Towards Radiation-Hard Optical Data Transmission for HEP Using Silicon Photonics

Q1, 2, 3,…

NOT A TALK,

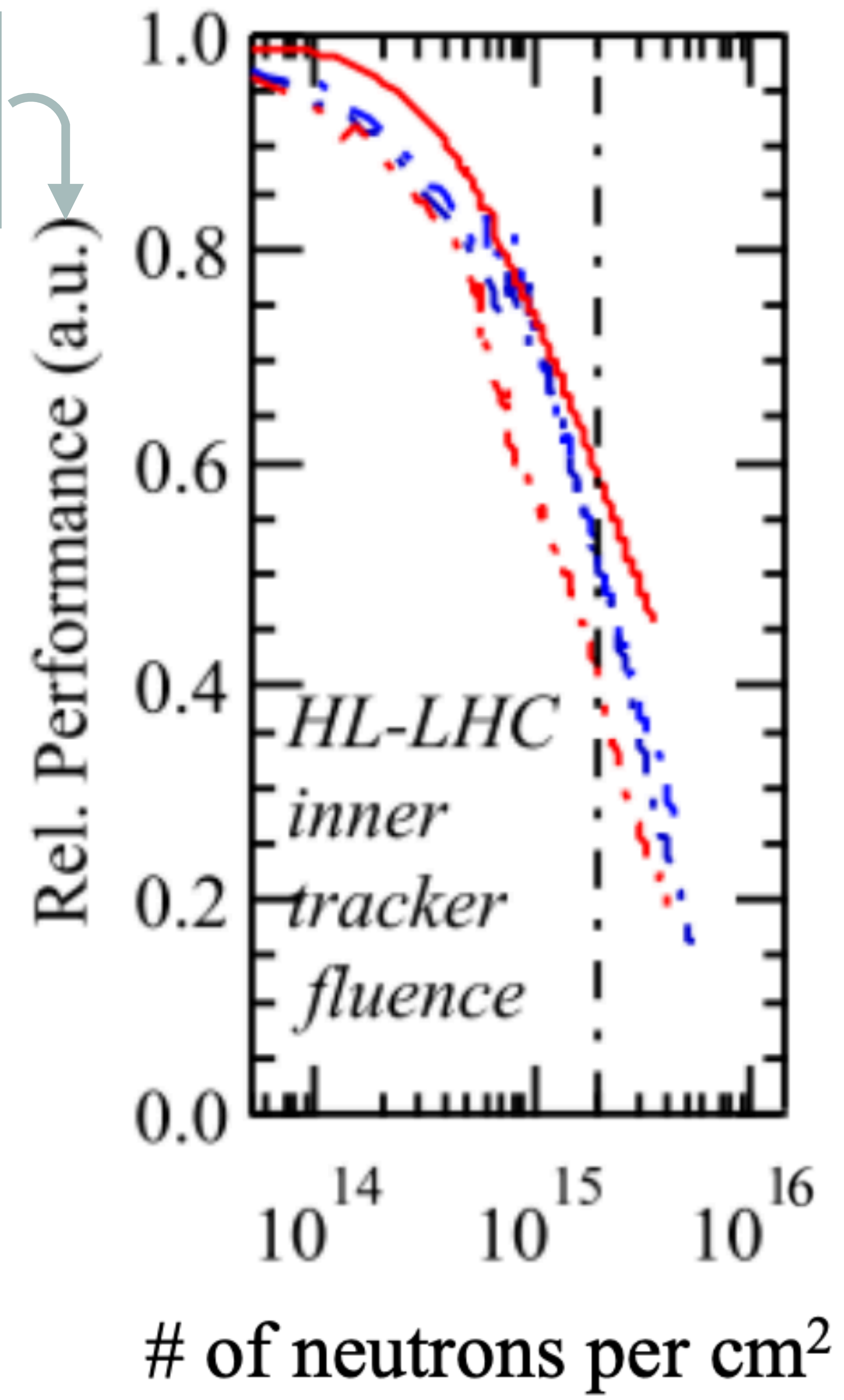
BUT (TRYING TO) ADDRESS THE OVERFLOW QUESTIONS FROM TUESDAY'S PRESENTATION !

Recap: Silicon Photonics

Current deployment for HL-LHC

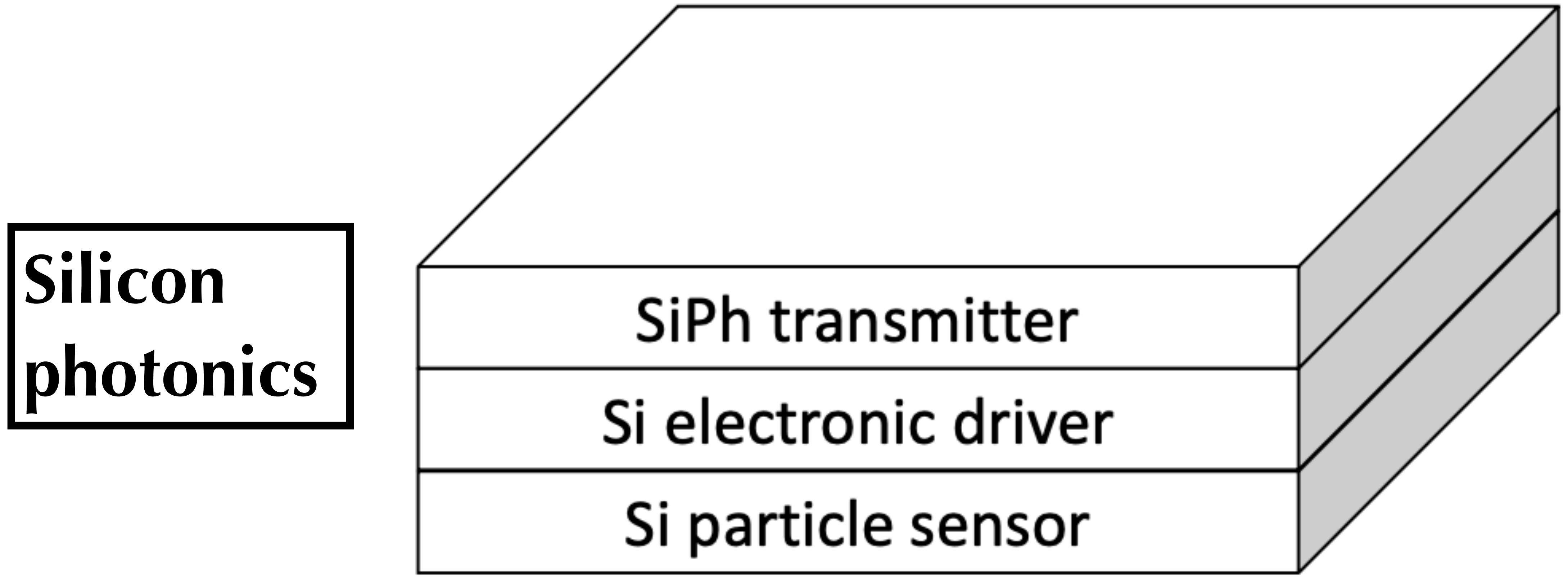
Q1 Output optical power

VCSELs (vertical cavity surface emitting lasers) **+ discrete PIN photodiodes + parallel fibers**



- **Breaks at 1MRad/10^{15} n_{eq}/cm^2**

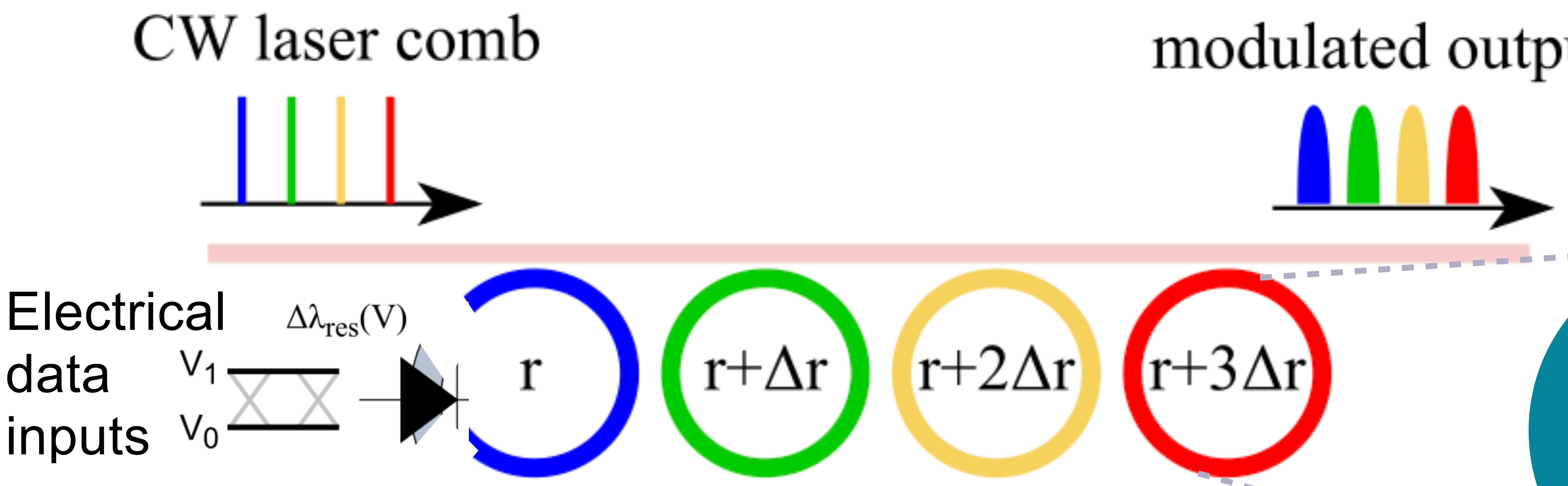
New solution to harsh HL-LHC environment

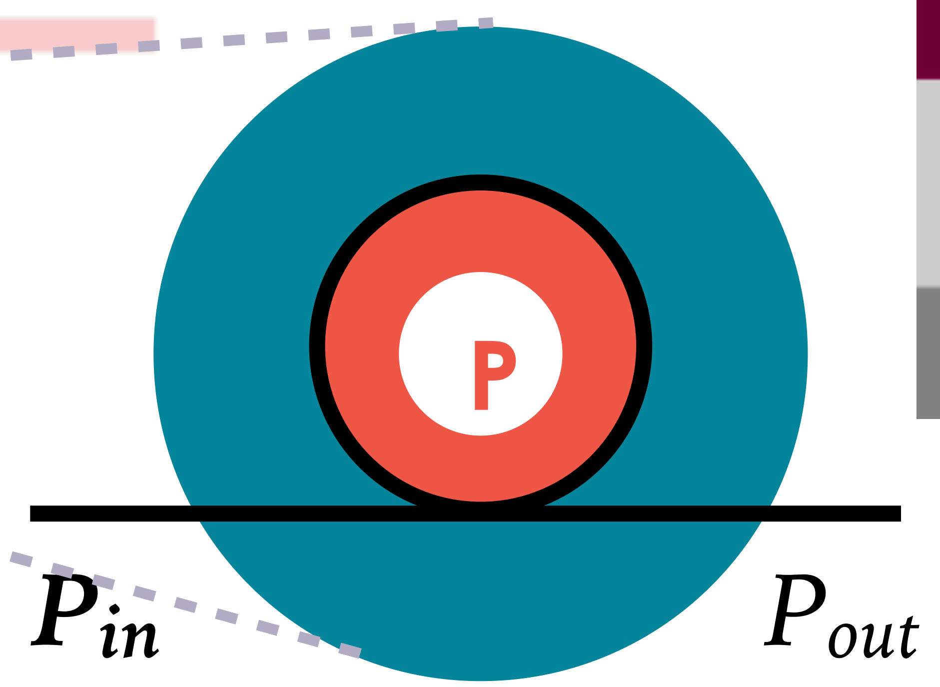


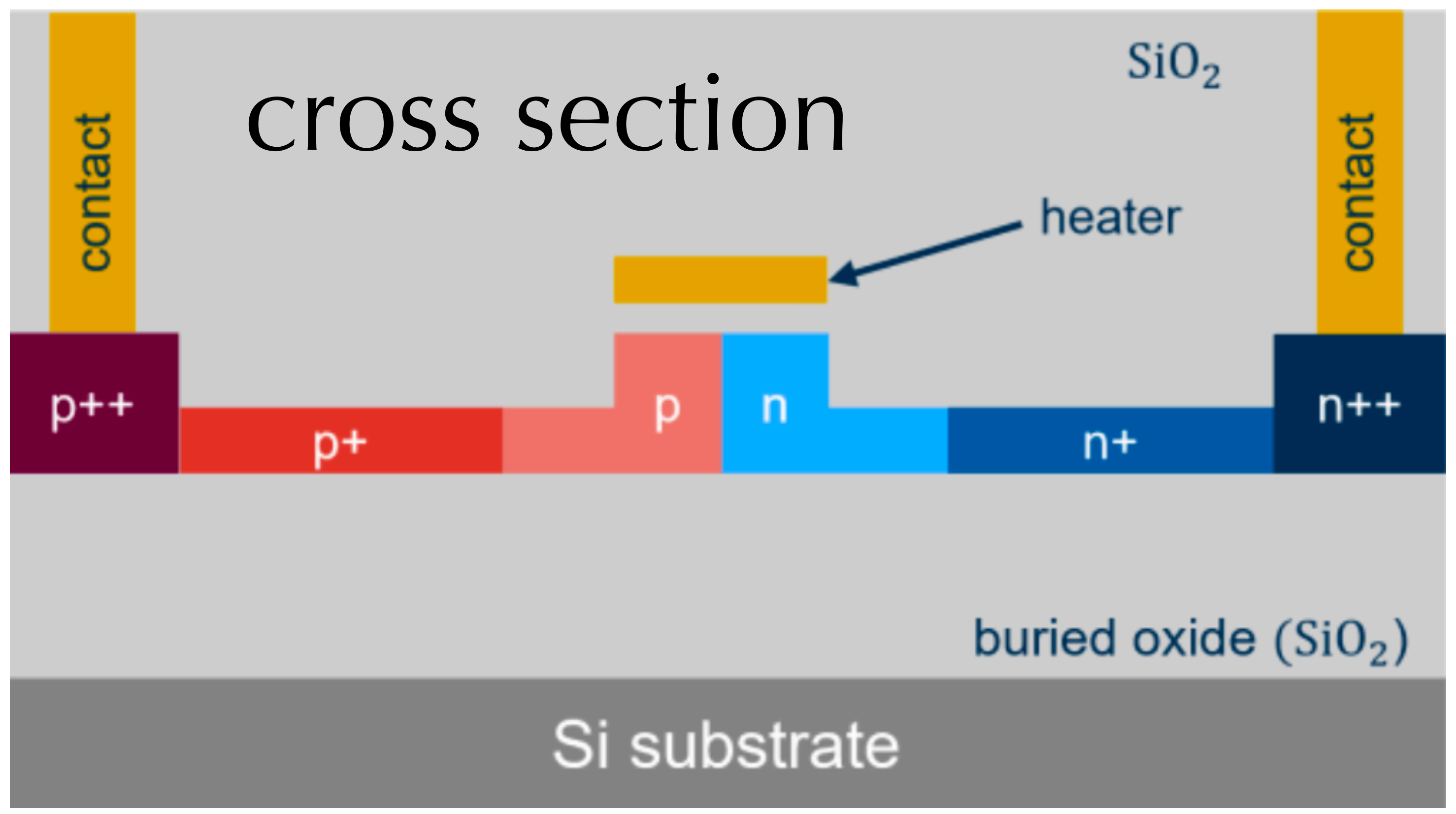
- Idea: fabricate photonic devices on silicon substrates infrastructure, tight integration with sensors and readout ASICs

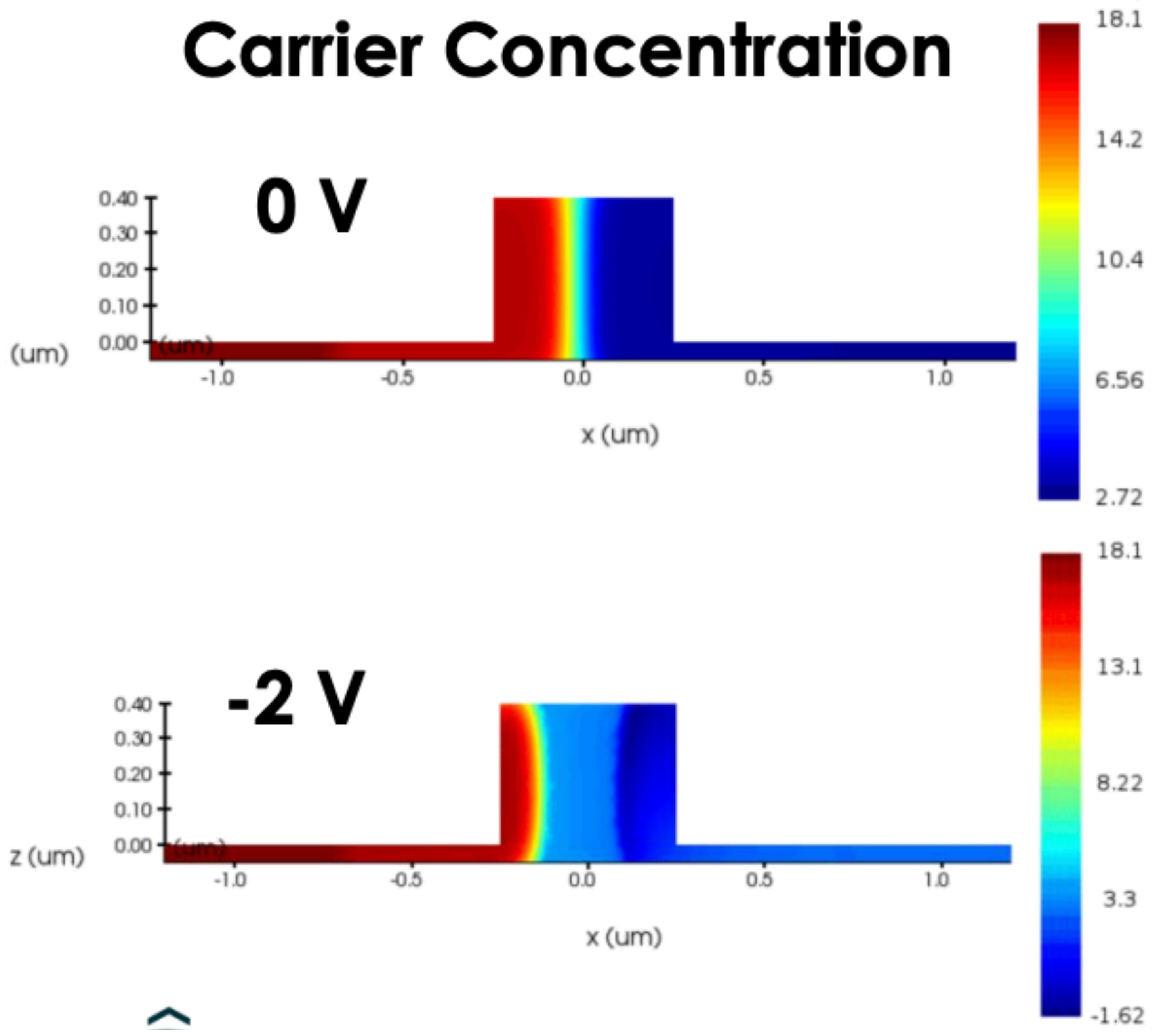
- **High radiation tolerance** (> 1GRad TID and > $5x10^{16}$ n_{eq}/cm^2)
- **Multiplexing**: wavelength, polarization

Recap: SiPh Transmitter Structure









- Key component: resonant ring modulator
- Modulation voltage changes (the electrical signal 0/1)

—> Carrier concentration changes

—> Refractive index changes

Index

$$\Delta n = -\frac{e^2\lambda^2}{8\pi^2 c^2 \varepsilon_0 n}\left(\frac{\Delta N_e}{m_e} + \frac{\Delta N_h}{m_h}\right)$$

electrons **holes**

—> Resonant wavelength changes nL = m·λres

—> Output optical power changes

Recap: SiPh Transmitter Performance Parameters

- **Modulation voltage** changes (the electrical signal 0/1)

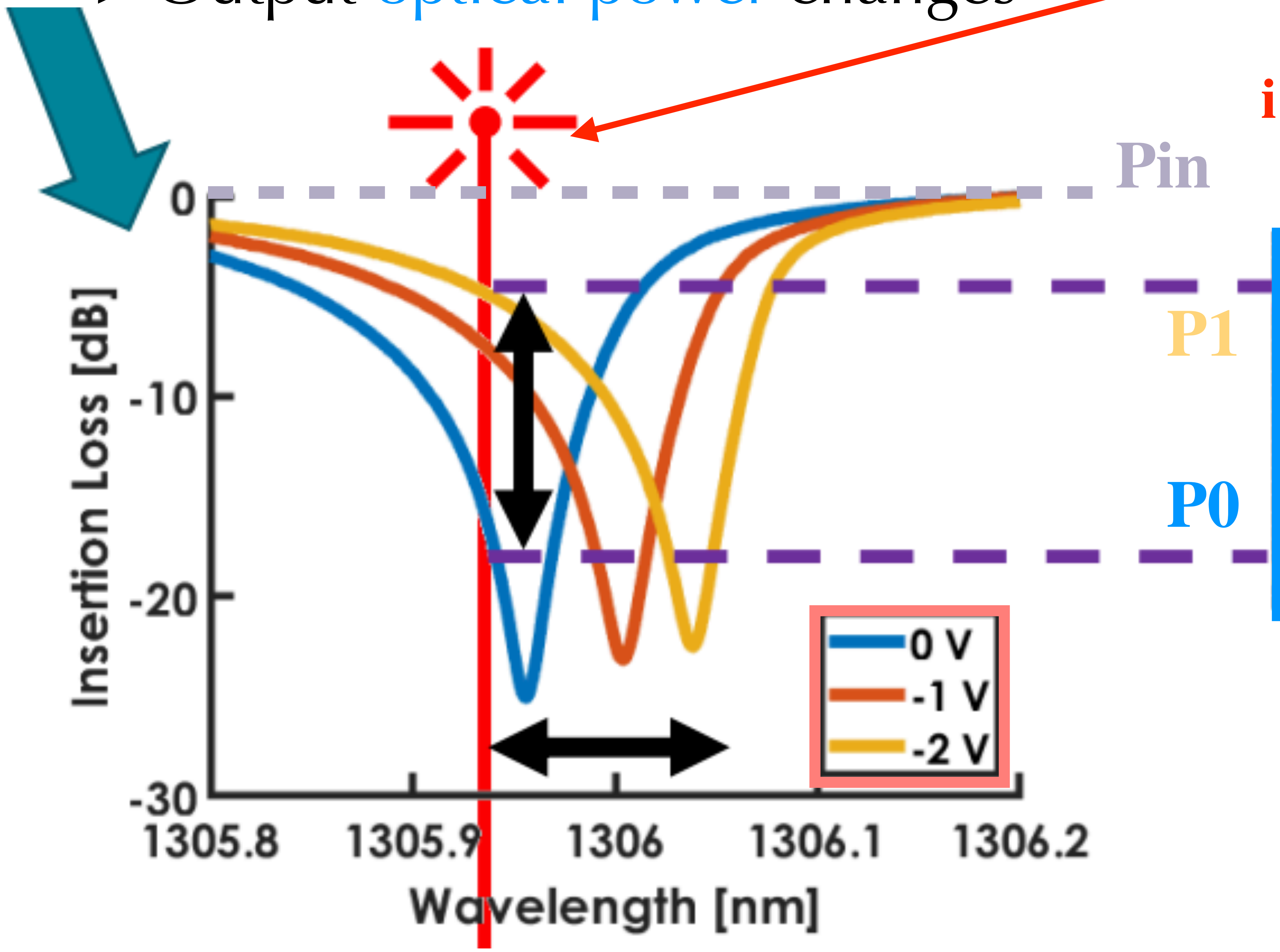
  —> …

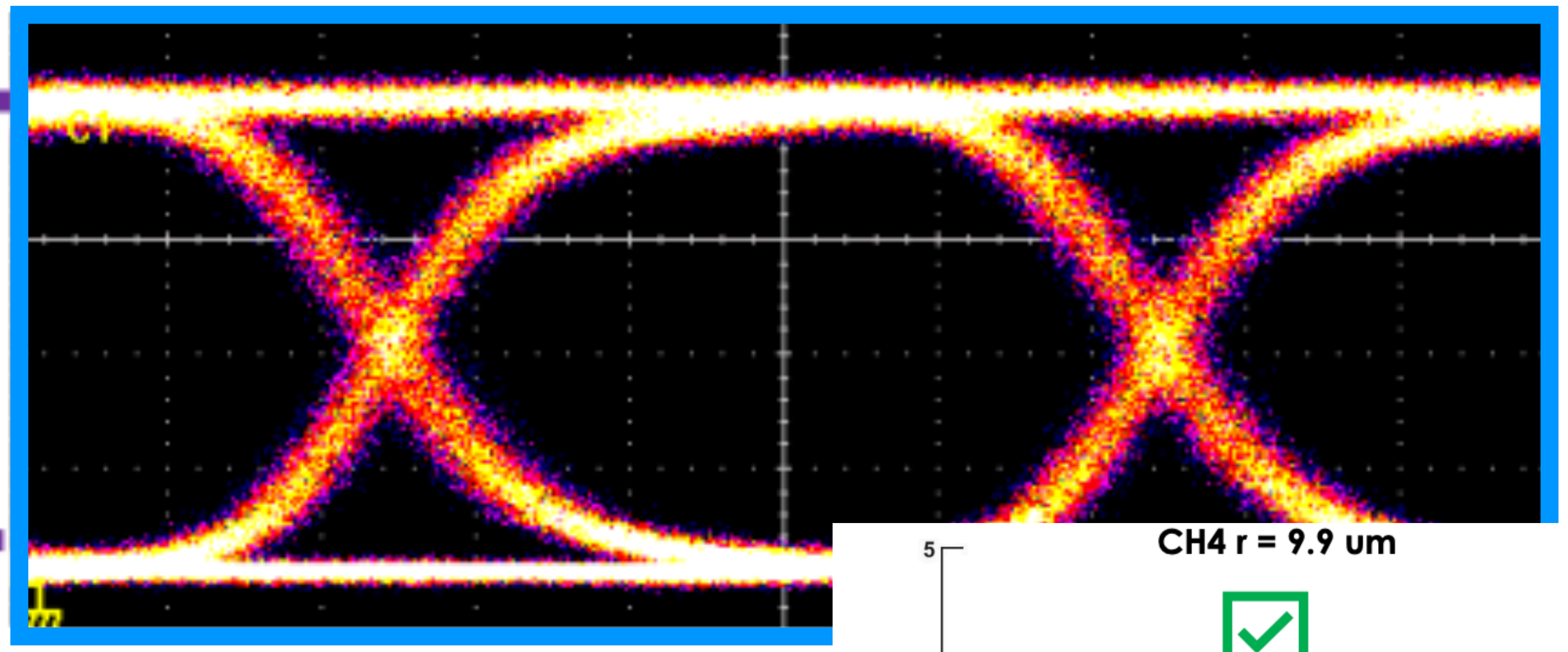
  —> Output optical power changes

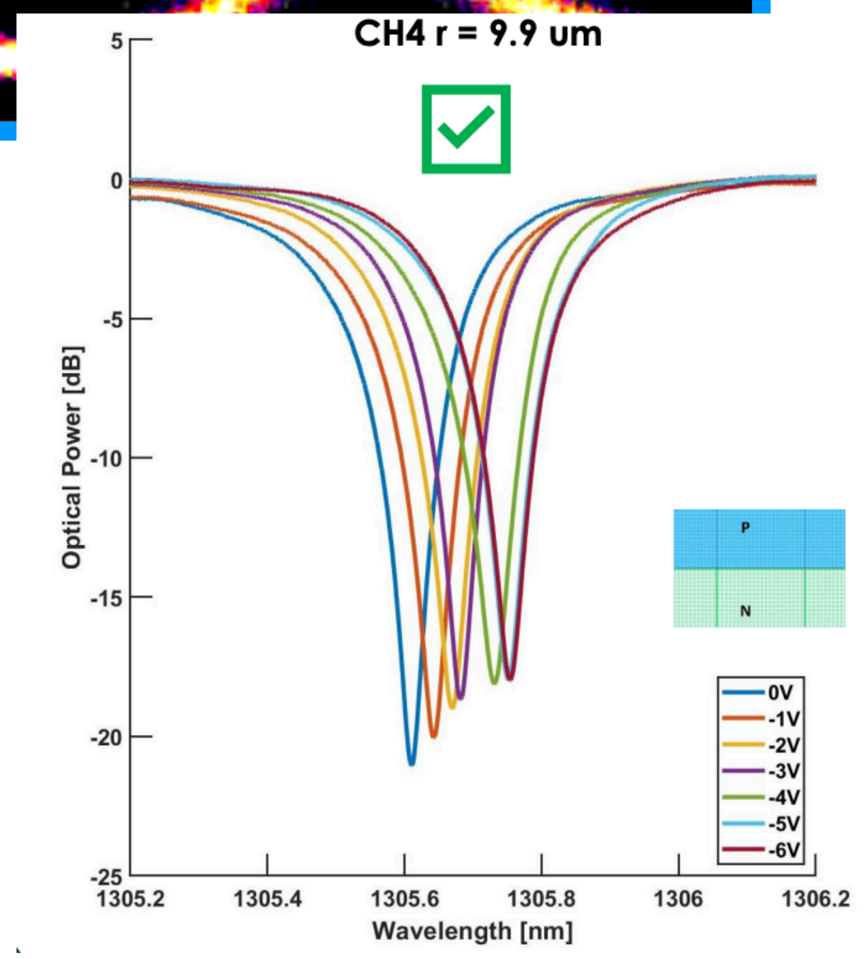
Choose λ_{laser} = λ_{opt}, where the eye diagram opening is the biggest,

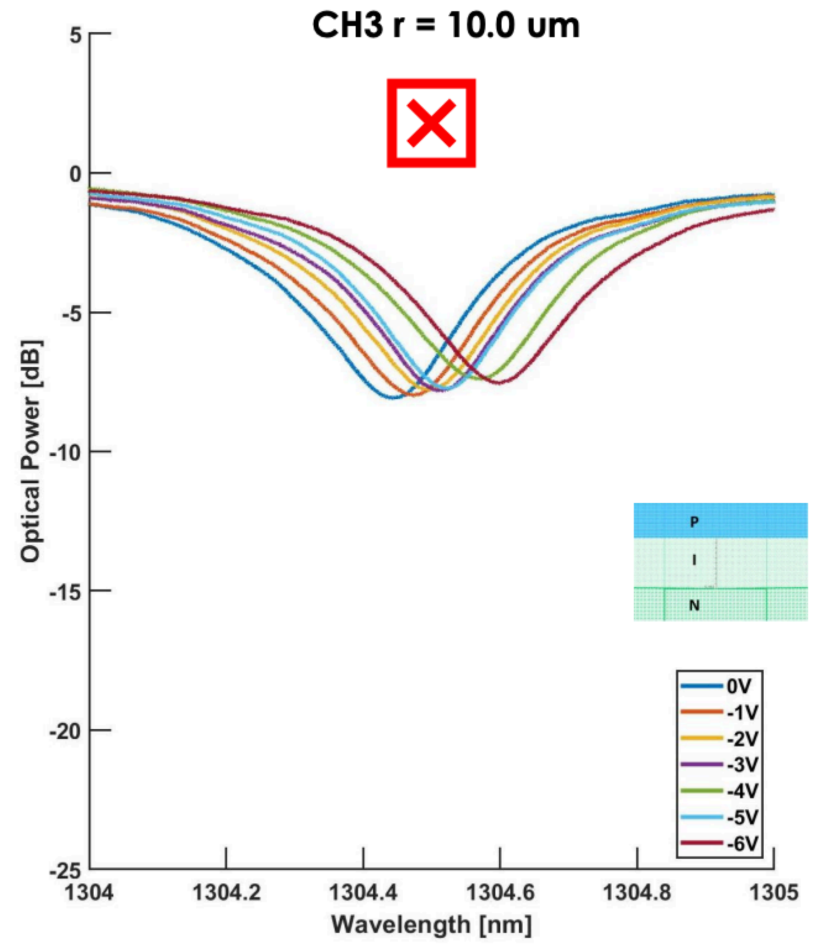
i.e. large P1 - P0

Large $\Delta\lambda/V$



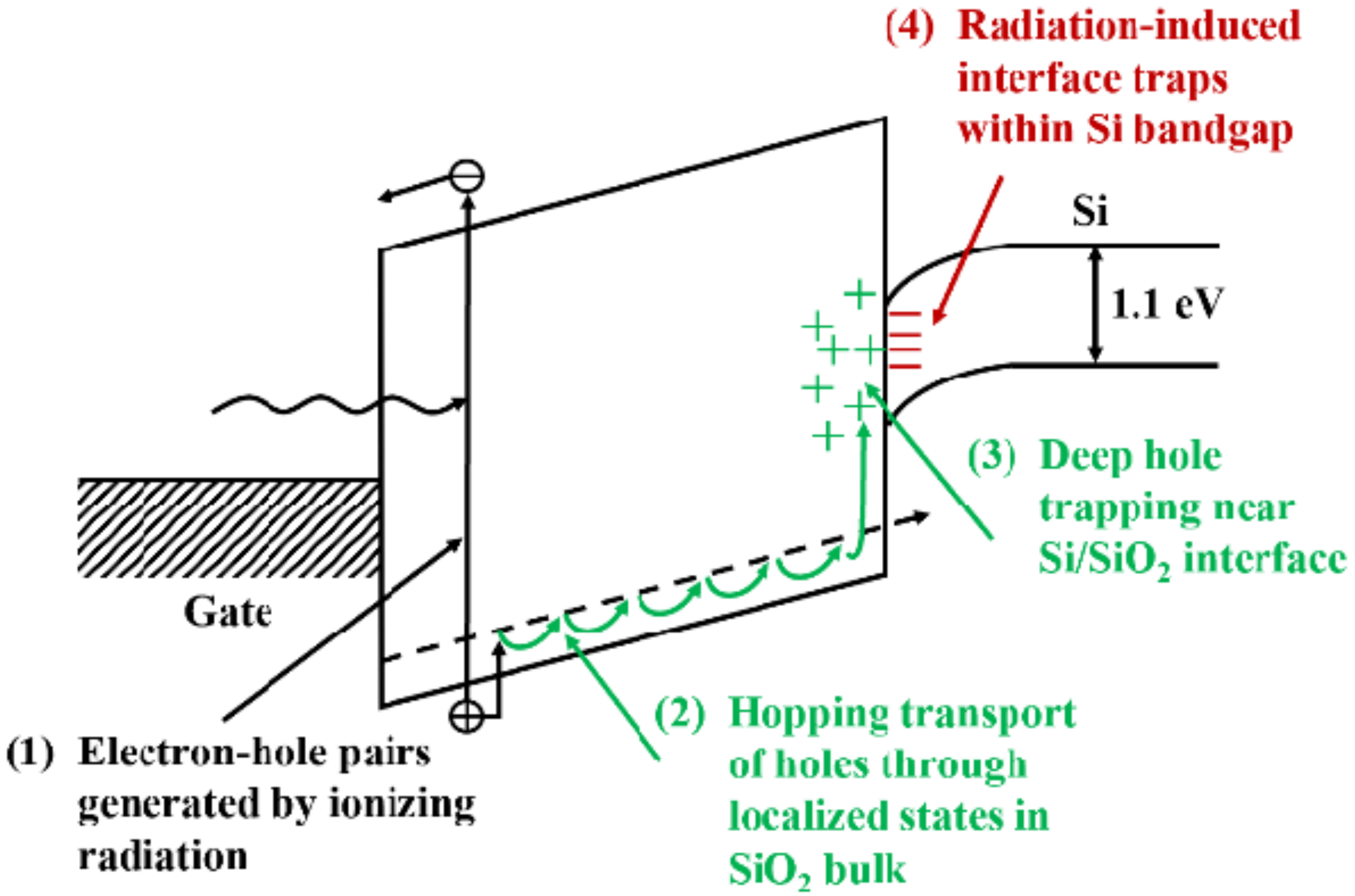


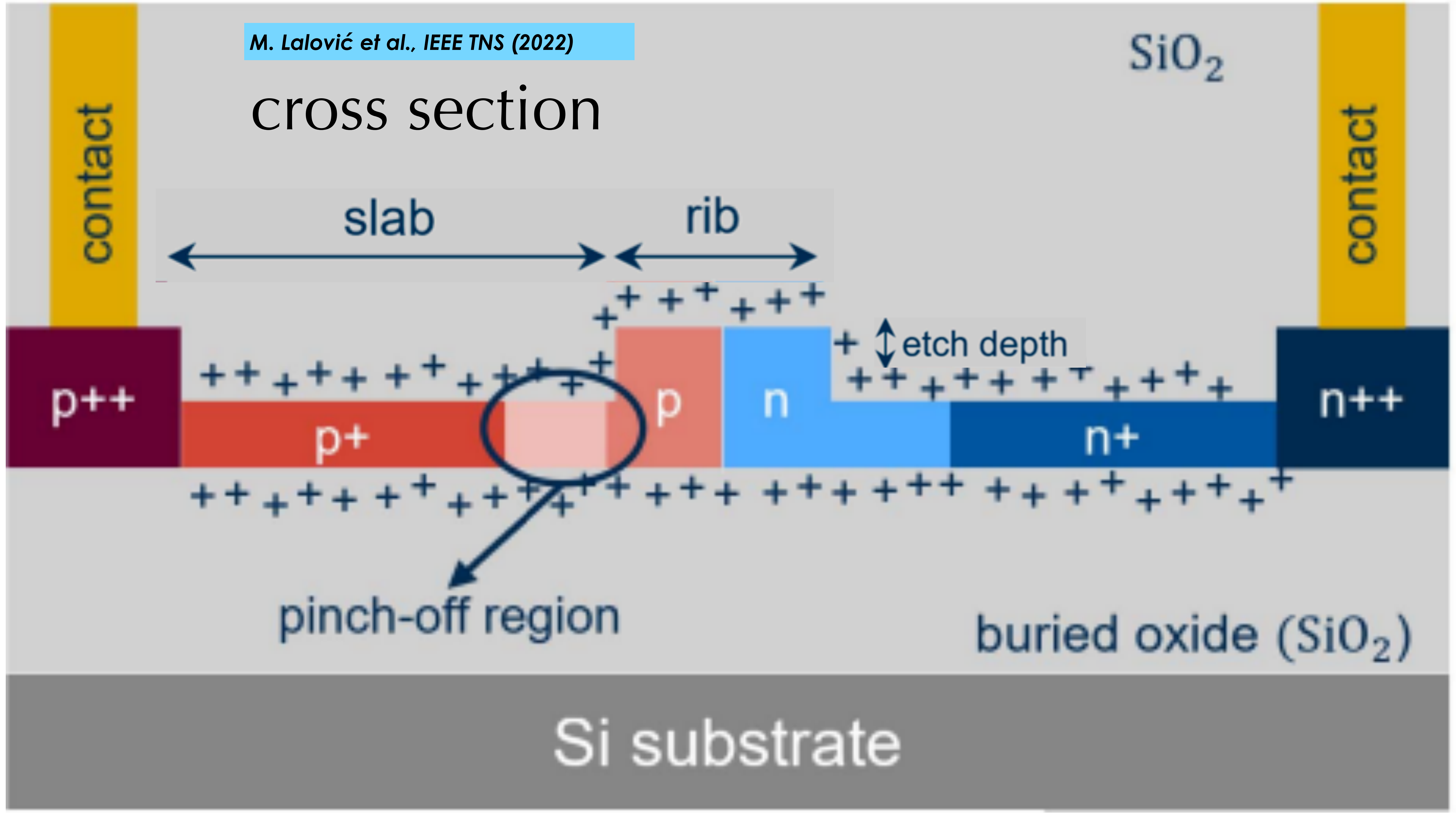




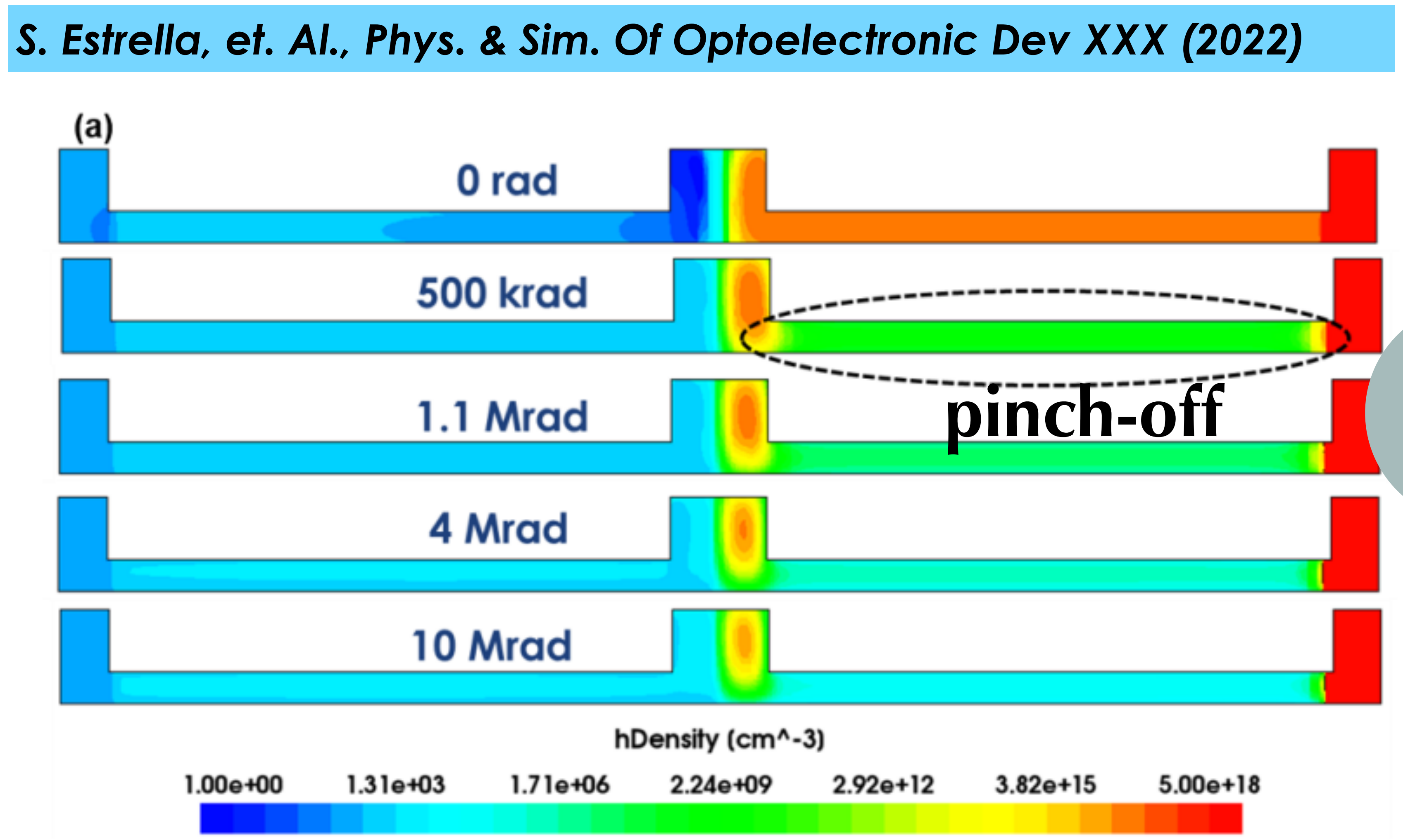
Radiation Effects: Total Ionizing Dose (TID)

- Main damage from ionizing
  —> Holes trapped at the SiO_2-Si interface
  —> fixed positive charges push the free holes in the p-doped Si away
  —> no conductive path between the p++ contact and the rib junction
  —> pinch-off region
  —> concentration variation fails





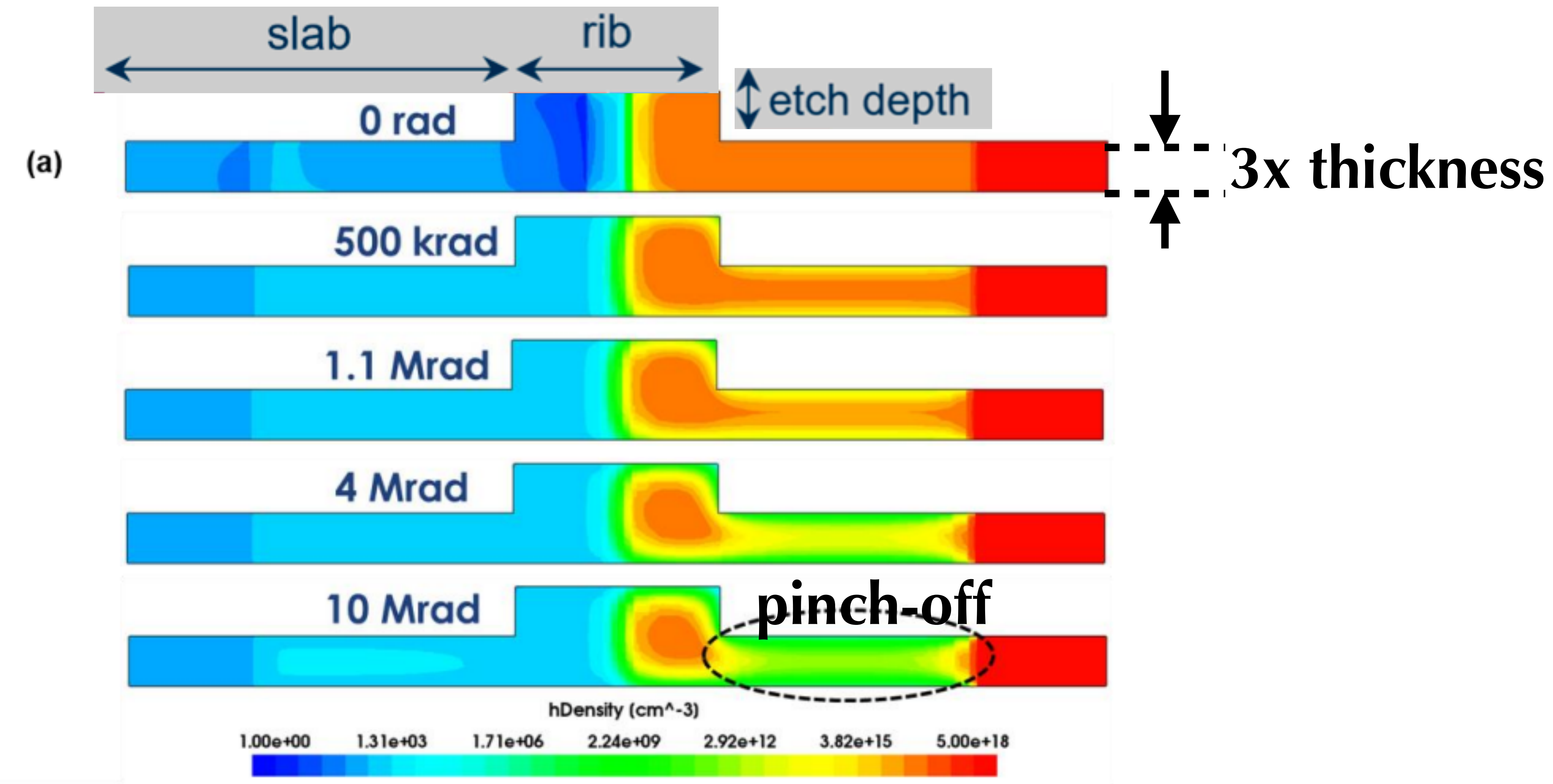
Radiation Hardness: Mitigate Pinch-off

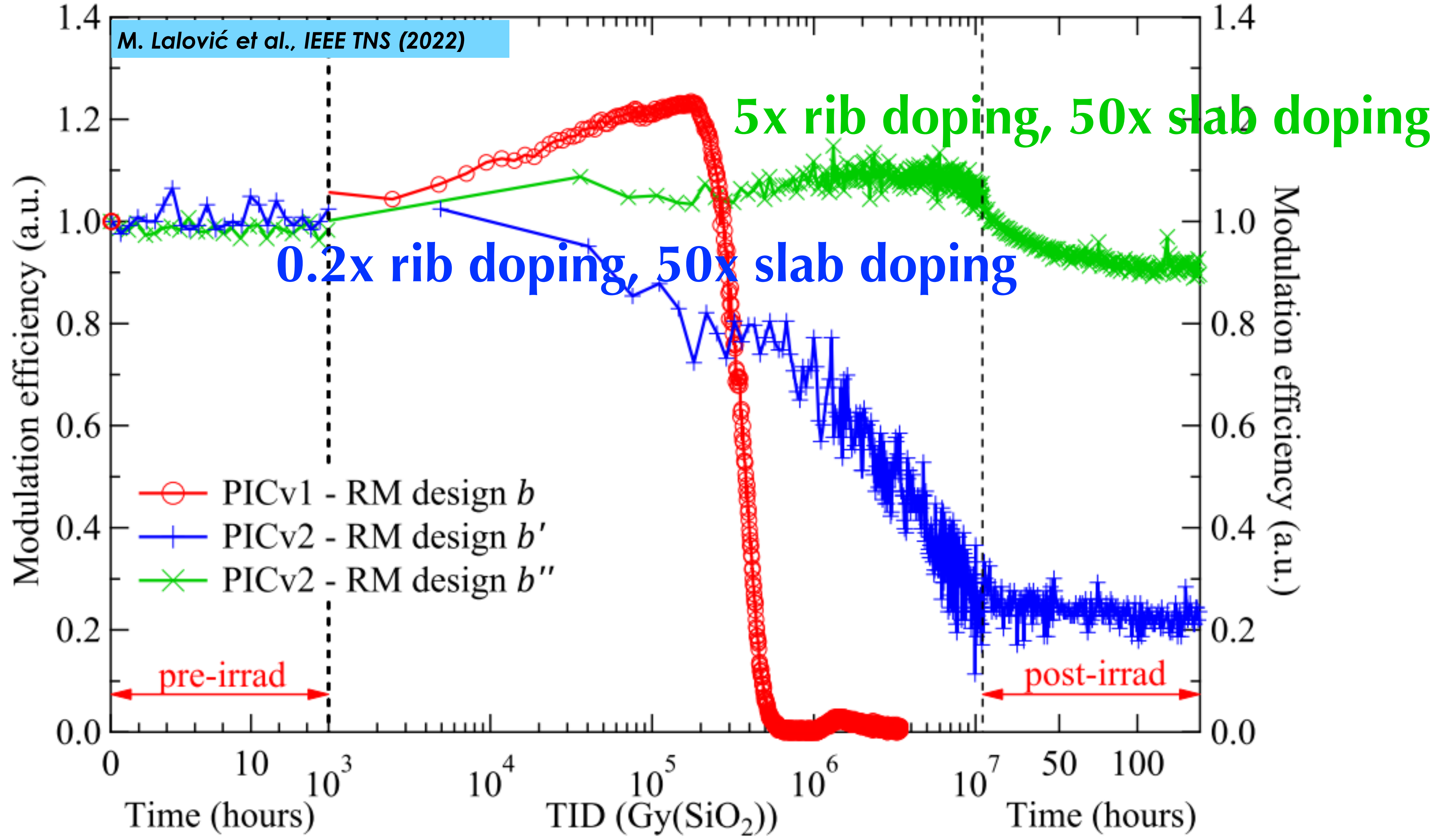


- Shallower etch/thicker slab/shorter slab length
- Higher dopant concentration throughout the slab

- Foundry process: pre-defined & cannot be customized, but offer pre-designed blocks that allow varying
  - etch depths/lab length
  - ring size
  - doping concentrations p/n, p/n+, p/n++,… highly doping omits p

Q2





Radiation Effects: Displacement Damage (DD)

Q3

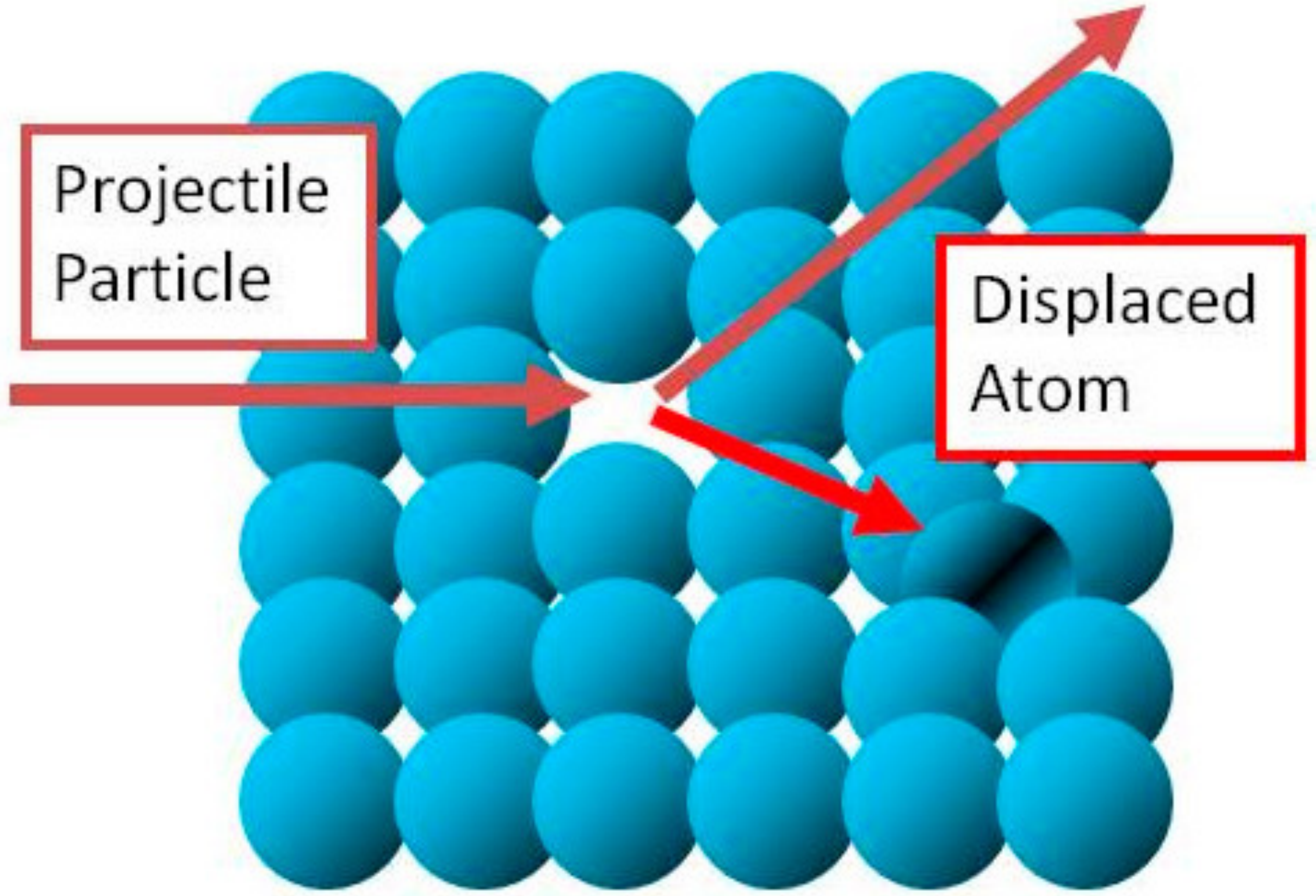
- DD: non-ionizing radiation (neutrons, protons, heavy ions) knocks the atoms out from their lattice sites

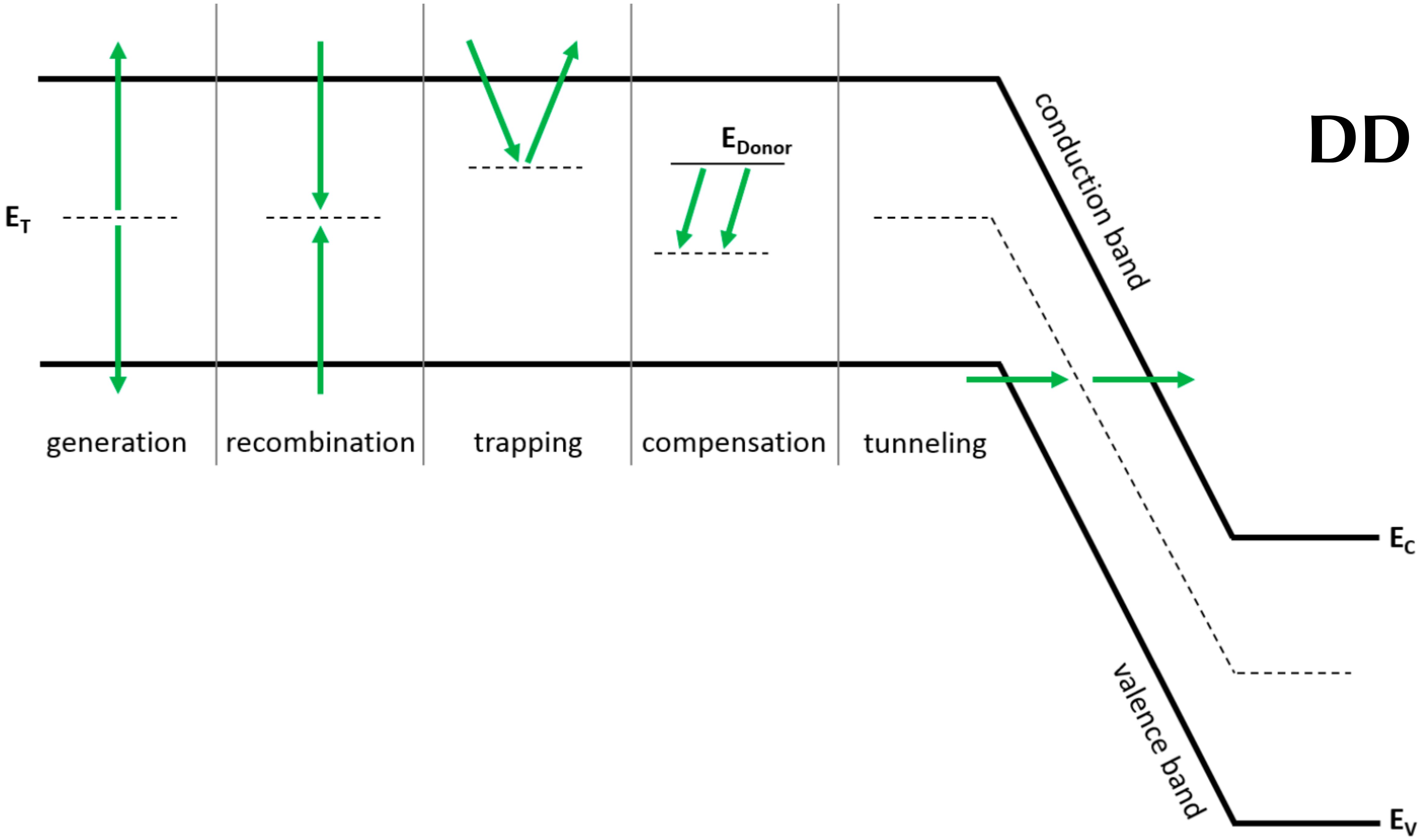
—>

Creation of defect states (E_T) within the bandgap
- recombination centers for charge carriers
- trapping sites for carriers
- compensation of donor and acceptor levels
- …

—>
- degradation of carrier mobility and lifetime
- type conversion of dopants
- …

—> Carrier concentration changes





DD should also matter !

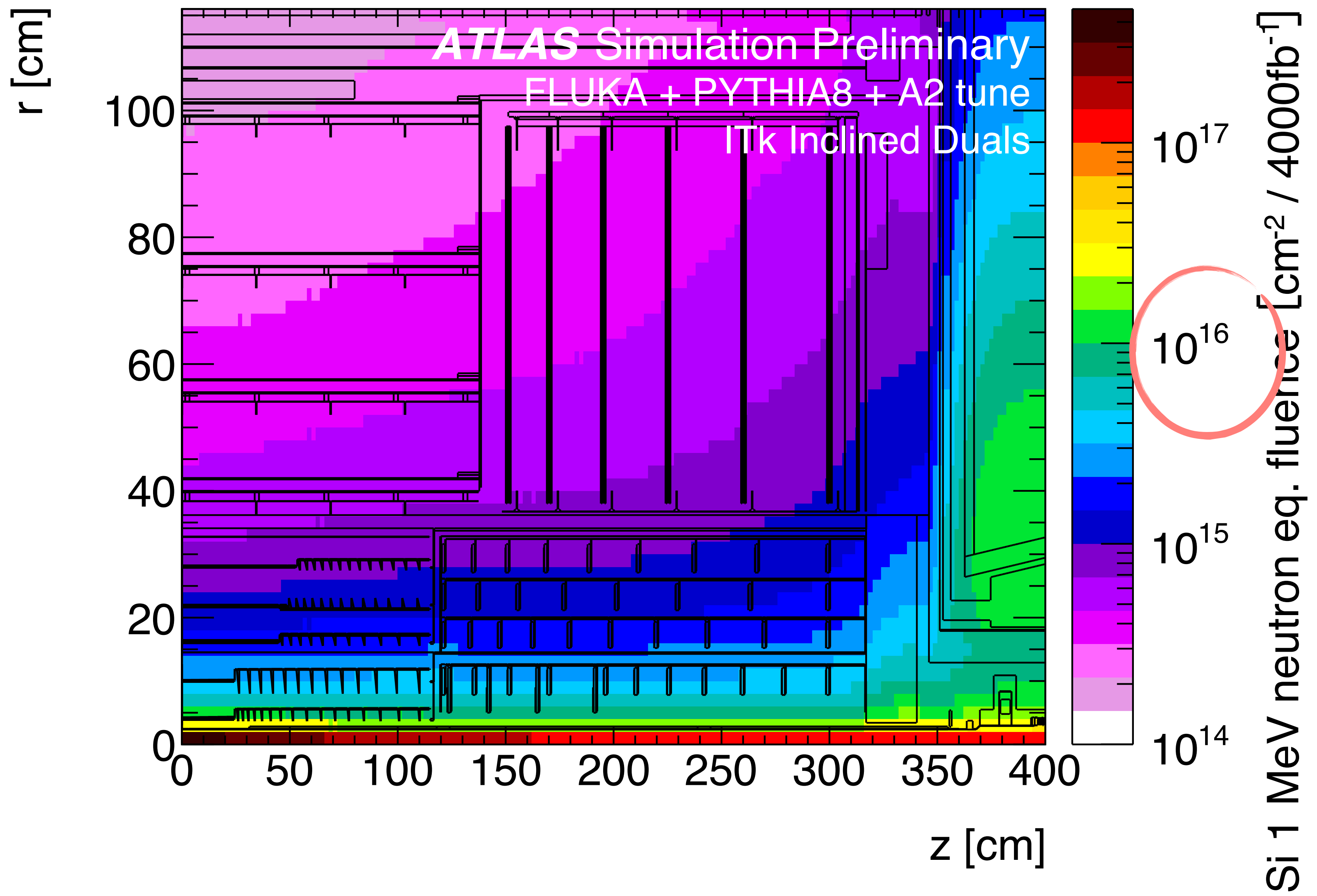
?

Radiation Effects: Displacement Damage (DD)

Q3

- Q: DD should also matter ?
- A: Device dependent

- In silicon, $1x10^{16}$ n_{eq}/cm^2 (1MeV) creates a defect density $O(10^{16}\ cm^{-3})$ << typical doping concentration in SiPh
  - p/n, p/n+, p/n++ usually 10^{17}, 10^{18}, 10^{19} cm^{-3}
  - Intrinsic devices (e.g., PiN) suffer, while highly (even nominally) doped devices are insensitive to DD

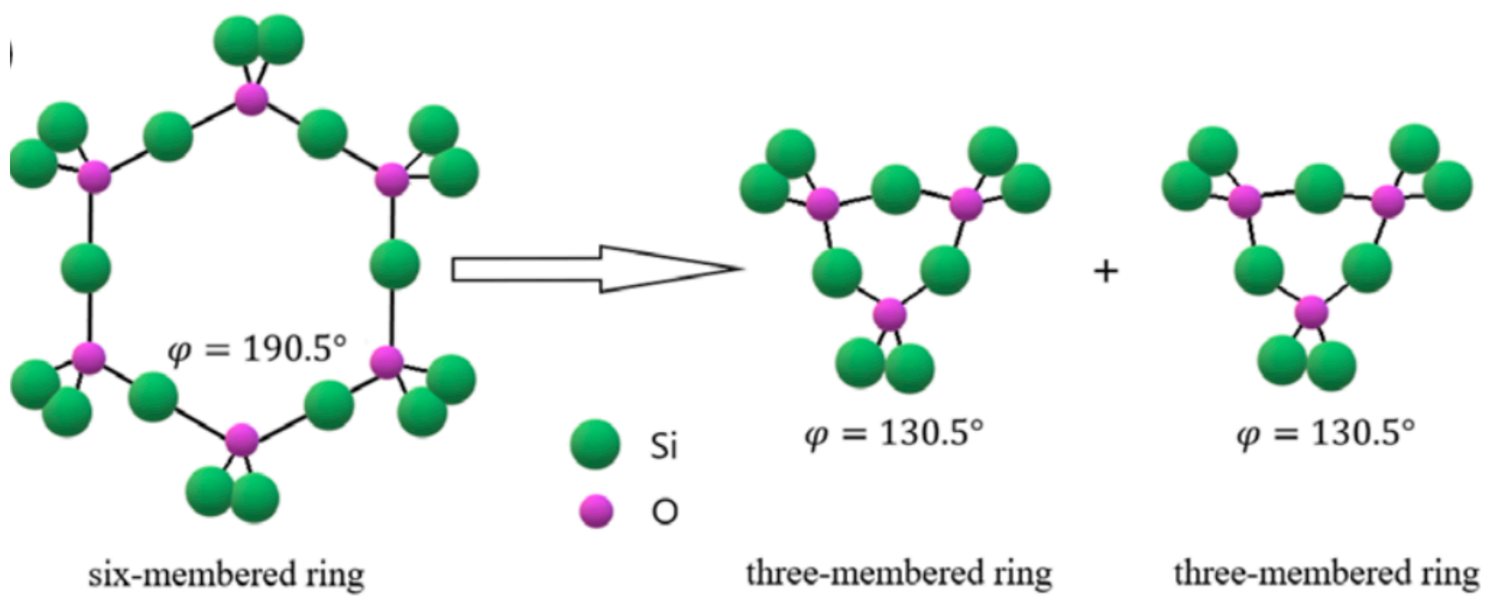


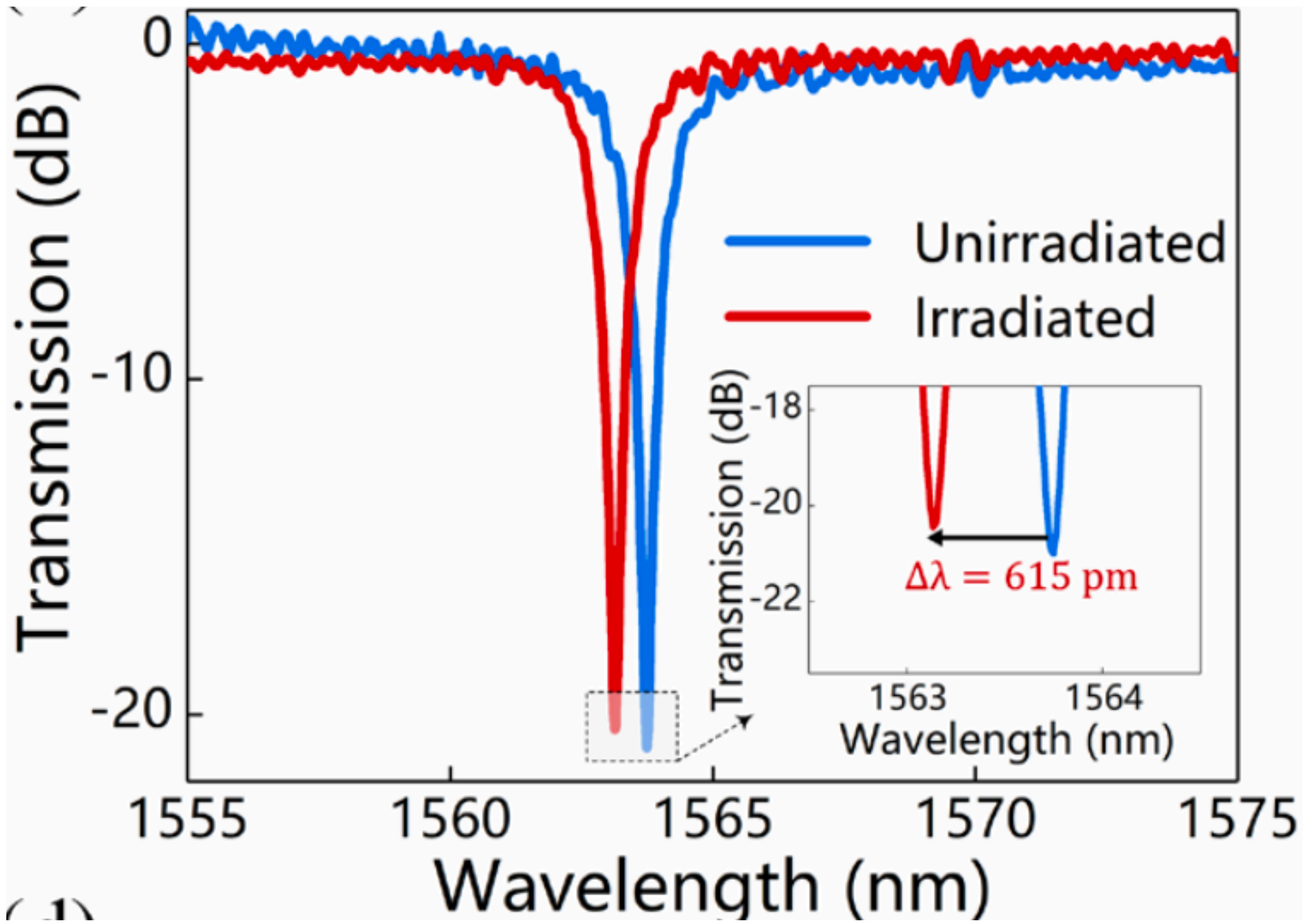
Radiation Effects: Displacement Damage (DD)

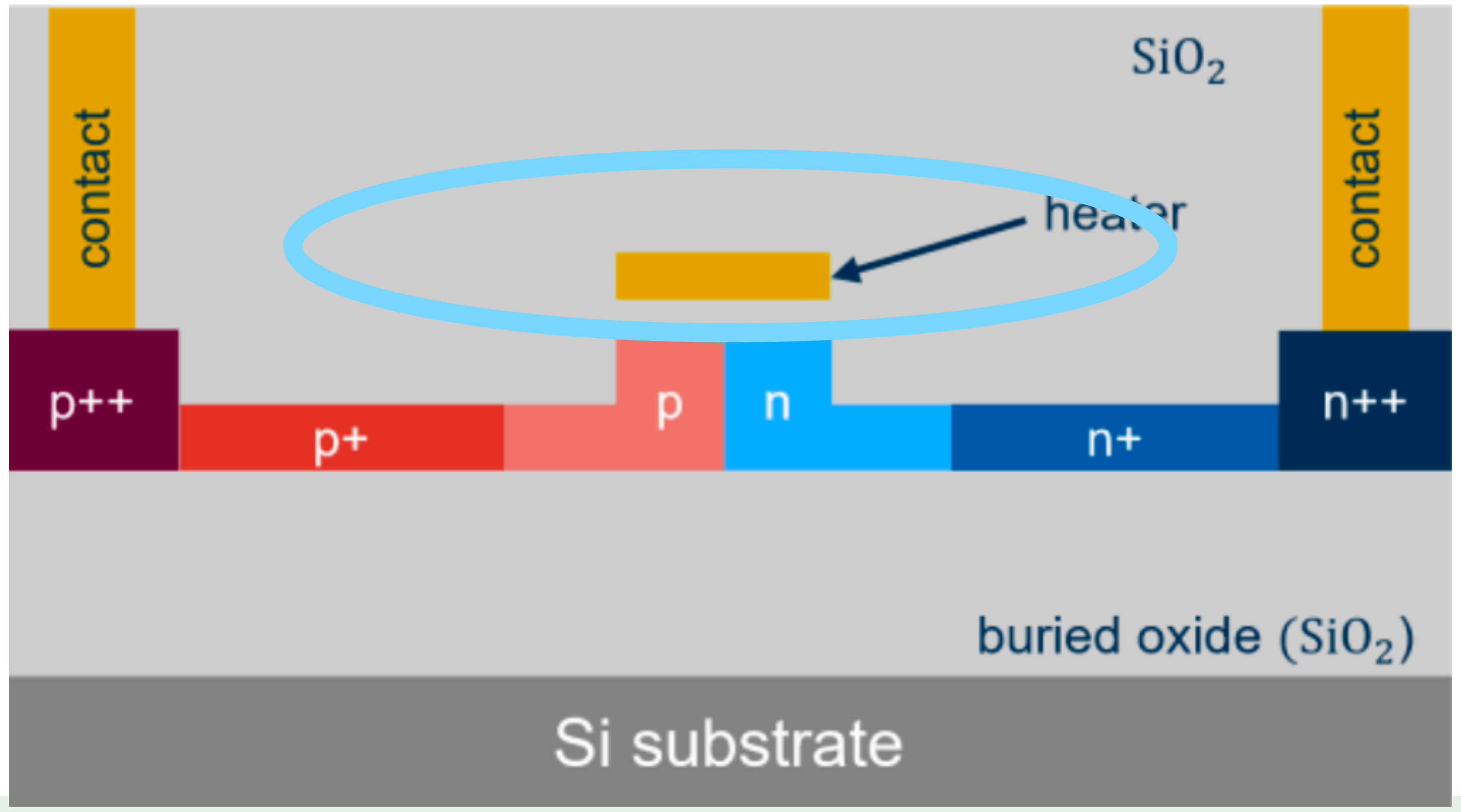
Q3

- Q: DD should also matter ?
- A: Device dependent, highly doped devices are insensitive

- However, a blue shift in λres is observed
  - Mainly due to structural changes in the SiO_2 network, resulting in a reduction in effective refractive index
- But this is not degradation!
  - Relative concentration change maintained, performance Δλ/V (⟷) and P1-P0 (↕) maintained
  - Only absolute working point shifted
    - Easy to fix, with a heater + feedback loop







Fiber Radiation Hardness

Q4

Current deployment for HL-LHC

- A graded index glass fiber
  - doped with fluorine (F-SiO_2) to decrease the number of strained bonds to increase radiation hardness
- only holds up to 1 MRad TID

- Radiation-induced attenuation (RIA)
  - by design for glass
  - ionization of atoms in the glass structure creates color centers that absorb light at different wavelengths
  - Strongly correlated with the fiber manufacturing process (dopant and doping level, production process, drawing conditions) and to the conditions (light power, temperature)

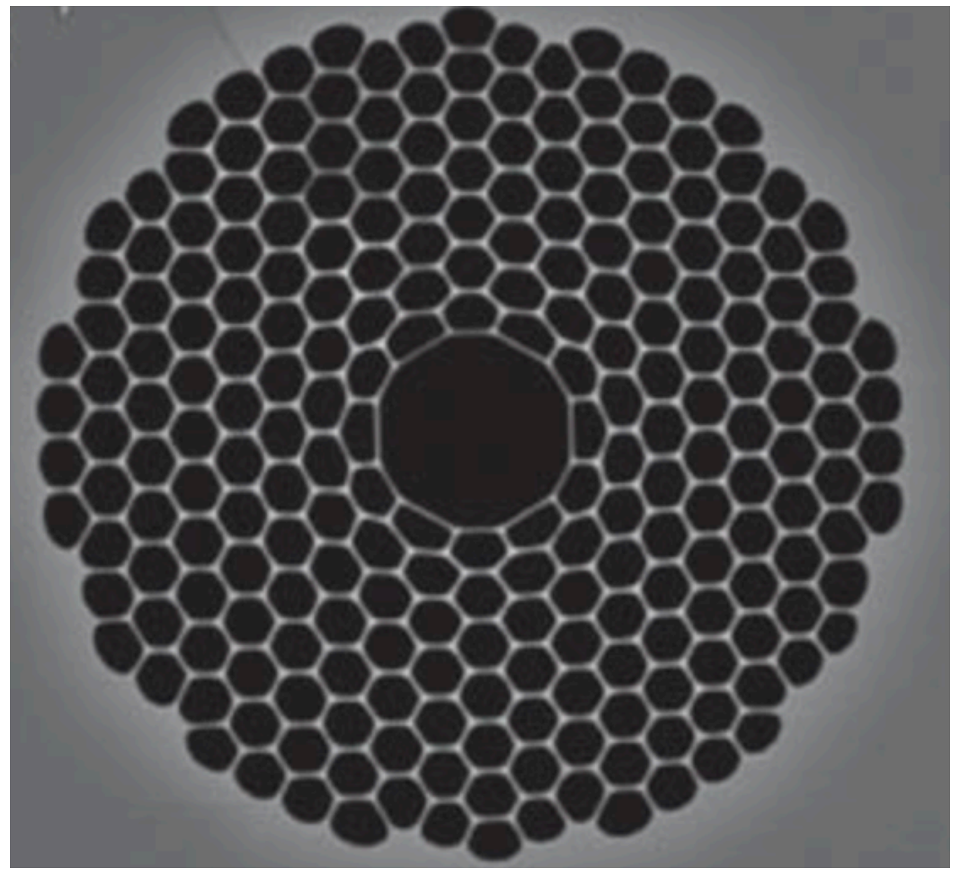
Fiber Radiation Hardness

Q4

Possible SiPh-compatible solution to HL-LHC

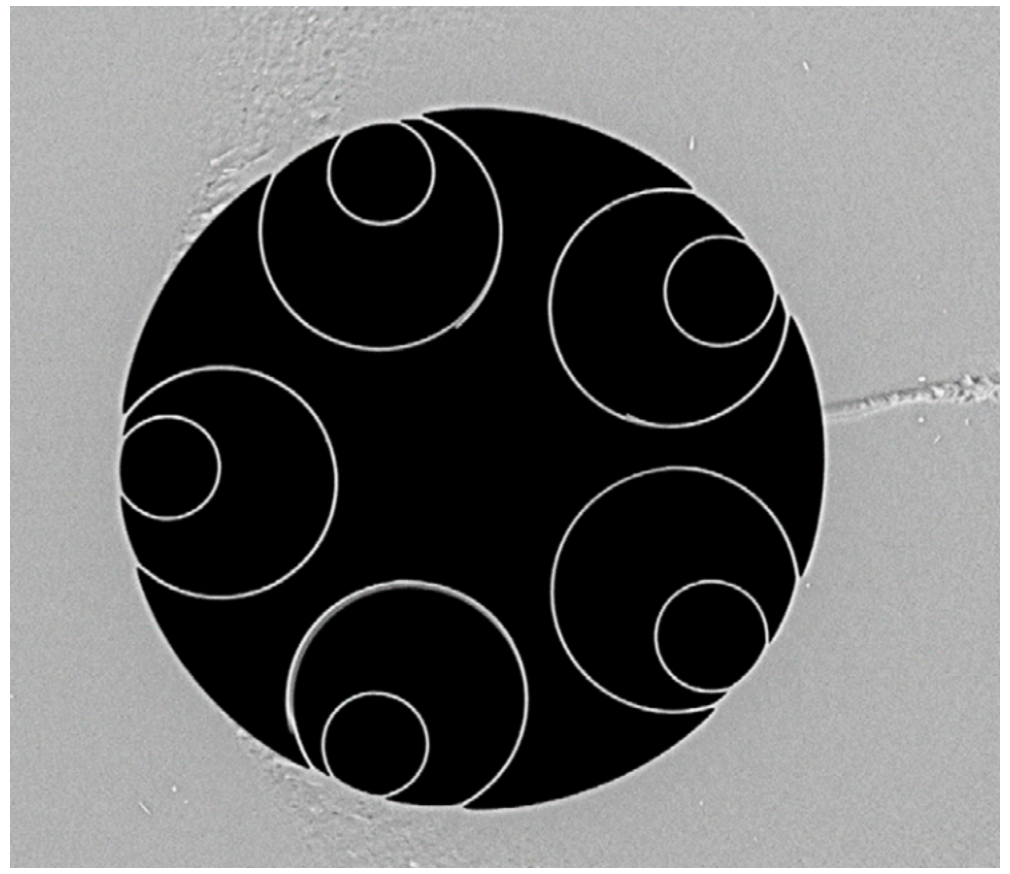
- Hollow-core fiber
  - Air-filled (or vacuum) core surrounded by a cladding structure of thin-walled glass tubes
  - Light travels in air/vacuum!

Hollow-core photonic bandgap fiber



- Periodic arrangement of high and low dielectric constant materials (glass and air) form photonic bandgaps
- Transverse propagation of light of a certain wavelength is forbidden and can be guided along the fiber

Hollow core Nested antiresonant fibre



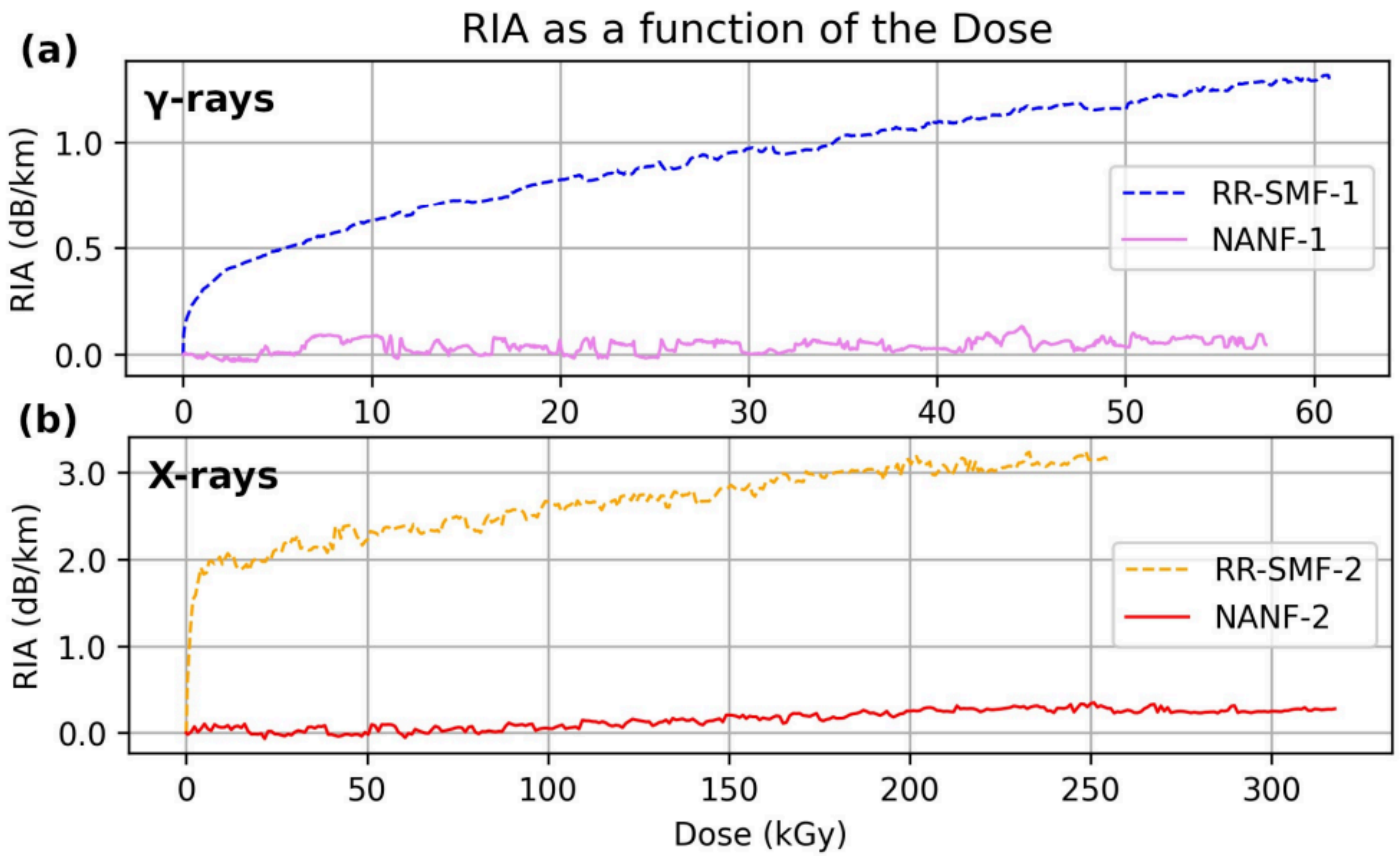
- Nested structure make light anti-resonate within the glass layers
- Fully reflected into the hallow core

Fiber Radiation Hardness

Q4

Possible SiPh-compatible solution to HL-LHC

- CERN's pushing this
  - So far to 30 MRad
  - Needs more study/tests



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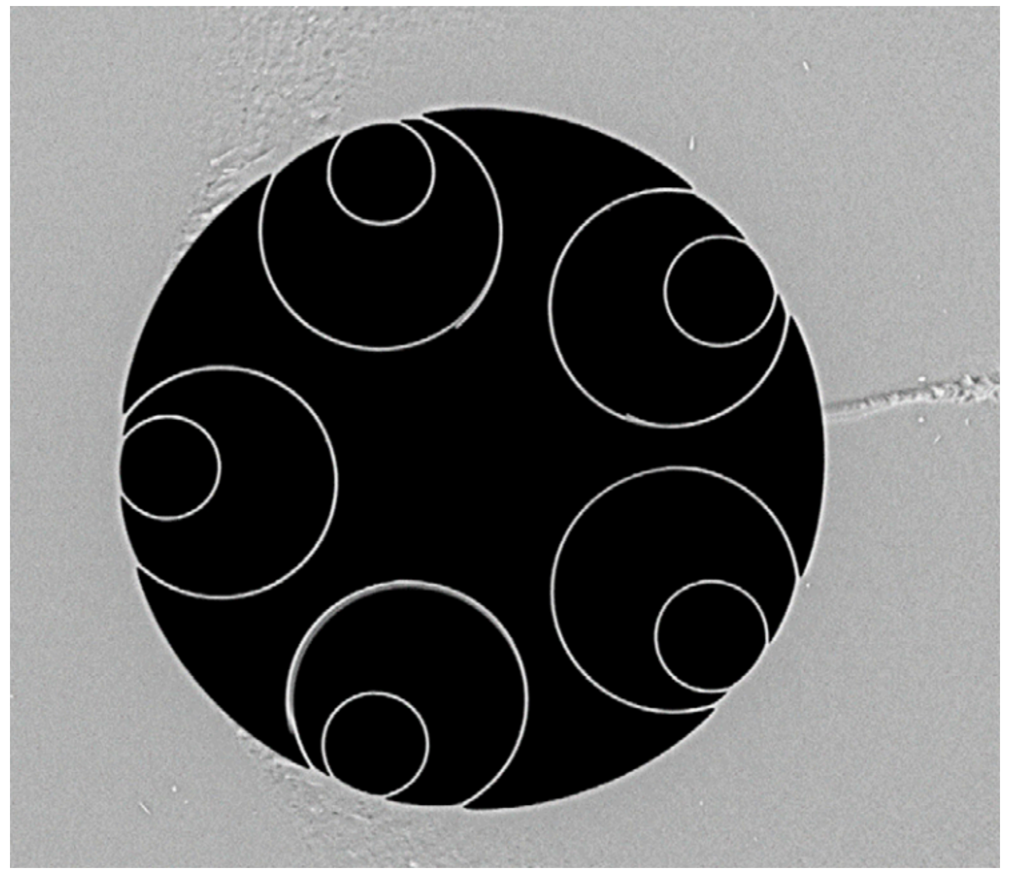

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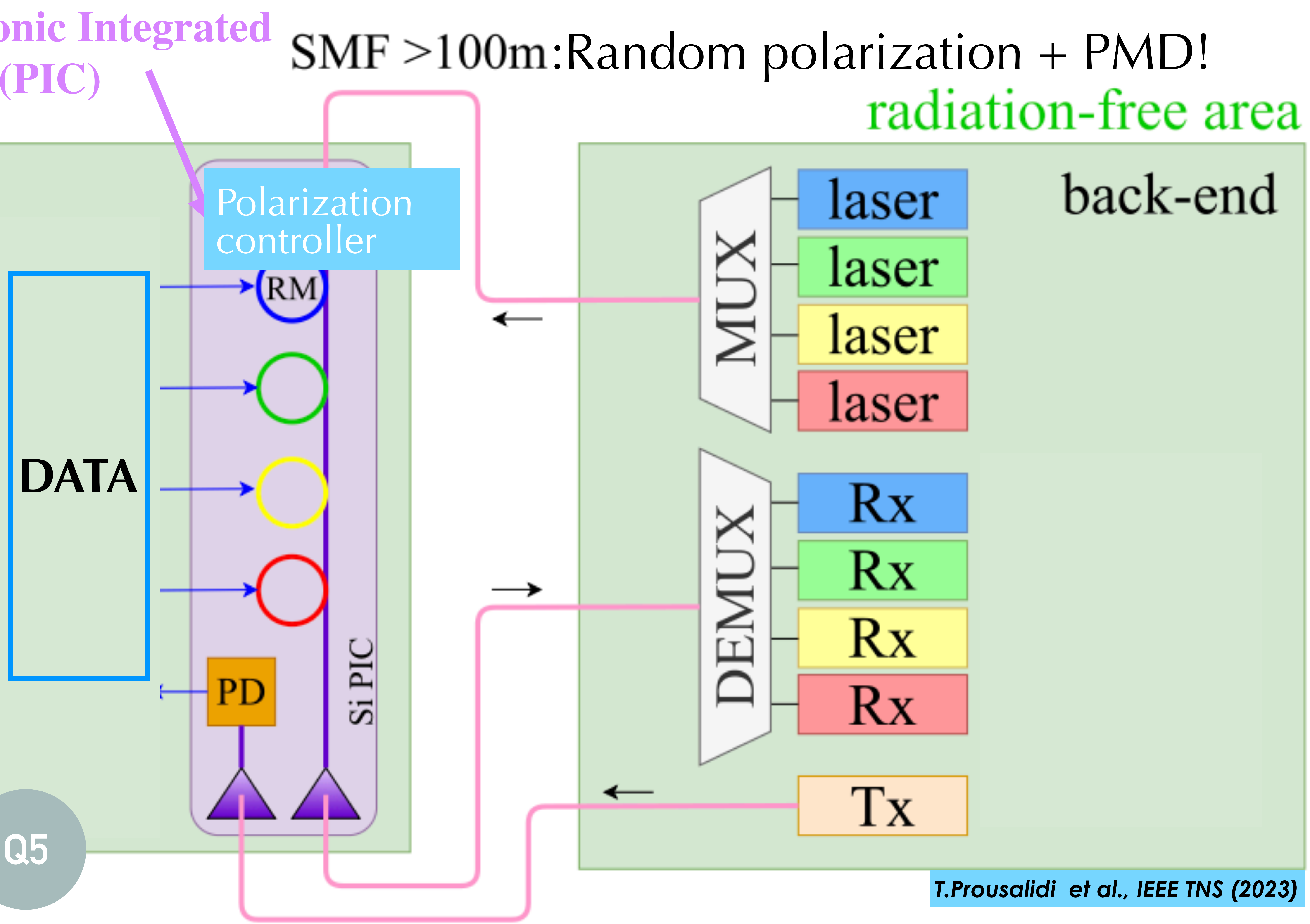
SiPh Transmitter: Polarization Controller



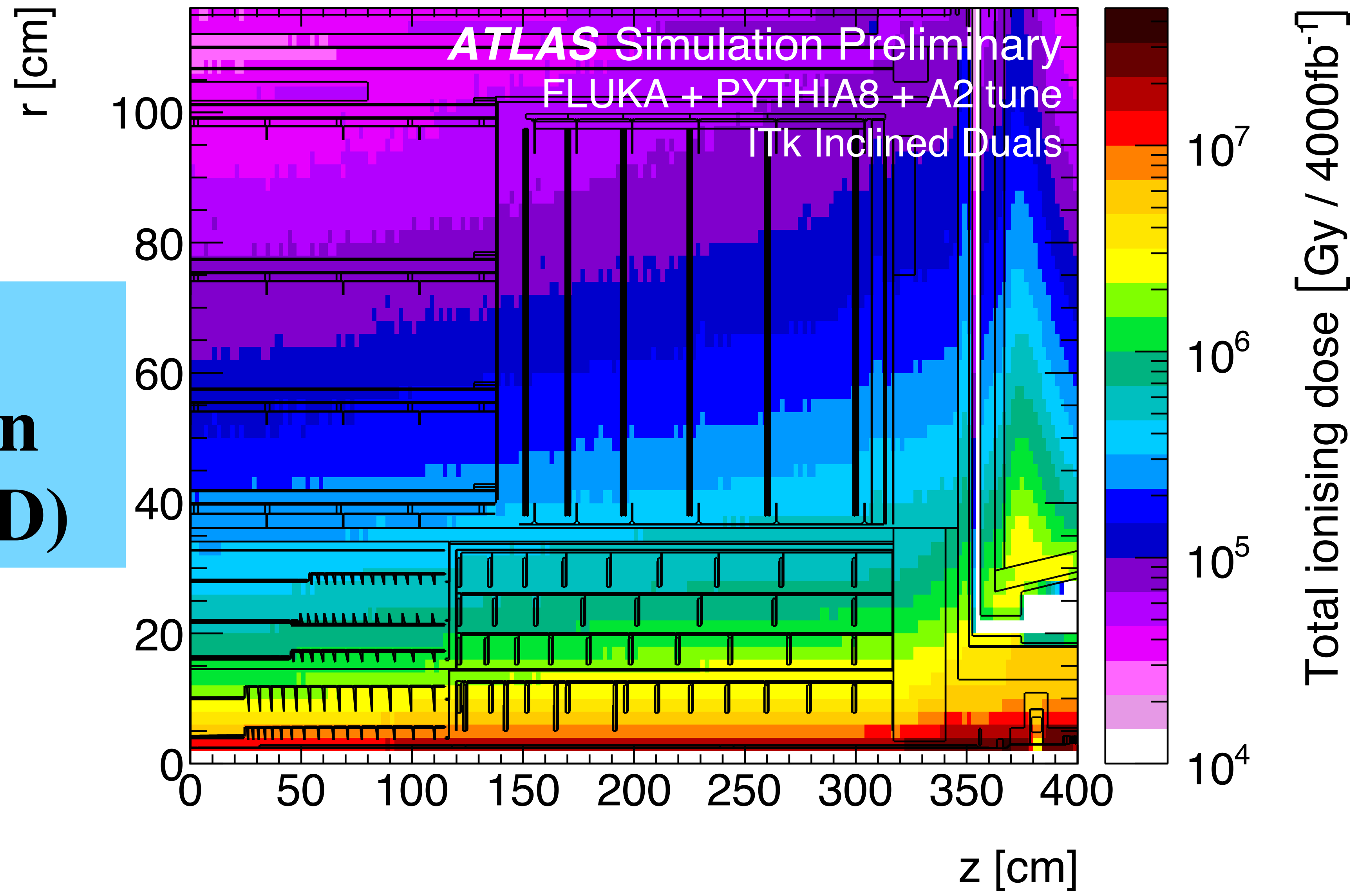
T.Prousalidi et al., IEEE TNS (2023)

- Need for a polarization control circuit
  - SiPhs are polarization sensitive (e.g. TE polarization has less loss than TM)
    - Designed to be TE mode operation
  - Fibers randomizes the polarization and causes polarization mode dispersion (PMD)
- Future: can also do polarization multiplexing
  - **Q: But then at back-end, how to recover polarization after the light travels through long-distance fiber?** Q5
  - **A: A marker (a small sine wave) on the original PC at the tx, then maximize the TE marker signal in the TE branch and the TM in the TM branch**

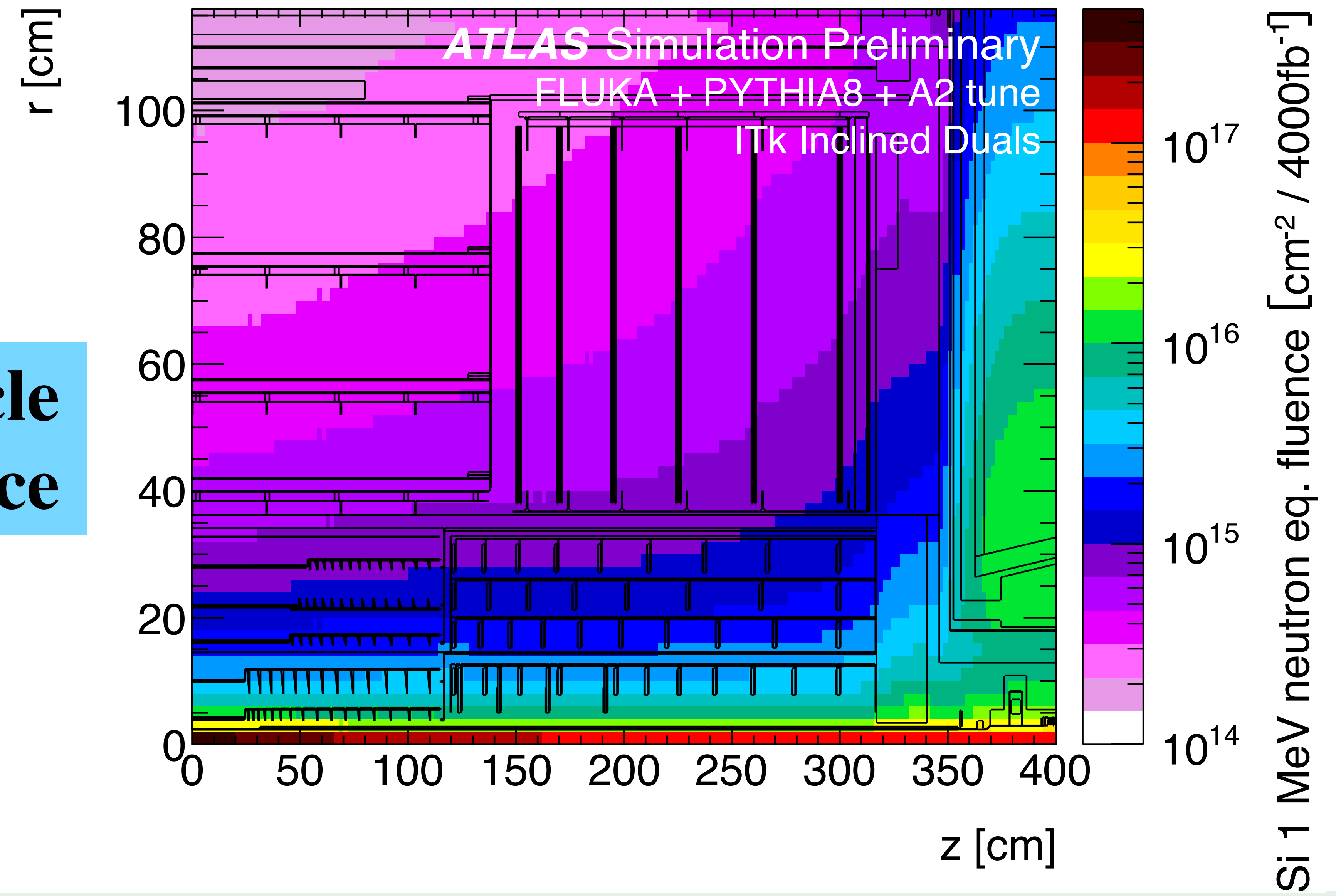
BACK UP

Introduction: Harsh Environment at the HL-LHC

Total Ionization Dose (TID)



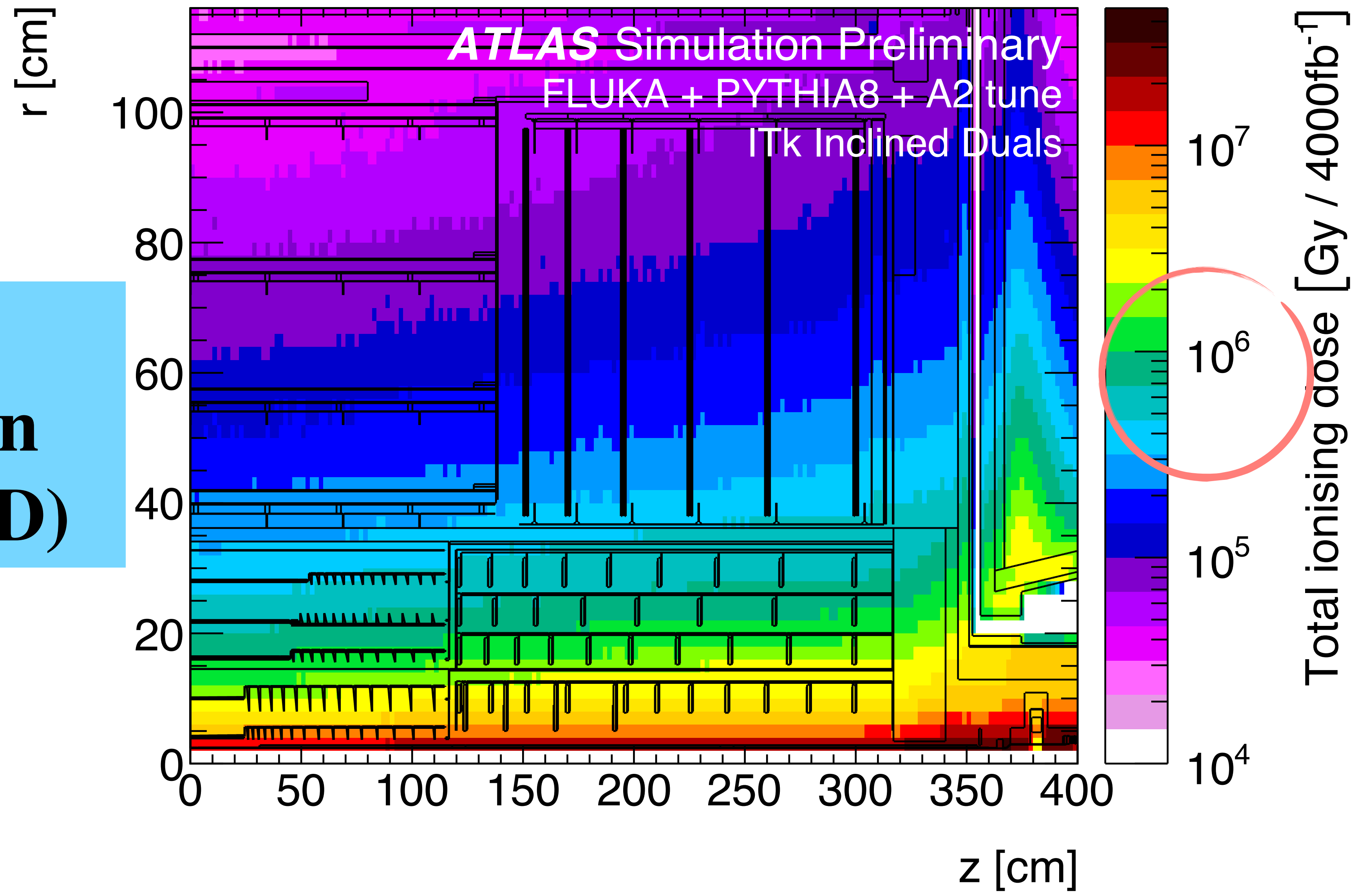
Particle Fluence



- The HL-LHC operation
  - Luminosity
    - Peak: 5-7 x 10^{34} $cm^{-2}s^{-1}$ -> **5-7x**
    - Integrated: 4000 fb^{-1} -> **10x**
  - Pile-up: up to <μ> ~ 132 (200?) -> **2-5x** (3-7?)
- Imposed significant challenge on our detectors, specifically, on **data transmission**
  - **5-7x** data rate
  - Radiation: 2.3×10^{16} n_{eq}/cm^2 and 1.2 GRad TID -> **5x**

Introduction: Current Technology Starts to Break

Total Ionization Dose (TID)



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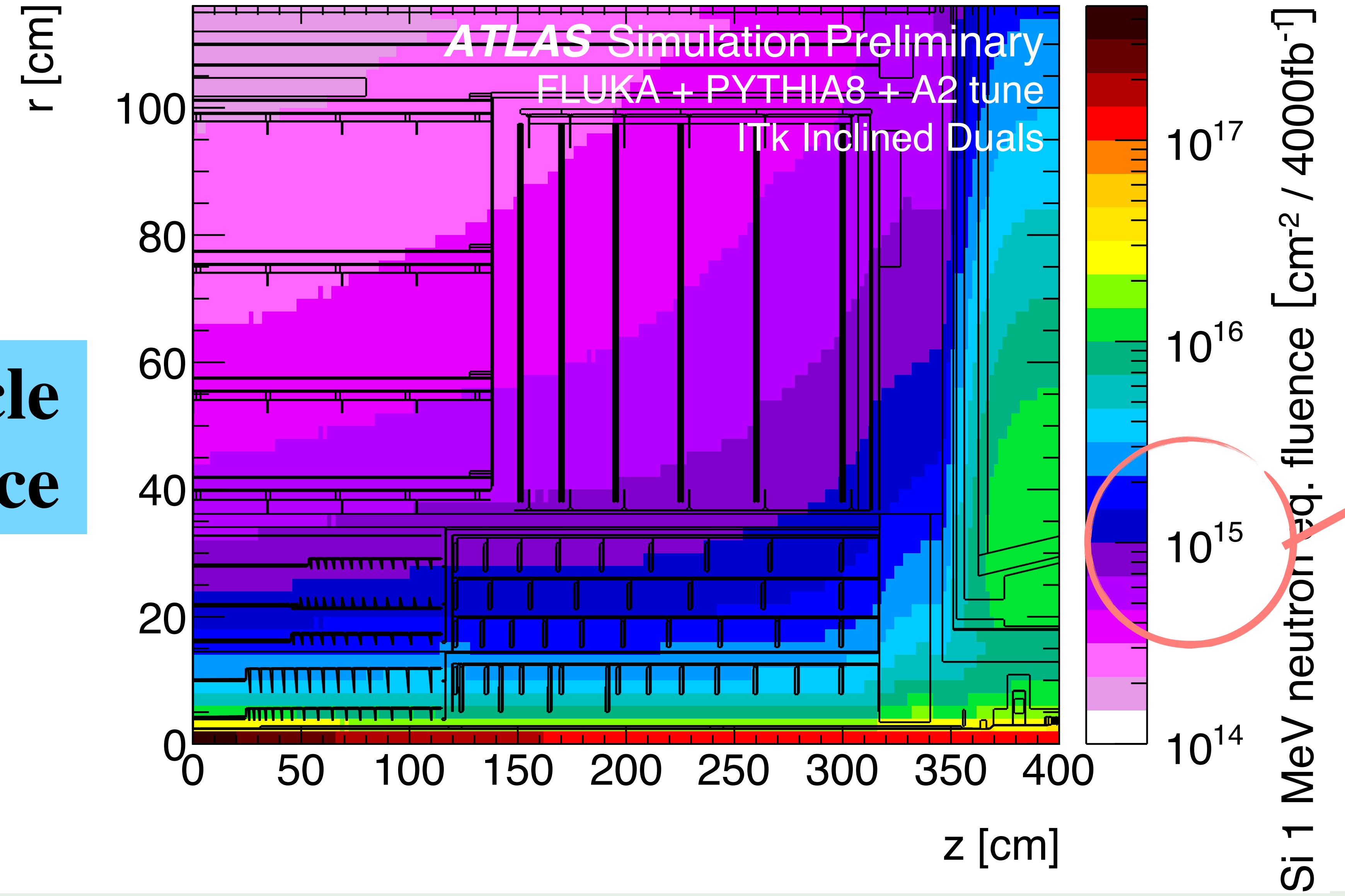
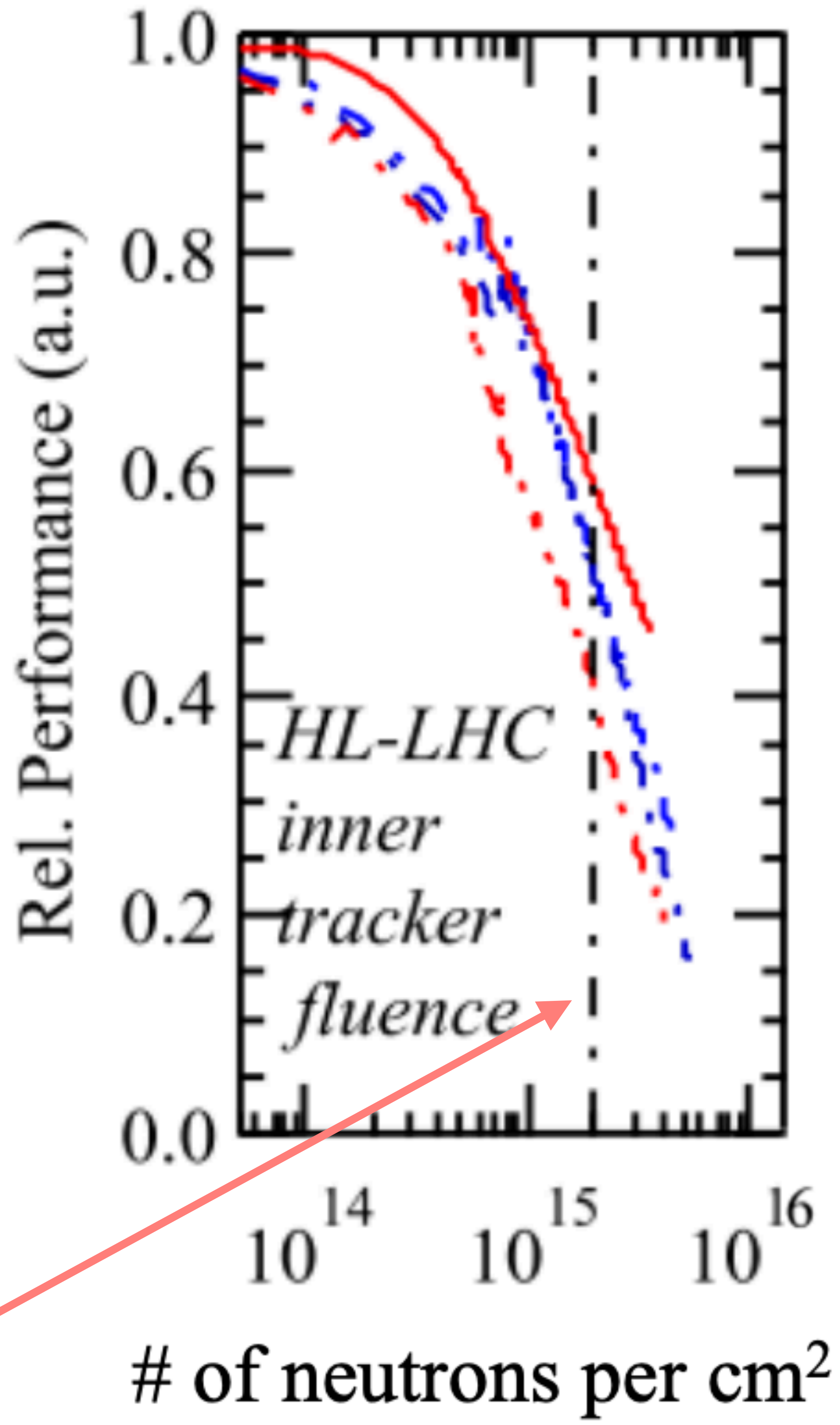
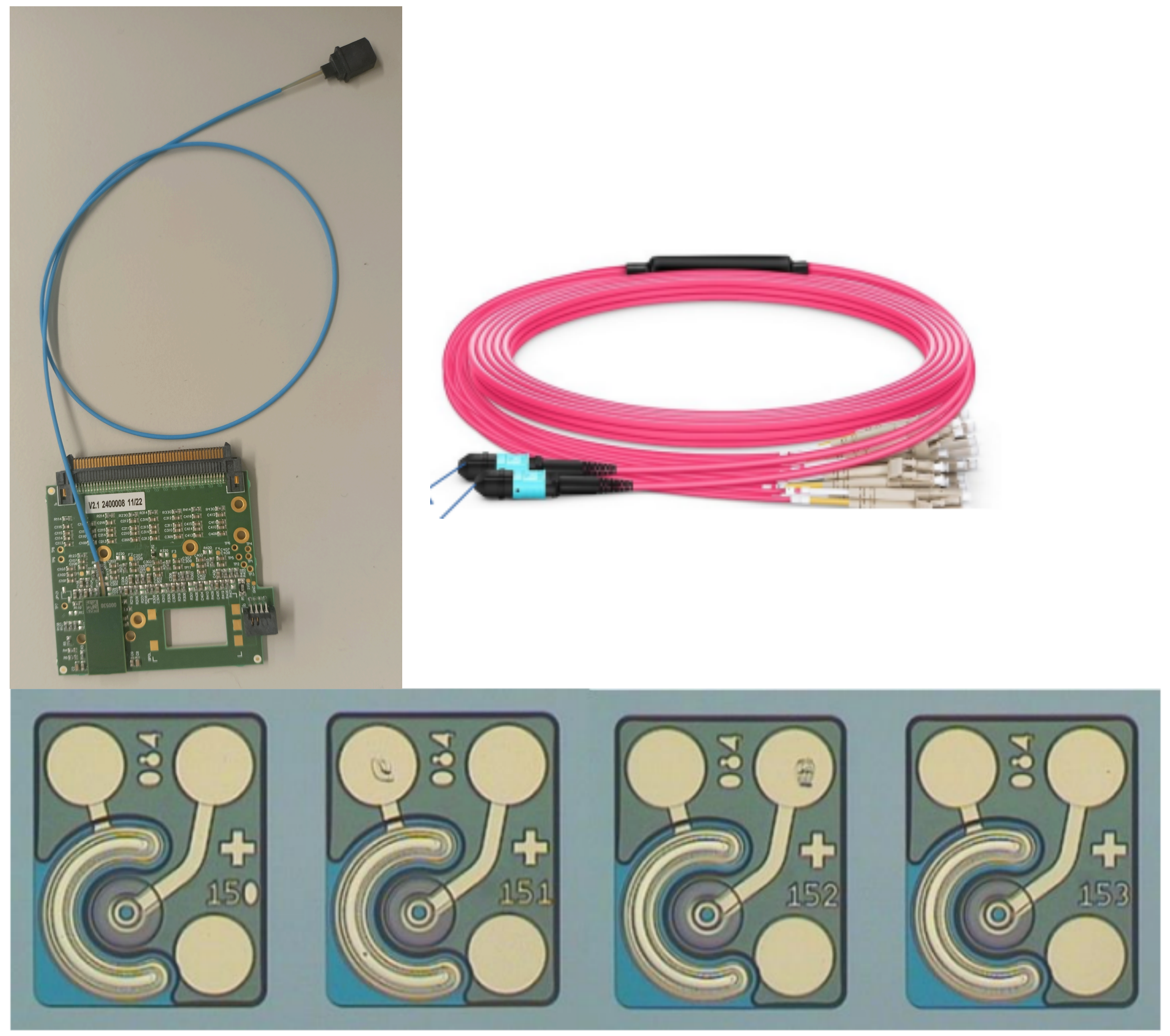




- Currently deployed for HL-LHC data transmission: VCSELs (vertical cavity surface emitting lasers) + discrete PIN photodiodes + parallel fibers
  - Bulky
  - High power consumption
  - Breaks at 1MRad/10^{15} n_{eq}/cm^2

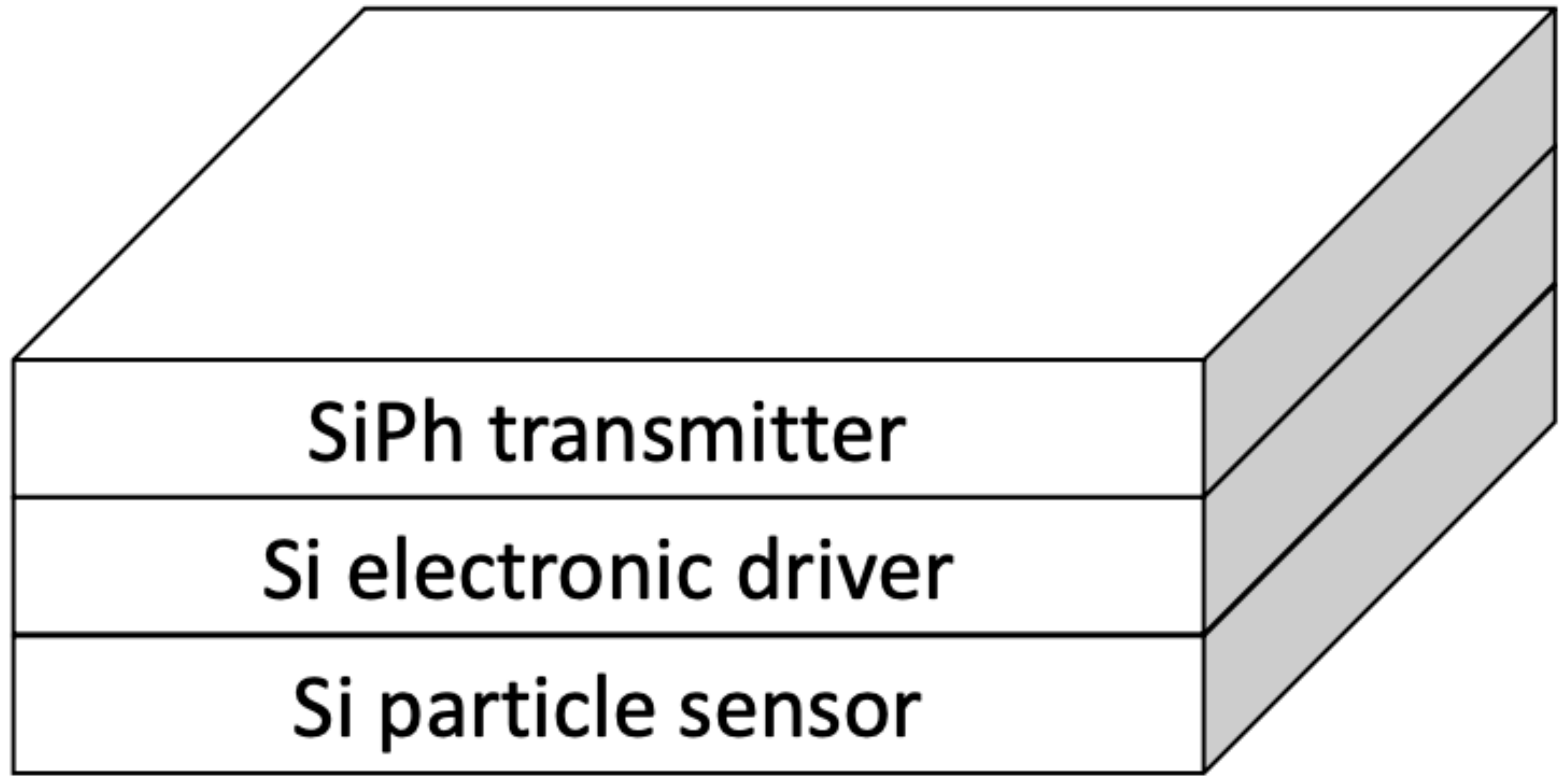


Introduction: Silicon Photonics (SiPh) is a Solution

- Idea: fabricate photonic devices on silicon substrates infrastructure

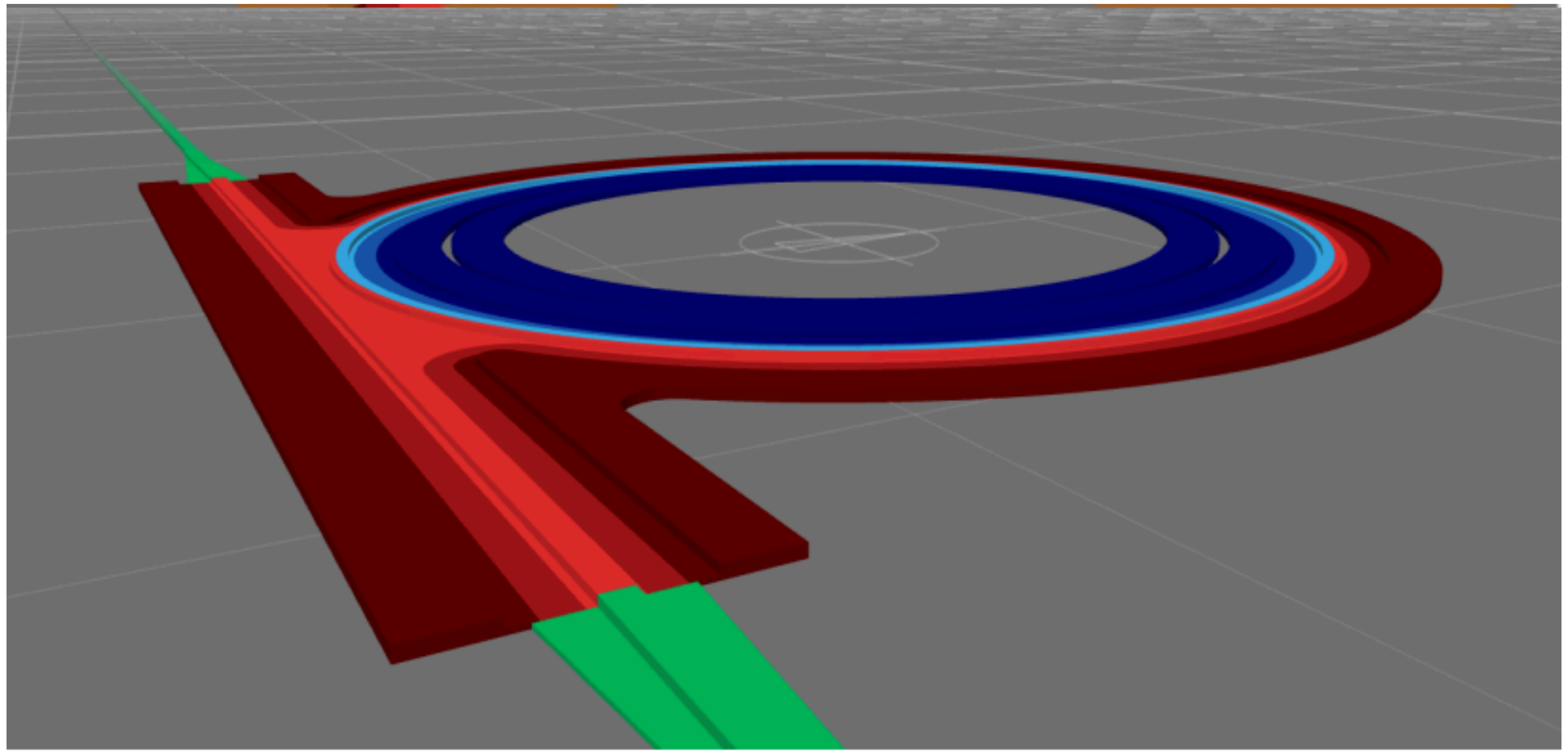
- Features:
  - Allows tight integration of optical components with particle sensors and readout ASICs —> **low mass**
  - Leveraging the existing and mature CMOS technology —> **easy to scale, low cost**
  - **Low power** consumption

  - **High radiation tolerance** (> 1GRad TID and > 5×10^{16} n_{eq}/cm^2)
  - Supports addition **multiplexing**: wavelength, polarization
  - Allows **high data rate** (>>Gb/s uplink, up to 5Gb/s downlink)



Outline

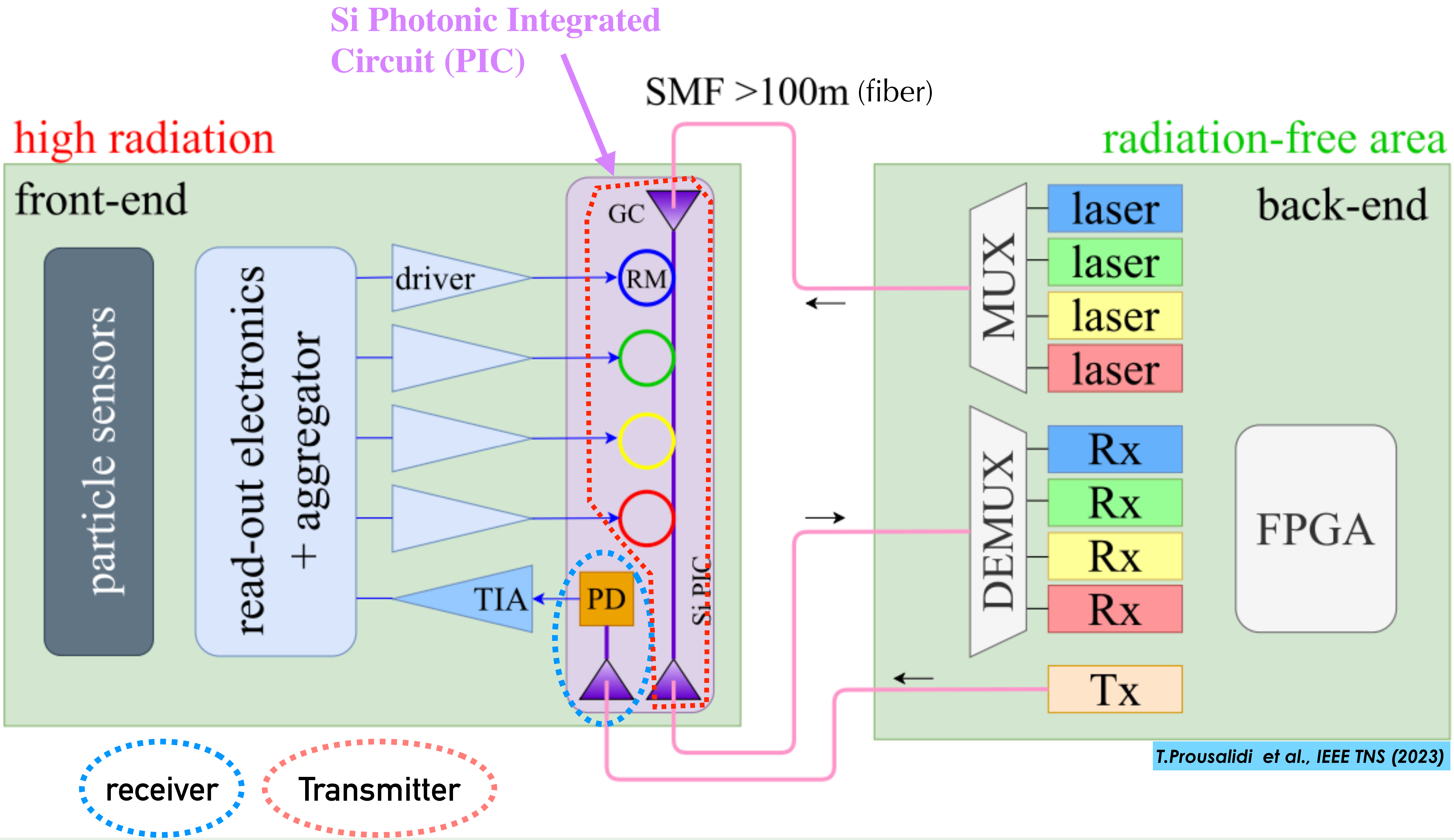
1. Structure of our silicon photonic transceiver and how it works



2. Radiation effects and methods for achieving hardness

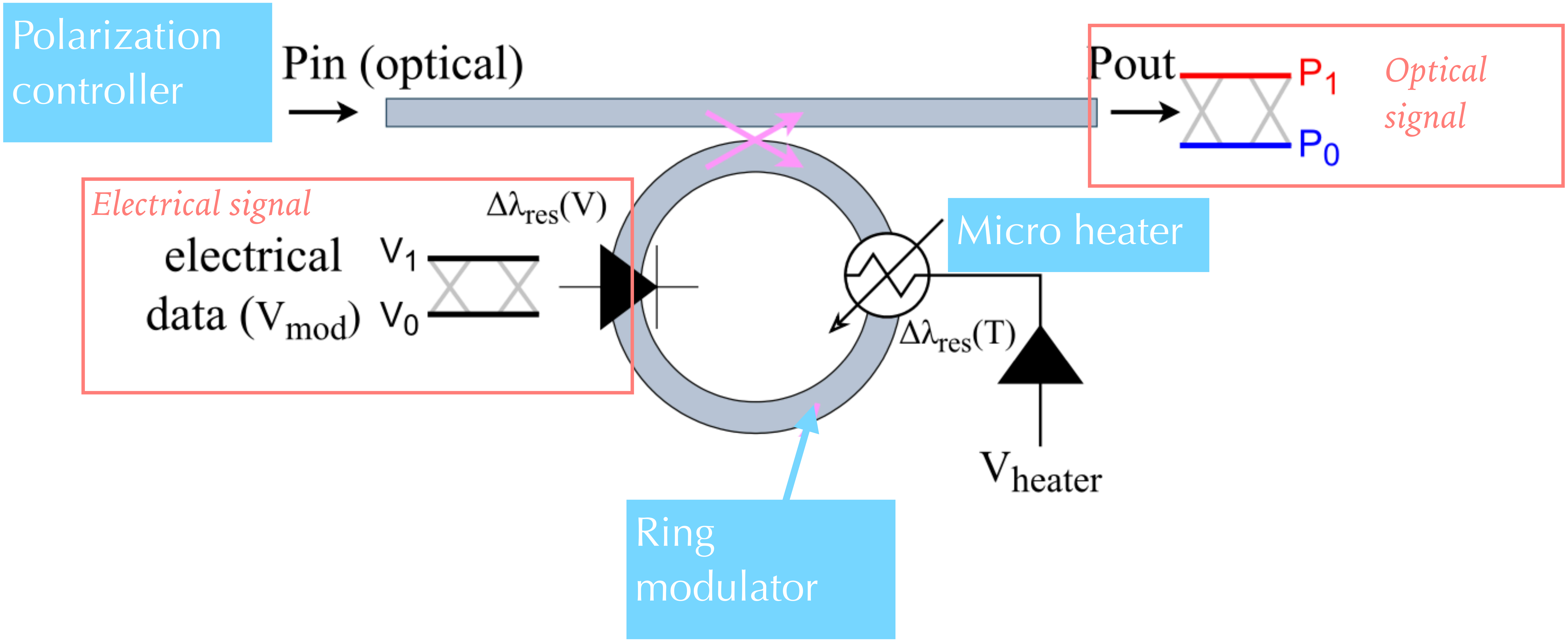
3. Our Irradiation runs and results

System Concept of a SiPh-based Data Link



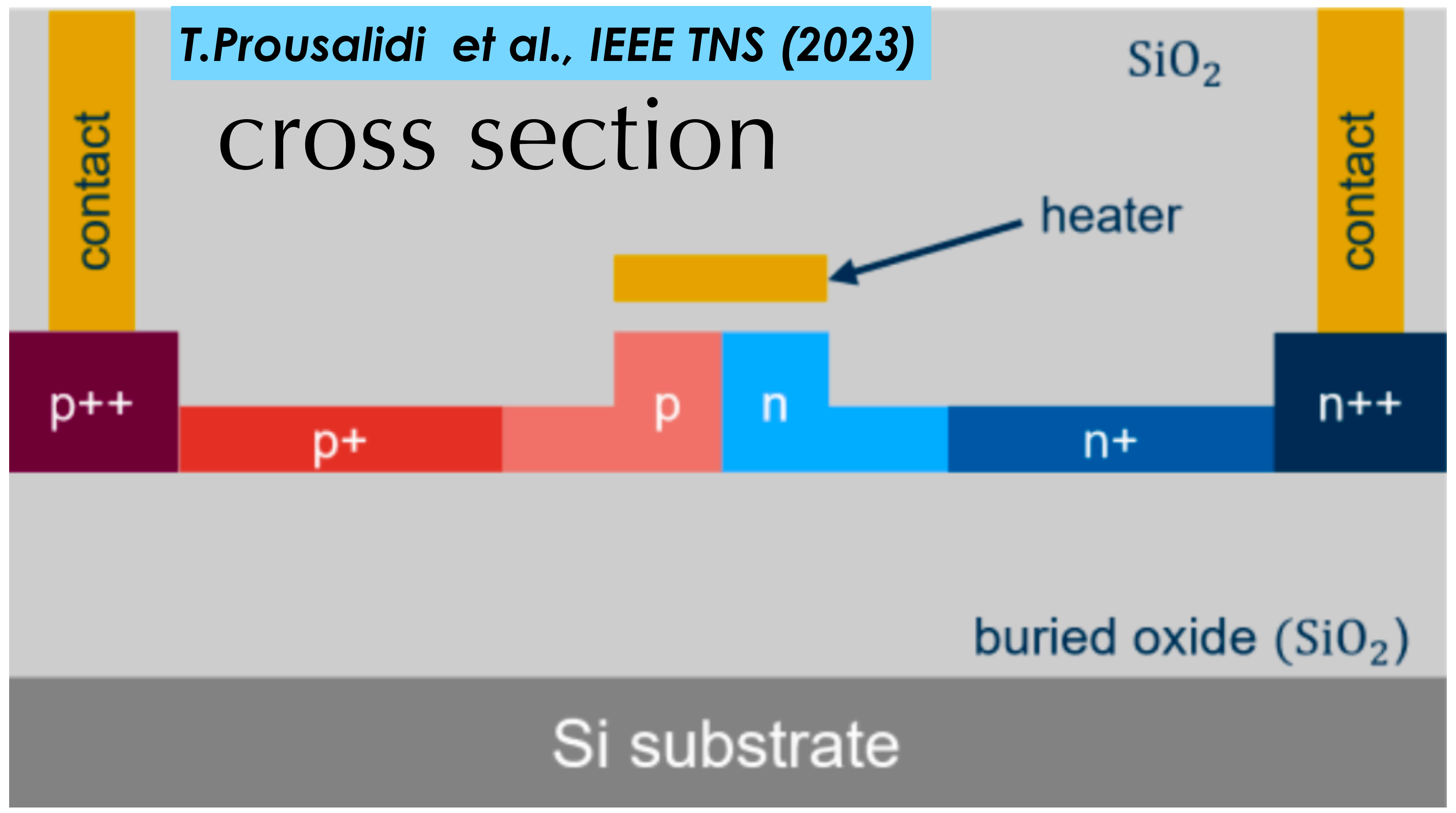
T.Prousalidi et al., IEEE TNS (2023)

Structure of the SiPh Transmitter



SiPh Transmitter: Ring Modulator (RM)

- Ring resonator
  - Reverse biased pn junction



  - Modulation voltage changes (the electrical signal 0/1)

    —> Carrier concentration changes

    —> Refractive index changes

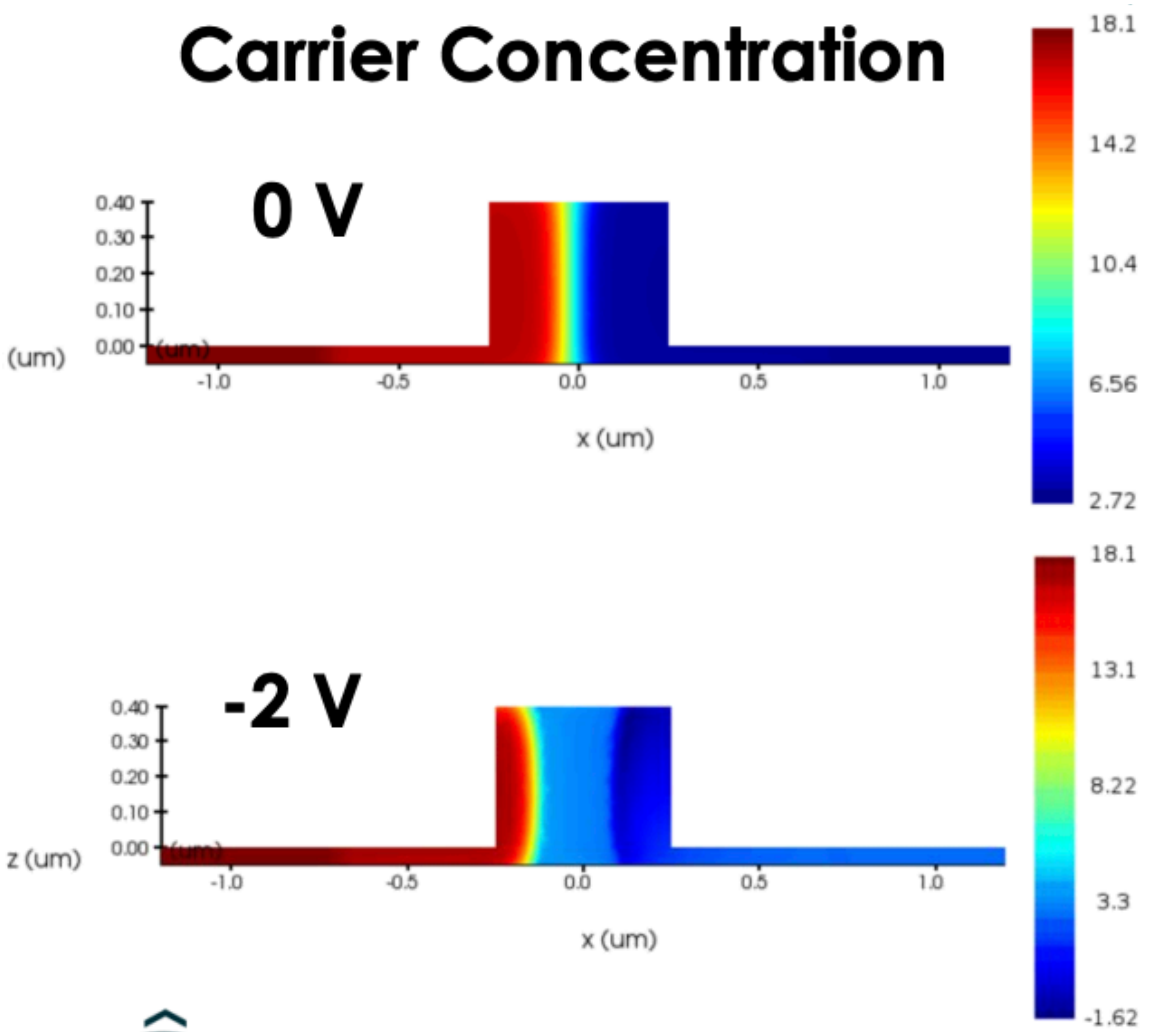
Index

$$\Delta n = -\frac{e^2 \lambda^2}{8\pi^2 c^2 \varepsilon_0 n} \frac{\Delta N_e}{m_e} + \frac{\Delta N_h}{m_h}$$

electrons **holes**

    —> Resonant wavelength changes nL = m·λres

    —> Output optical power changes



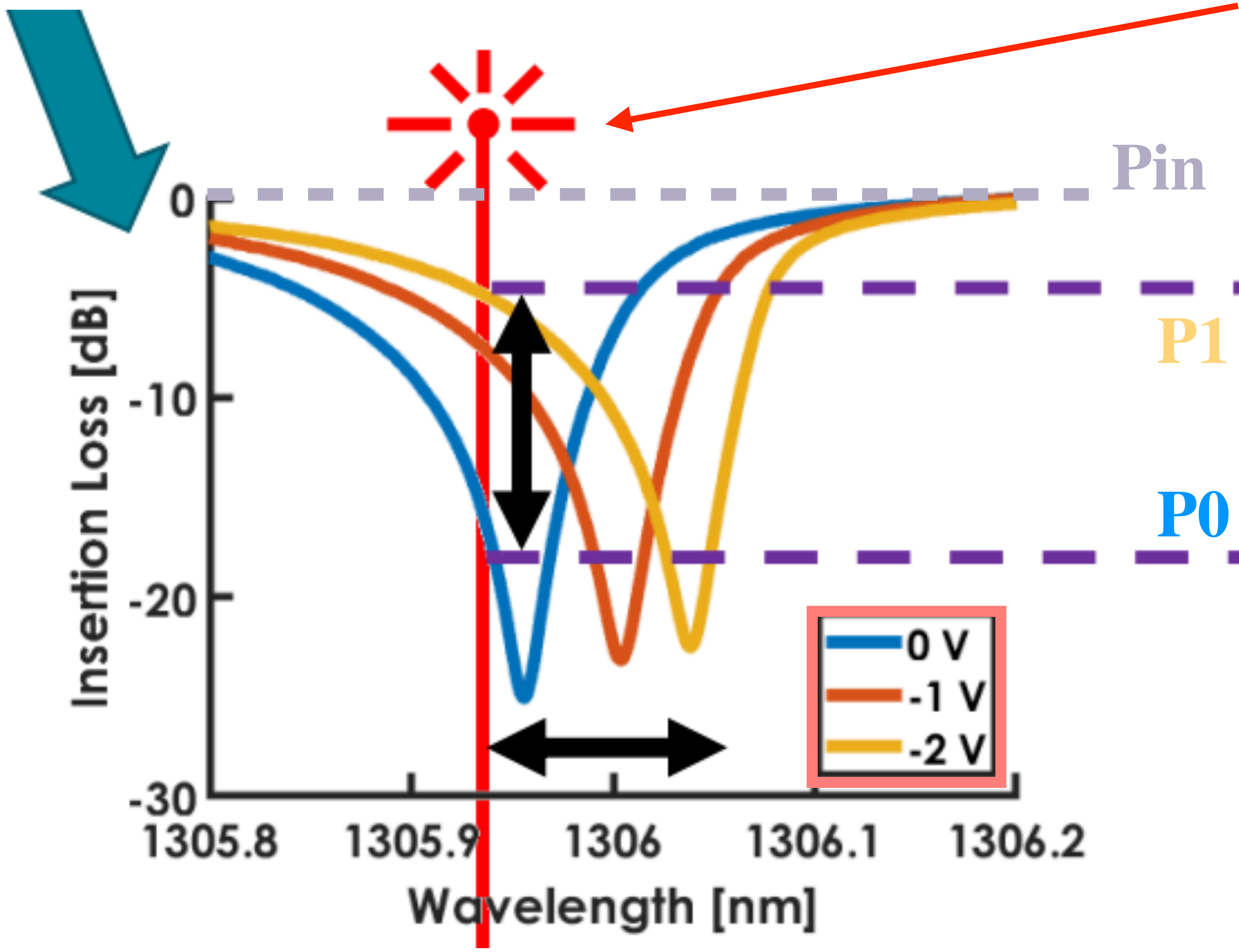
SiPh Transmitter: Ring Modulator (RM)

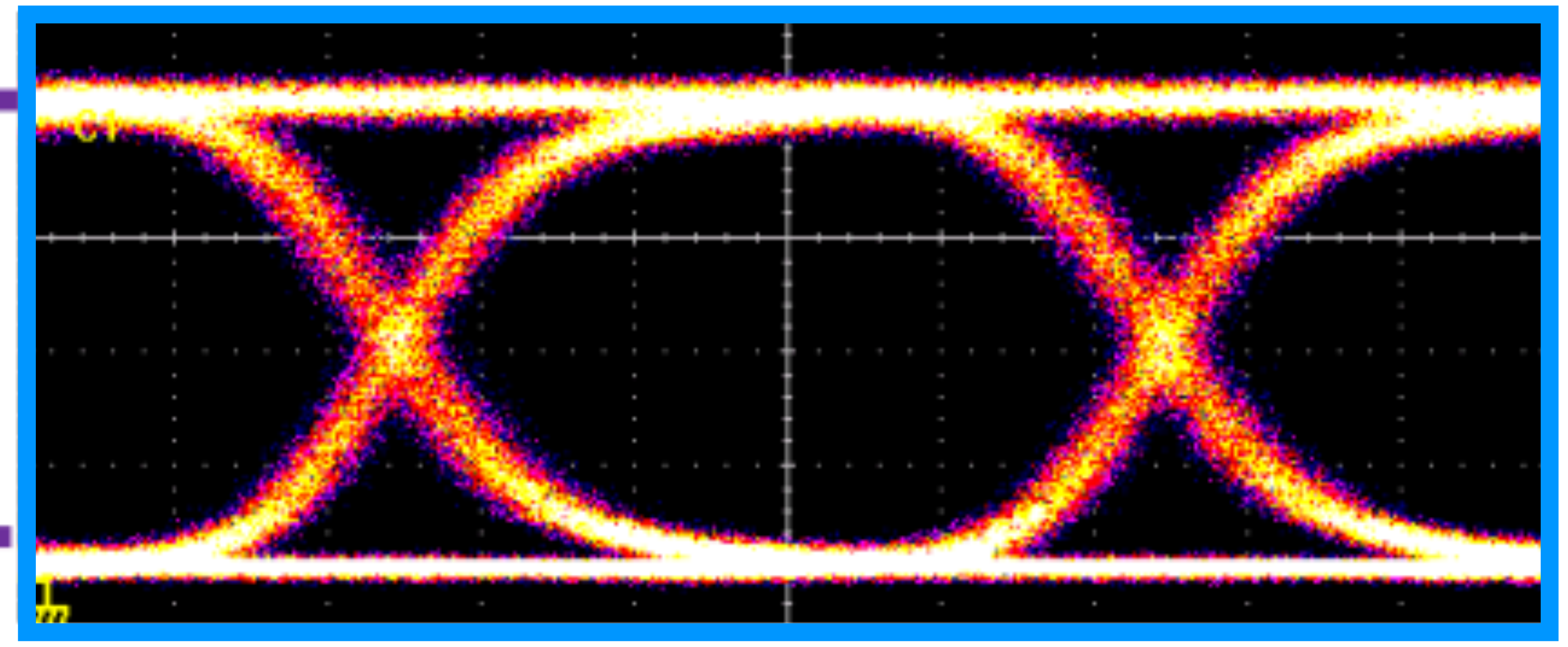
- Ring resonator
  - **Modulation voltage** changes (the electrical signal 0/1)

    —> …

    —> Output optical power changes

Choose λ_{laser} = λ_{opt}, where the eye diagram opening is the biggest,
i.e. maximizes the optical modulation amplitude (OMA) = P1 - P0





- Other performance parameters
  - Extinction ratio (ER) = P1/P0
  - Insertion loss (IL) = Pin - P1
  - Modulation efficiency = Δλ/V

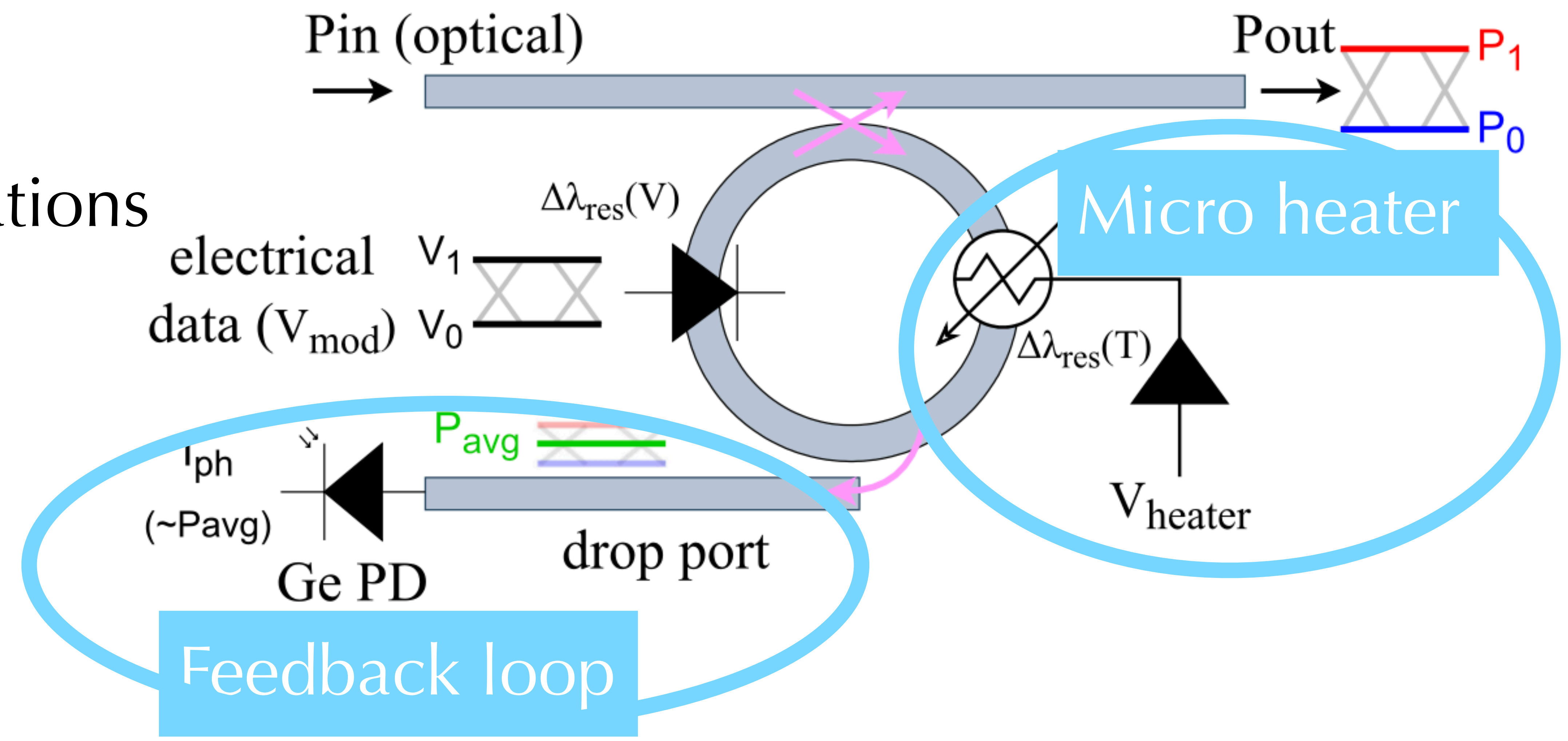
SiPh Transmitter: Thermal Tuning

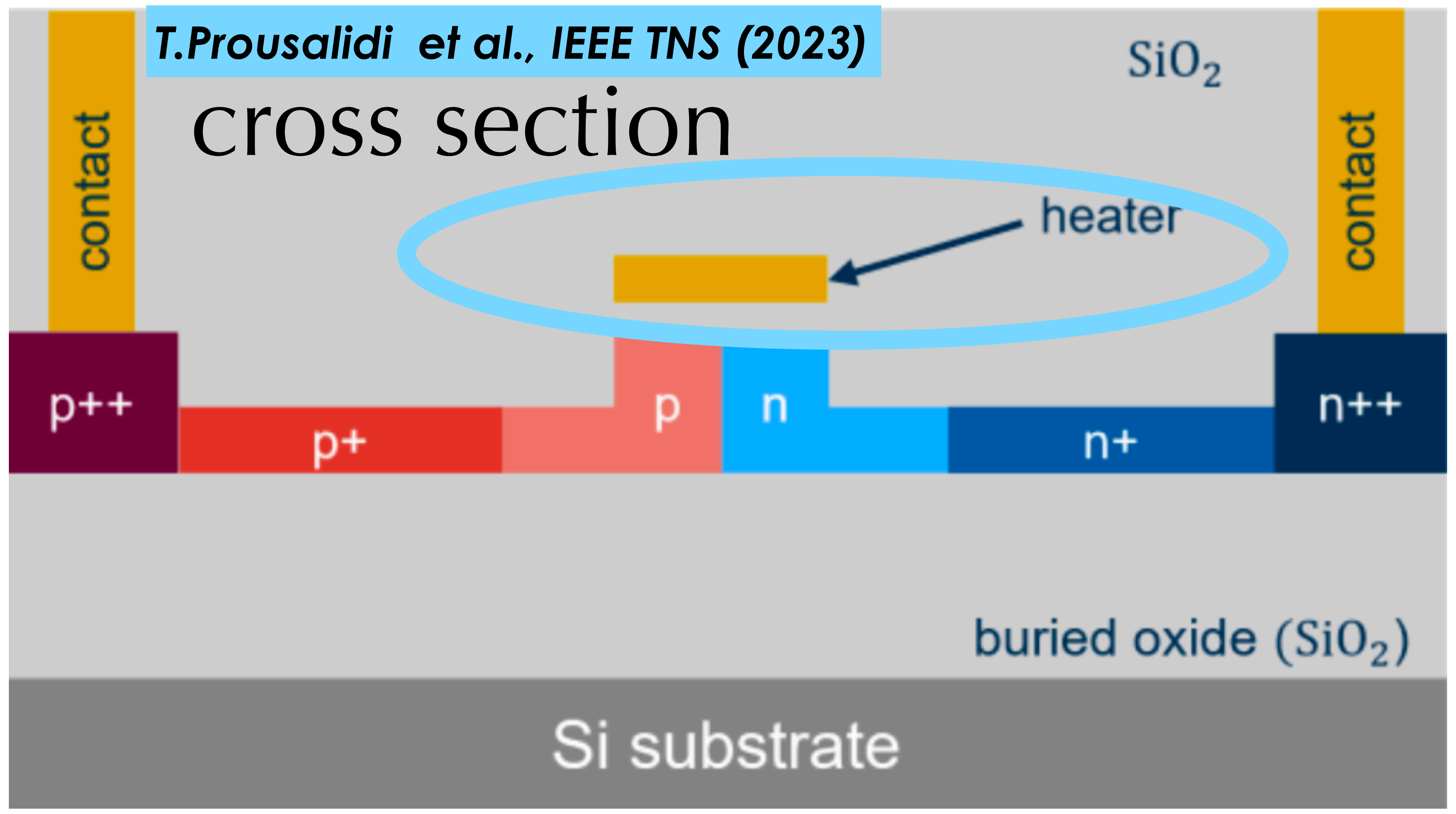
- Si has high thermo-optic coefficient
  - Resonant wavelength λres is sensitive to temperature fluctuations $\Delta\lambda_{res} / \Delta T$ = 70pm/°C
- λres varies also due to fabrication process

—> λ_{opt} is detuned λ_{laser}

- A thermal tuning mechanism to compensate for the variations
  - A tungsten microheater
    - Excellent thermal conductivity
  - A feedback loop

—> Robust to temperature (over ~50°C range) and laser fluctuation

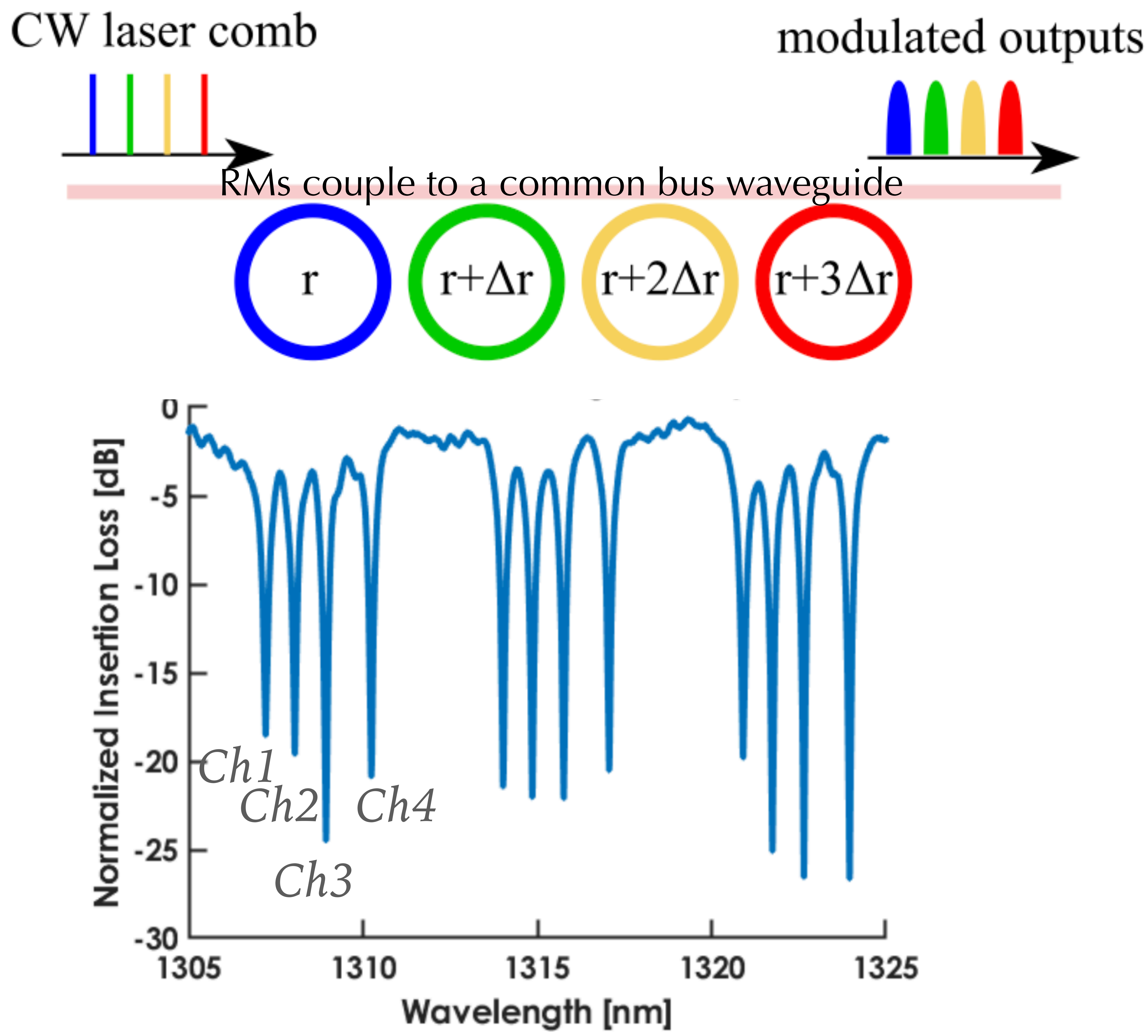




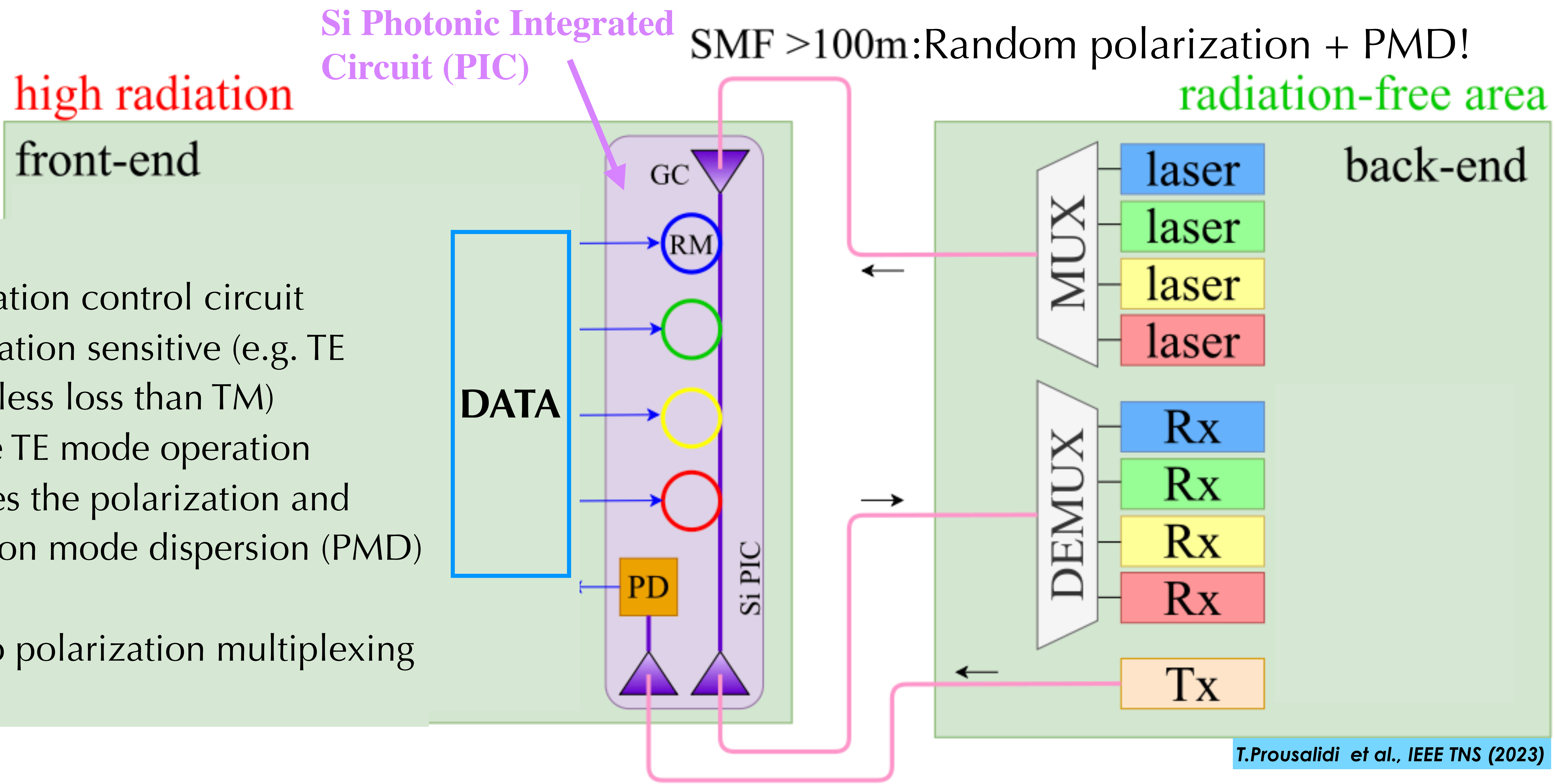
SiPh Transmitter: Wavelength Division Multiplexing (WDM)

- Multiplexing: multiple data channels are transmitted simultaneously over a single optical fiber
- WDM: each channel operates at a different wavelength
  - Cascaded RMs with different radii:
    $r \propto nL = m \cdot \lambda res$

- Now: 4-channel
  - 4 RMs with 9.9, 10.0, 10.1, 10.2 um radii
  - λres evenly spaced (150 nm)
- New: 10-channel, to be tested
- Future: dense WDM



SiPh Transmitter: Polarization Controller



- Need for a polarization control circuit
  - SiPhs are polarization sensitive (e.g. TE polarization has less loss than TM)
    - Designed to be TE mode operation
  - Fibers randomizes the polarization and causes polarization mode dispersion (PMD)
- Future: can also do polarization multiplexing

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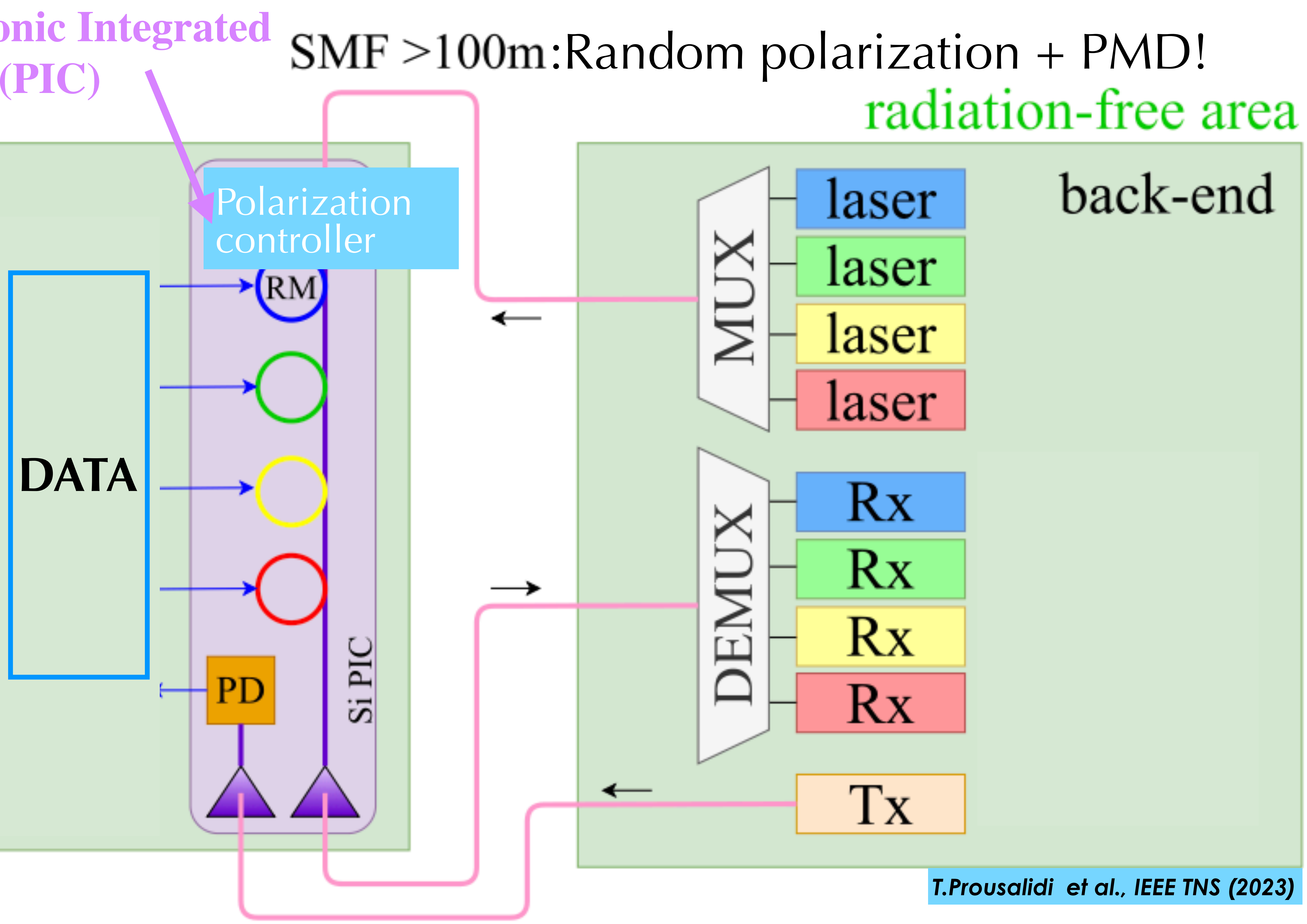
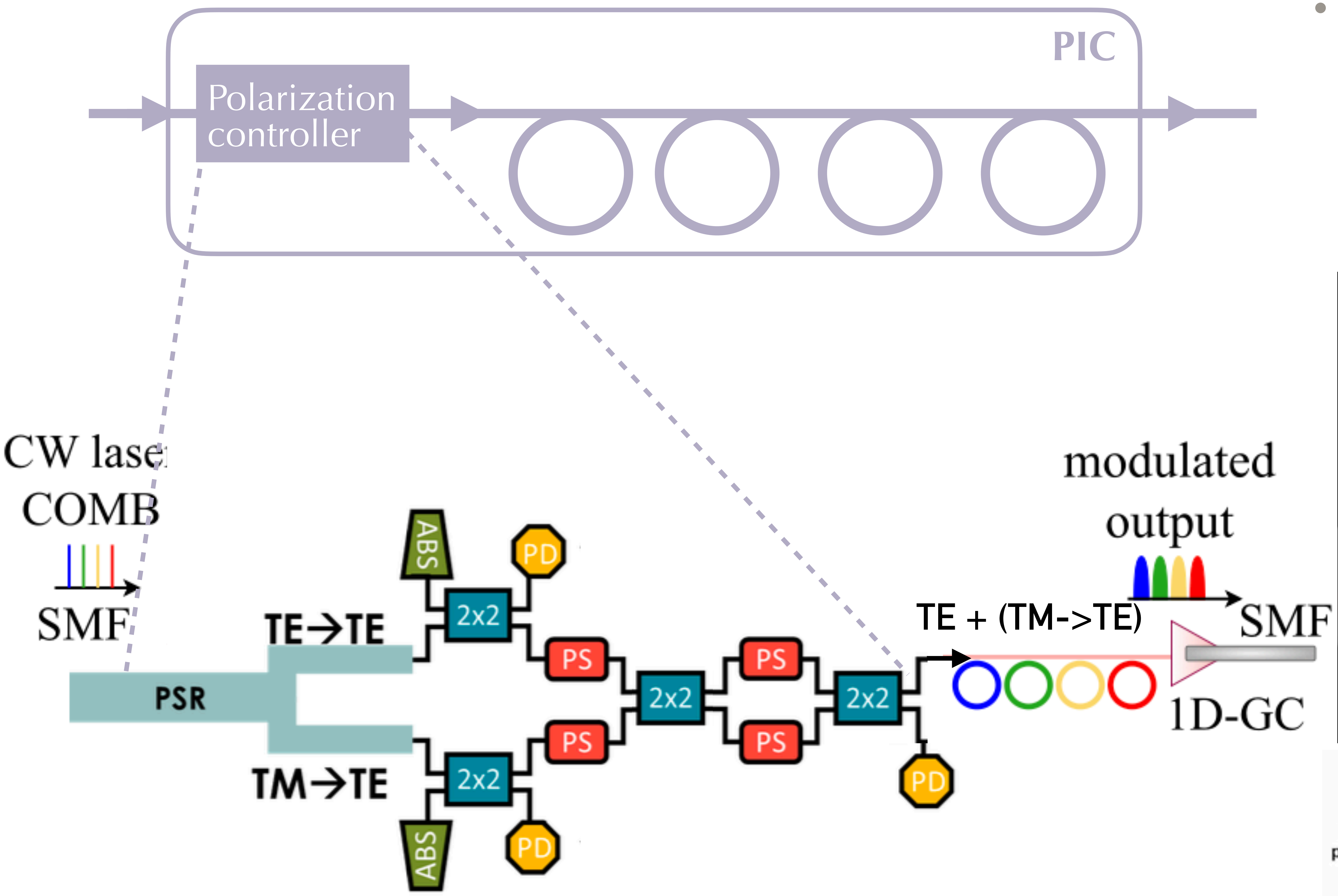
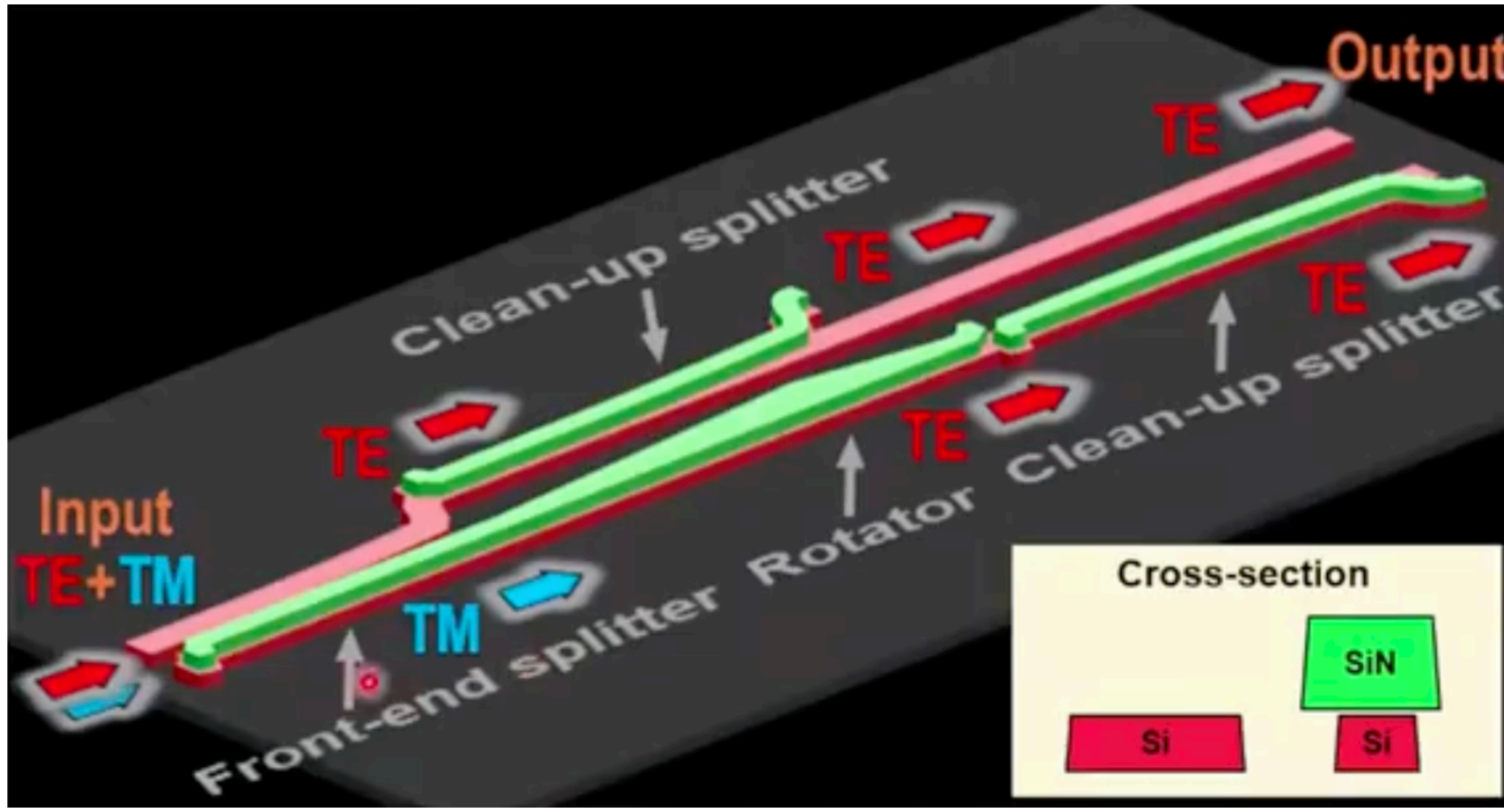
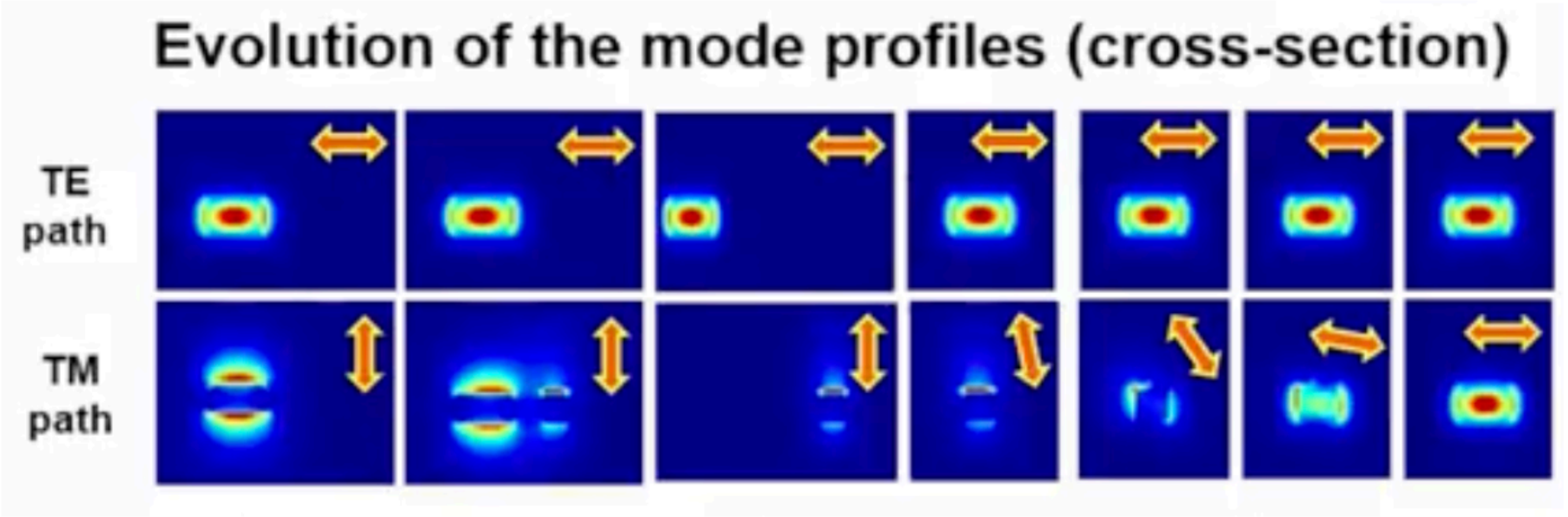


SiPh Transmitter: Polarization Controller



- On-chip polarization controller
  - Polarization Splitter-Rotator (PSR) simultaneously splits and rotates the polarization
    - Hybrid Si and SiN waveguide structure





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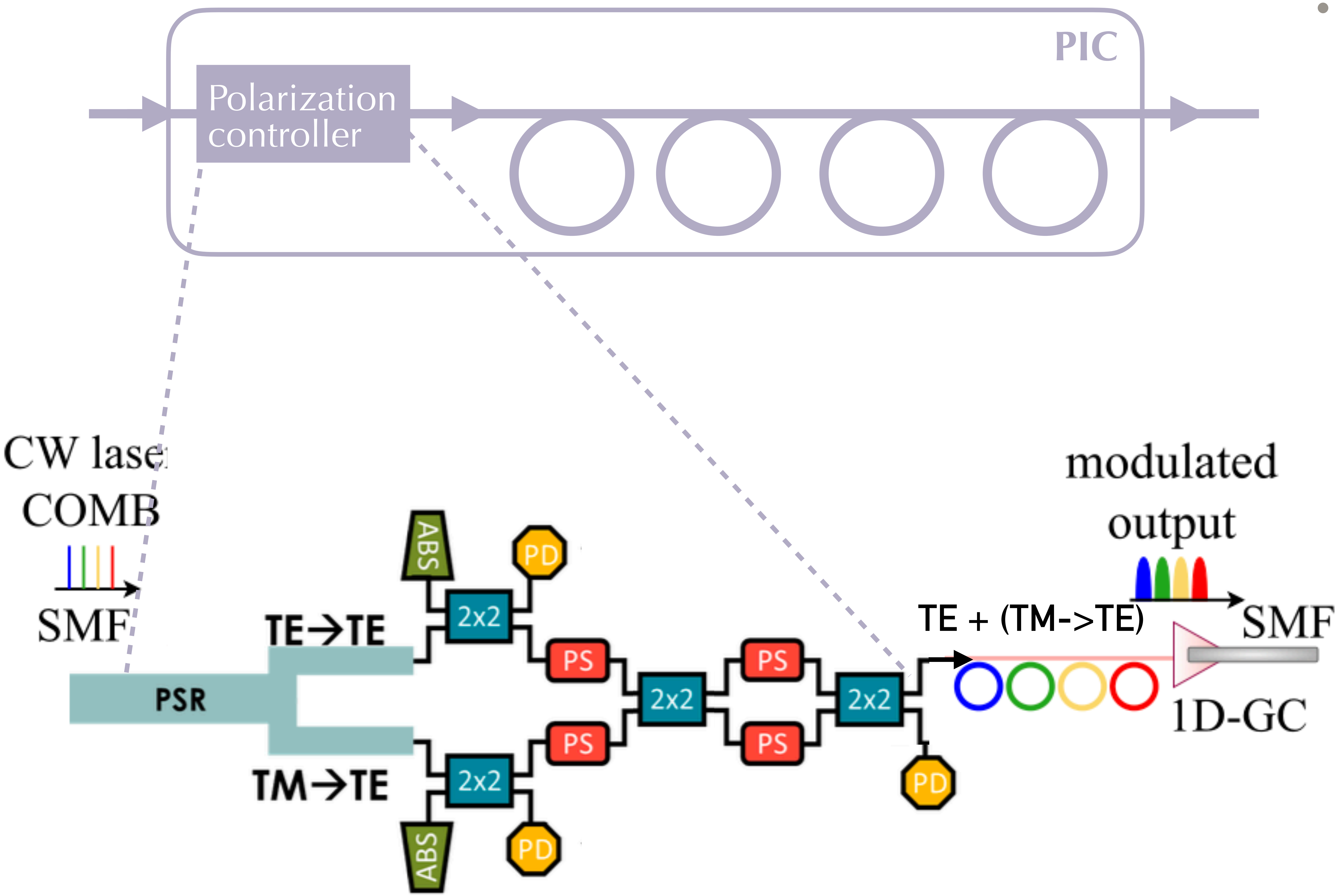
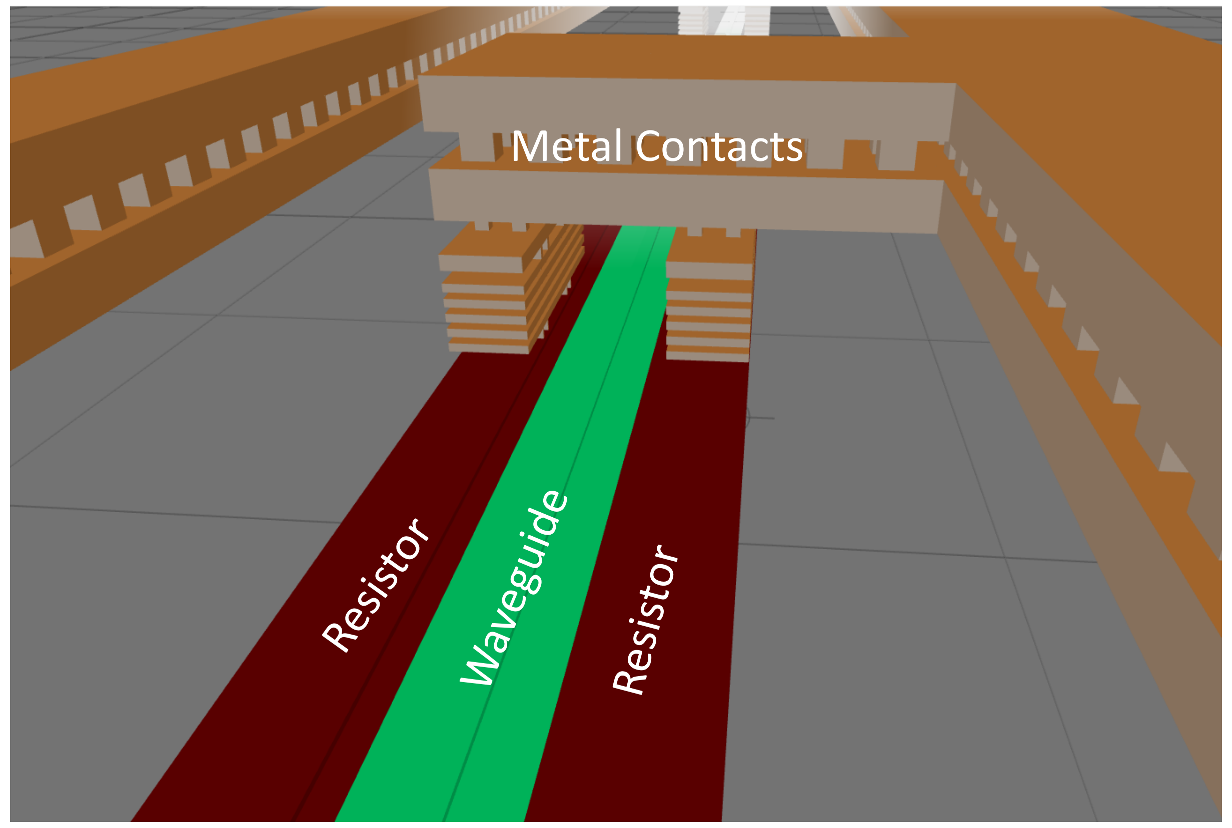


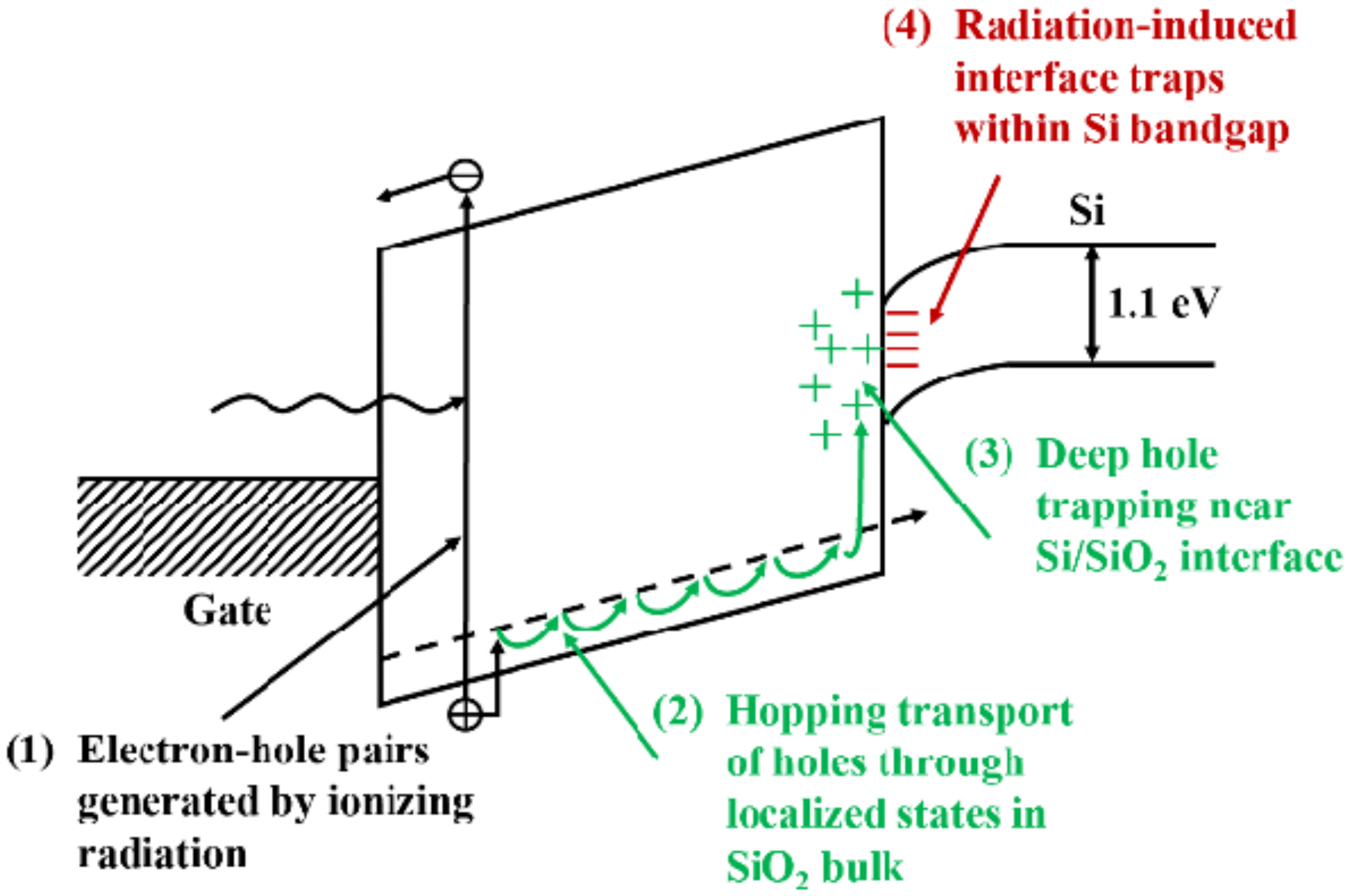
- On-chip polarization controller
  - Polarization Splitter-Rotator (PSR) simultaneously splits and rotates the polarization
    - Hybrid Si and SiN waveguide structure
  - **Thermal phase shifters (PS)** adjusts the phase
    - p-doped polysilicon resistor alongside to the waveguide

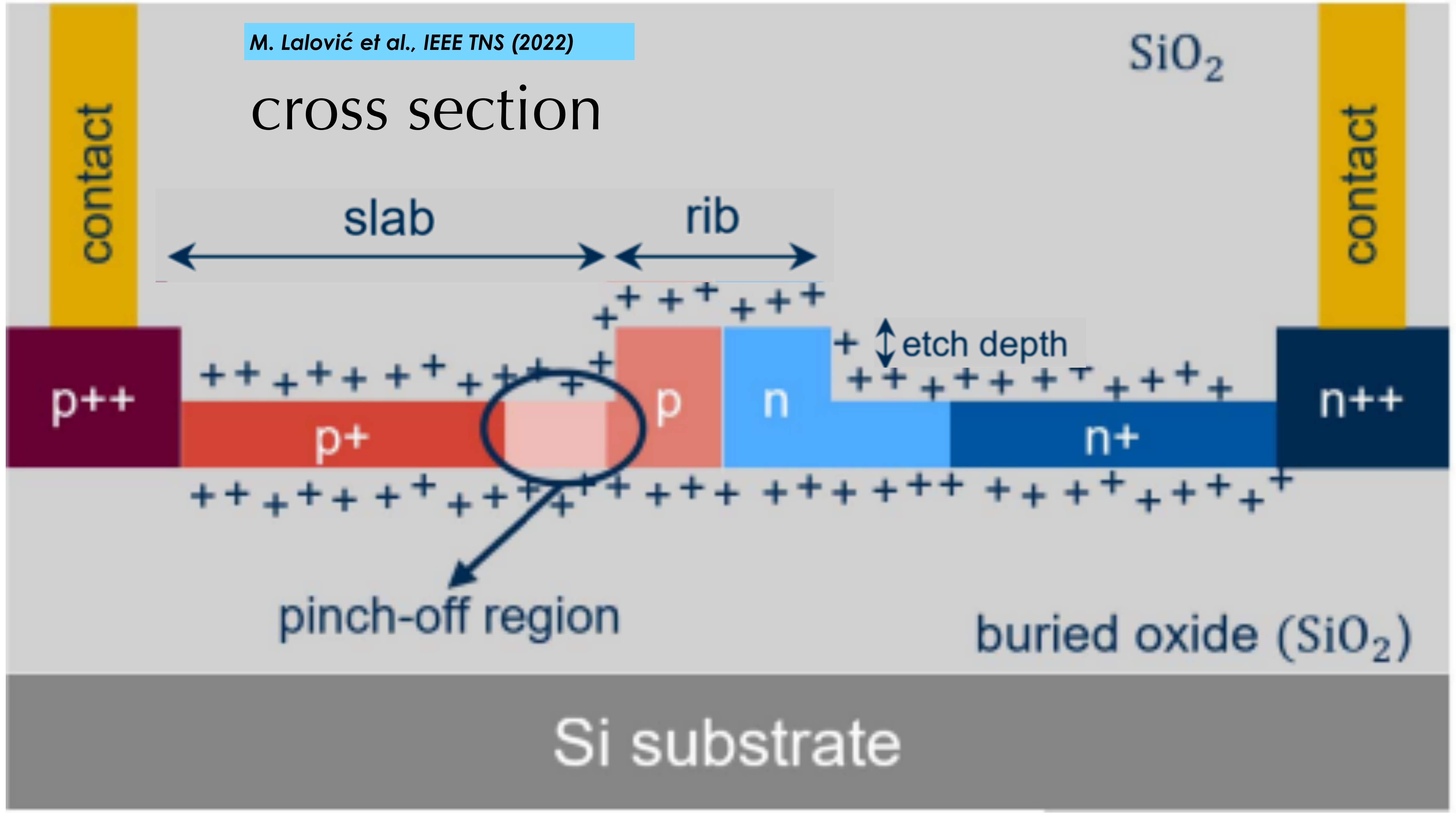


  - **2x2 multimode interferometers (MMIs)** for recombination

Radiation Effects: Total Ionizing Dose (TID)

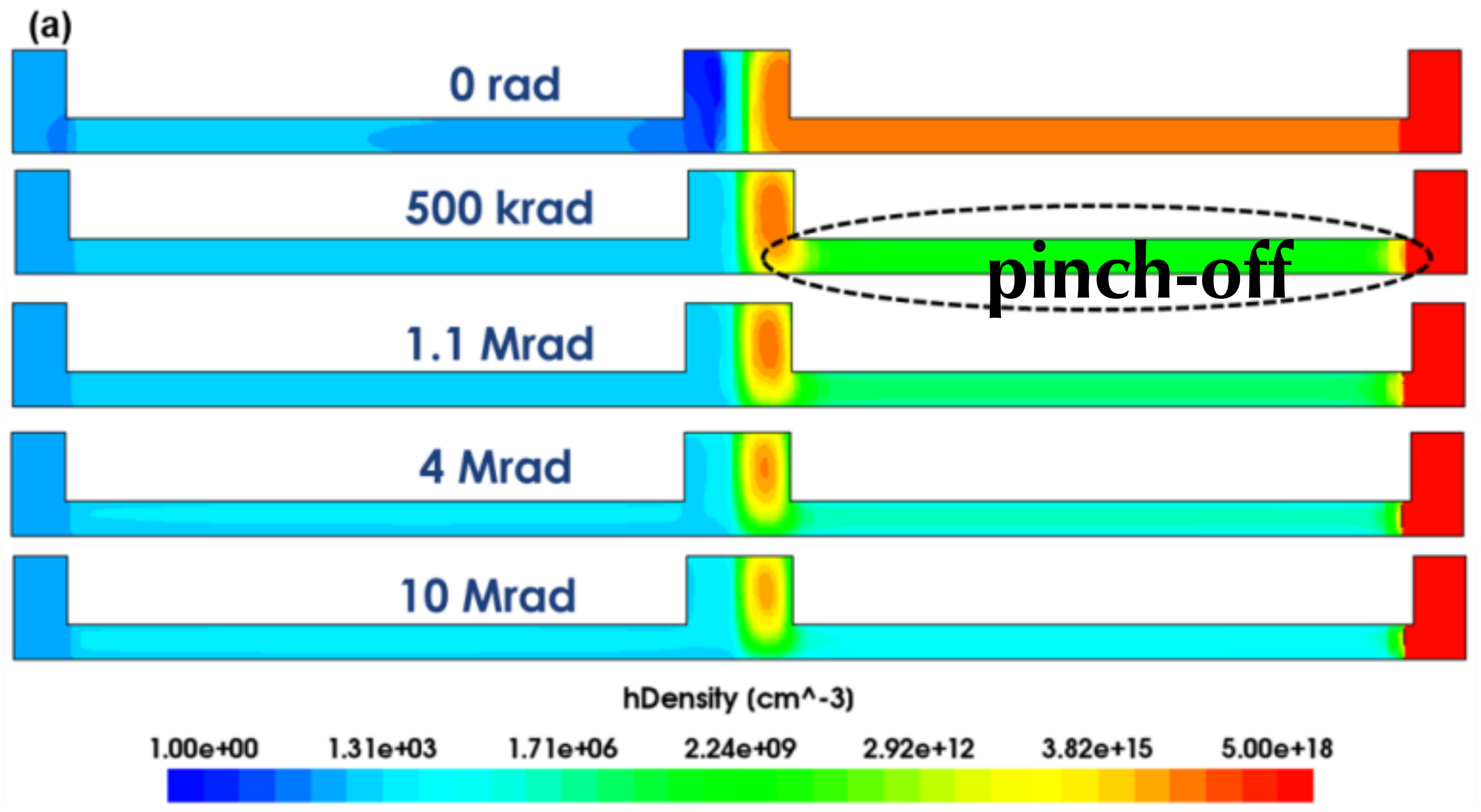
- Main damage from ionizing
  —> Holes trapped at the SiO_2-Si interface
  —> fixed positive charges push the free holes in the p-doped Si away
  —> no conductive path between the p++ contact and the rib junction
  —> pinch-off region
  —> concentration variation fails

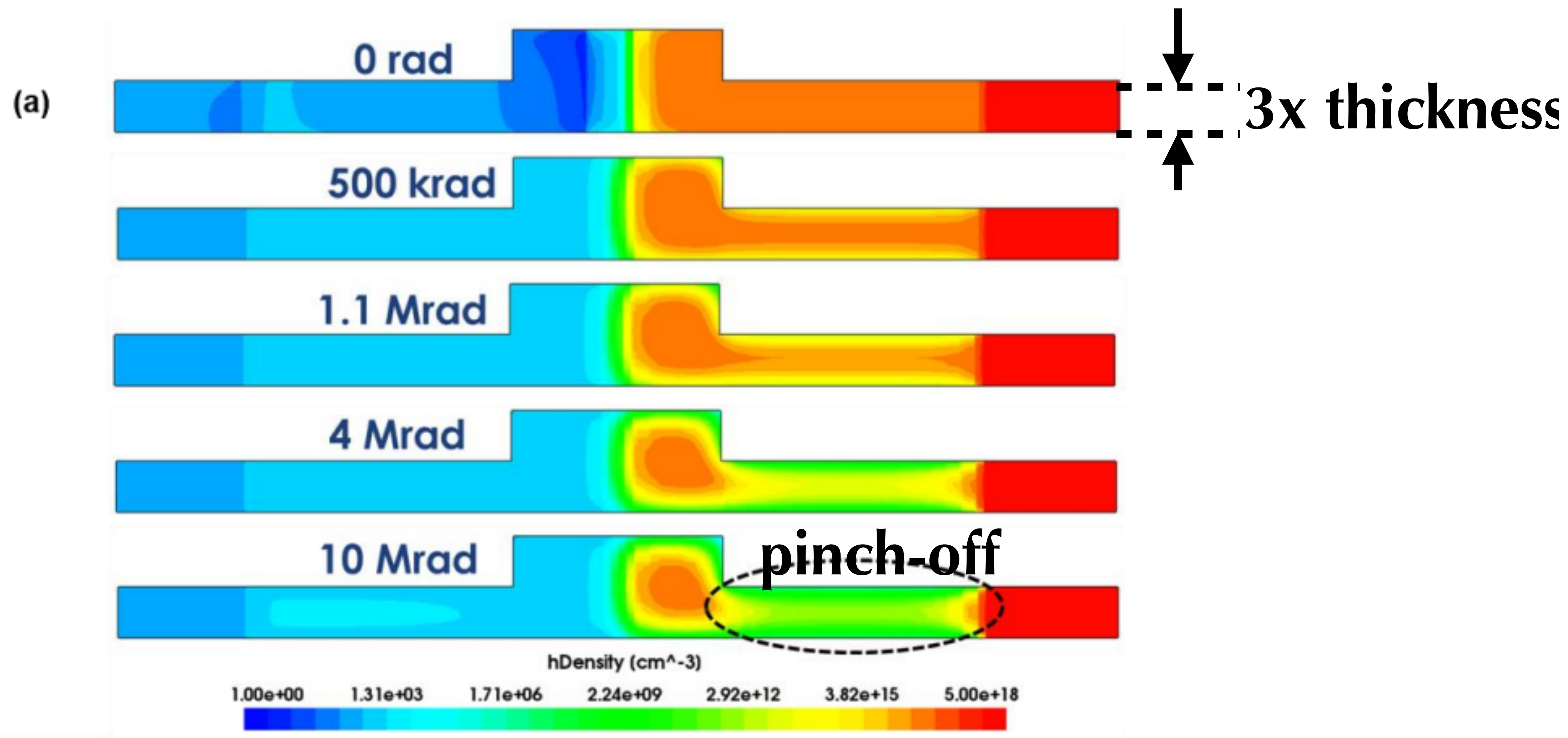




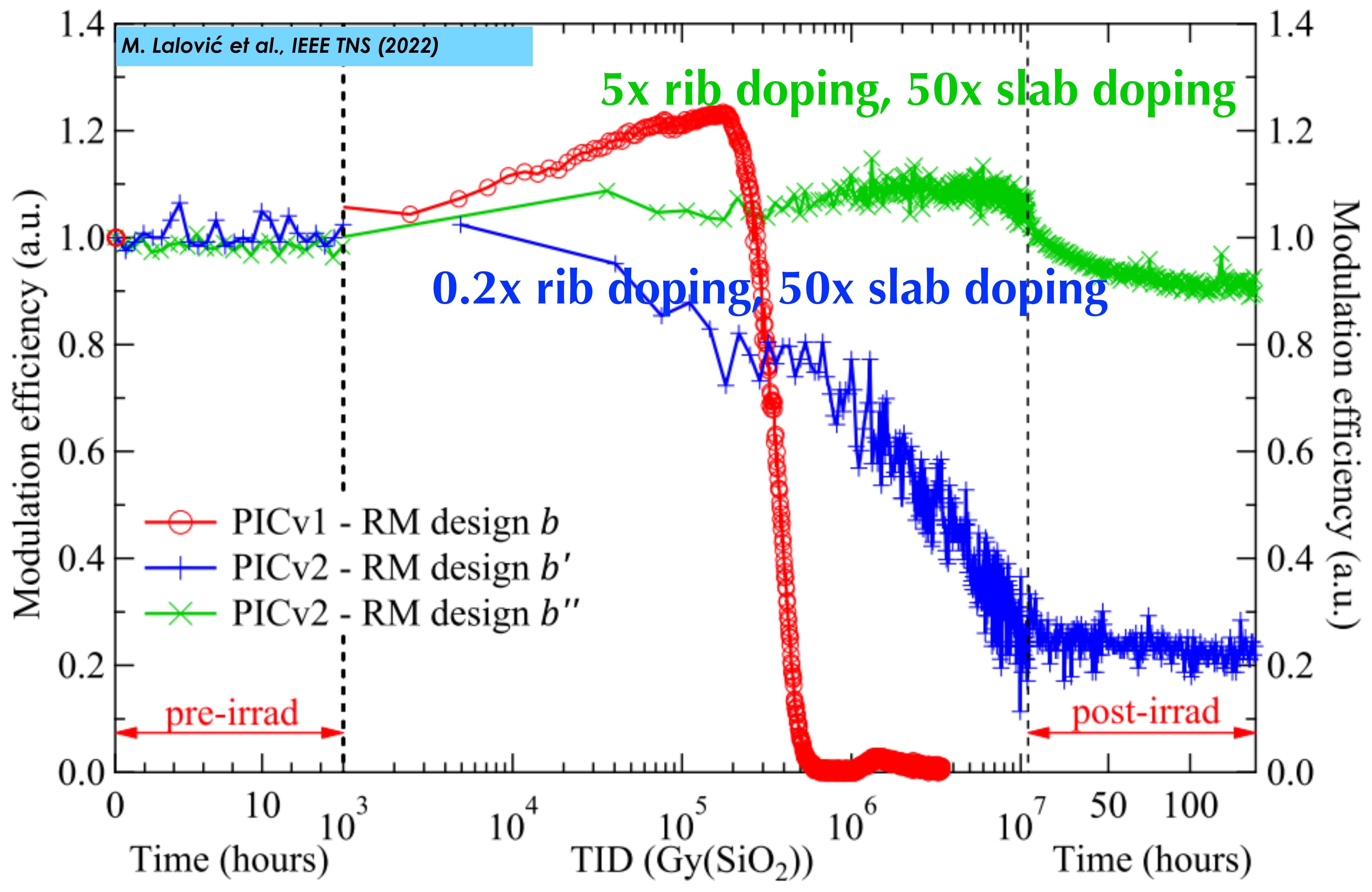
Radiation Hardness: Mitigate Pinch-off

S. Estrella, et. Al., Phys. & Sim. Of Optoelectronic Dev XXX (2022)



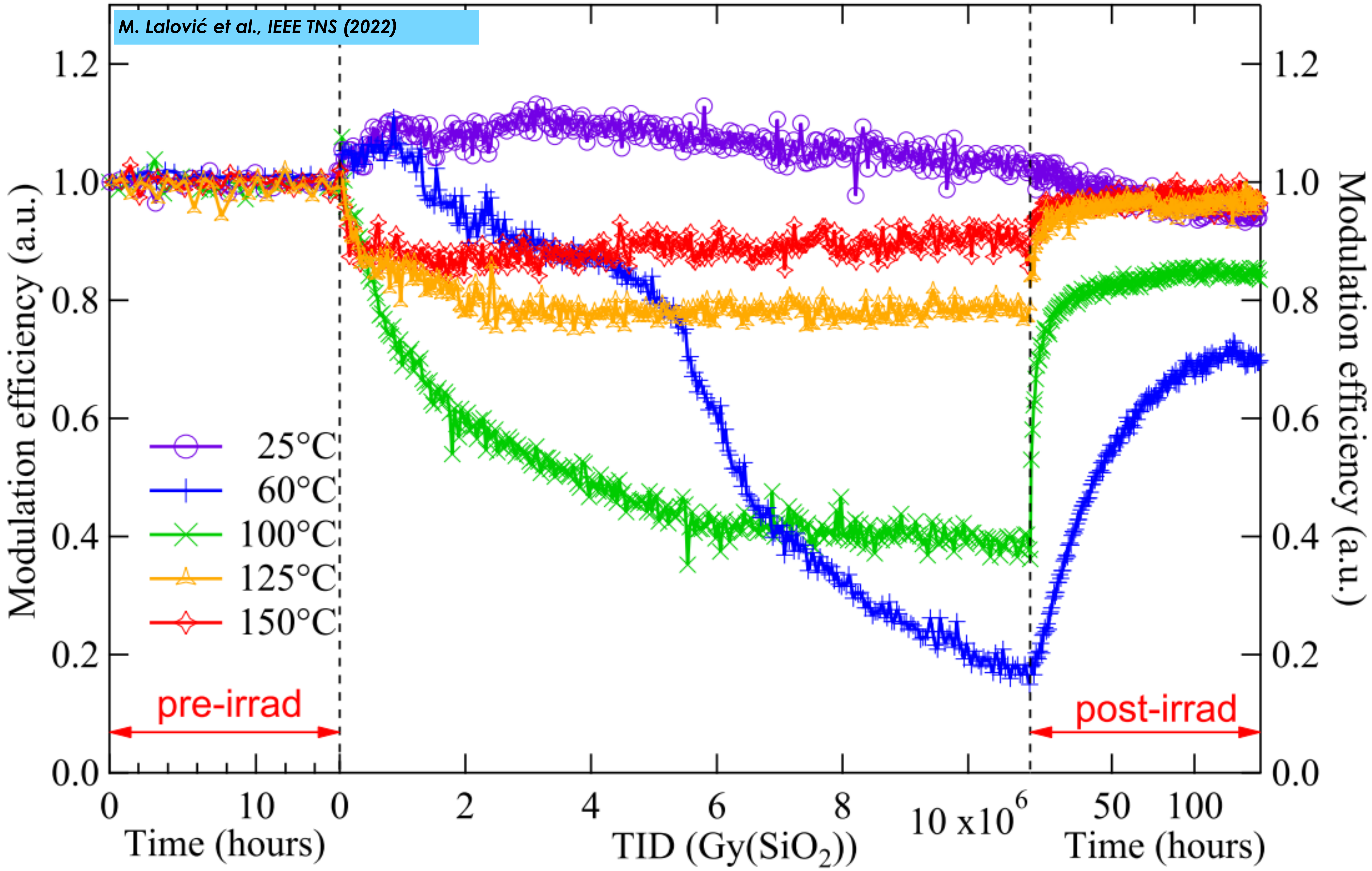


- Shallower etch/thicker slab/shorter slab length
- Higher dopant concentration throughout the slab
- Does not come for free: trade off modulation efficiency



Radiation Hardness: Recovery

- High temperature annealing recovers the TID damage



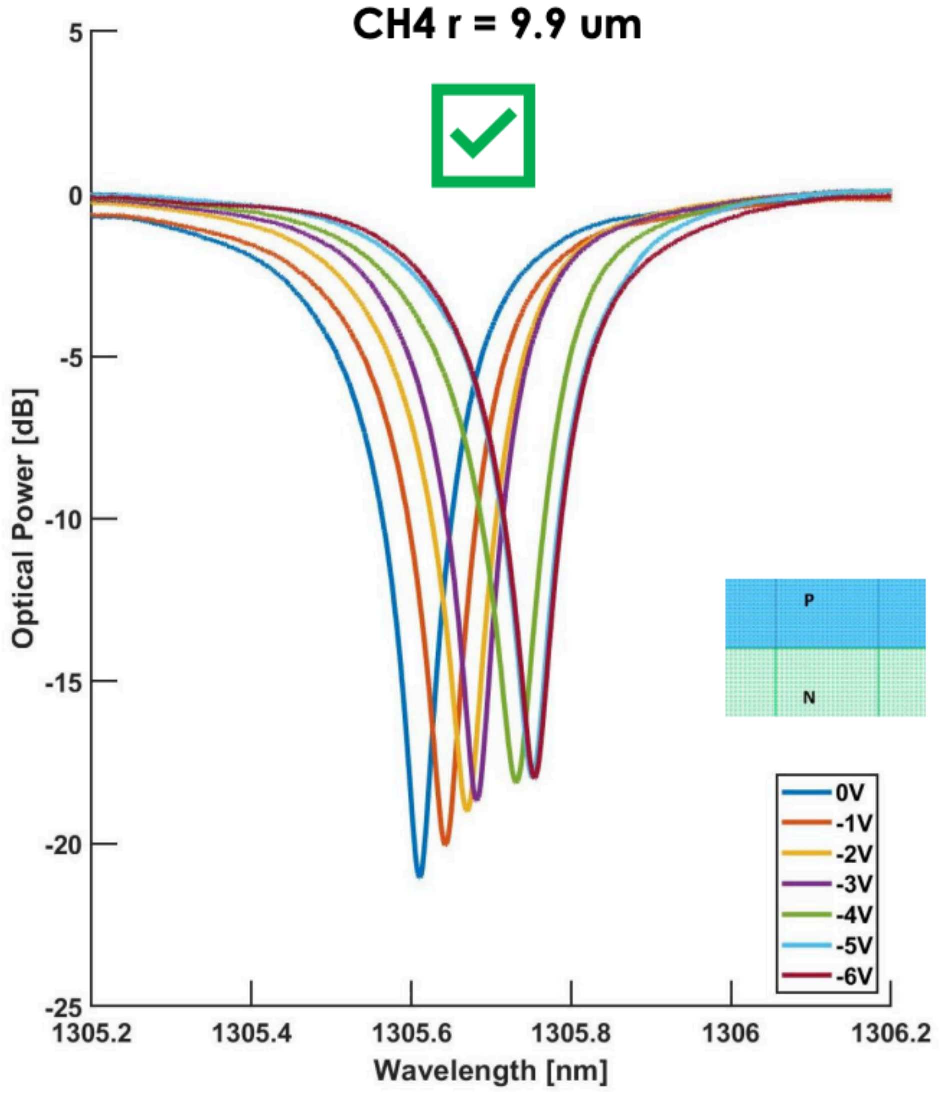
Our Devices

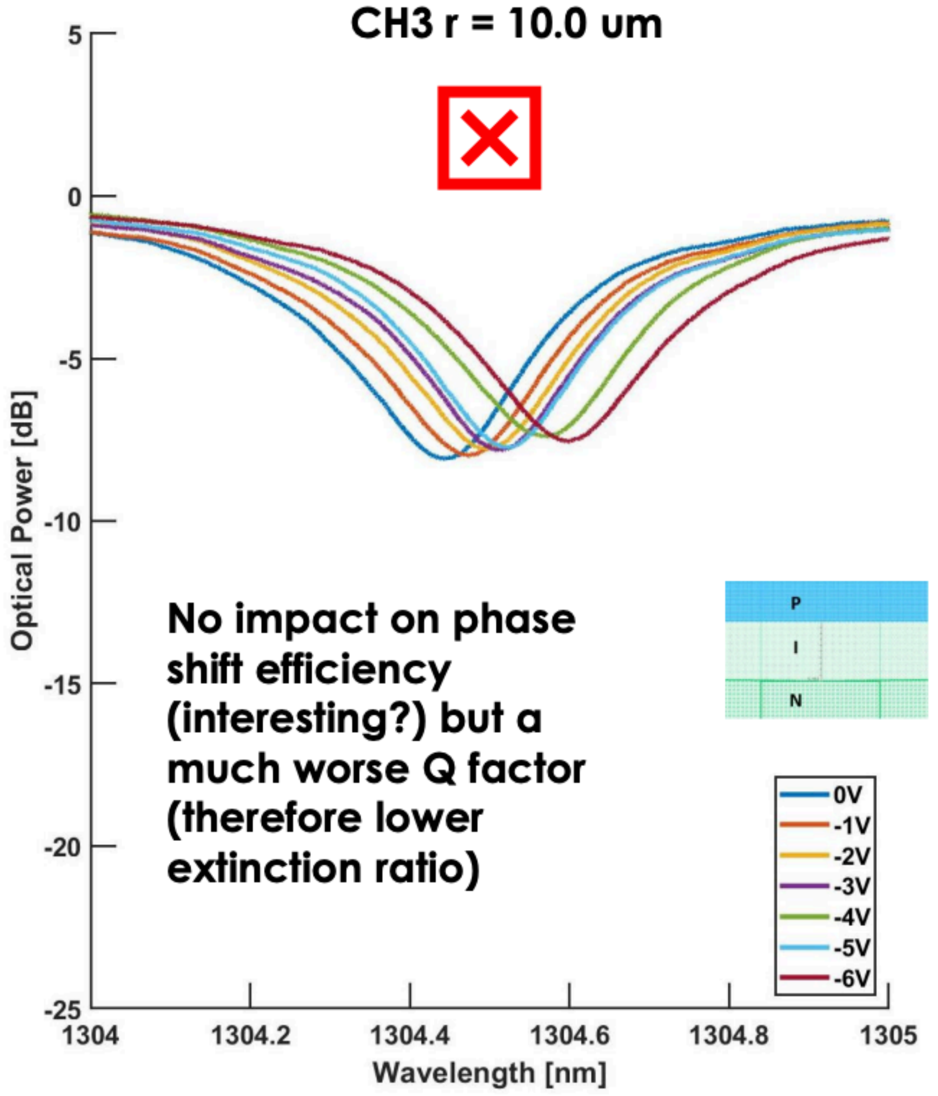
- **Ring modulators**

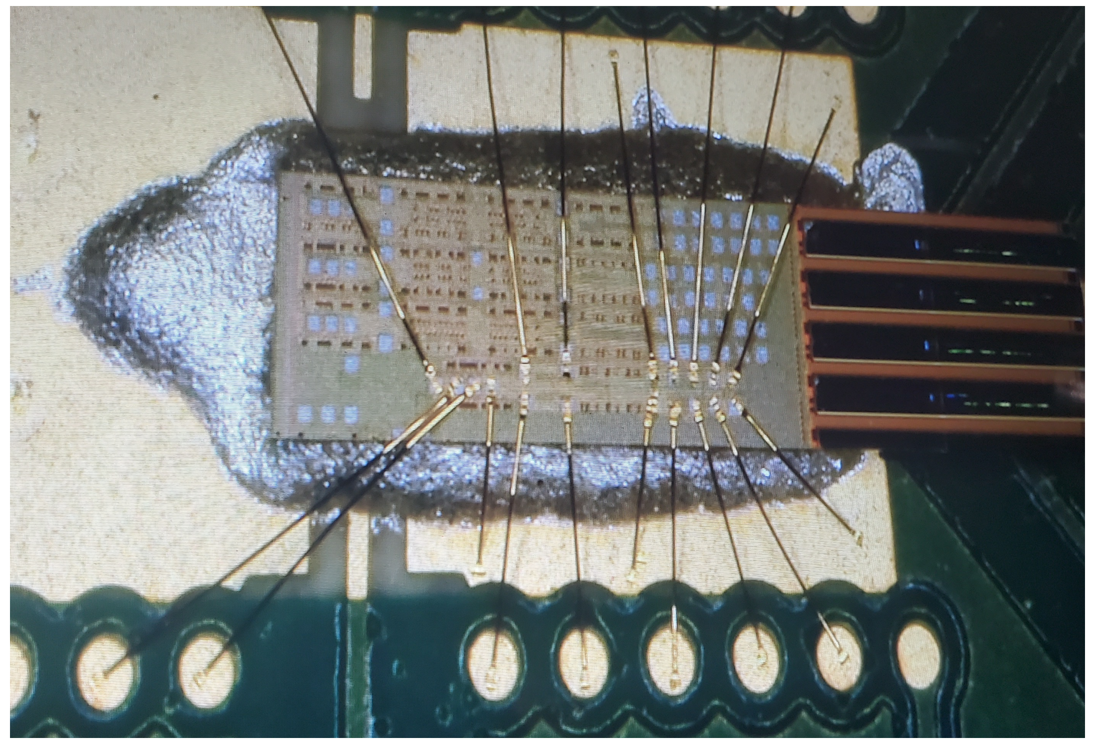
2022
- PiN junctions for forward bias —> not promising
- **4 channel nominally doped WDM**
  - **3 nominal PN channels**
  - **1 channel w/ design error (lower doping PiN)**

2023
- 4 channel highly doped WDM
- 10 channel highly doped WDM

Future
- D(dense)WDM







- **Polarization controller**

2023
- **PSR+PS for TE operation**

2024
- PSR+PS w/ additional amplifier for TE operation

Future
- W/ recovery circuit for polarization multiplexing

Irradiation Runs

- **Ring modulators**
  - …
  - **4 channel nominally doped WDM**
    - 3 nominal PN channels
    - 1 channel w/ design error (lower doping PiN)
  - …

Three irradiation runs with the **X-ray machine**
1. Only the channel w/ designed error was irradiated
2. No optical input, only electrical
3. No optical input, only electrical

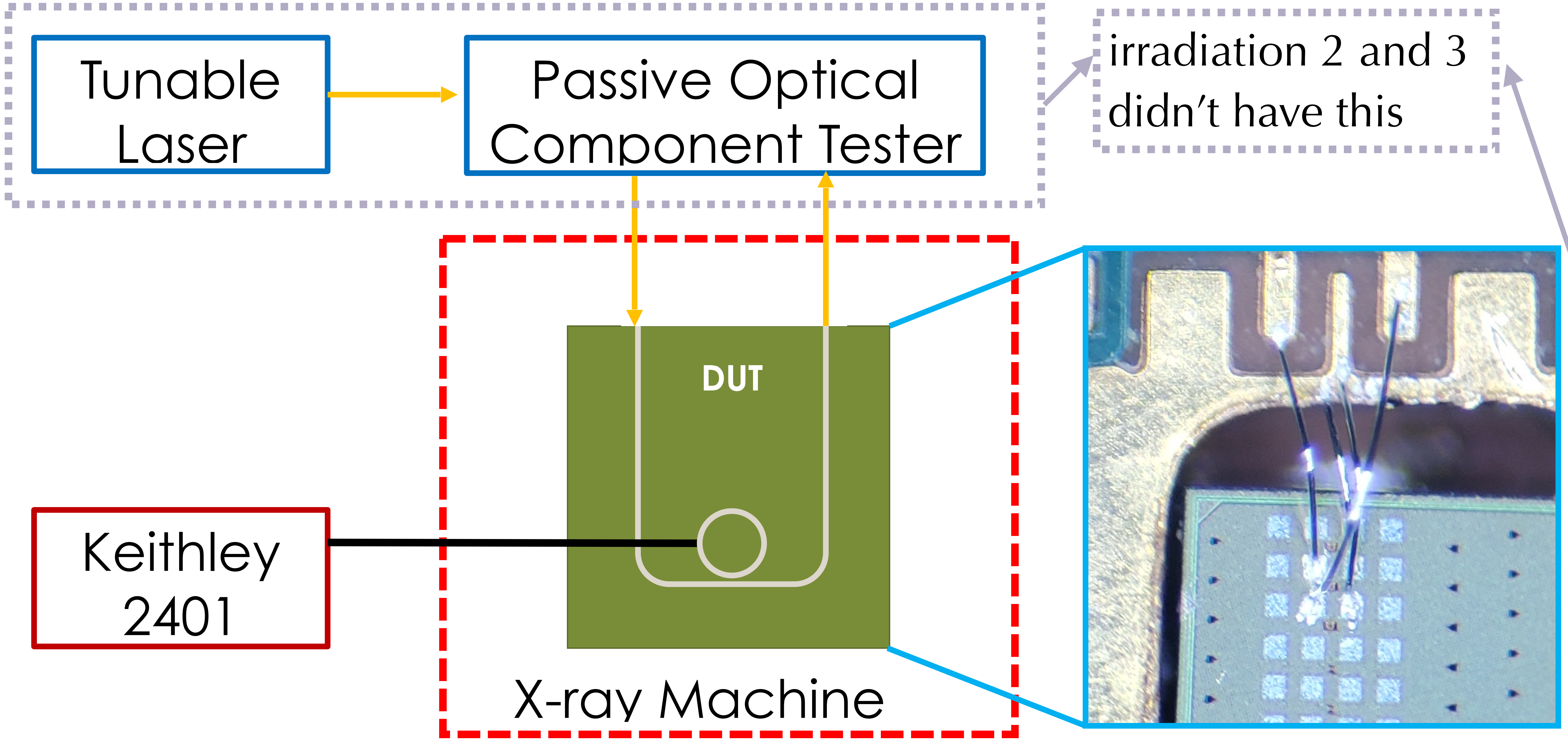
- Other caveats
  - Currently, the RMs and polarization controllers are **NOT** integrated on the same chip, they are separate devices being irradiated separately
  - **Lower TID** than desired for polarization controller irradiation

First SiPh polarization controller radiation results

Two irradiation runs with **Krypton-85 source**

- **Polarization controller**
  - **PSR+PS for TE operation**
  - …

Irradiation Setups: Ring Modulator (XRM)

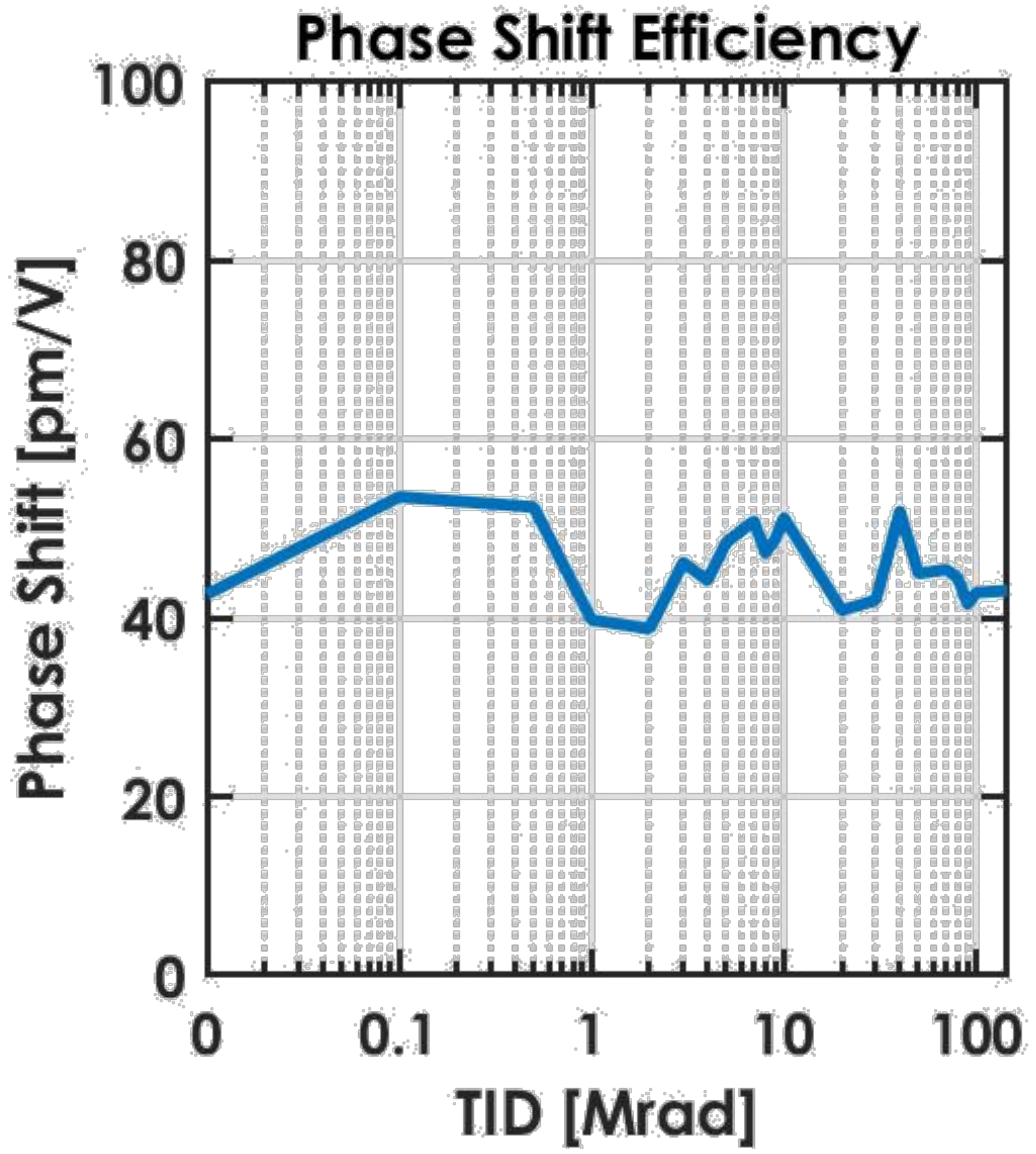


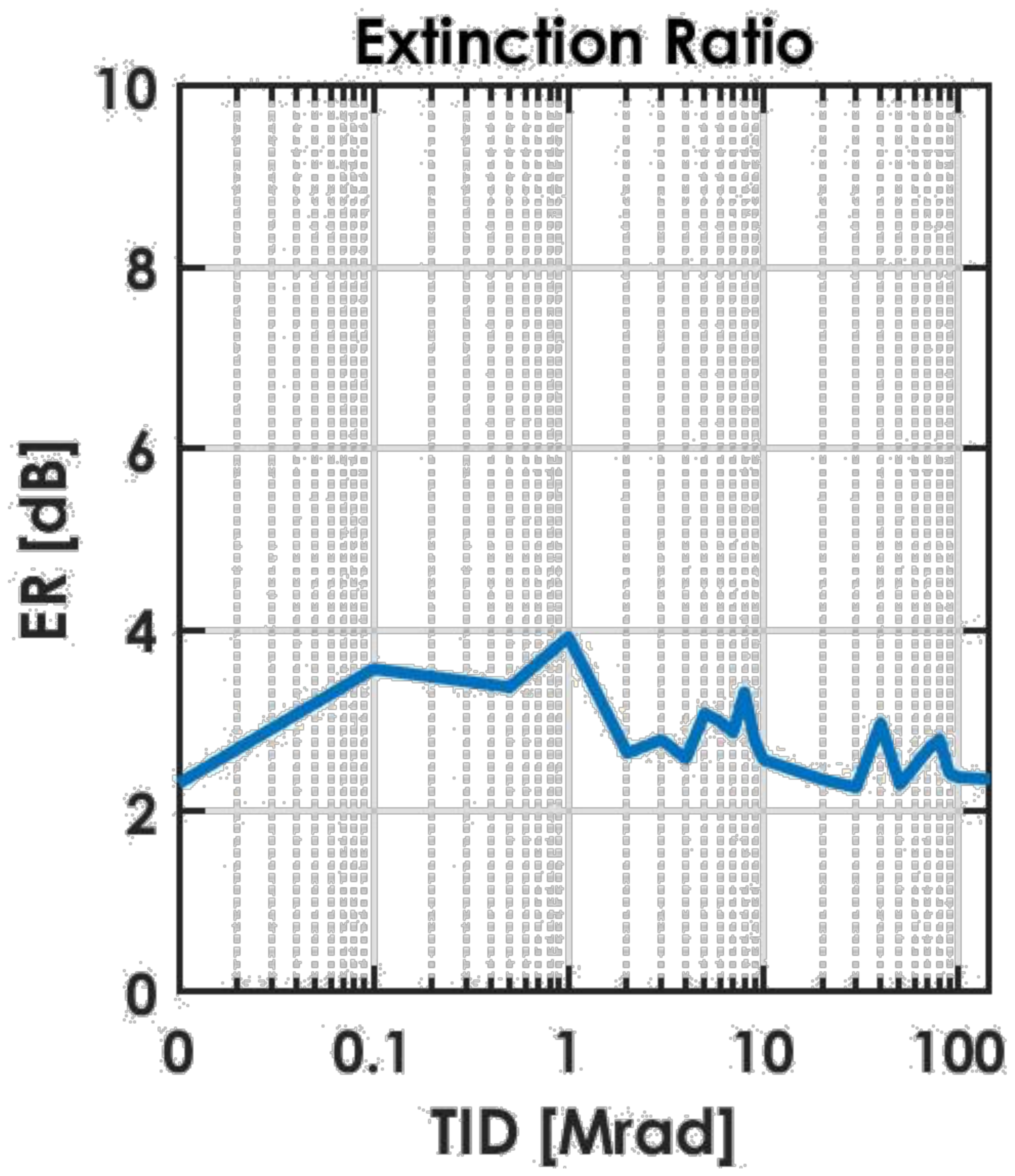
- X-ray Irradiation
  - Beam spot and dose map calibrated
  - Dose rate 1.95 MRad/hr
  - IV sweep/optical readout at a fixed interval
  - Track the key metrics over TID:
    - Leakage current
      - Increases with TID due to trapped charge
    - Optical performance
      - ER = P1/P0
      - OMA = P1 - P0
      - Modulation Efficiency Δλ/V

Irradiation Results: Ring Modulator (XRM)

Run 1: channel with design error

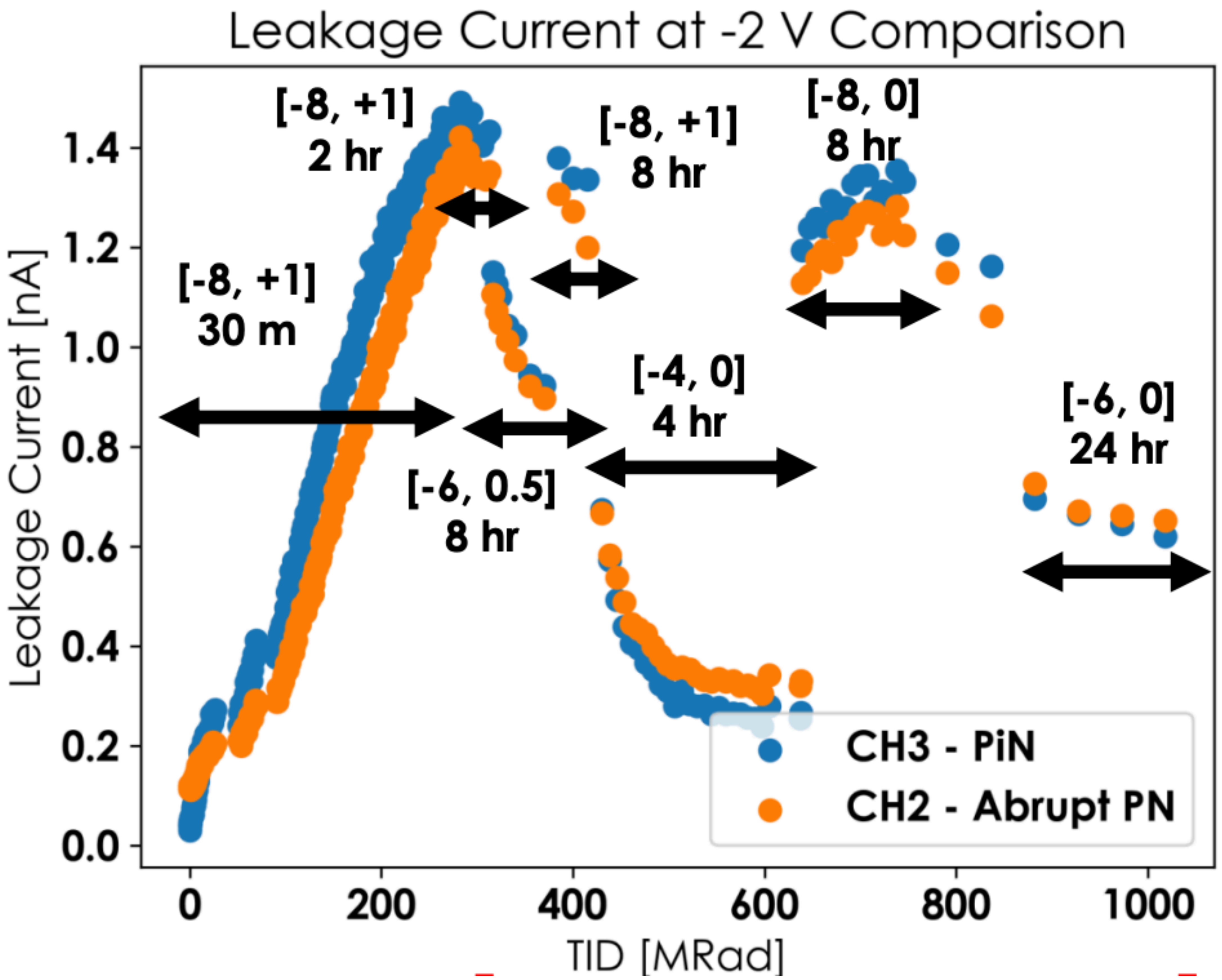
- No degradation observed to 100MRad
  - Modulation Efficiency Δλ/V
  - ER = P1/P0





Run 2

- No appreciable difference between design error / correct channels

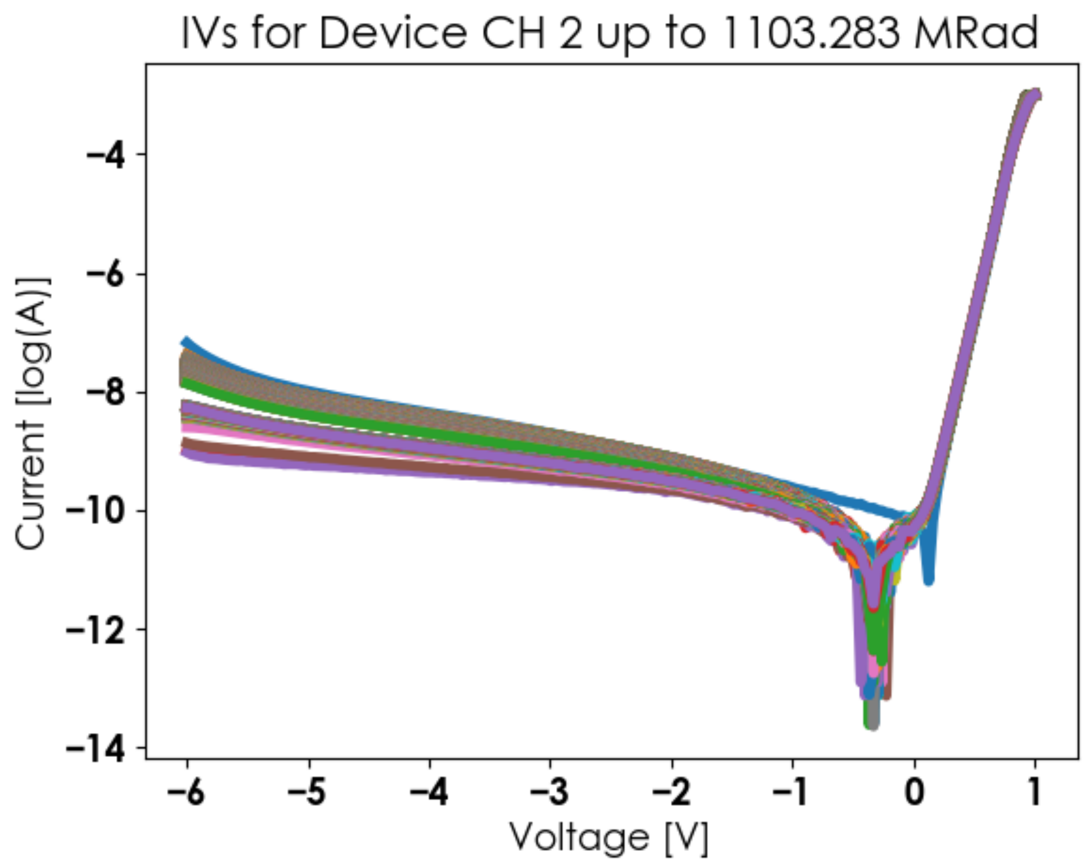


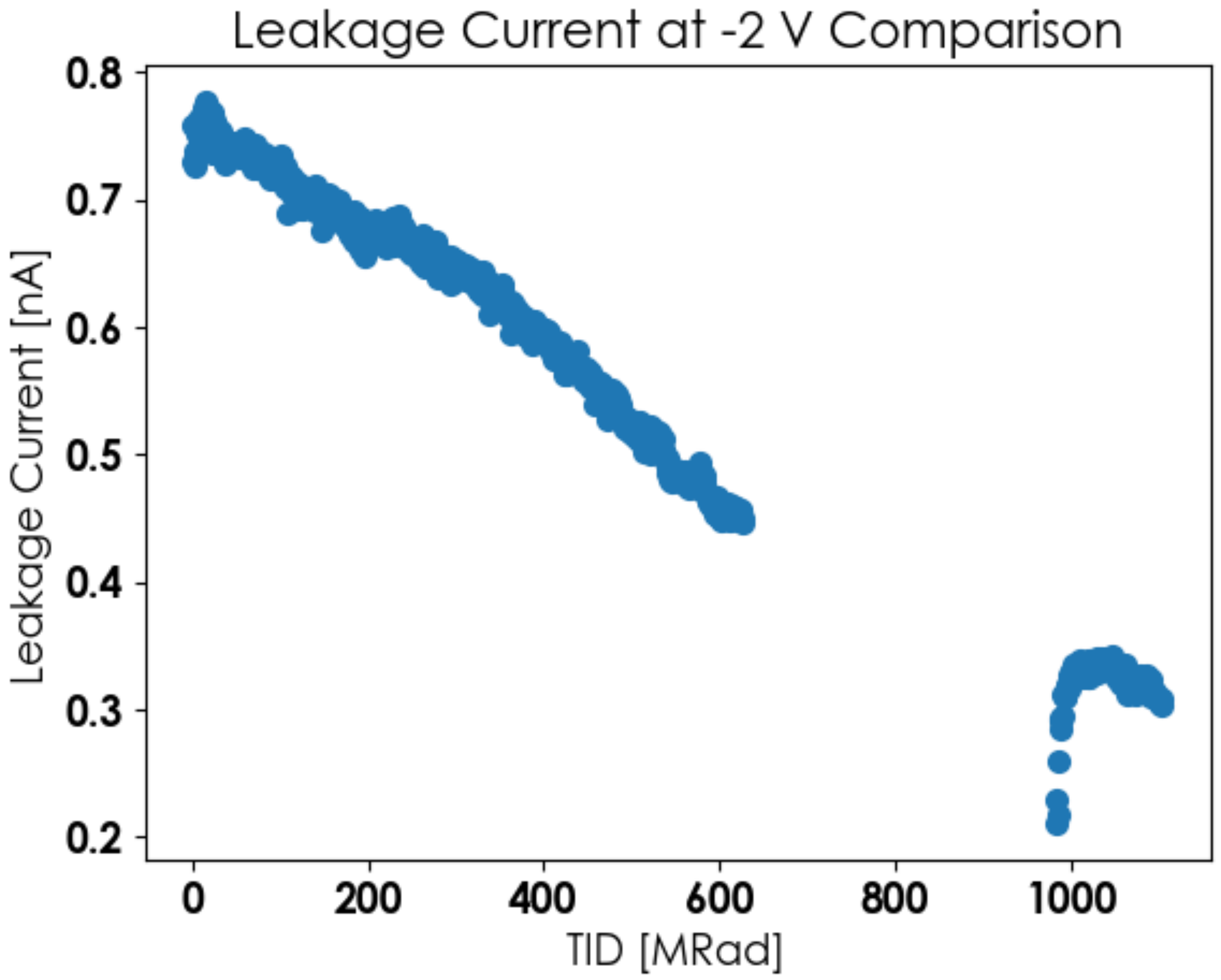
Irradiation Results: Ring Modulator (XRM)

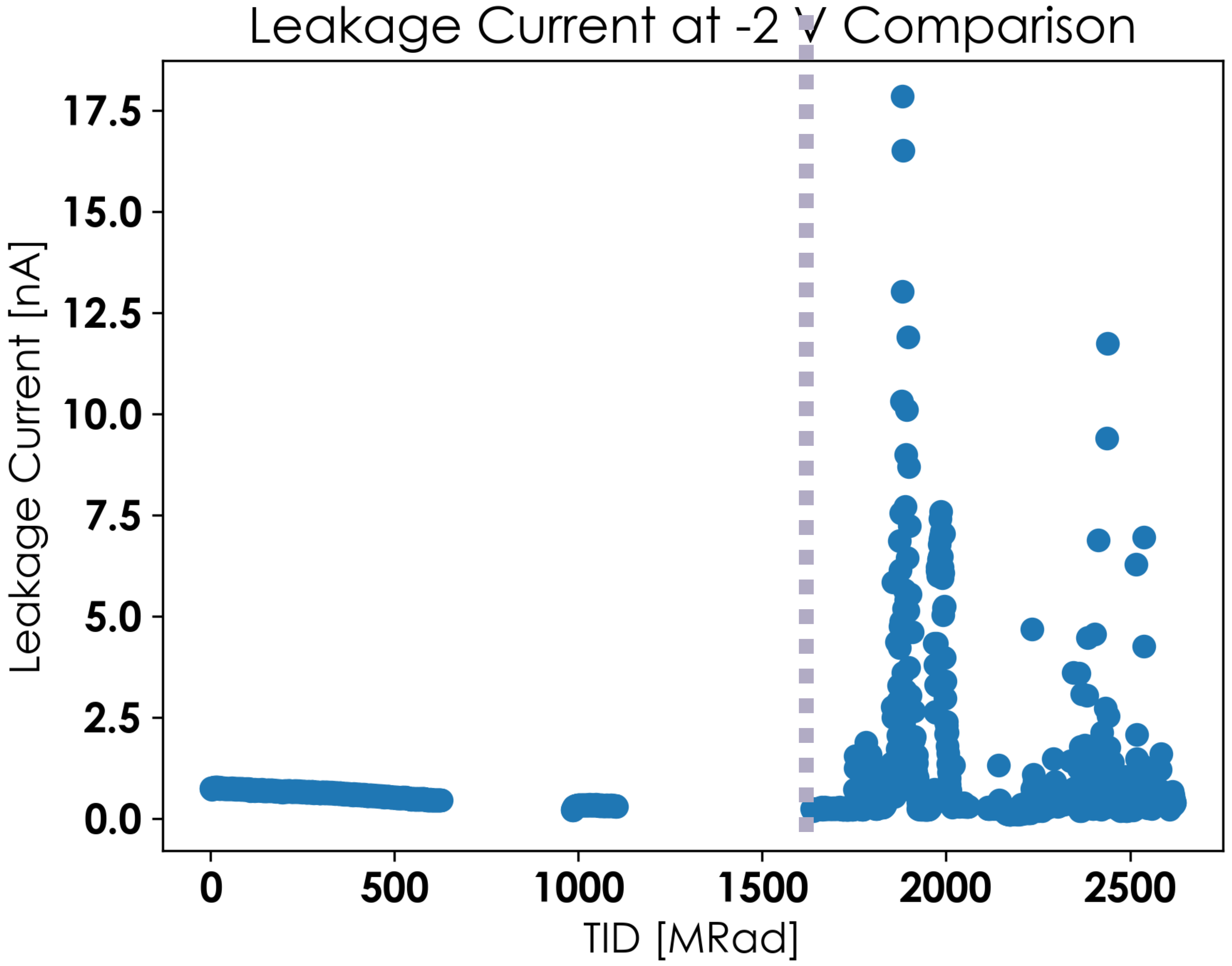
Run 3

- No degradation observed to 1 GRad
- Starts to break over **1.5 GRad**

- Combine 1+2+3 runs
  - Optical performance holds up to 100 MRad
  - Electrical to 1GRad





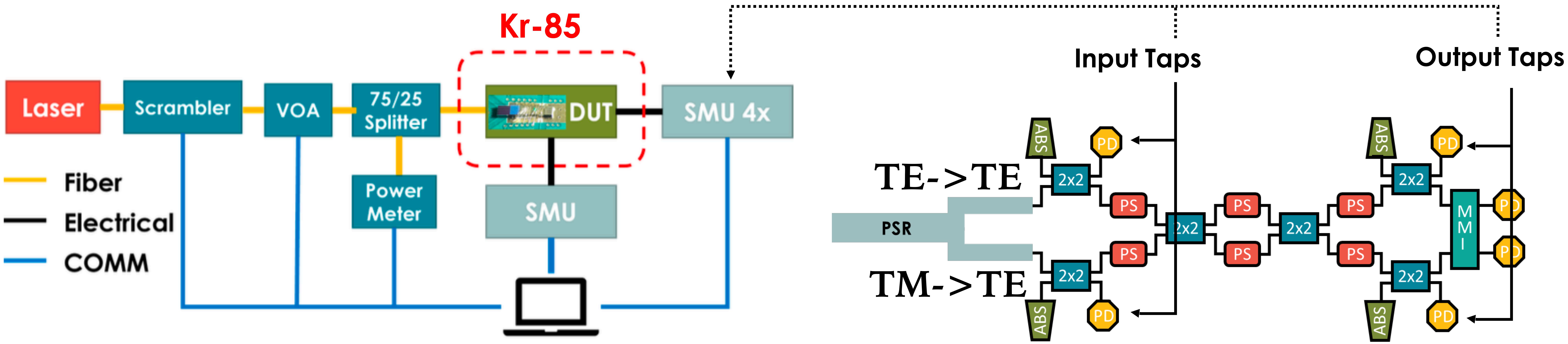


Irradiation Setups: Polarization Controller (Kr-85)

- Kr-85 Irradiation
  - Dose rate 7 rad/s
  - Polarization scrambler randomly rotates through all polarizations
  - Step VOA (variable optical attenuator) to adjust the input power
  - Optical powermeter to monitor the input power
  - IV sweep on thermal phase shifter

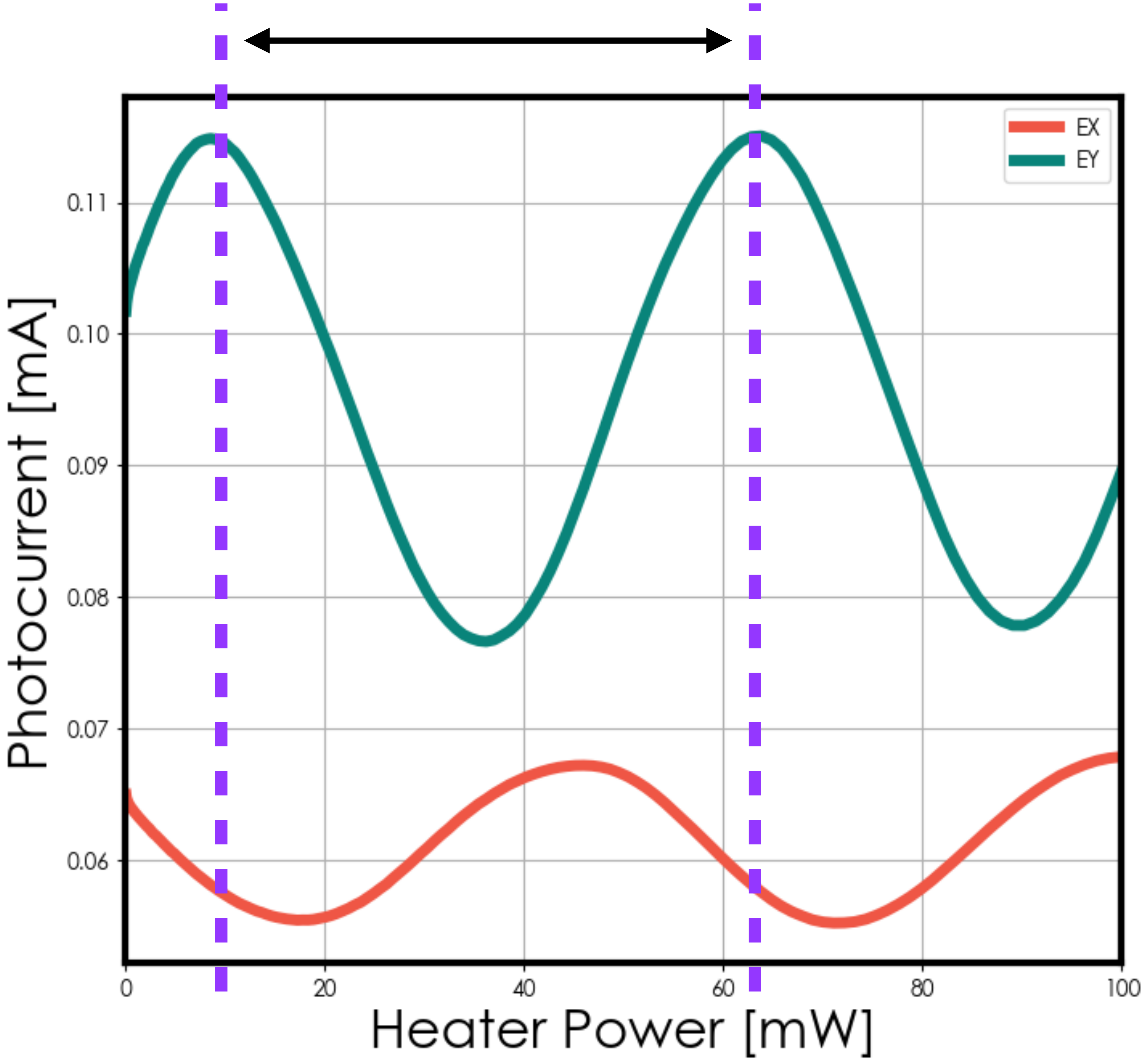
What we measure

- IV sweep on each PD (Photodiode)
  - Input taps to measure the PSR performance, output taps to measure PS performance
- Track the key metrics over TID

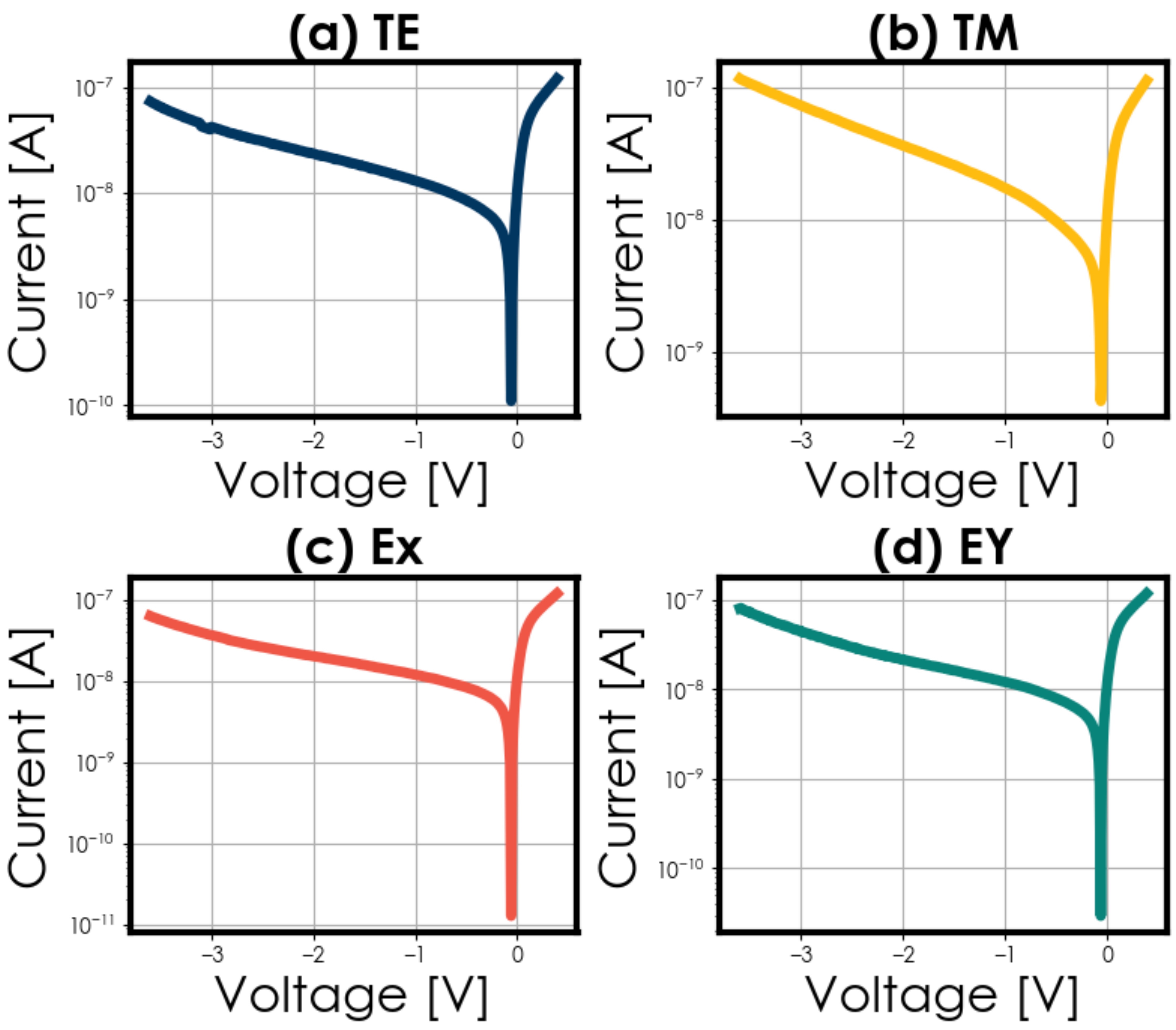


Irradiation Results: Polarization Controller (Kr-85)

Ppi = Power needs to shift the phase 180°



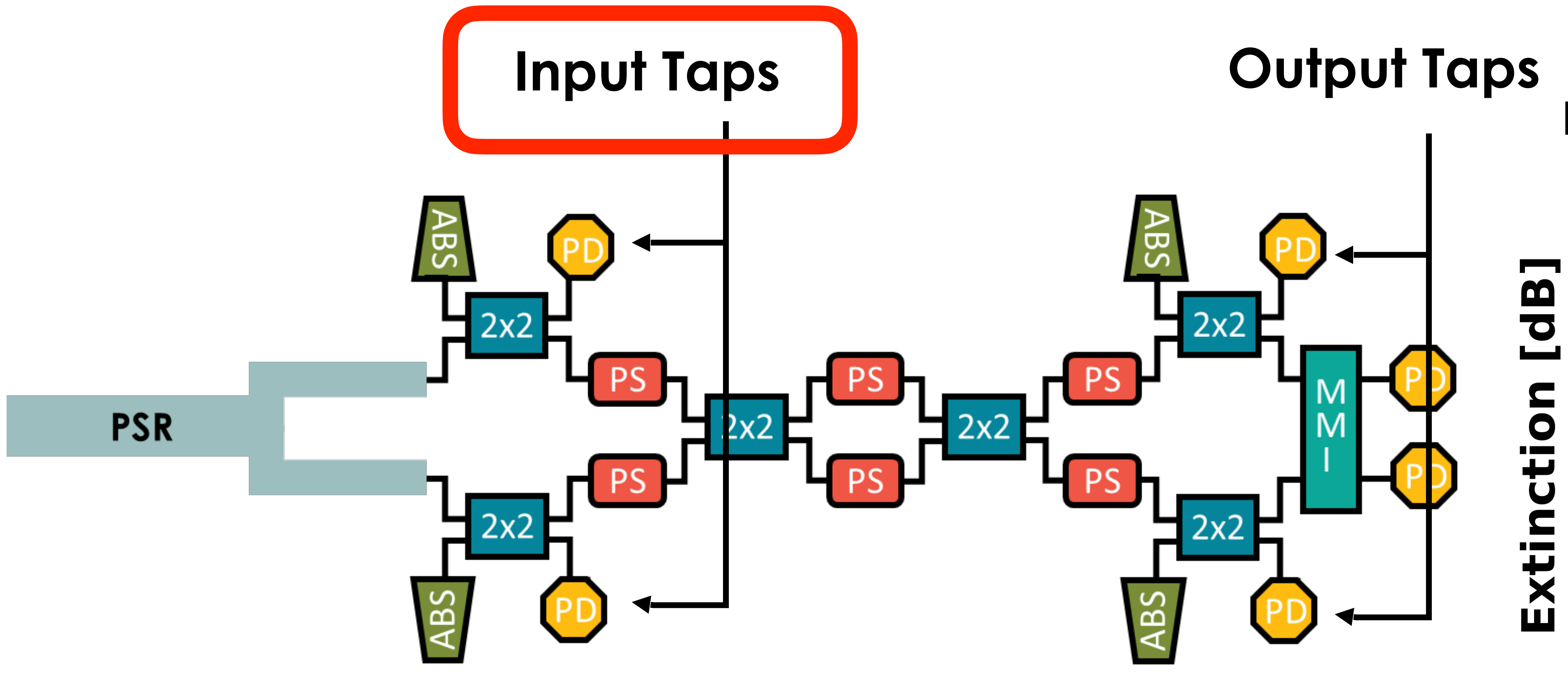
Dark Current

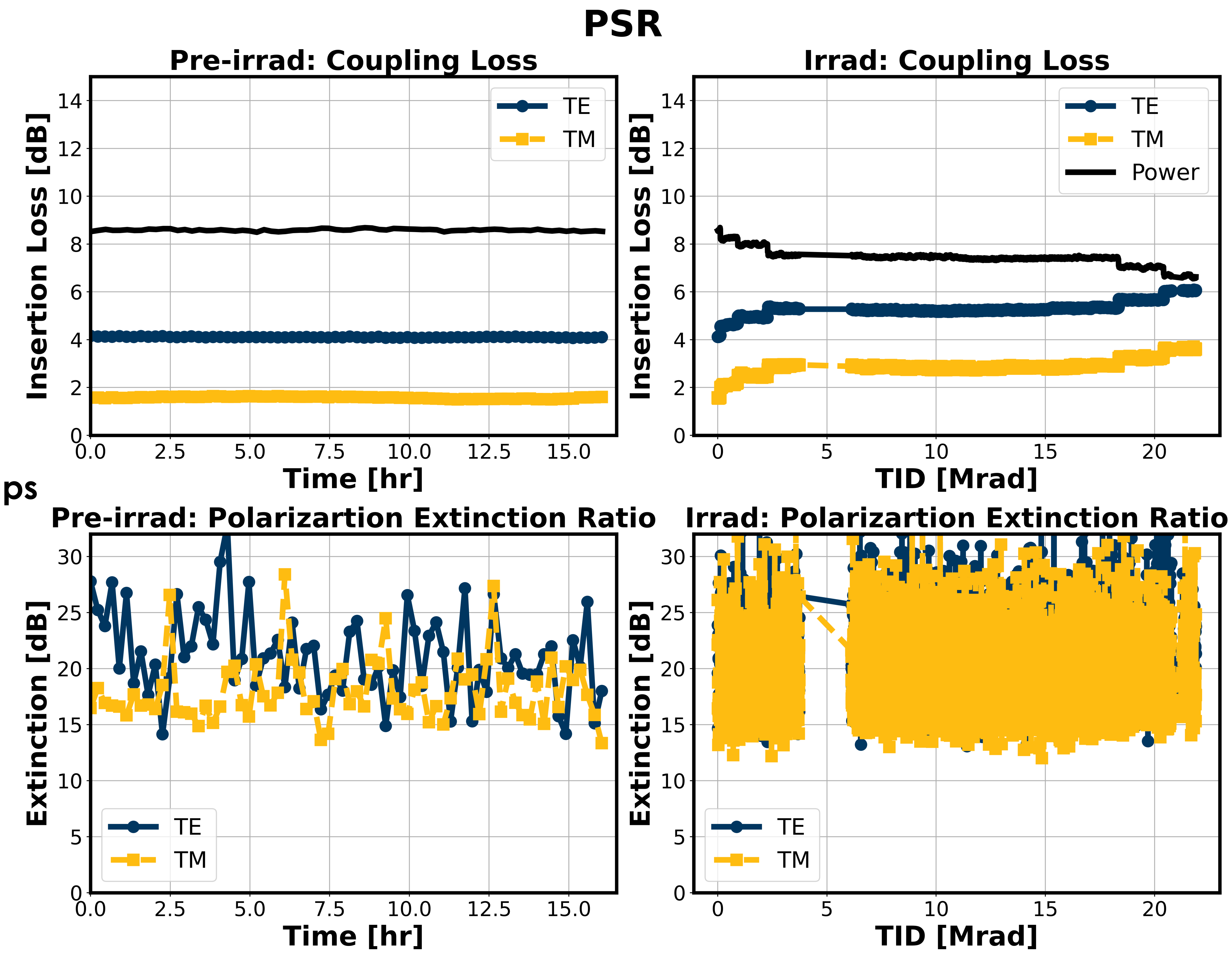


Irradiation Results: Polarization Controller (Kr-85)

PSR performance

- No degradation observed to 24 MRad

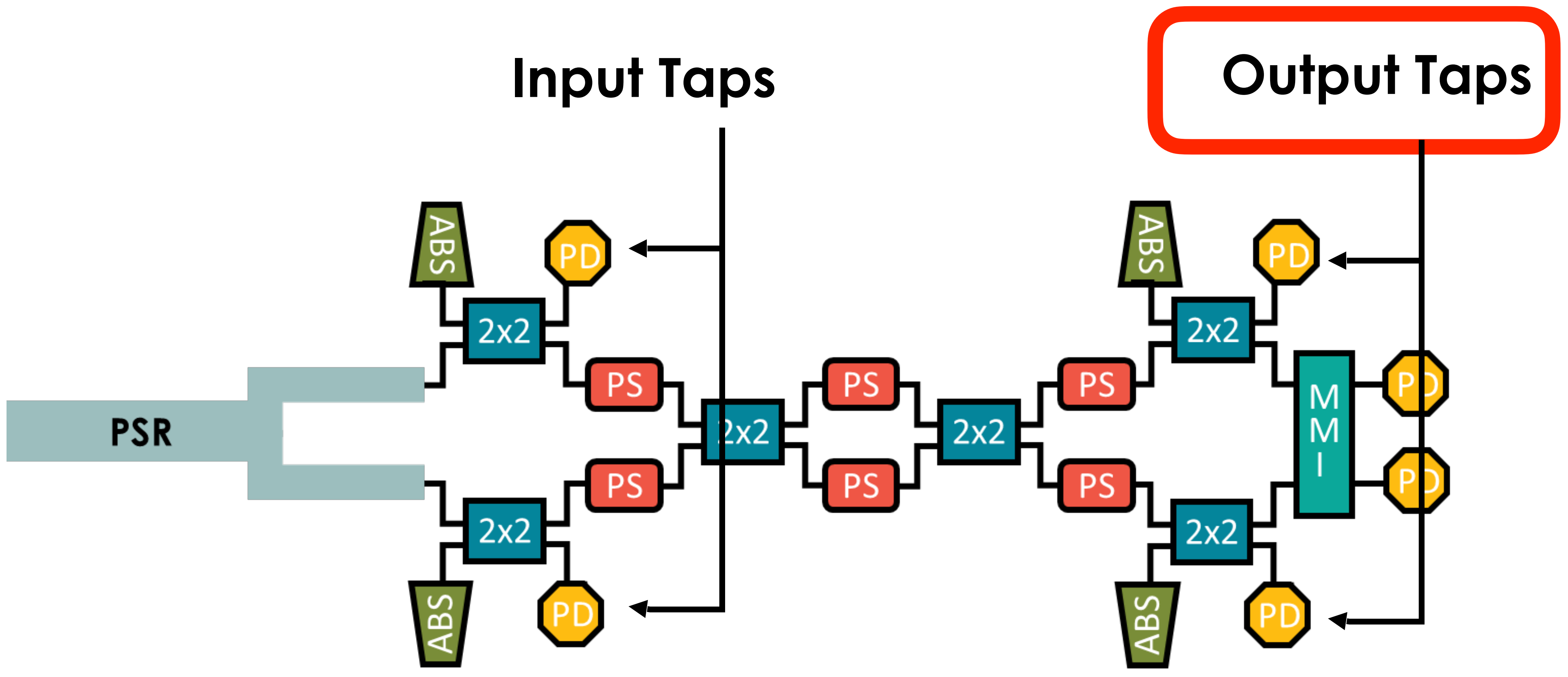


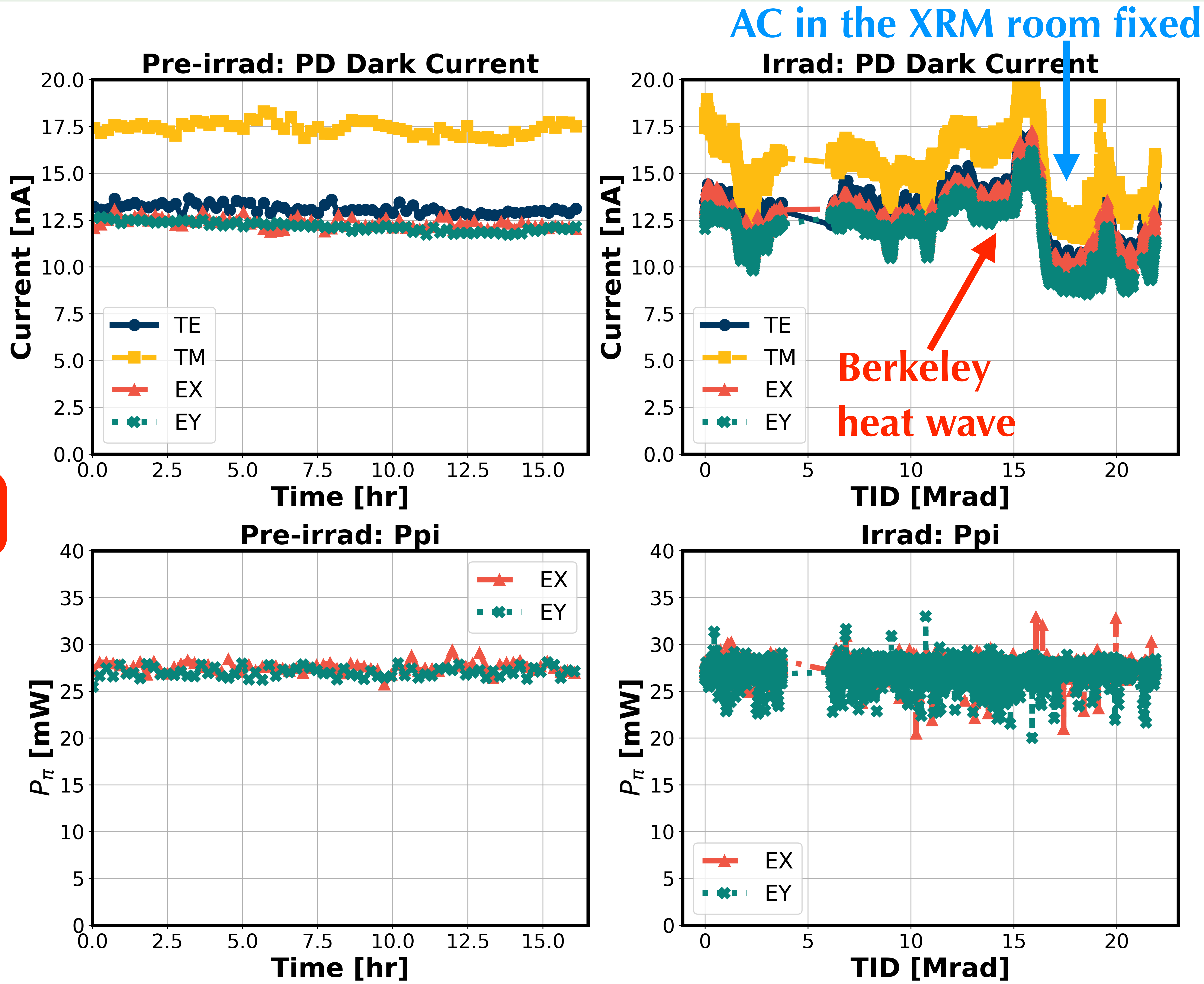


Irradiation Results: Polarization Controller (Kr-85)

PS performance

- No degradation observed to 24 MRad





Summary and Next Steps

- Silicon photonics is an excellent candidate for the development of the next generation optical links for HEP
  - High bandwidth (multiplexing)
  - Radiation hard
- Key components of SiPh devices have irradiated and the radiation-tolerance is excellent
  - Ring modulators
  - Polarization controller

- Next
  - Higher dose for polarization controller
  - Dose rate effects
  - Ring modulator and polarization controller integration
  - RD53/Quad integration