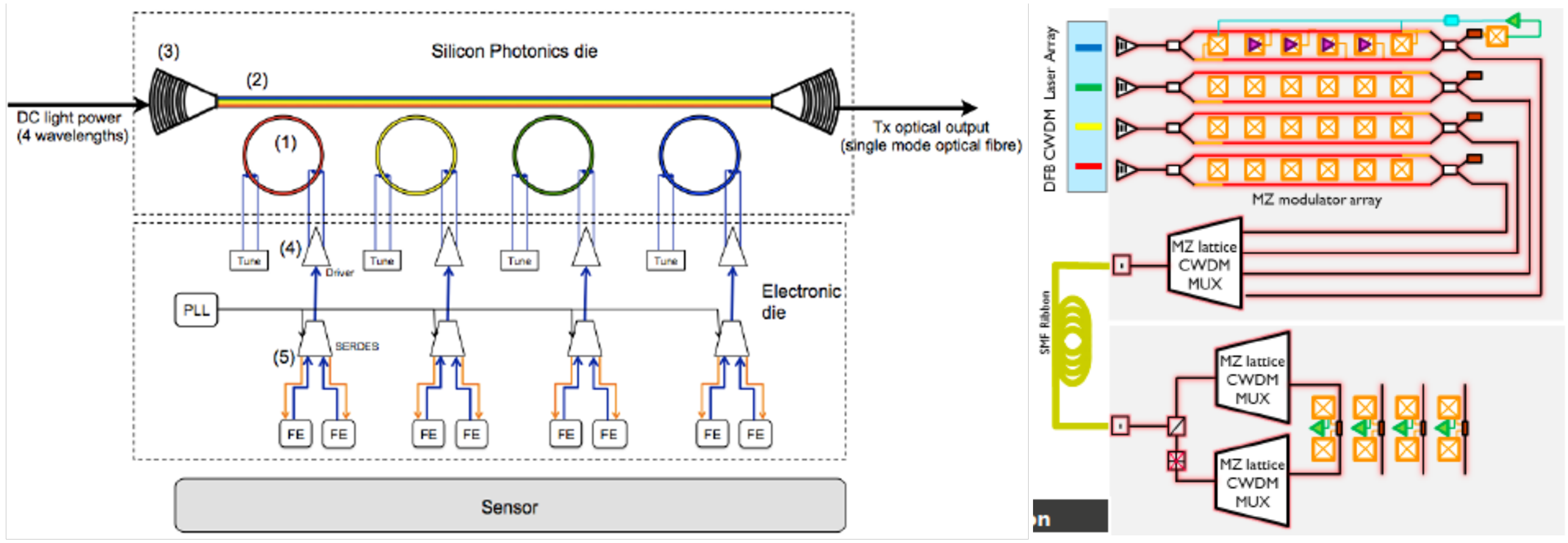
NRZ
PAM-4
QPSK
…

Wavelength Division Multiplexing (WDM)
Spatial Division Multiplexing (SDM)
Polarisation Division Multiplexing (PDM)
…

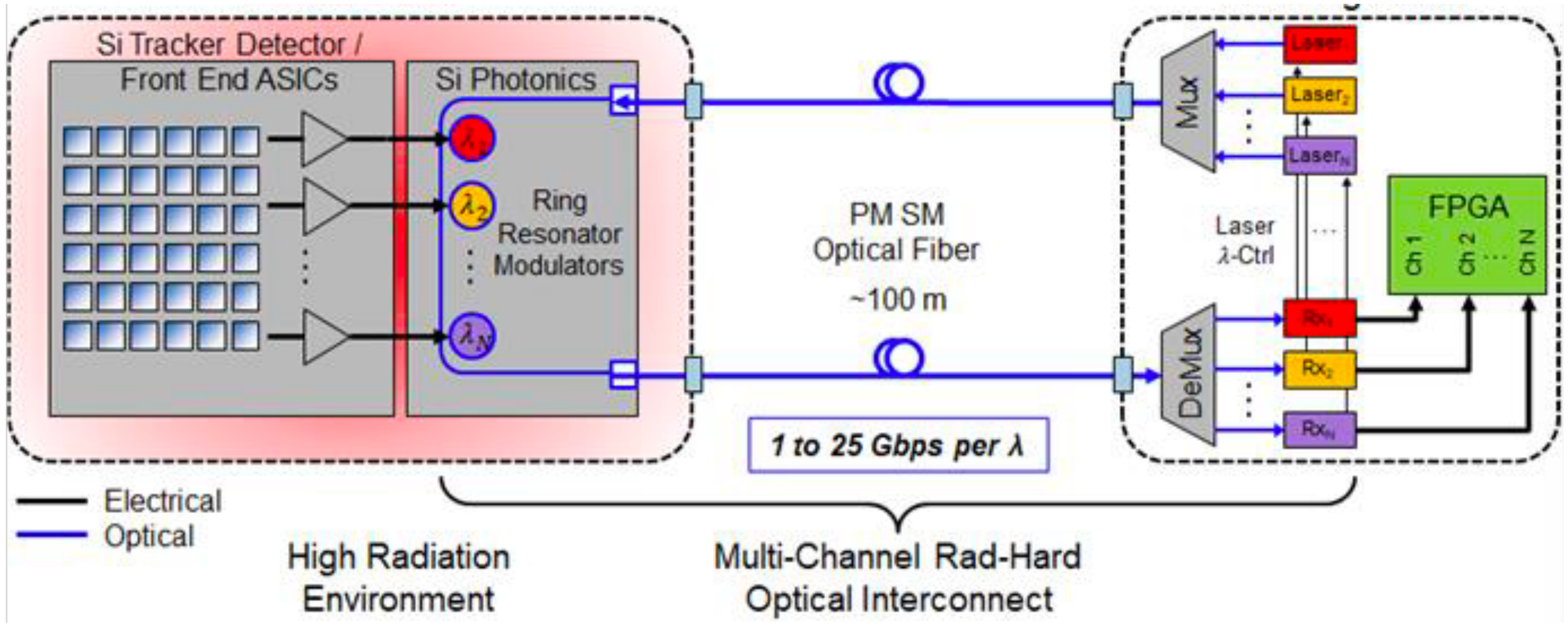
Silicon Photonics systems for HEP

Possible architectures

- **High data rate: one fibre per Silicon Sensor (CERN, INFN, KIT)**
  - Use CWDM 4x25 Gb/s=100 Gb/s
  - Can use both MZM or RM
- **Many “low” rate over one fibre (LBNL, FNAL, UCSB & Freedom Photonics)**
  - Use DWDM
  - Separate RM from one or more detectors add different λ’s on the same fibre

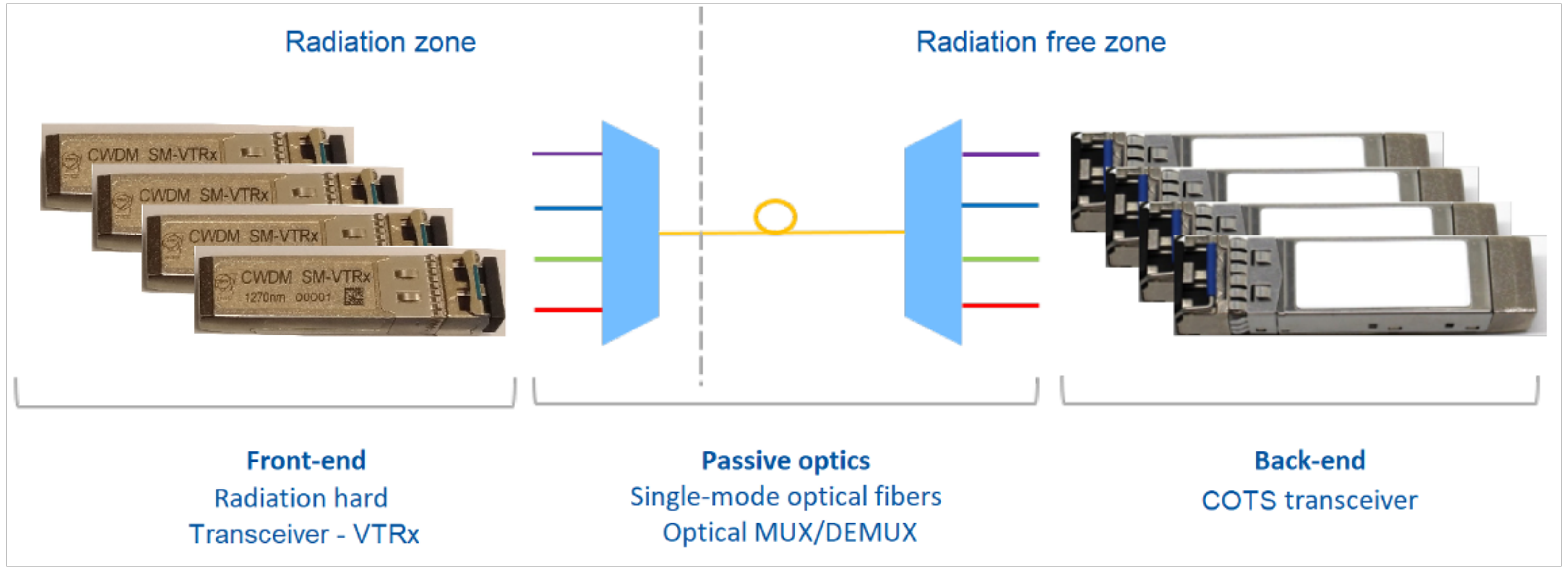


https://doi.org/10.1117/12.2615266

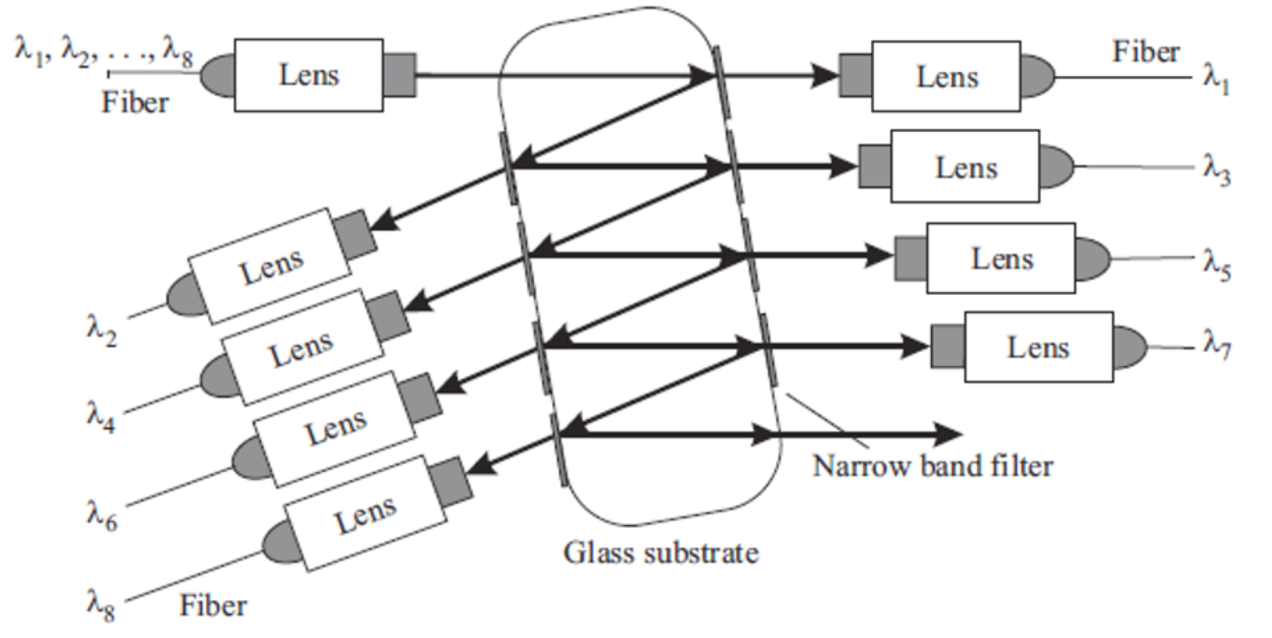


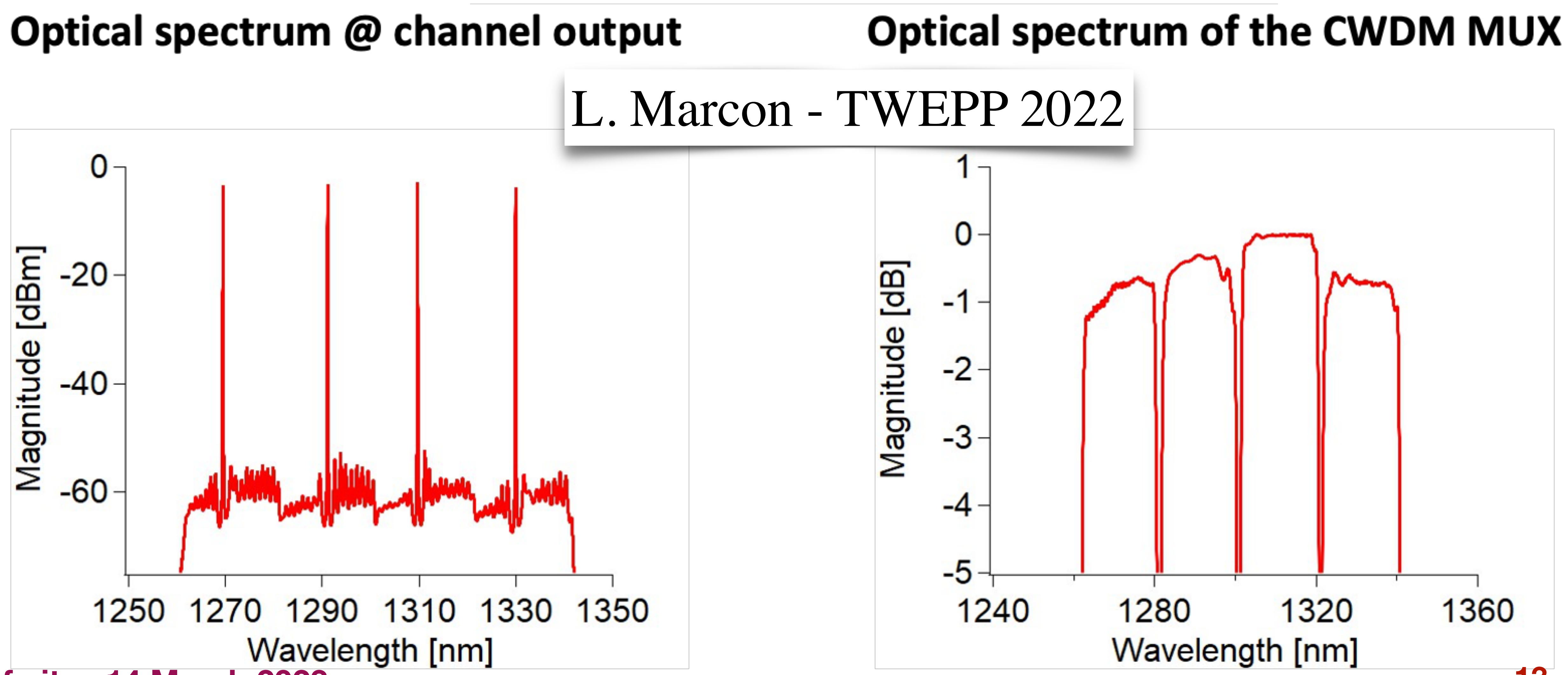
Silicon Photonics

CWDM testing



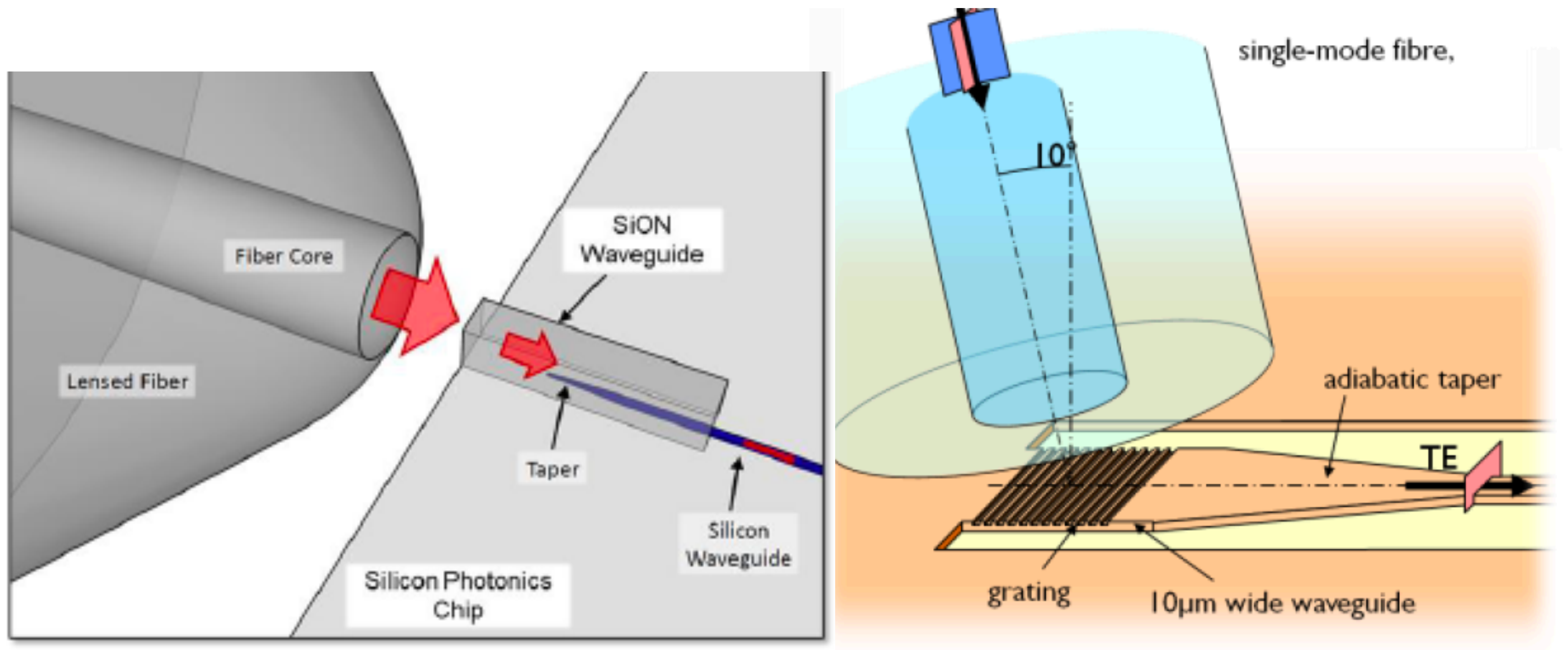
- CWDM tested at O-band (1310 nm)
  - Nice to be repeated for C-band (1510 nm)
- Both laser sources and MUX have started to be tested for operations in the cavern
  - Neutrons ~few 10^{14} n/cm^2
  - Gamma ~11 kGy

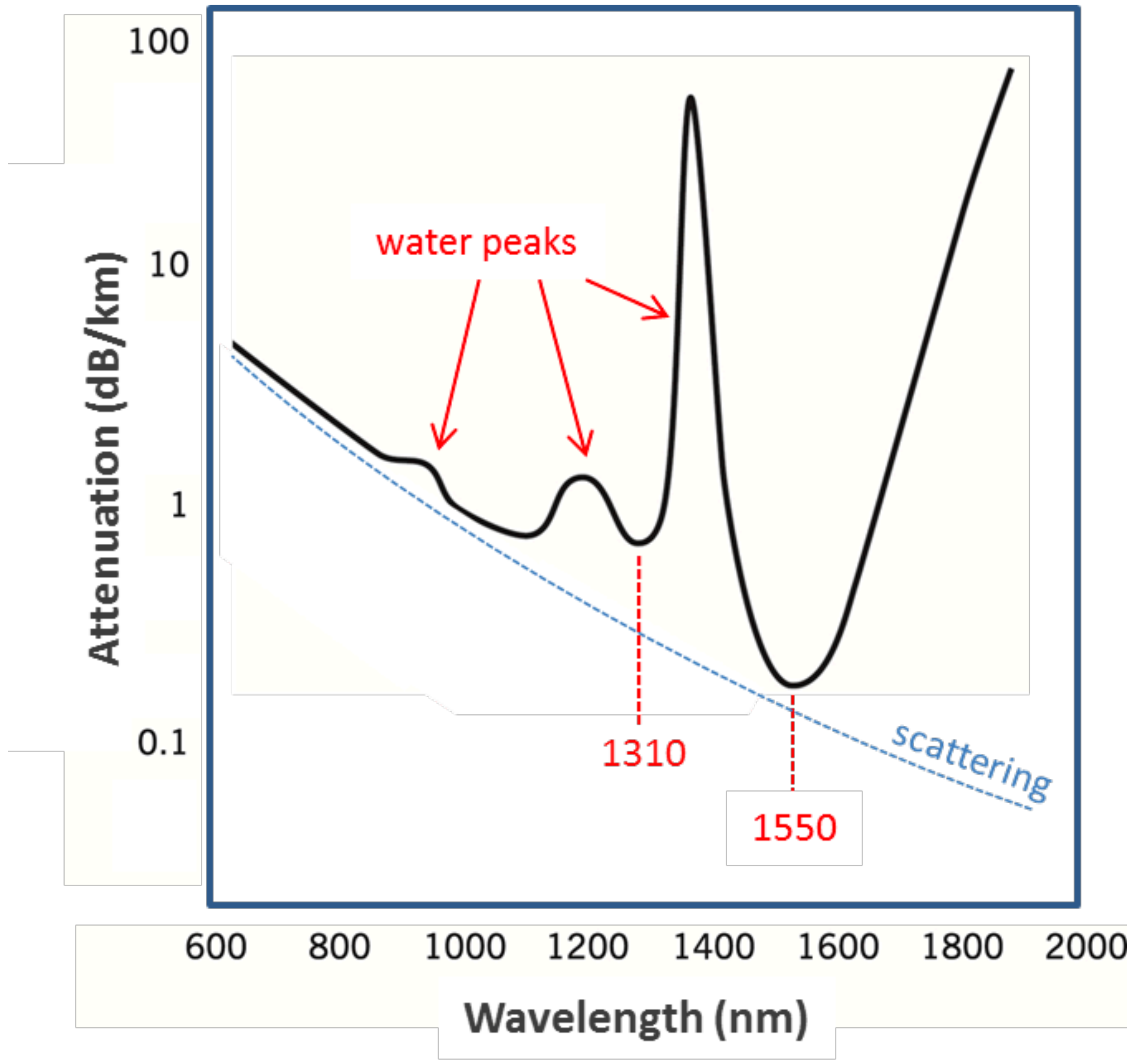




Silicon Photonics open issues

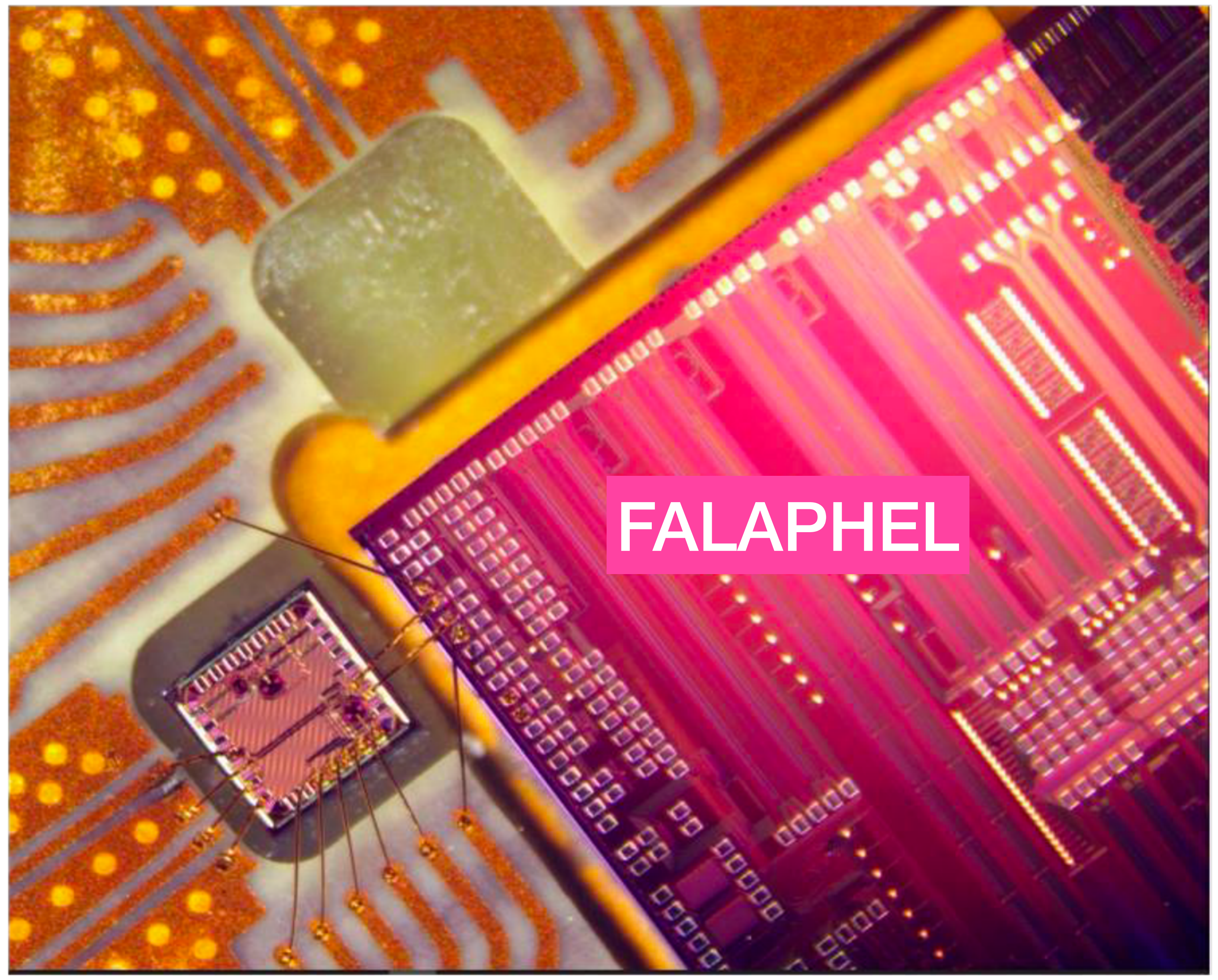
- **Modulator choice**
  - RM temperature sensitive wrt MZM but require lower driving voltages
- **Multiplexing scheme**
  - CWDM (few λ) vs DWDM (many λ)
  - Explore space division multiplexing (SDM) and polarisation division multiplexing (PDM)
  - Photonics switches needed
- **Fibre qualification and optical band**
  - Fibre characteristics (Chromatic Dispersion, Polarisation, Attenuation, radiation hardness, non-linear effects …)
  - Look at trends in data centres: O-band for 100G, C-band for 400ZR





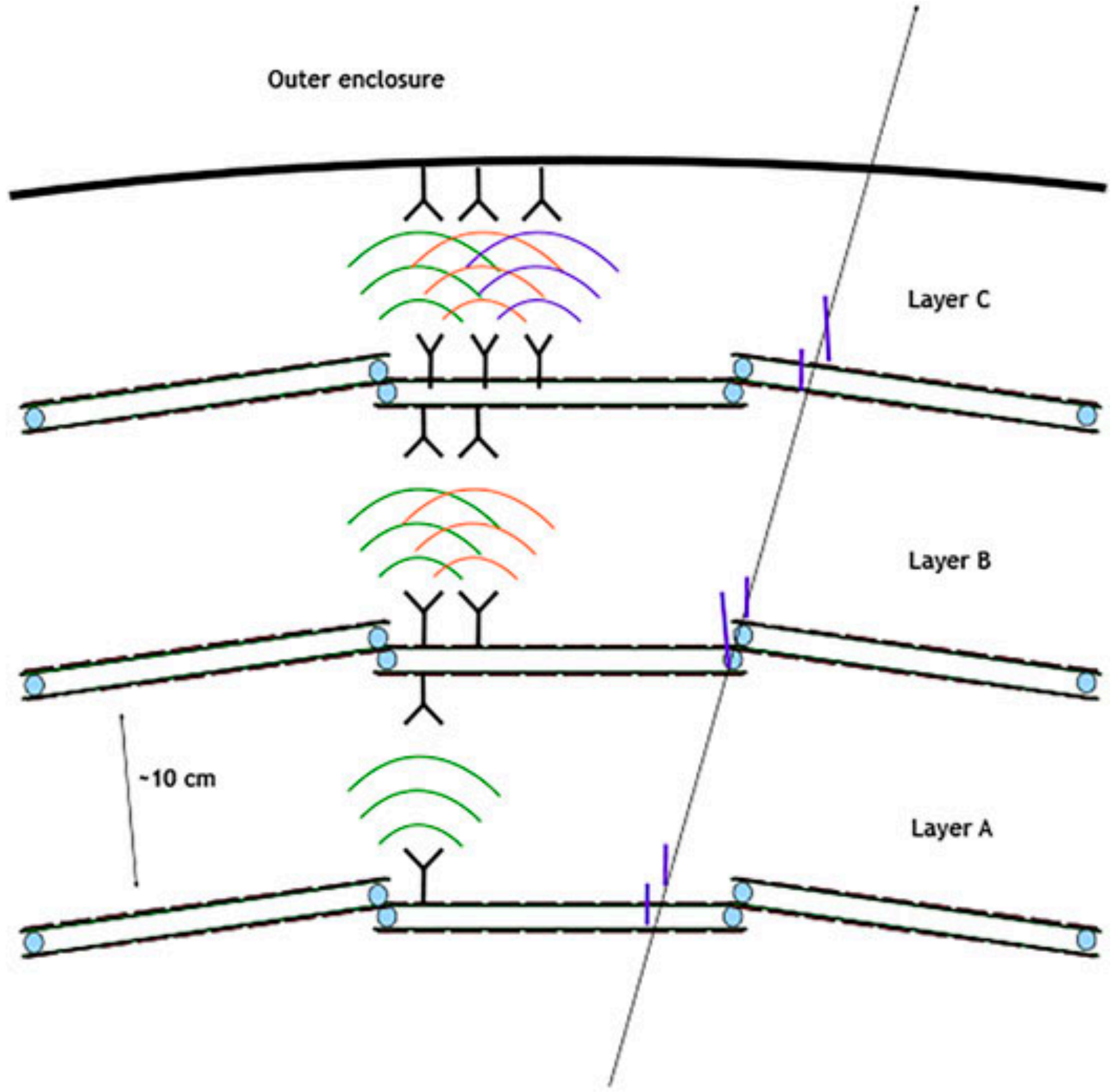
Silicon Photonics open issues

- **Radiation tolerance**
  - *Process dependent SiPh chip (doping)*
    - Only few foundries tested so far, think of whom will be available at the time
  - Explore ultimate device limits in view of FCC-hh
    - Might be difficult to find irradiation sources (what's happening in nuclear fusion ?)
  - Explore radiation hardness of SiPh laser sources and fibres
- **Packaging**
  - Integration of driver and PIC: flip-chip/wire-bond/TSV/TGV
  - Laser integration on-chip for low-radiation applications?

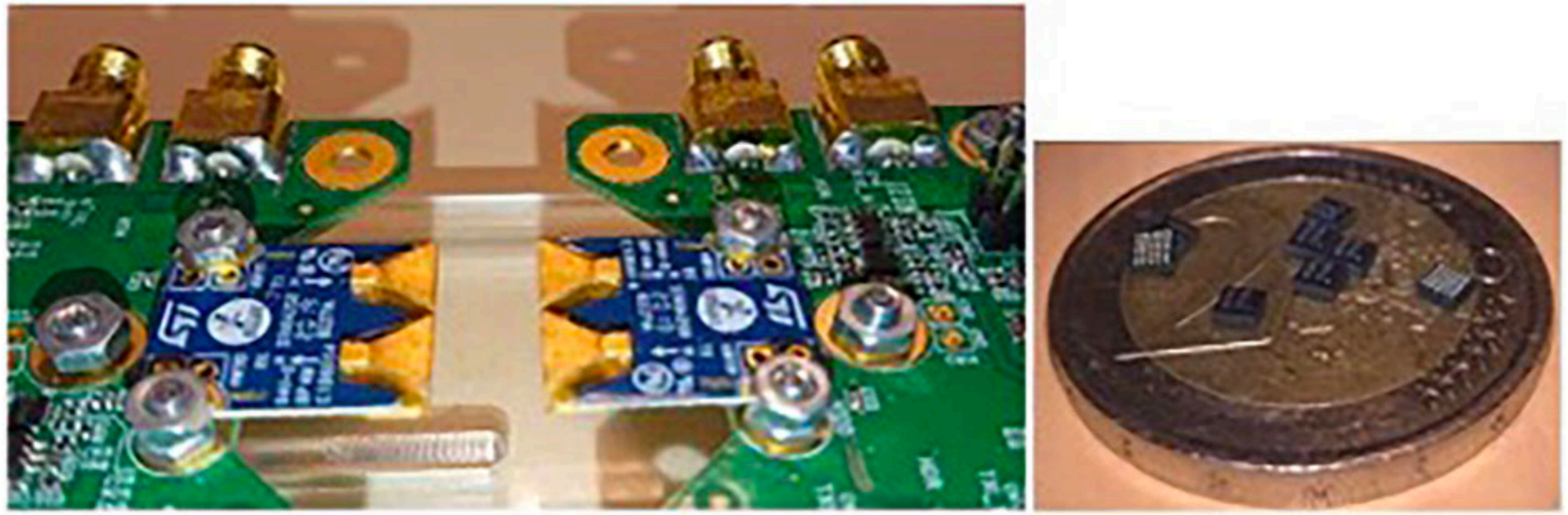


Wireless RF based links

(WADAPT project - AIDAINNOVA) - CEA, IPHC, Uppsala, Bergen, Wuppertal, Heidelberg, Gangneung-Wonju



- **Use 60 GHz carrier with modulation (up to ~10 Gb/s)**
  - "Short range" (~68 dB attenuation at 1 meter)
  - Small antenna footprint
  - Several COTS chips exist
    - Antenna can be integrated on chip or in package with good efficiency
    - Inter-module transmission



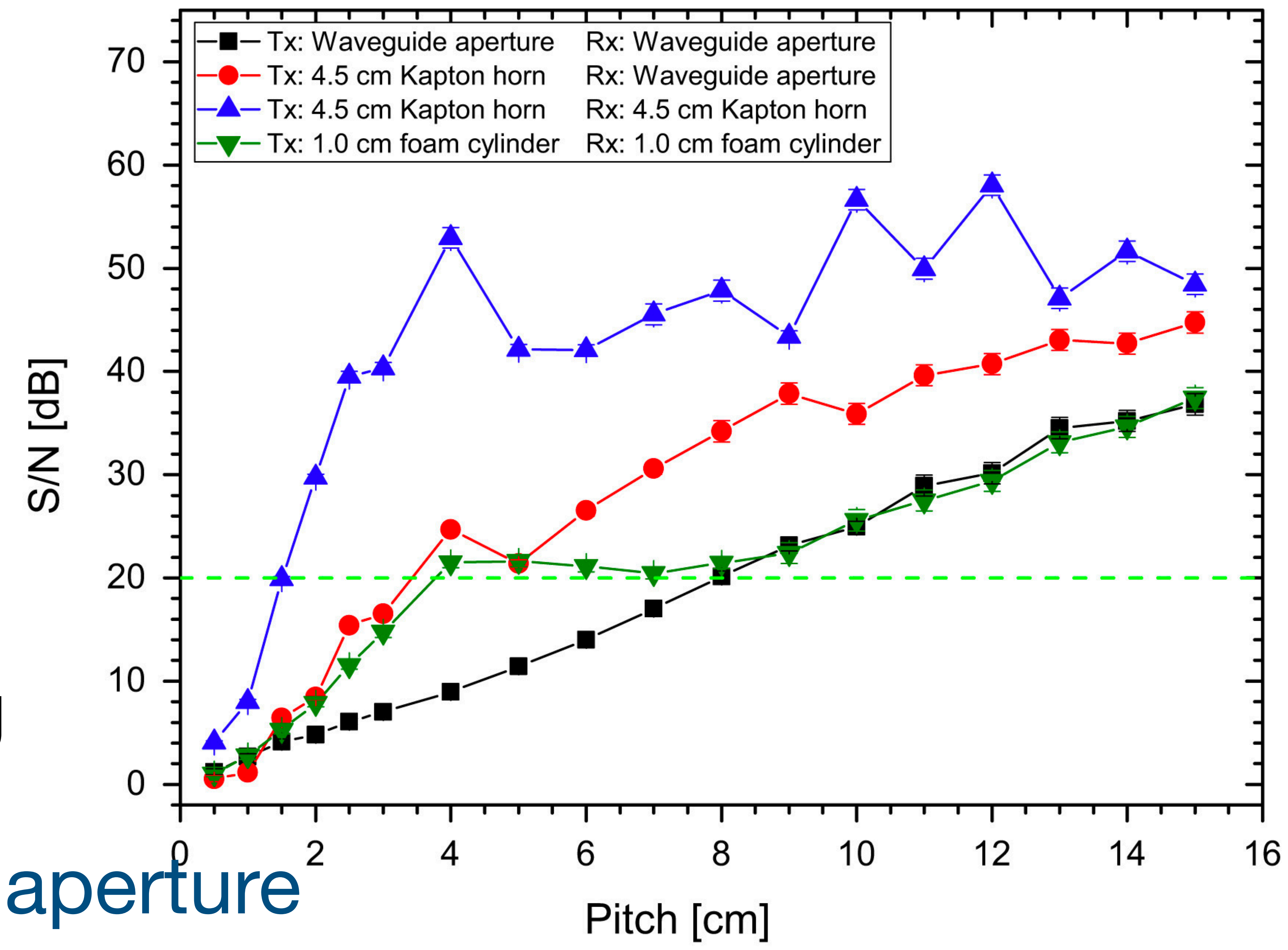
ST Microelectronics ST60 contactless connectivity transceiver in BGA.

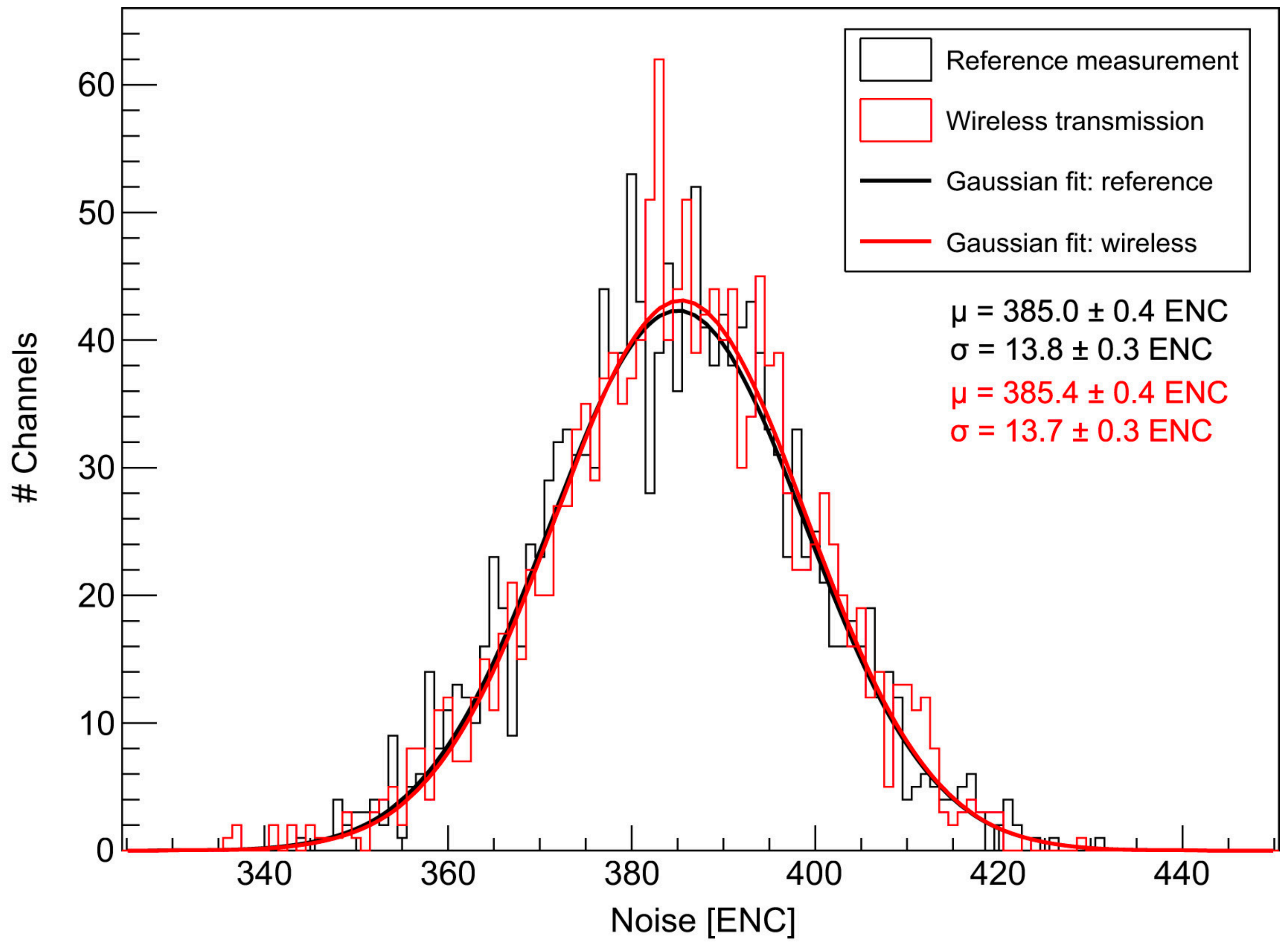
https://doi.org/10.3389/fphy.2022.872691

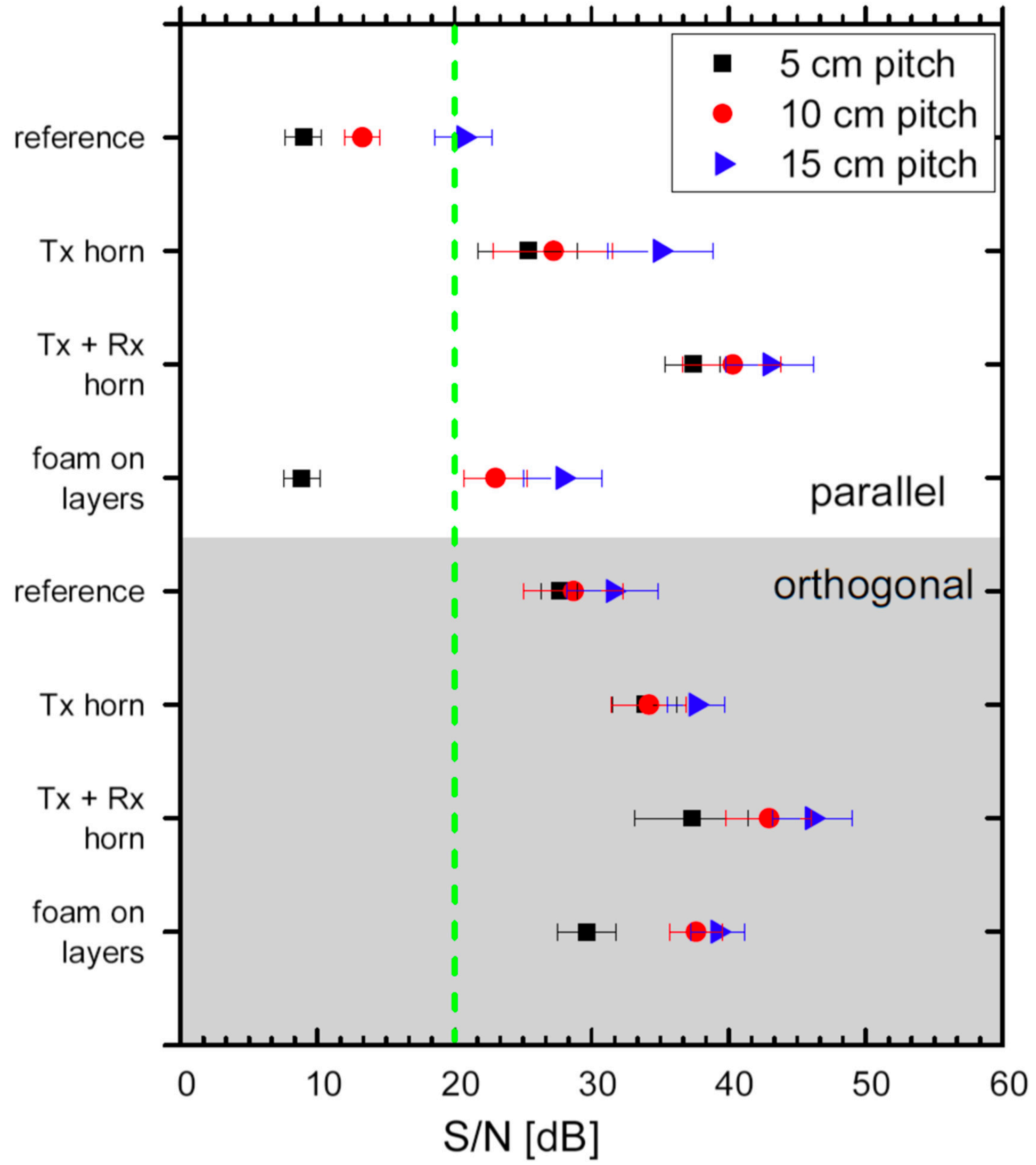
Wireless RF

Status of R&D

- **Channel cross talk can be reduced using**
    - Foam cylinders on top of the waveguide aperture
    - Operate different chips using frequency channeling
    - Orthogonal polarisation
- **Noise pickup negligible**
- **Radiation tests performed**







Wireless RF

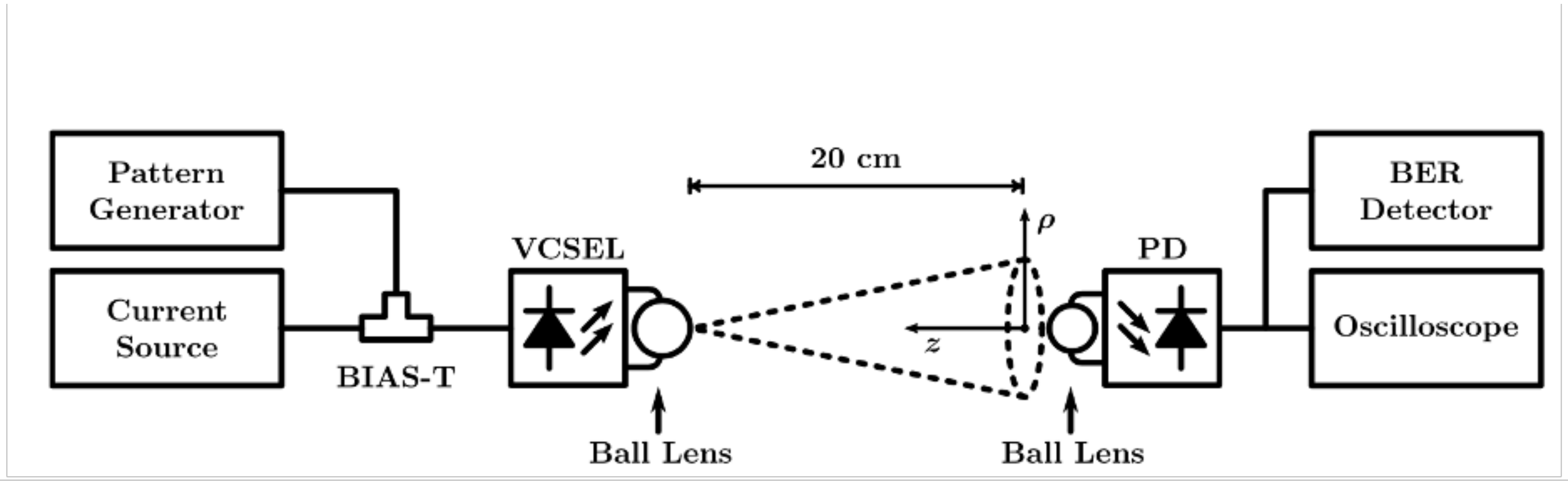
Radiation tolerance

- **Commercial ST60 chips tested**
- **At Turku (Finland) 14 MeV protons**
  - Survided up to 10^{14} N_{eq}/cm^2 and 7.4 MRad
- **At CERN (CLEAR)**
  - Exposed to 300 Mrad some (10 dB) degradation found, plus 80 MHz central frequency shift
  - Planning to use radiation hardened design (ST C65SPACE) or test 45 nm PD-SOI

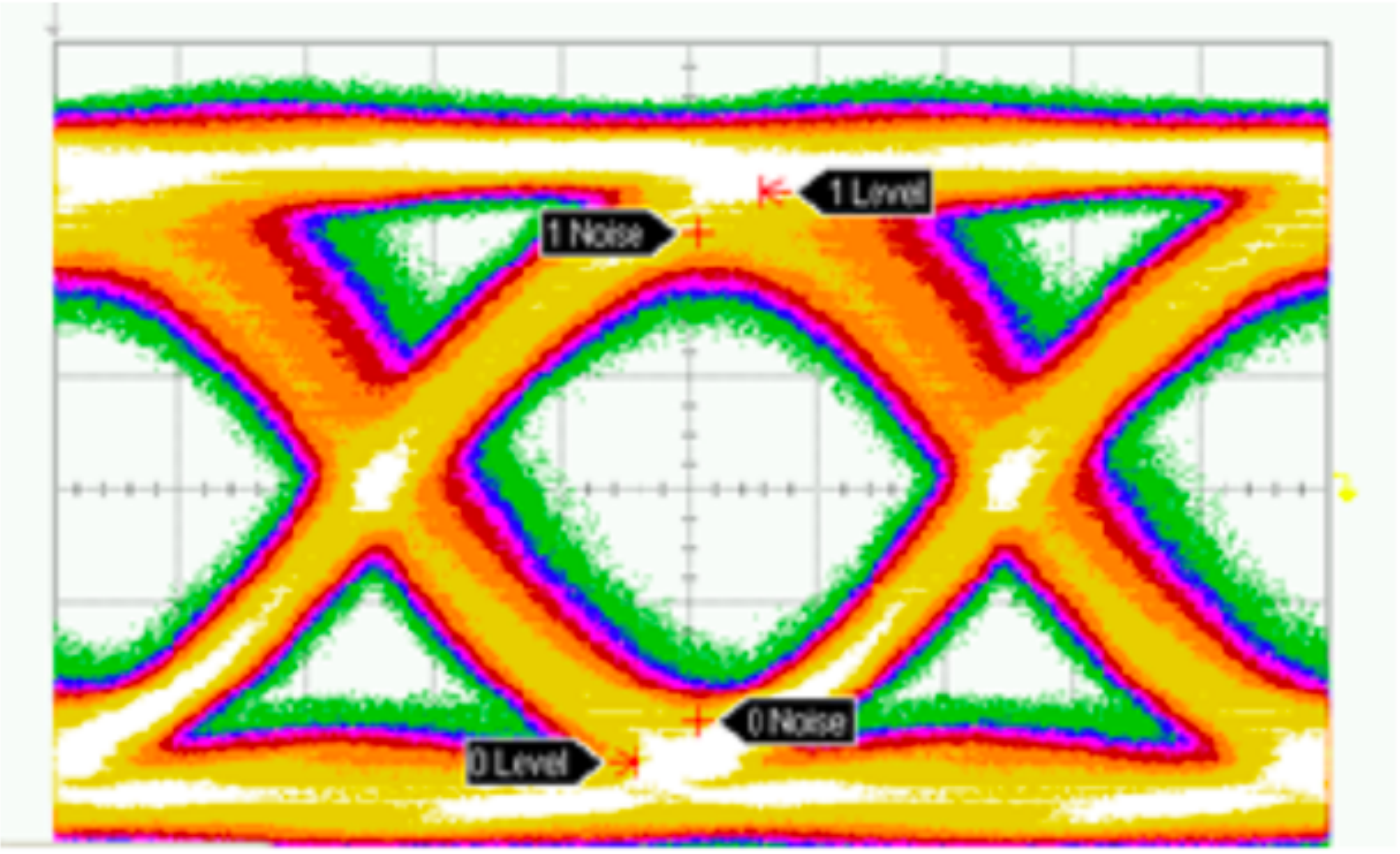
Free Space Optical (FSO) based links

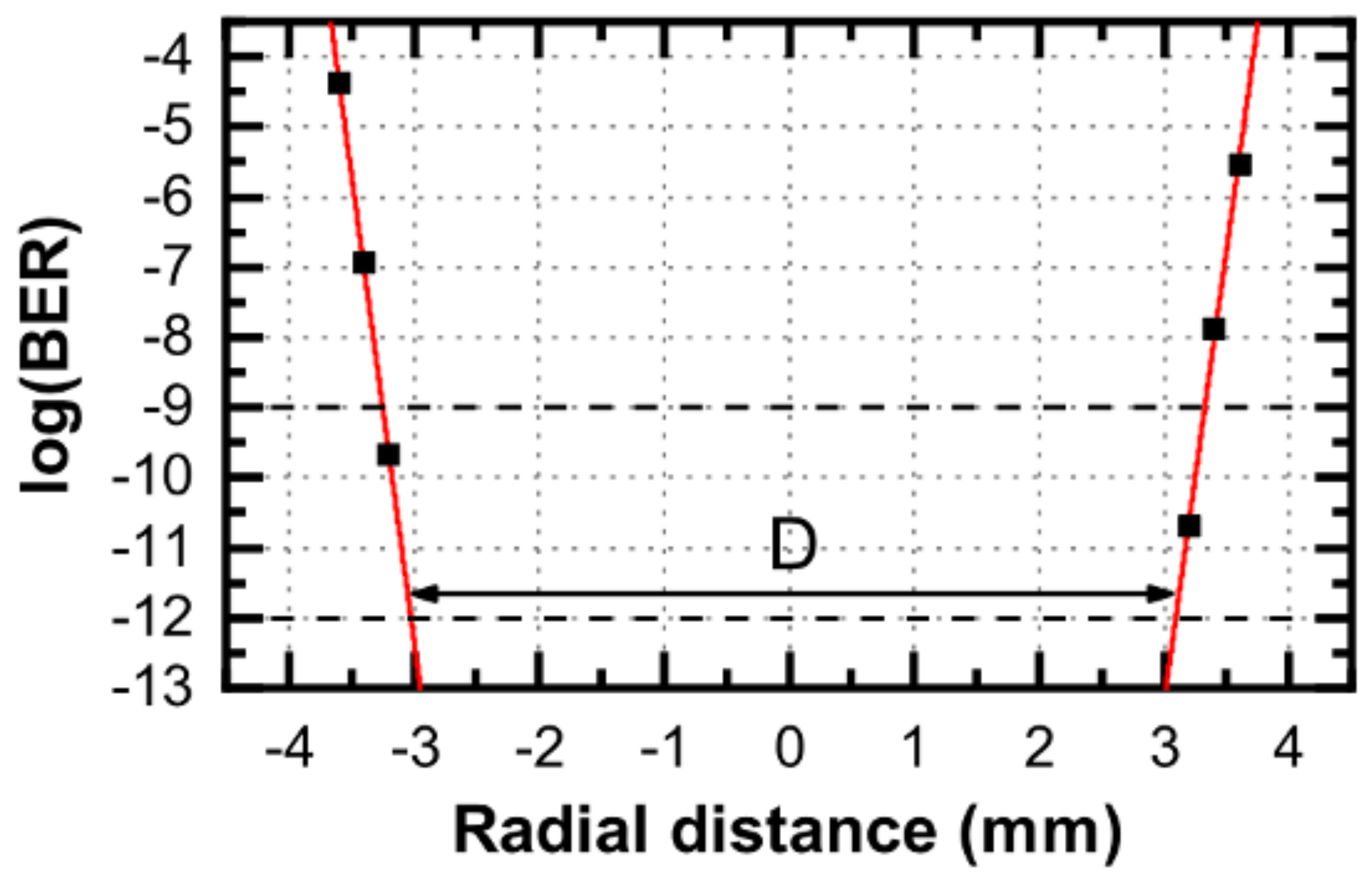
(INFN Phos4brain project)

VCSEL 10 Gb/s 1310 nm, 2 mW output optical power (7.5 mA forward current) + beam collimation ball lens PIN diode (50 μm diameter, -3dB bandwidth 12 GHz, TIA integrated) + focusing ball lens



BER $<10^{-12}$ @ 10 Gb/s up to 20 cm distance
Misalignment up to ±3 mm





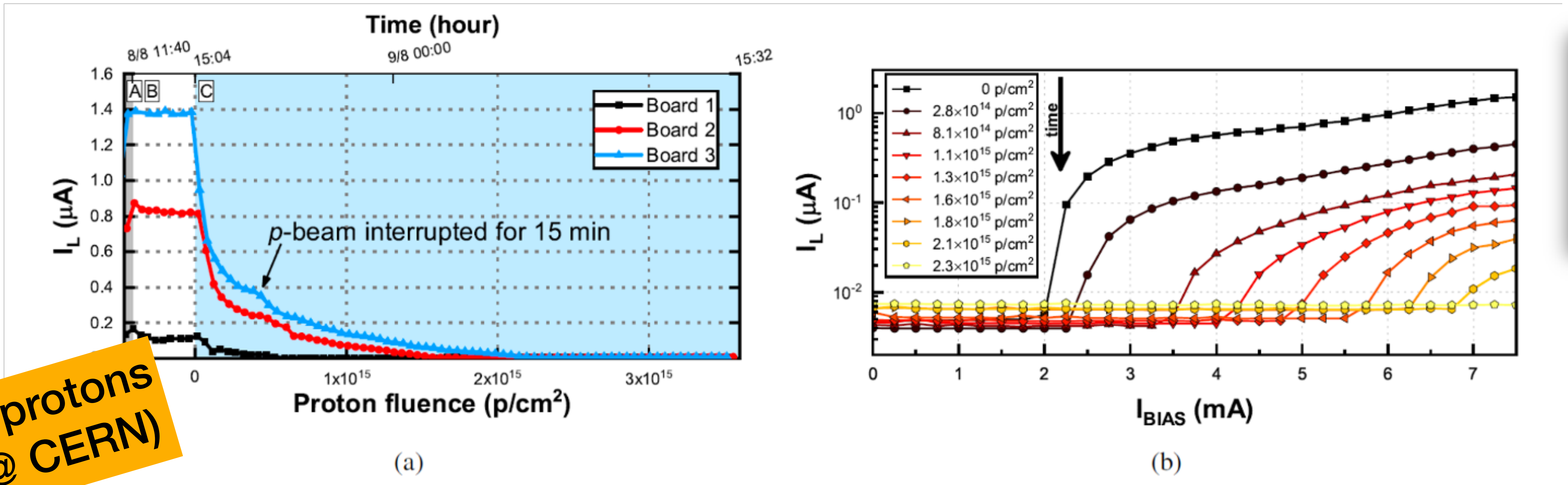
Limited cross-talk (precision mounting)
@ 3 cm distance ~-55 dB
@ 10 cm distance ~-30 dB

FSO

Radiation tolerance (TID & SEE)

Good TID resistance (tested up to ~250 Mrad)

SEE ~10^{14} n_{eq}/cm^2

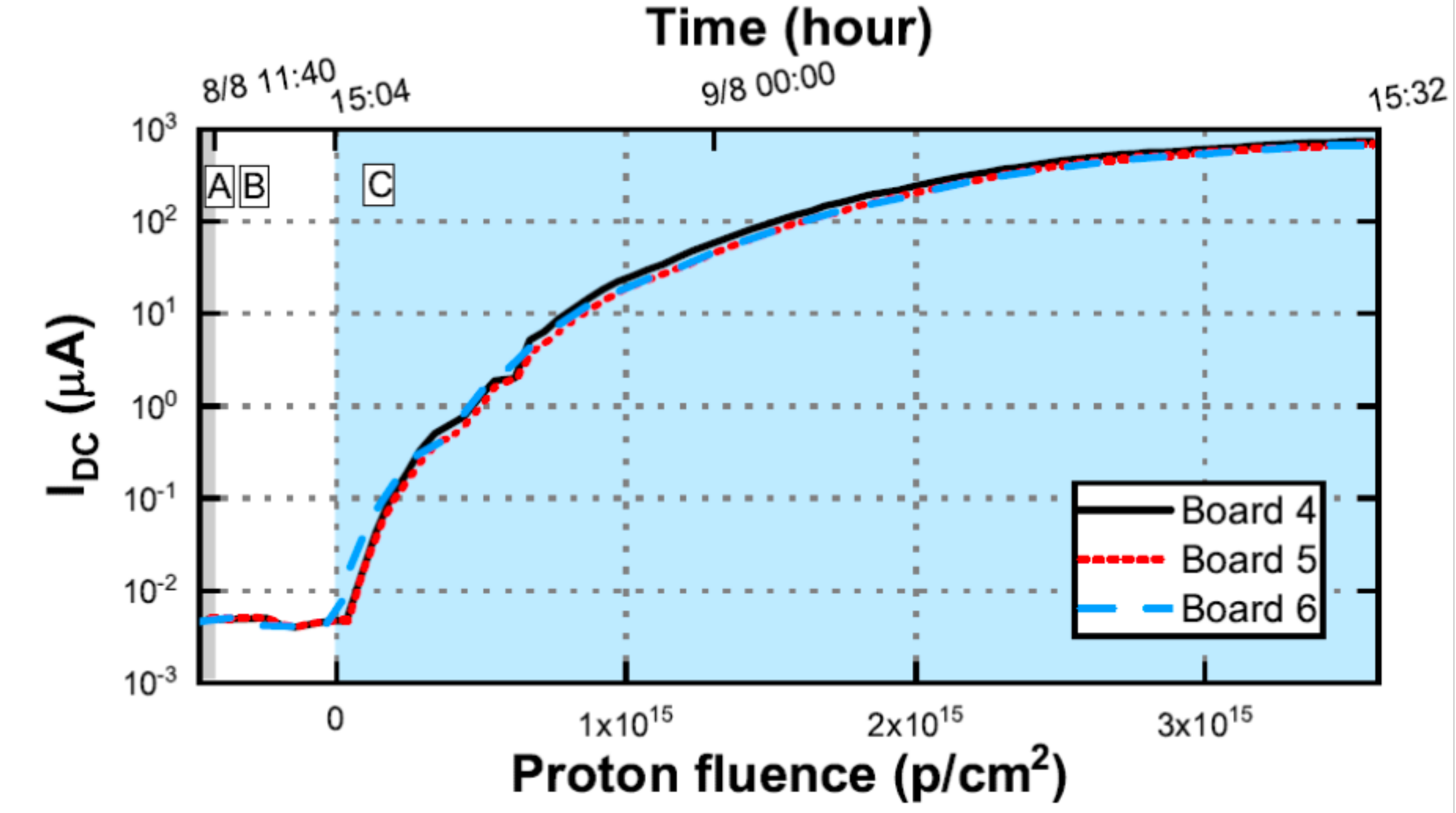


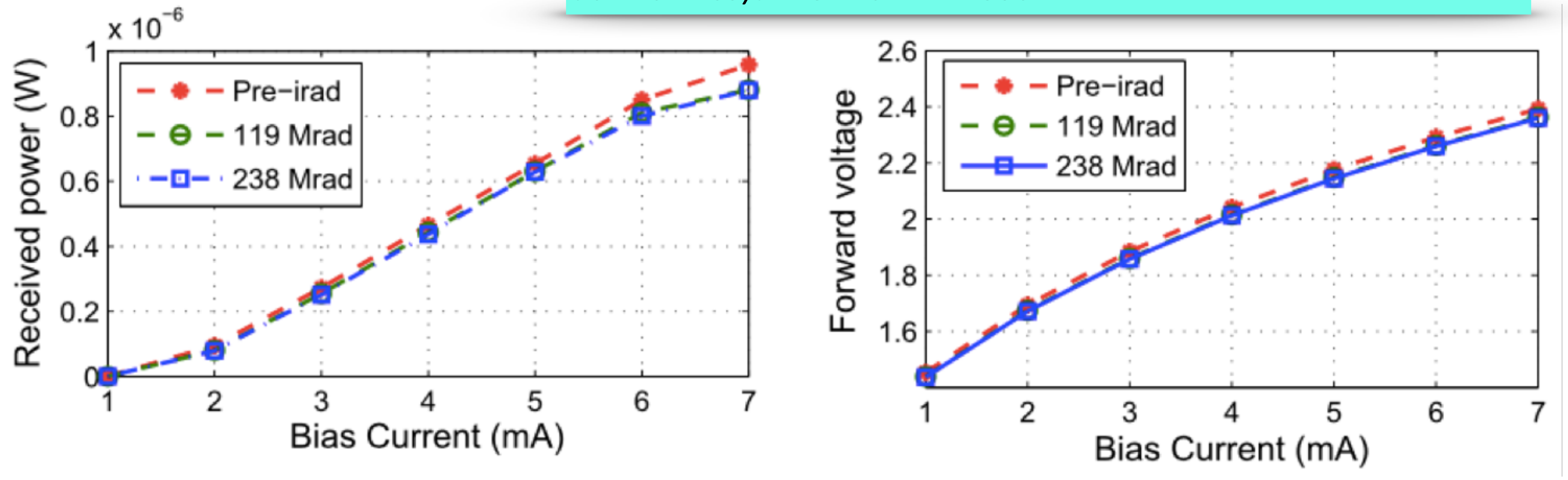
24 GeV/c protons (IRRAD @ CERN)

Figure 4: (a) I_L as a function of time. Different colored areas indicate Area A: cooling ramp; Area B: idle; Area C: p-beam ON (b) L-I curves of Board 3

A. Messa et al., "Optical Wireless Systems for High Energy Physics: Design and Characterization", 2019 21st International Conference on Transparent Optical Networks (ICTON), Angers, France, 2019, pp. 1-4, doi: 10.1109/ICTON.2019.8840158.

W. Ali et al., "Design and Assessment of a 2.5-Gb/s Optical Wireless Transmission System for High Energy Physics," in IEEE Photonics Journal, vol. 9, no. 5, pp. 1-8, Oct. 2017. doi: 10.1109/JPHOT.2017.2723301





FSO perspectives

A lot to explore

- **Higher speed**
  - Complex modulation schemes like OFDM (Orthogonal Frequency Division Multiplexing) can reach 100 Gb/s
    - Based on FFT, requires high power but can allow very high speeds
- **Higher ranges**
  - Might be useful for reducing material budget inside big volumes
  - Use of ball-lenses
  - Typically imply smaller data rates - but several meters can be reached

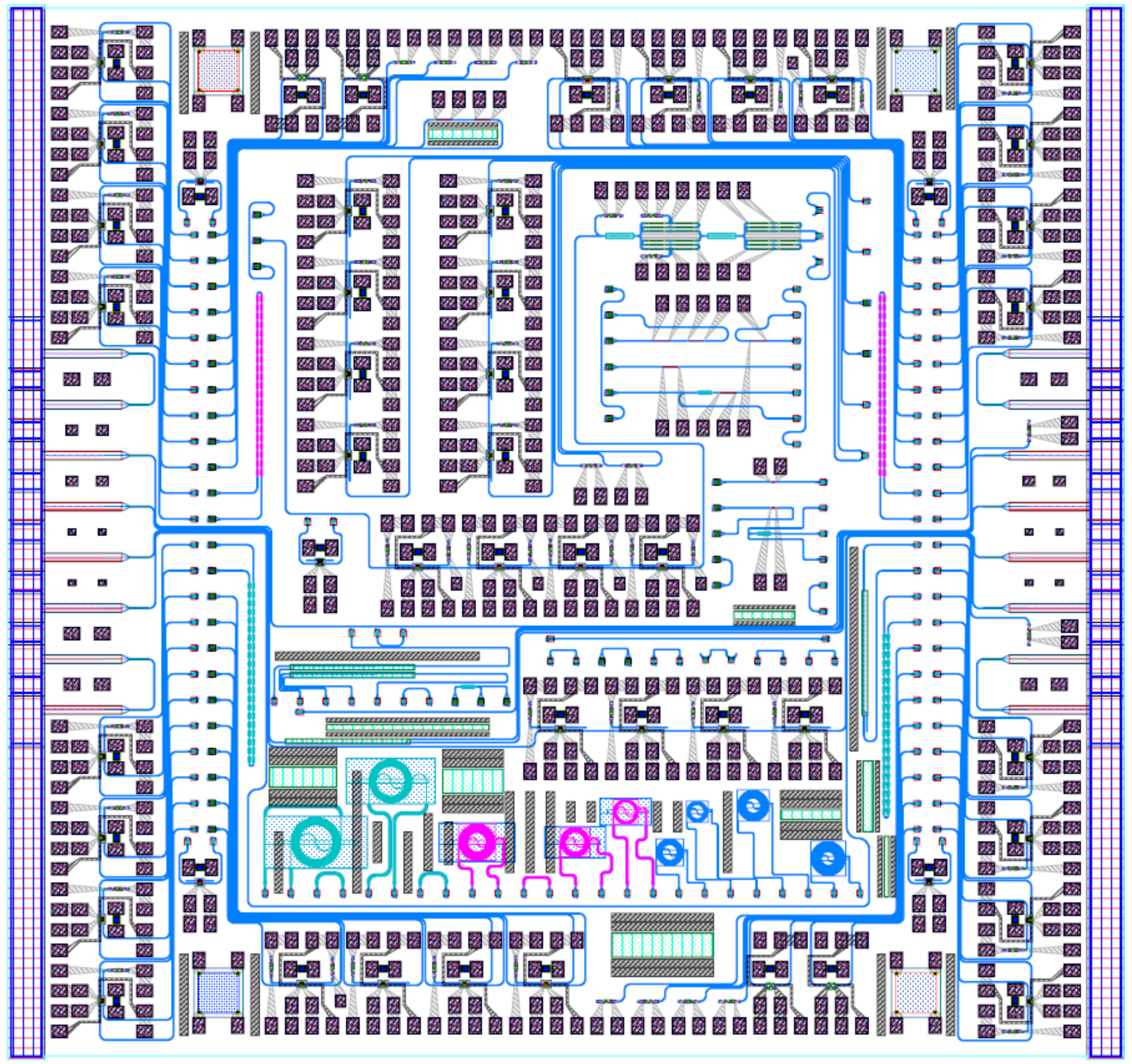
General system aspects

- Backend boards use FPGAs
    - Links (and ASIC) should be made compatible with FPGA developments as much as possible
- Latency (introduced by FEC or protocols) must be considered especially for “real-time” applications (Triggers)
- Main limitations in data rate might not be the physical layer (opto-electronics could reach >40 Gb/s) but rather the ASIC (Serializers and drivers) and their radiation tolerance **(see Stefan Biereigel talk)**

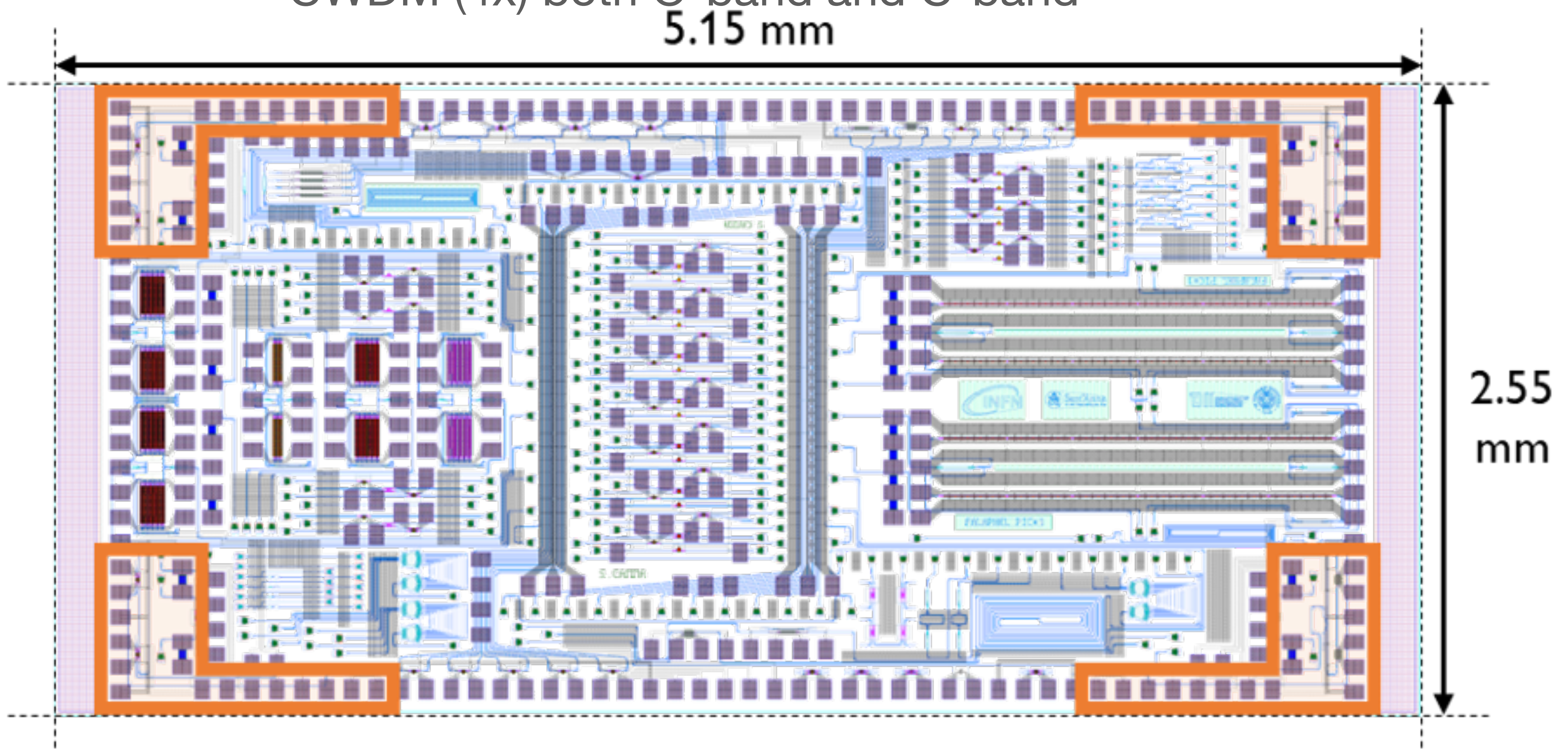
Community competences

Silicon Photonics

- CERN - Established R&D program through EP-R&D WP6 and WP2 (2023-28)
  - PIC design (IMEC), RM and MZM and engineered radiation tolerance tests
  - Polarisation control, laser sources, optical MUX
  - System aspects (Modulation format, FEC, optical band, interface to COTS back end)
  - EIC development and integration studies
  - Targeting 4x CWDM
- INFN - (FALAPHEL, IGNITE) (2023-26)
  - PIC design (IMEC), RM, MZM, FMZM, EA, C-band
  - EIC development and integration studies
  - Targeting 4x CWDM



CERN PICV3 (ISIPP50G) - 5x 5 mm2 submitted Oct 2022
CWDM (4x) both O-band and C-band



INFN PICV2 (ISIPP50G) - 2.5x 5 mm2 submitted Oct 2022
CWDM (2xRM) C-band

Community competences

Silicon Photonics

- KIT
  - PIC design (IMEC), RM, MZM
  - Photonics & ASIC packaging
  - Targeting 4x CWDM
- US (LBNL, FNAL, UCSB, Freedom Photonics)
  - PIC design (Global Foundries), Laser sources, radiation tolerance tests
  - Targeting DWDM with 1 fibre x N detectors

Collaborative issues

Resources and diversity

- Broad phase space requires to explore several solutions
  - Some “immediate” needs for HL-LHC (last phase) are currently being discussed
  - Looking far in future would it be possible to integrate several link technologies ? (“HEP 5G”)
- New modulation schemes must be deployed for any kind of links
- Co-packaging (including sensors) needs close collaboration with ASIC developments
- Rad-hard testing might become an issue
  - 250 MGy and 10^{17} n/cm^2 for FCC-hh

Conclusions

- Wired electrical links offer ultimate (and lightweight) short-range solution in very rad-hard environments, but need to improve modulation scheme to afford more bandwidth
- Silicon photonics likely to offer a viable solution
    - Vigorous R&D in progress but need to explore many corners and more groups and synergies sought
- Wireless links, both RF and optical, could be employed to bring lightweight intelligent solutions to data transfer, but need more R&D for integration with mechanics and increase radiation robustness

Thank you for your attention