Comparison of the radiation hardness of silicon Mach-Zehnder modulators for different DC bias voltages

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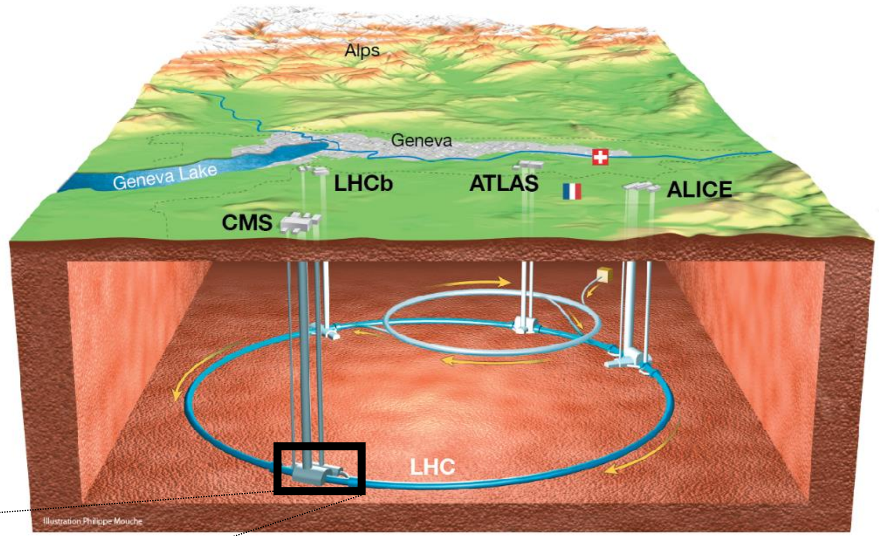
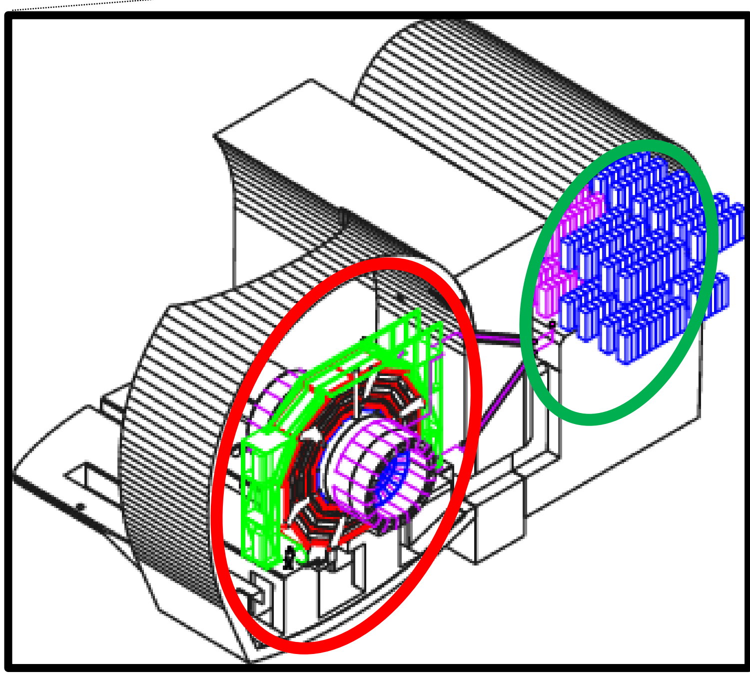
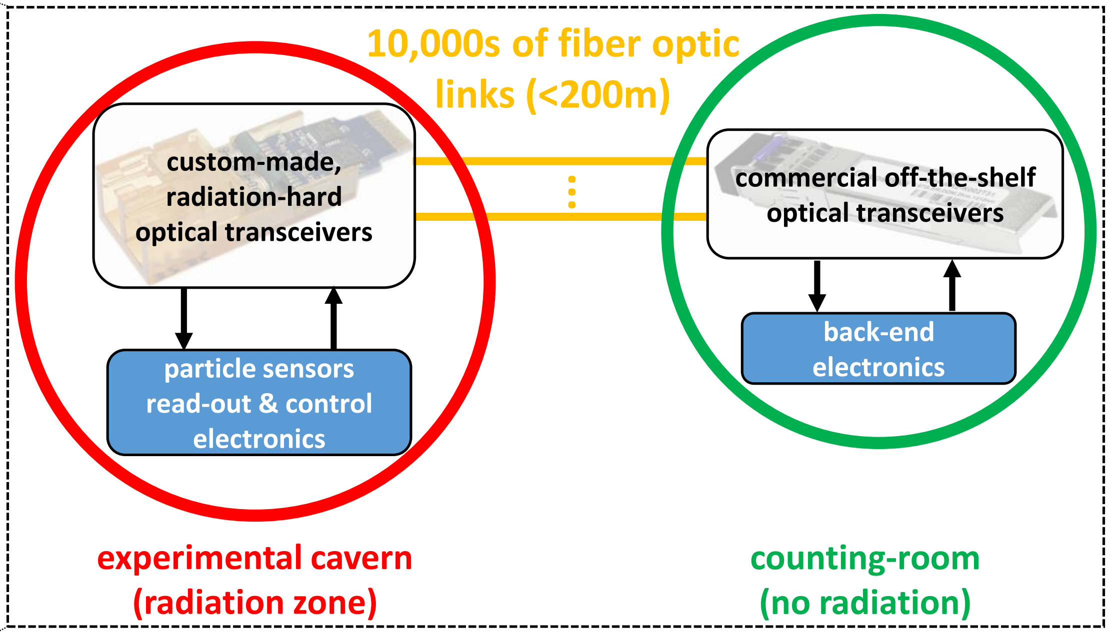
Radiation-hard fiber optic links are the backbone of the experiments' read-out systems







HL-LHC luminosity upgrades will entail more particle collisions

LHC has currently reached its nominal luminosity.

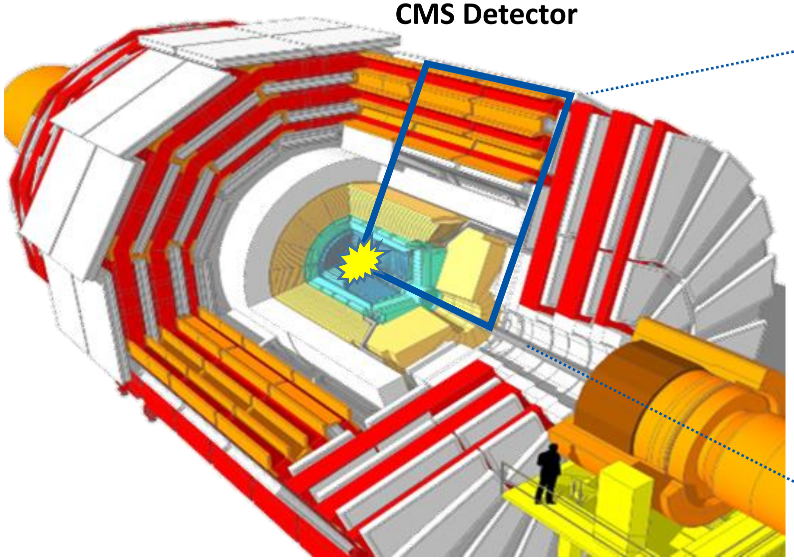
Upgrade to High-Luminosity (HL)-LHC around 2024 will increase luminosity by 5x.

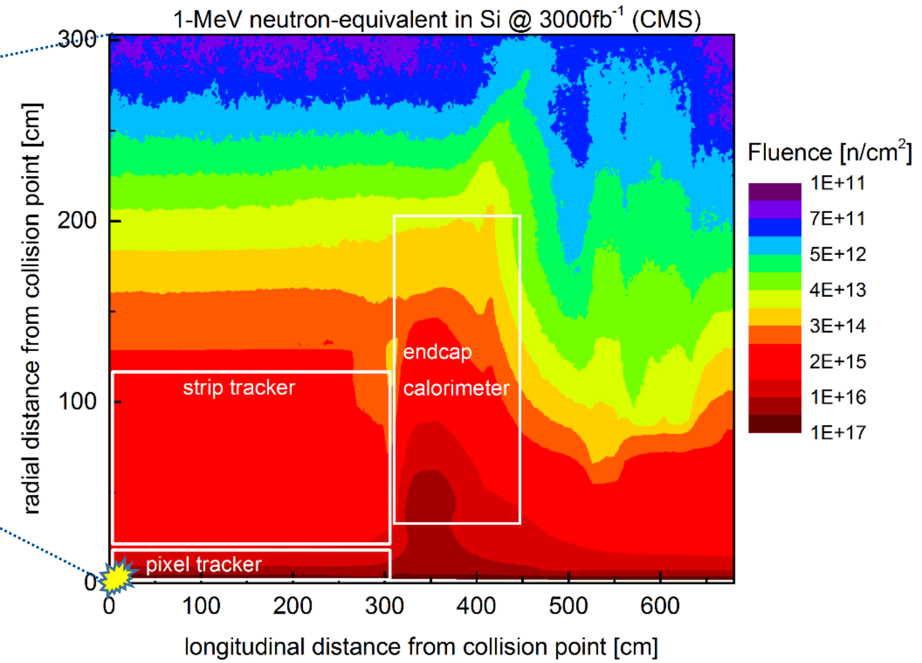
➔ **5x higher radiation levels** in innermost detector regions

- 1-MeV neutron fluence higher than $6 \times 10^{15} n/cm^2$
- Total Ionizing Dose (TID) of at least $1 MGy$

} during 10-year operational lifetime

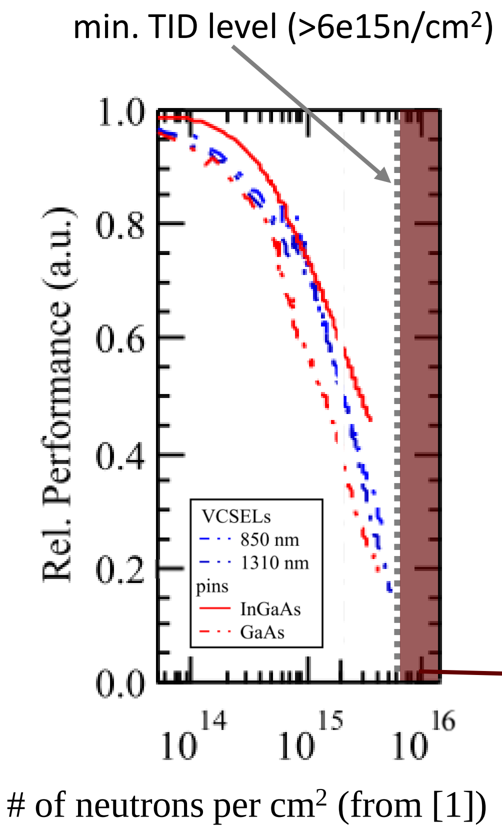
CMS Detector

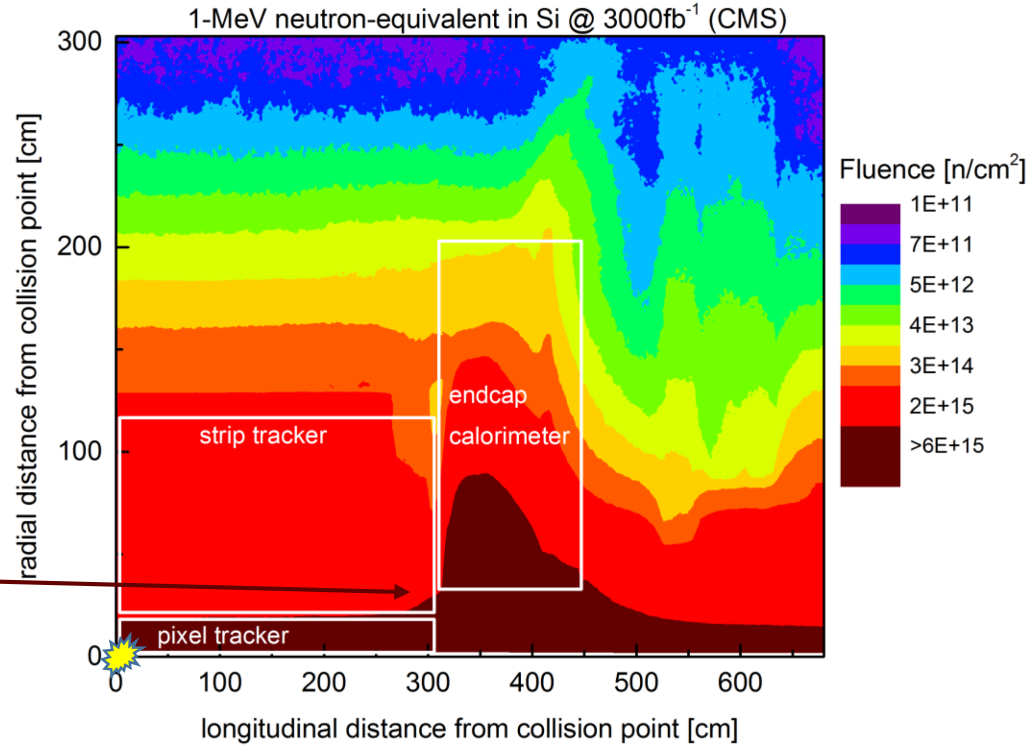




➔ **new optical transceivers that can withstand expected radiation levels in HL-LHC are required to read-out pixel tracker**

Lasers degrade too much to be considered for innermost detector regions

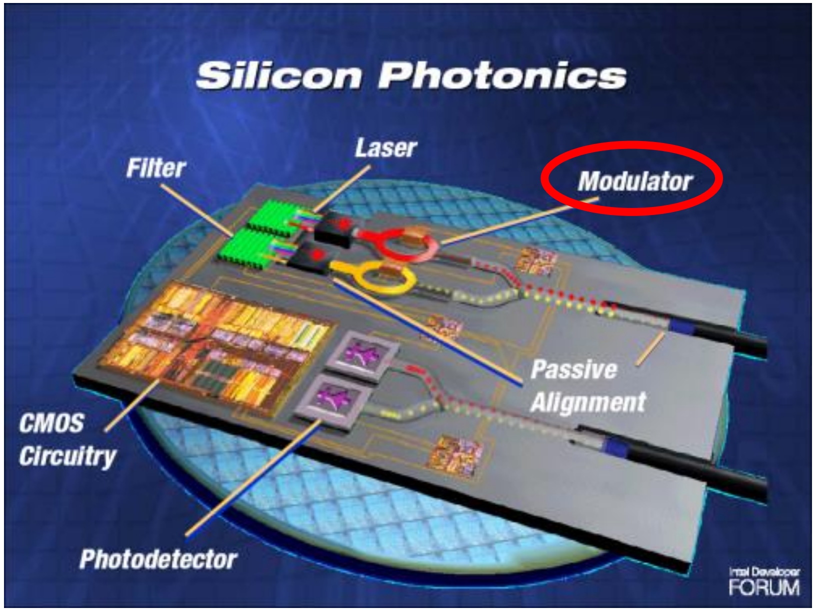




Neutron-induced **increase in threshold current and decrease in slope efficiency** for Vertical Cavity Surface Emitting Lasers (VCSELs) cannot be compensated for beyond the capabilities of the driving electronics.

➔ no tight integration with detector modules possible in harshest environments of HL-LHC

Silicon Photonics as alternative: CMOS-compatible electro-optic integrated circuits



from [2]

Technology promises:

CMOS-compatible → low cost devices

Integration with electronic circuits → chips with increased functionality & reduced power

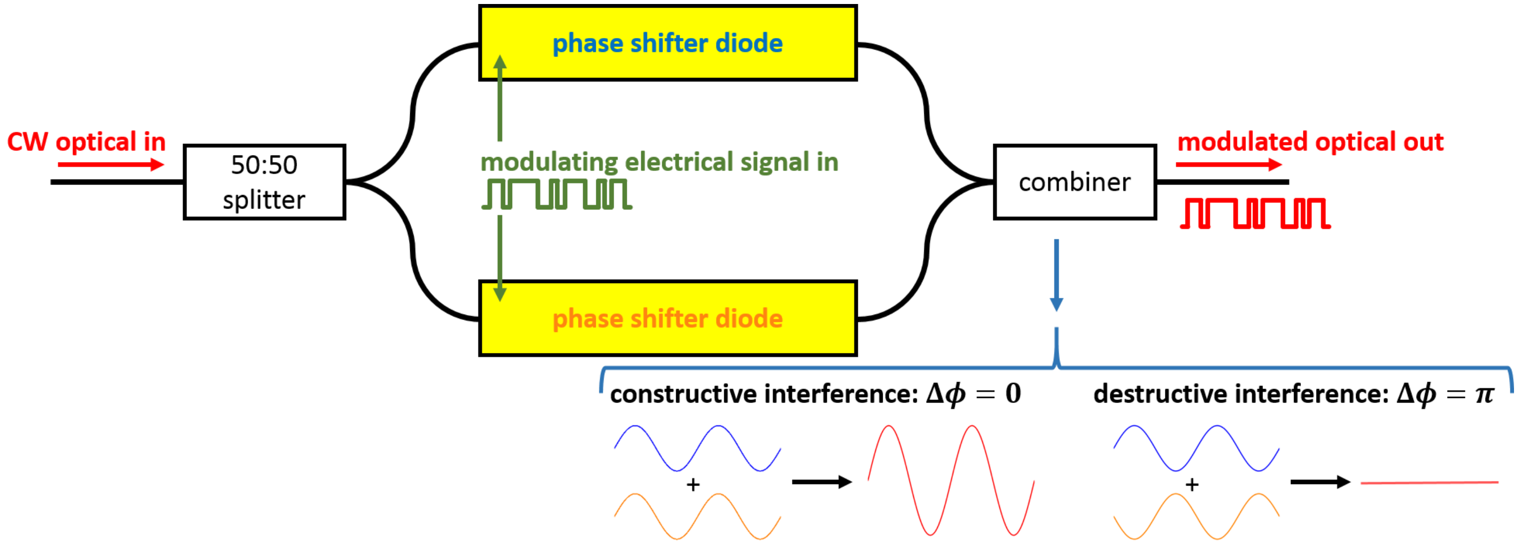
Our hope:

Design customized Silicon Photonics (SiPh) devices with a radiation-hardness similar to those of silicon pixel sensors currently used in HEP experiments

→ SiPh Mach-Zehnder modulator is being investigated for transmitting side

Mach-Zehnder modulator translates phase modulation to amplitude modulation

Schematic of an interferometric Mach-Zehnder Modulator (MZM)



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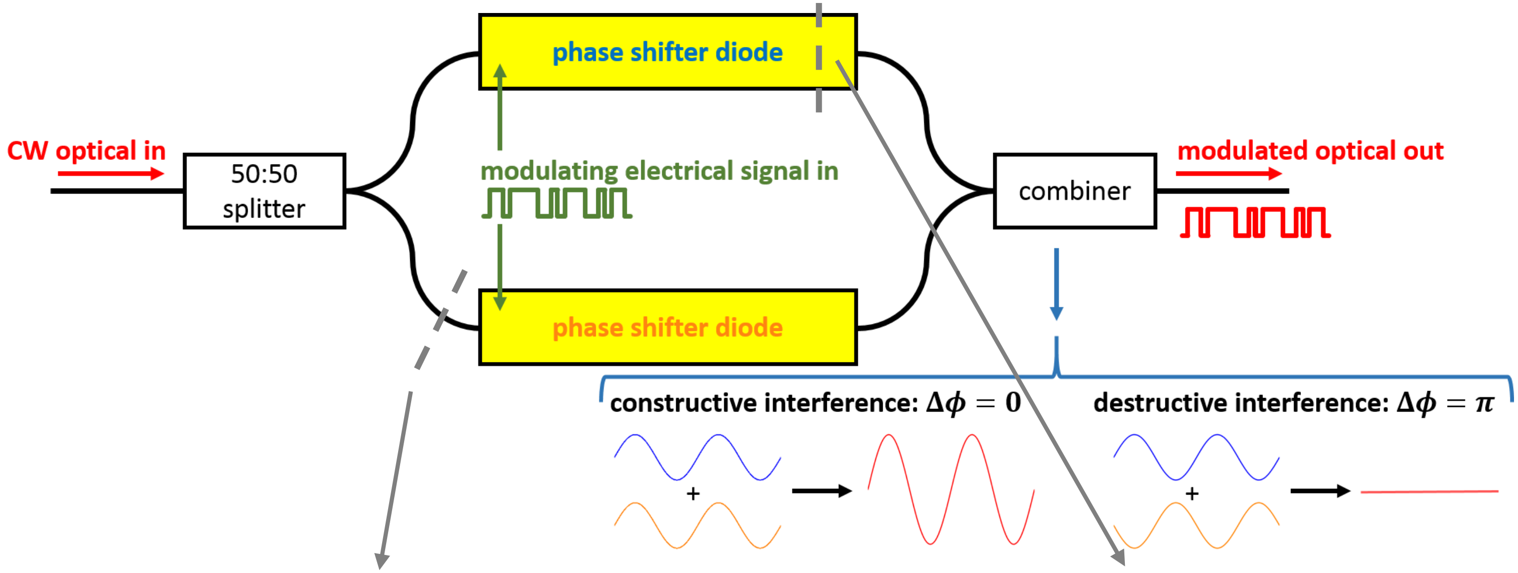
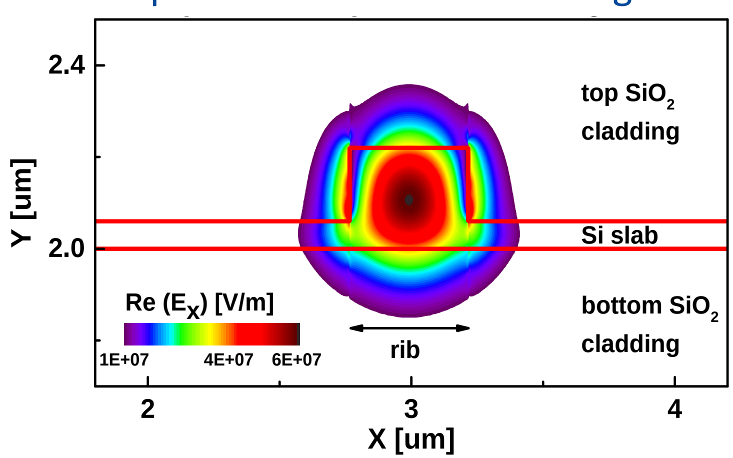
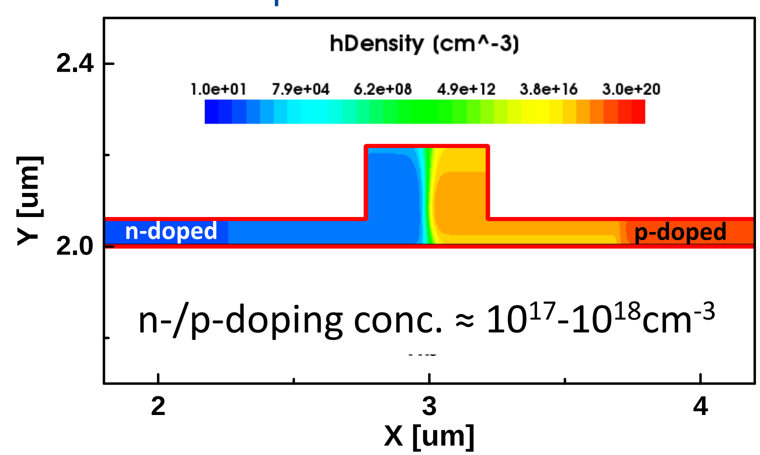


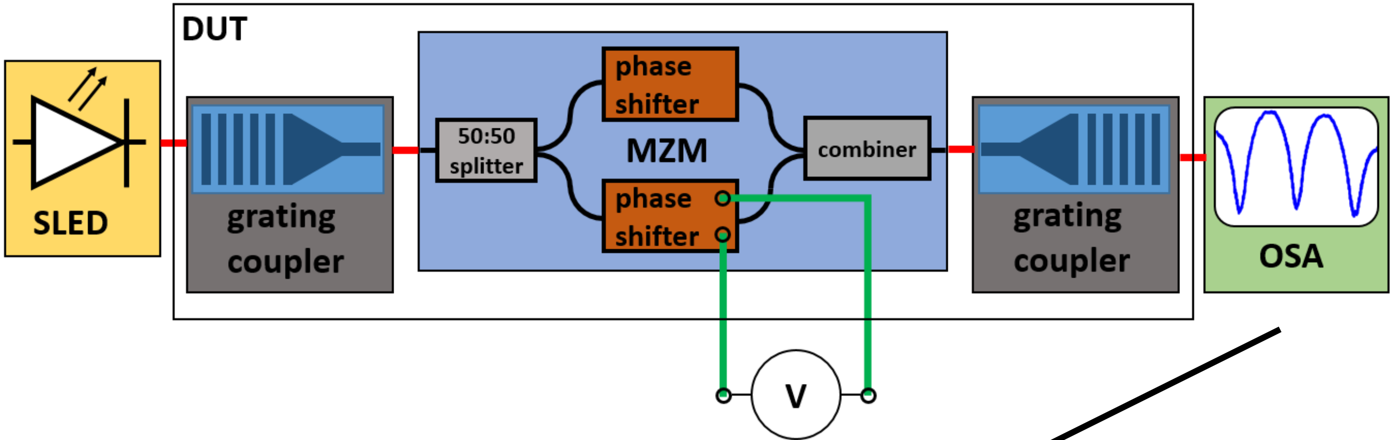
Optical mode in silicon waveguide

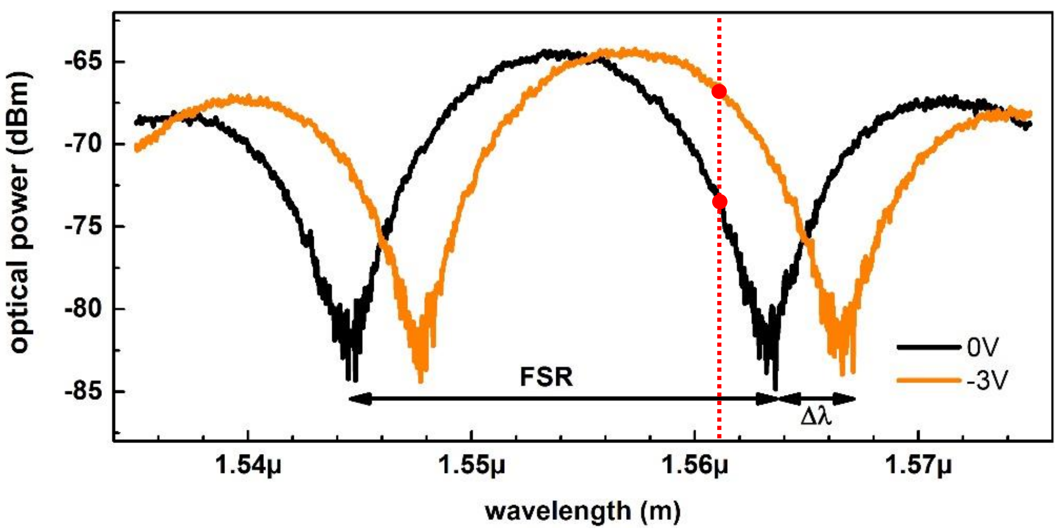


pn-diode in silicon



Phase shift can be determined by measuring MZM's transmission spectra





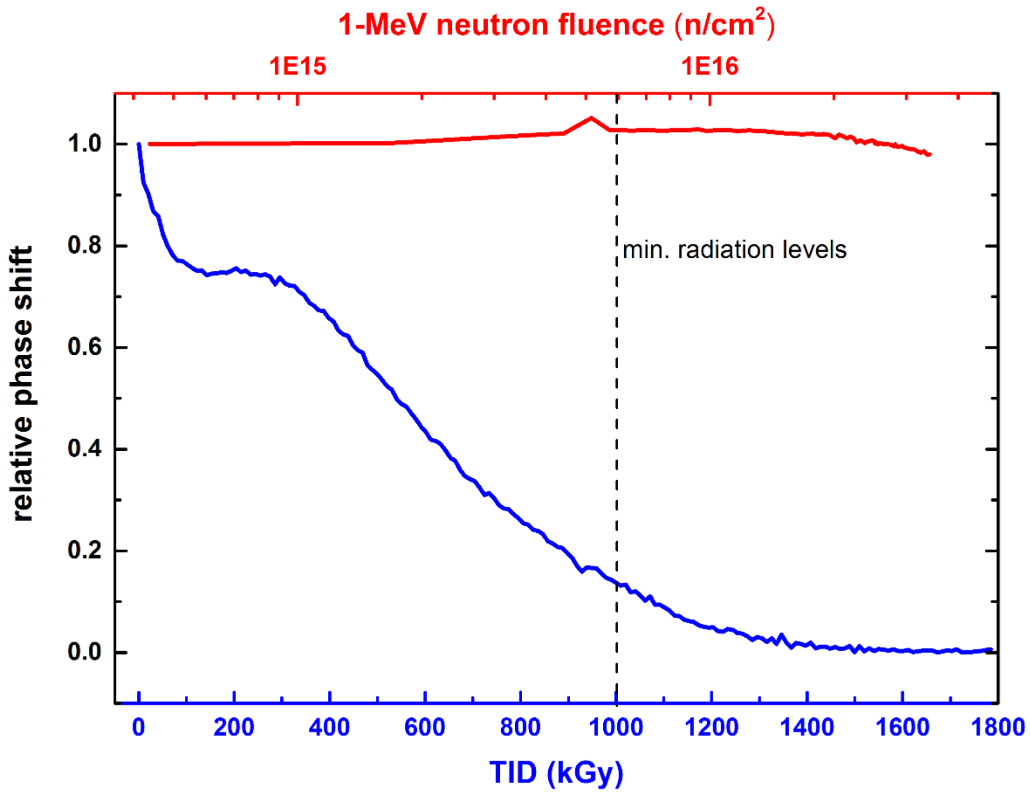
wavelength shift $\boldsymbol{\Delta\lambda}$ is measured

➔ phase shift can be calculated

$$\Delta\phi(V) = \frac{2\pi\Delta\lambda(V)}{FSR}$$

the larger the phase shifter the more efficient the device

Standard SiPh MZMs are insensitive to high neutron fluence but not to TID



Silicon Photonic (SiPh) Mach-Zehnder Modulators (MZMs) show no significant performance degradation due to displacement damage.

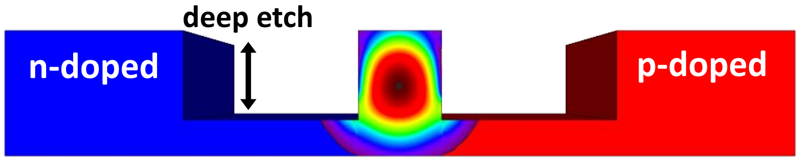
But: devices are very sensitive to ionizing radiation [3].

➔ **Can MZM design be customized to increase resistance to ionizing radiation?**

Custom-designed SiPh test chip was fabricated in Multi-Project Wafer run

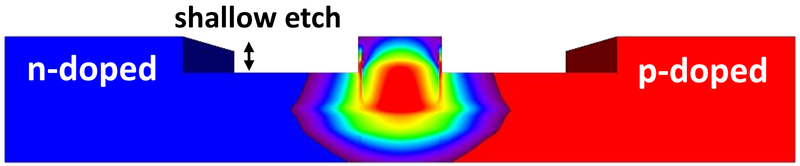
4 different types of phase shifter diodes were fabricated by imec in 2015 [4] and evaluated for their radiation hardness:

lateral pn-junctions, **deep etch depth**



+ high modulation efficiency
• medium modulation bandwidth
• medium radiation-hardness expected

lateral pn-junctions, **shallow etch depth**

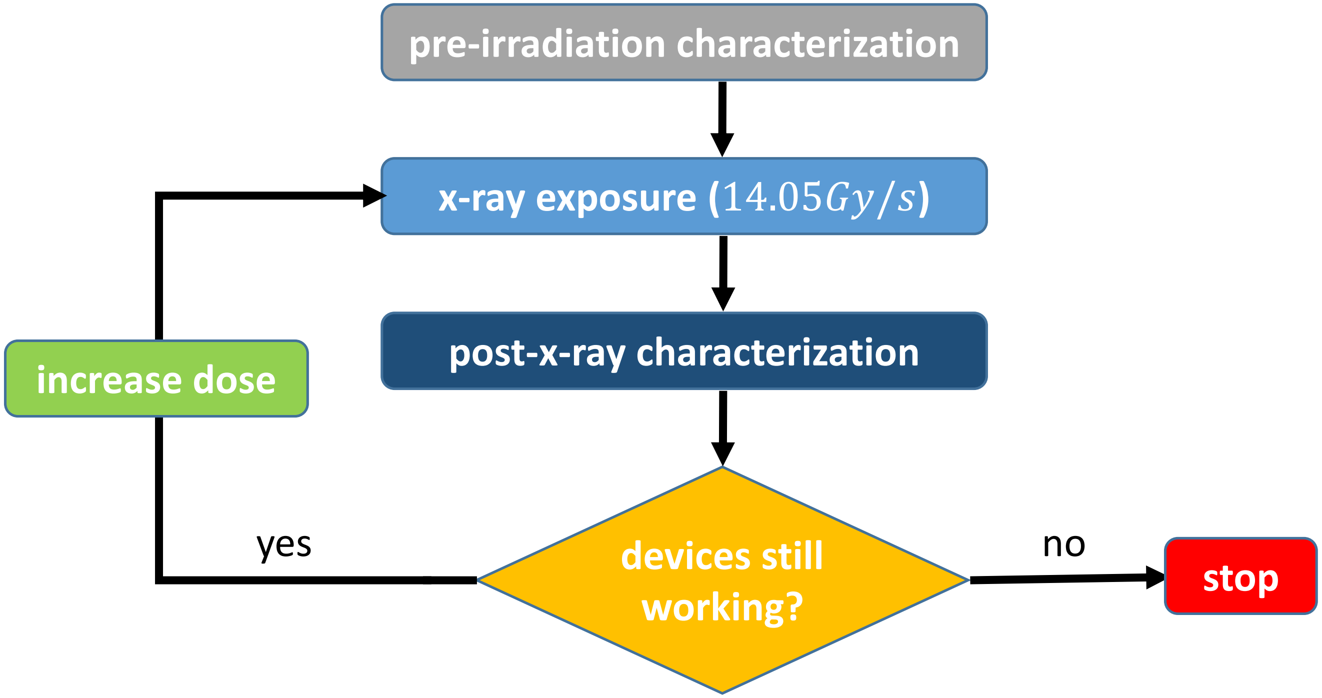


- low modulation efficiency
+ high modulation bandwidth
+ high radiation-hardness expected

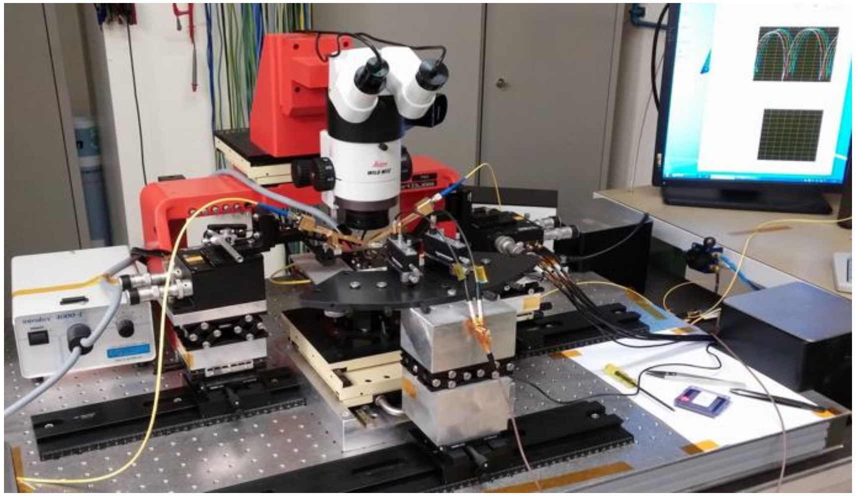
In addition: Samples have two different p- and n-doping concentrations in the waveguide

- **nominal doping**
- **2x nominal doping**

First, MZM samples were stepwise exposed to x-rays and manually tested



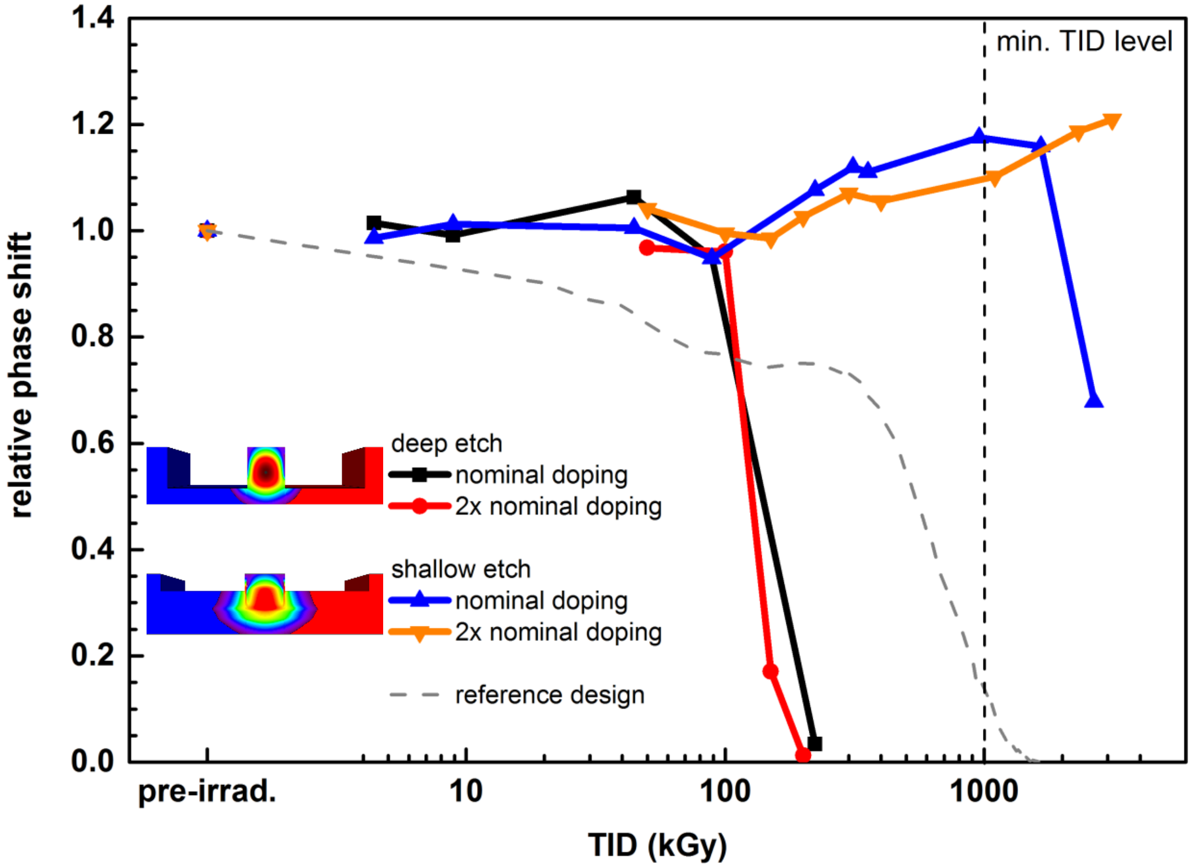
Due to lack of time, dice could not be pigtailed and bonded to PCB
➔ not biased during irradiation
➔ measured manually on probe station



No annealing between irradiation steps

Irradiation and measurements at room temperature

Shallow etch MZMs withstand longer than deep etch MZMs during un-biased irradiation

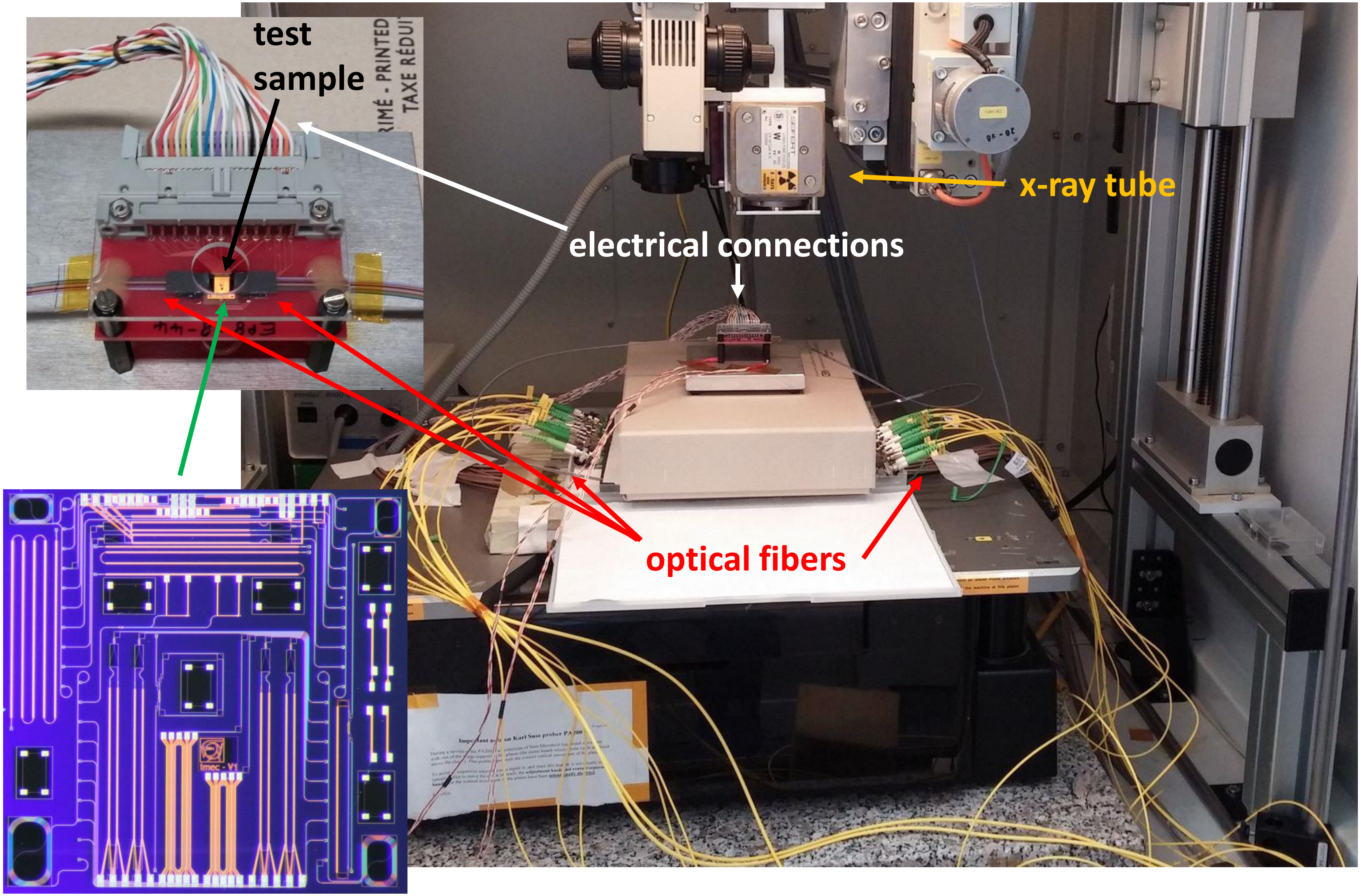


Independent of doping levels used,

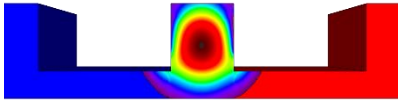
- phase shift of deep etch MZMs degrades at TID levels far below minimum requirement
- shallow etch MZMs do not degrade up to a TID of more than 2MGy [5]

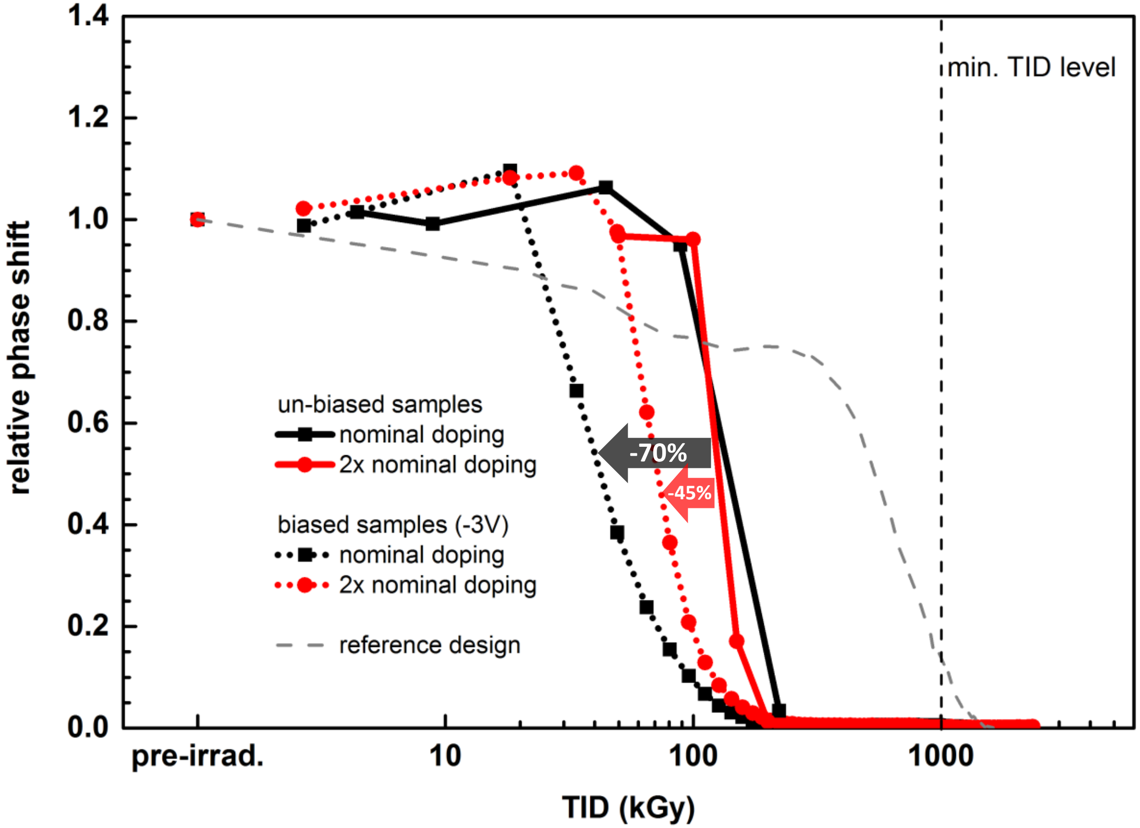
➔ **What changes when MZMs are biased and measured online during irradiation?**

Second, MZMs were pigtailed and bonded to measure the phase shifts during irradiation



Bias during irradiation accelerates phase shift degradation in deep etch MZMs



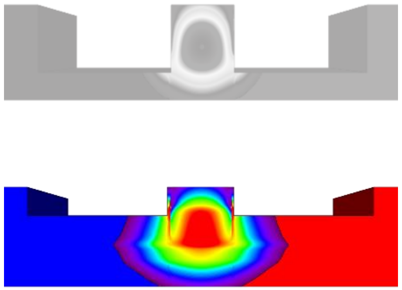


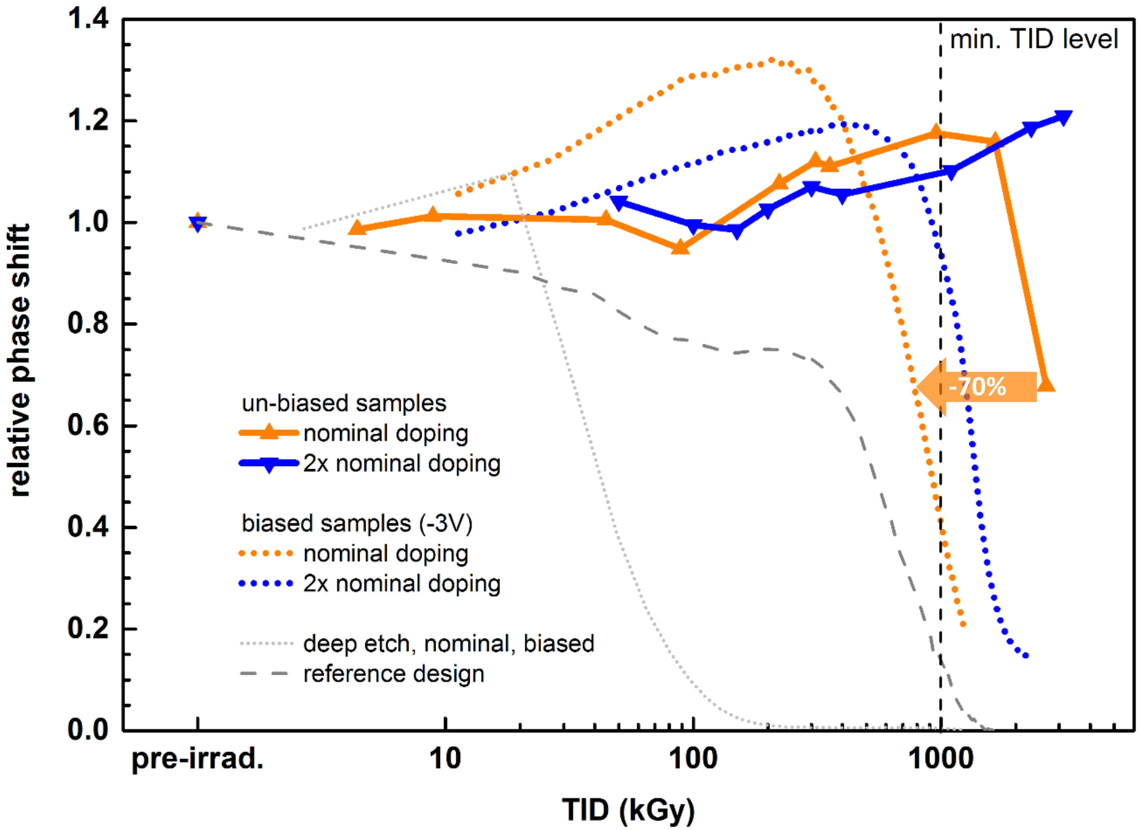
Phase shift reduction of biased MZMs to 50% occurs at

- 30% (nominal) -70%
- 55% (2x nominal) -45%

of TID (130kGy) at which un-biased MZMs degraded to 50%.

Shallow etch MZMs also degrade faster but still meet requirements





Like deep etch MZM, radiation hardness of shallow etch sample is also reduced to 30% when biased.

Phase shift of shallow etch MZM with 2x nominal doping degrades to 50% only at 1380kGy.

➔ **Highly doping shallow etch MZMs could be deployed in future HEP experiment**

Conclusion & Outlook

- LHC luminosity upgrades will require new optical transceivers with improved radiation hardness
  - $> 1MGy$ & $6 \times 10^{15} n/cm^2$
- Customized SiPh MZMs were irradiated with x-rays to asses their resistance against ionizing radiation
- Irradiation tests showed that MZMs degrade faster when reversed biased during irradiation
  - similar behavior to CMOS transistors

➔ **MZMs with a shallow etch waveguide and high doping concentrations show no significant degradation up to 1.4MGy**

  - could be installed in detector regions of HL-LHC where VCSELs would degrade too quickly

What's next:

- Irradiate biased MZMs at low temperature
- Assess radiation hardness of Ge/Si-photodiodes
- Design and test radiation-hard MZM voltage driver

References

[1] S. Seif El Nasr-Storey, S. Detraz, L. Olantera, G. Pezzullo, C. Sigaud, C. Soos, J. Troska, F. Vasey, and M. Zeiler, "Neutron and X-ray Irradiation of Silicon Based Mach-Zehnder Modulators," Journal of Instrumentation, vol. 10, 2015.

[2] https://ic.tweakimg.net/ext/i.dsp/1109883395.png

[3] S. Seif El Nasr-Storey, F. Boeuf, C. Baudot, S. Detraz, J. M. Fedeli, D. Marris-Morini, L. Olantera, G. Pezzullo, C. Sigaud, C. Soos, J. Troska, F. Vasey, L. Vivien, M. Zeiler, and M. Ziebell, "Effect of radiation on a Mach-Zehnder interferometer silicon modulator for HL-LHC data transmission applications," IEEE Transactions on Nuclear Science, vol. 62, no. 1, pp. 329–335, 2015.

[4] M. Zeiler, S. Detraz, L. Olantera, G. Pezzullo, S. Seif El Nasr-Storey, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "Design of Si-Photonic structures to evaluate their radiation hardness dependence on design parameters," Journal of Instrumentation, vol. 11, 2016.

[5] M. Zeiler, S. Detraz, L. Olantera, S. Seif El Nasr-Storey, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "Radiation hardness evaluation and phase shift enhancement through ionizing radiation in silicon Mach-Zehnder modulators," in *Radiation Effects on Components and Systems (RADECS)*, 2016.

[6] S. Seif El Nasr-Storey, F. Boeuf, C. Baudot, S. Detraz, J. M. Fedeli, D. Marris-Morini, L. Olantera, G. Pezzullo, C. Sigaud, C. Soos, J. Troska, F. Vasey, L. Vivien, M. Zeiler, and M. Ziebell, "Modeling TID Effects in Mach-Zehnder Interferometer Silicon Modulator for HL-LHC data Transmission Applications," IEEE Transactions on Nuclear Science, vol. 62, no. 6, pp. 2971–2978, 2015.

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