Radiation hardness evaluation and phase shift enhancement through ionizing radiation in silicon Mach-Zehnder modulators

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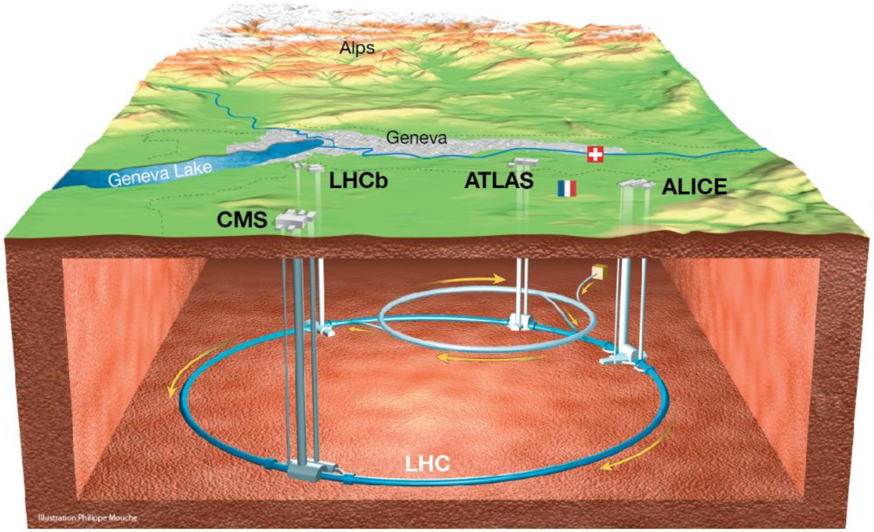
Experimental Results

Summary

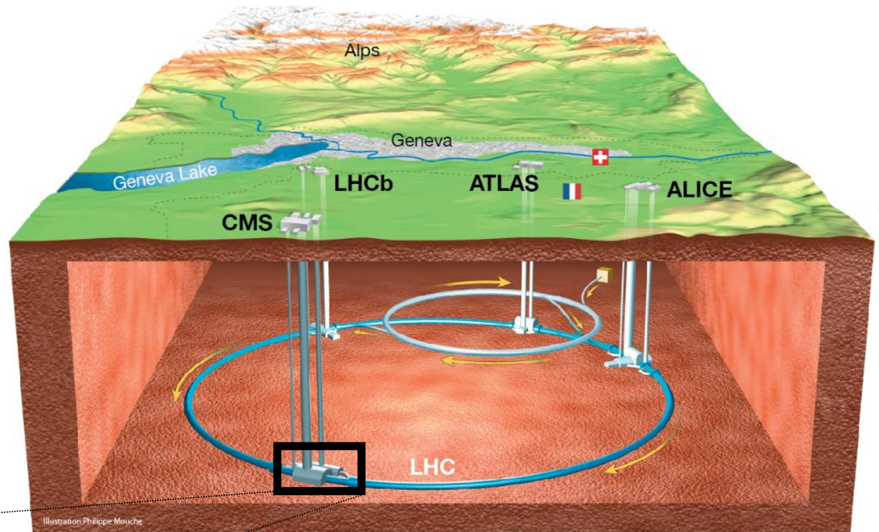
CERN conducts research to find answers to fundamental questions about our universe

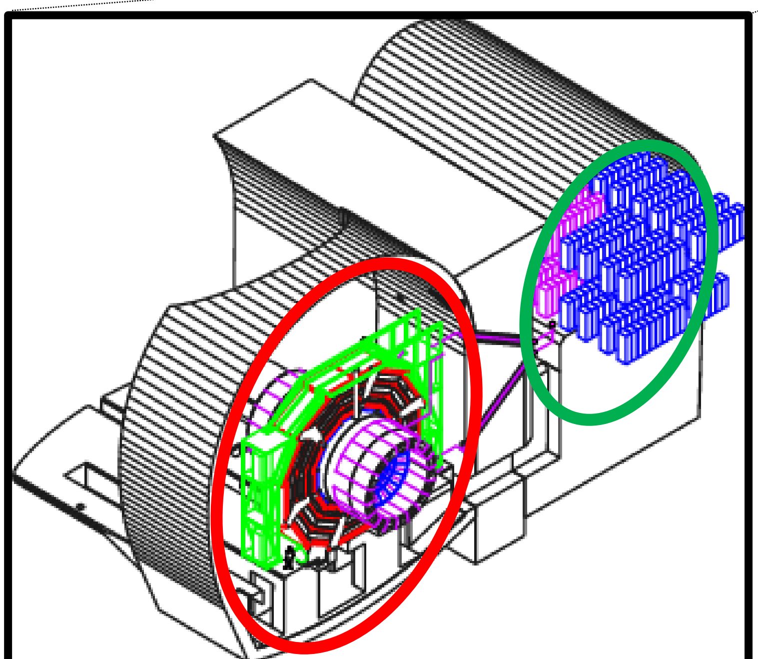


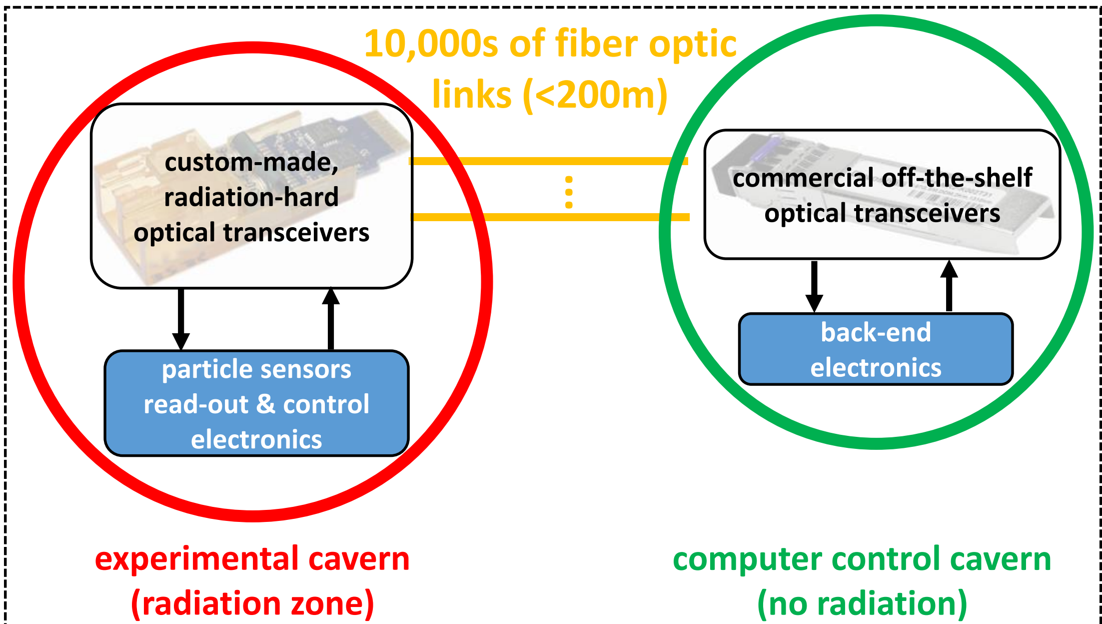
For that purpose, CERN

- operates the Large Hadron Collider (LHC).
  - proton-proton collision at 14TeV, 40MHz
- hosts High Energy Physics (HEP) experiments.
  - ALICE, ATLAS, CMS, LHCb, etc.
- develops required technologies.
  - (opto)-electronic data links, sensors, vacuum, cooling, etc.

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







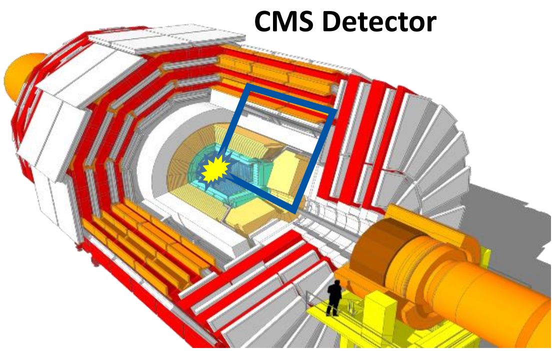
HL-LHC luminosity upgrades will entail more particle collisions

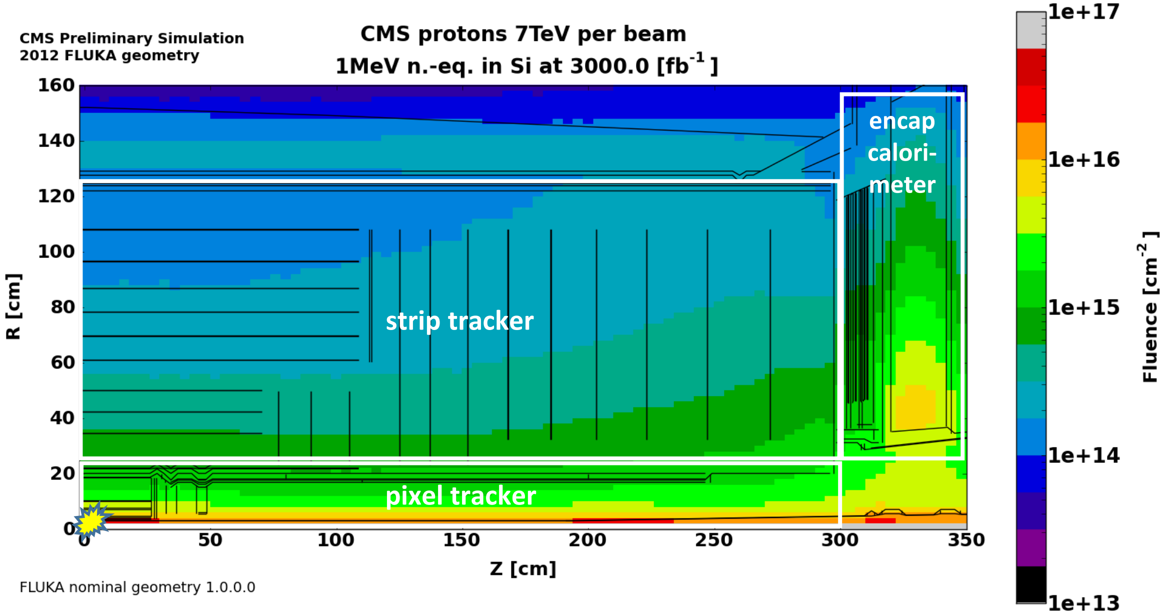
LHC currently runs at nominal luminosity.

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

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

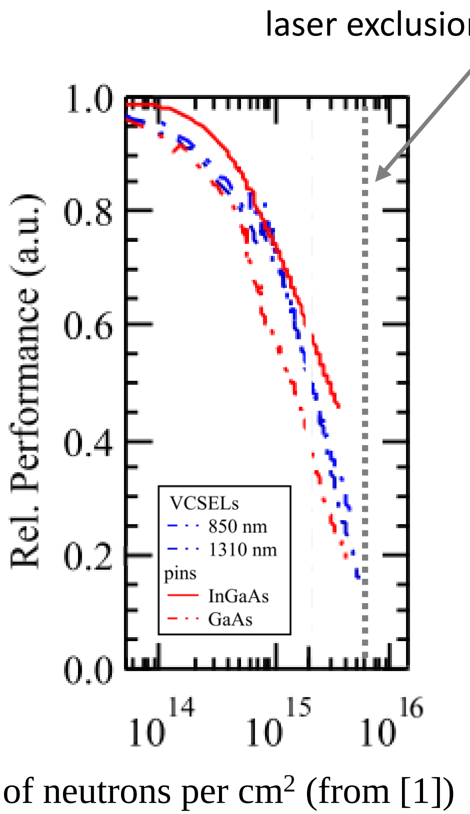
1-MeV neutron fluence up to $3 \times 10^{16} n/cm^2$ ⎫
Total Ionizing Dose (TID) of at least $1 MGy$ ⎭ during 10-year operational lifetime

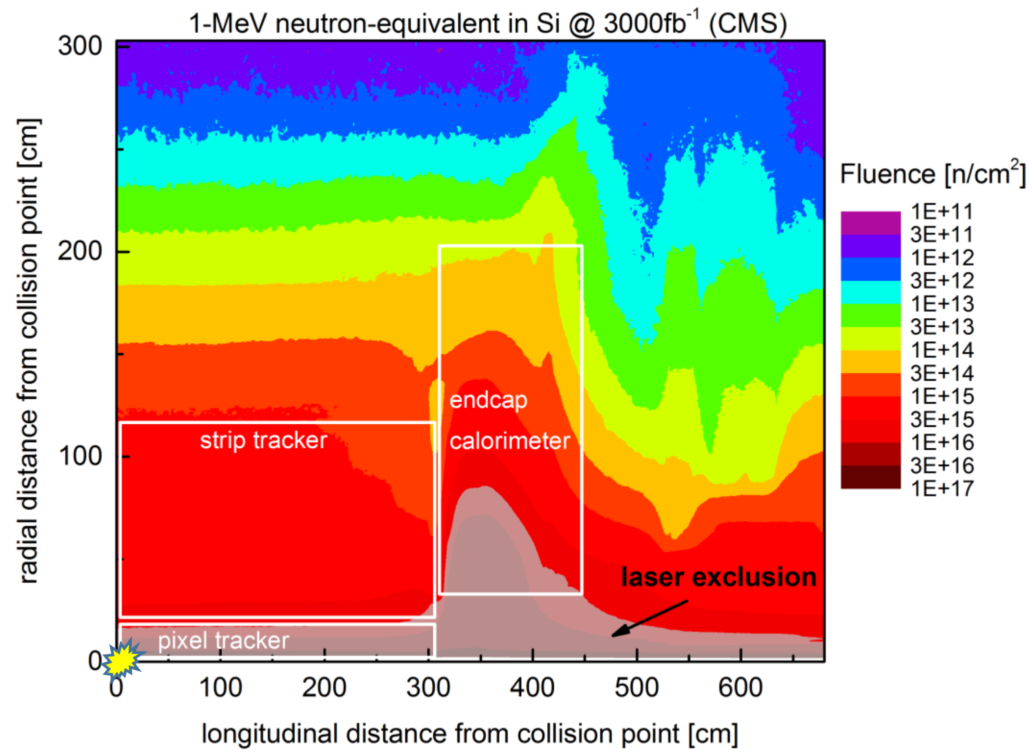




➔ **new optical transceivers that can withstand expected radiation levels in HL-LHC are required to read-out sensor data**

Lasers degrade too much to be considered for innermost detector regions

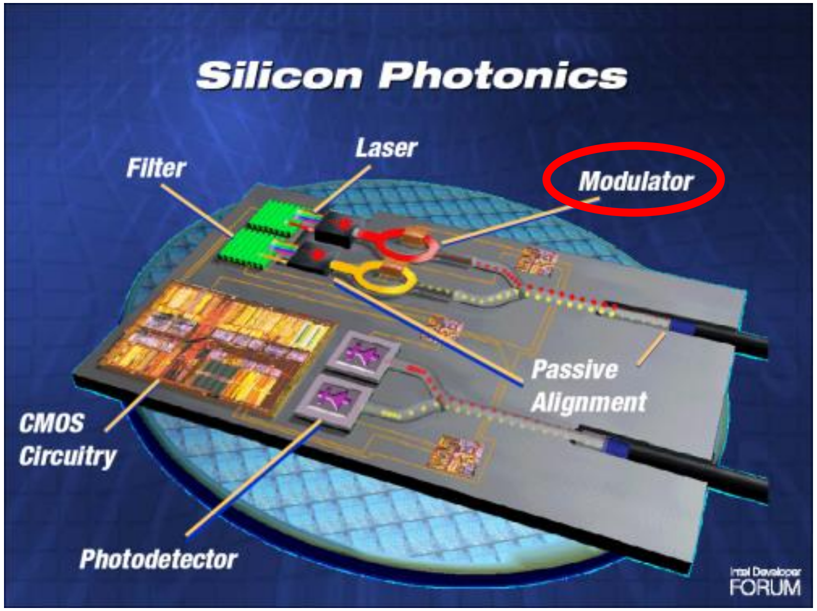




Neutron-induced **increase in threshold current and decrease in slope efficiency** for Vertical Cavity Surface Emitting Lasers (VCSELs) cannot be compensated for beyond the capabilities of the driving electronics.

➔ 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 reduced power & increased functionality

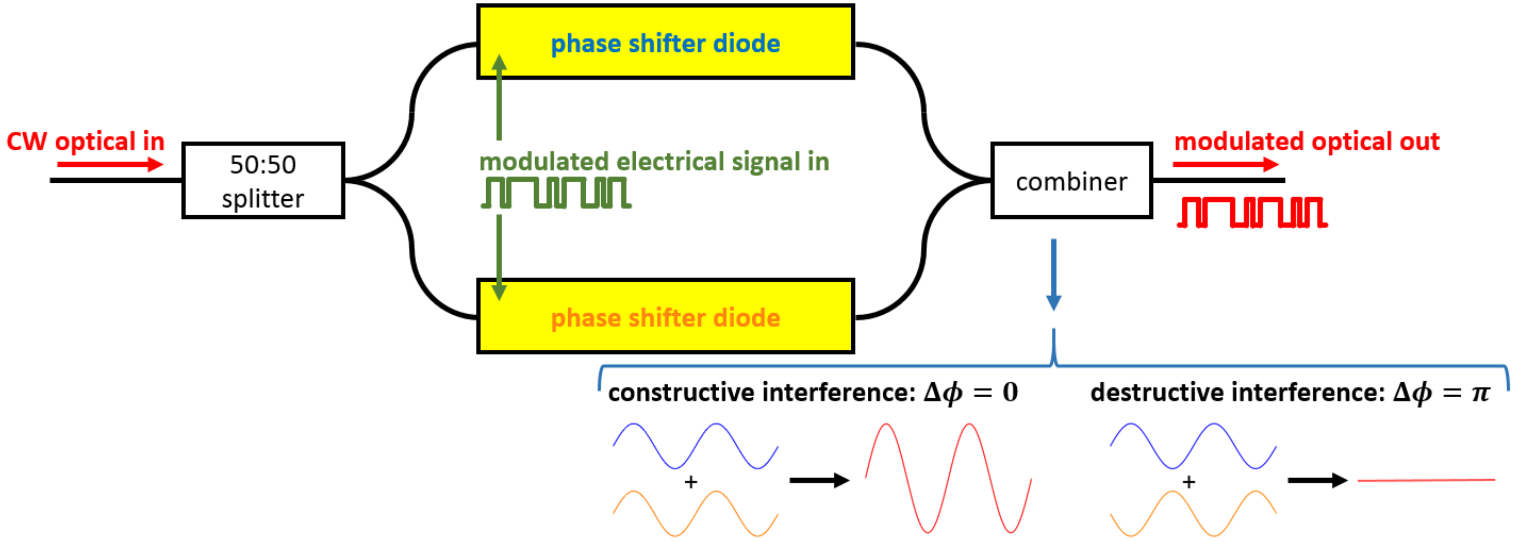
Our hope:

Radiation-hardness similar to those of silicon pixel sensors currently used in HEP experiments

→ Silicon Photonics (SiPh) Mach-Zehnder modulator is being investigated

Phase modulation in the arms of an Mach-Zehnder interferometer leads to amplitude modulation

Schematic of an interferometric Mach-Zehnder Modulator (MZM)



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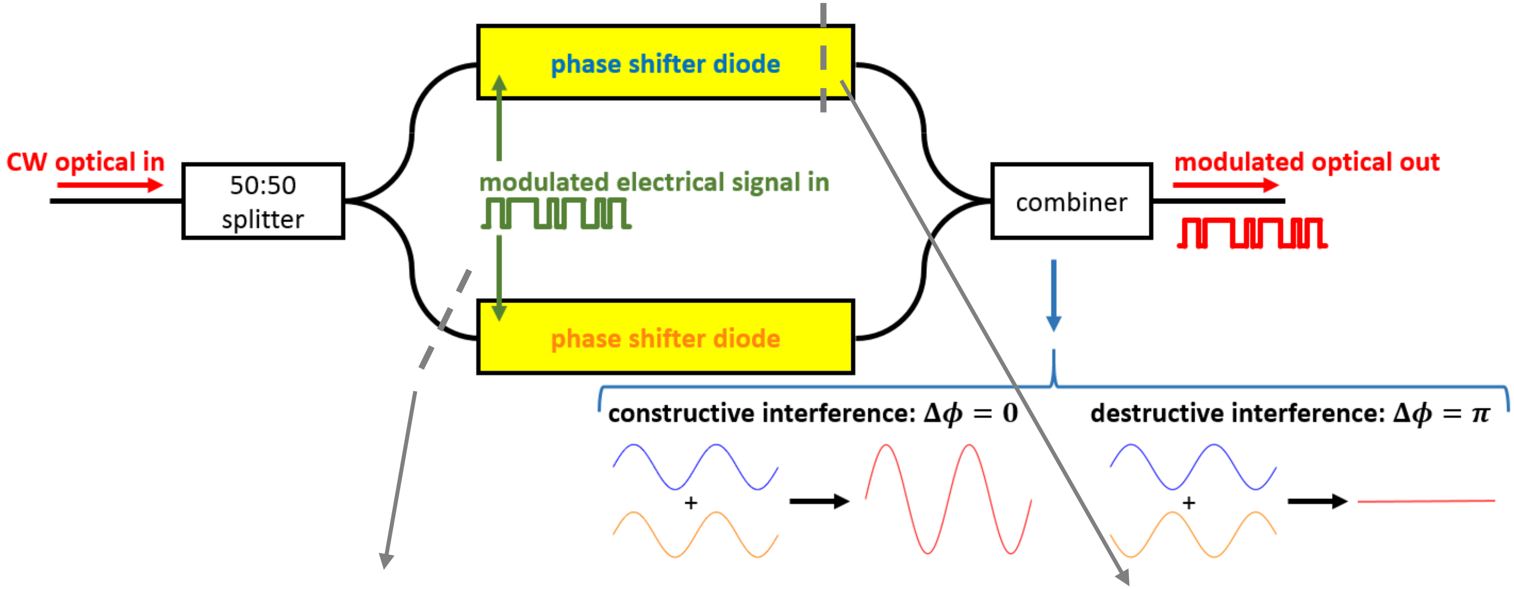
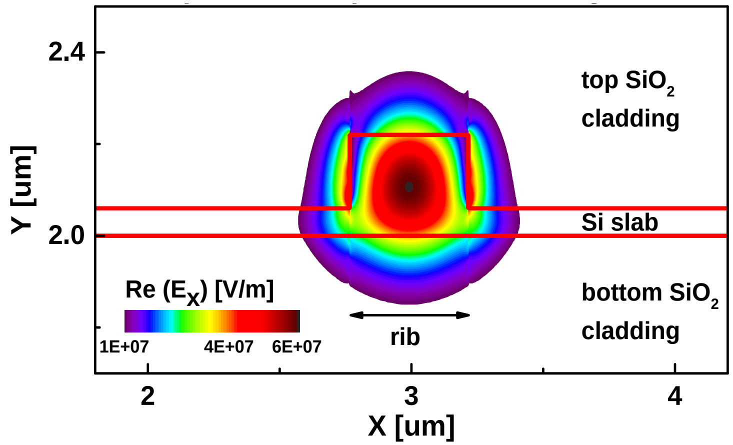
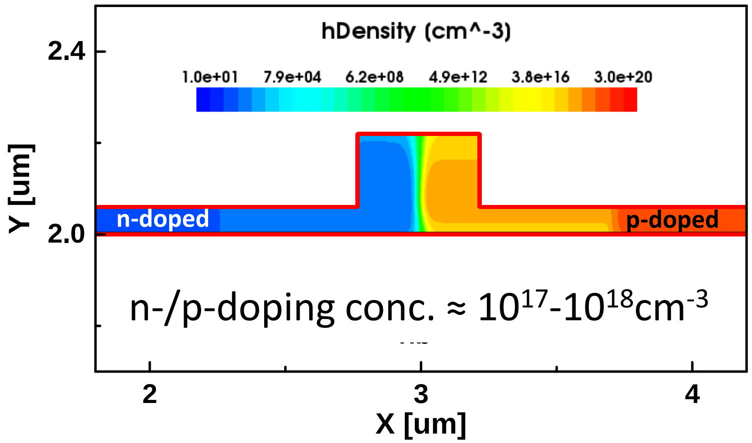


Optical mode in silicon waveguide

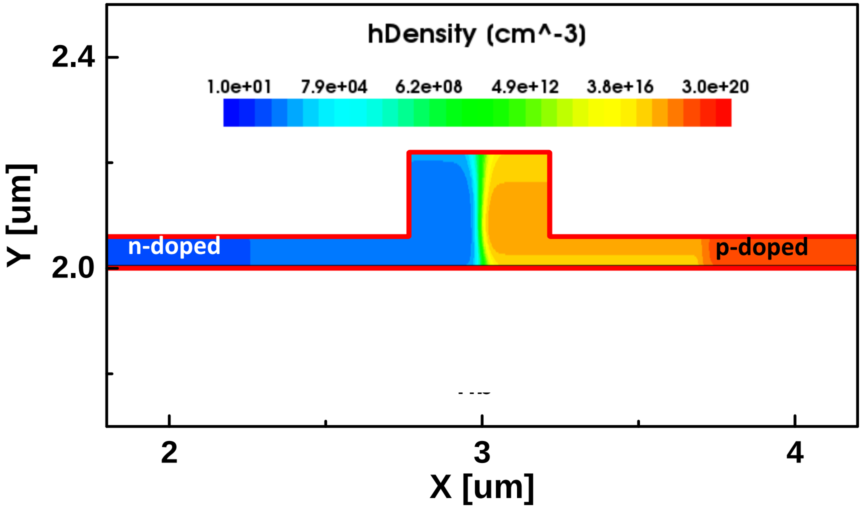


pn-diode in silicon

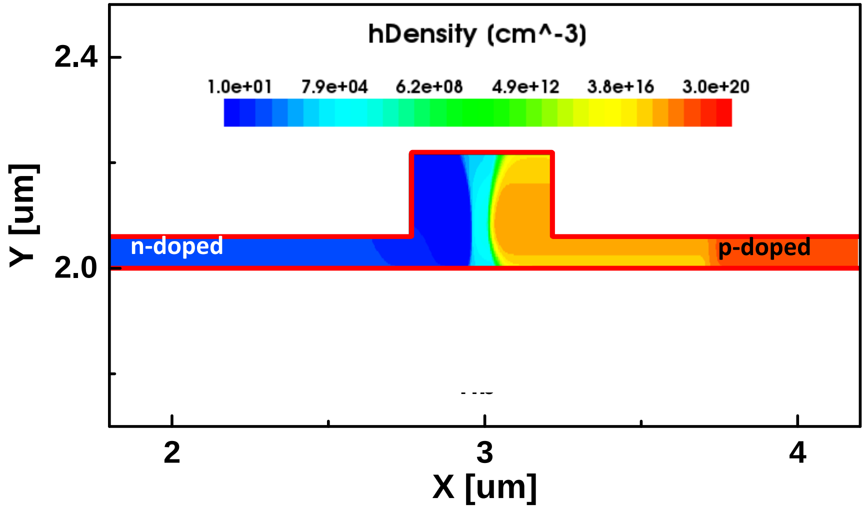


Voltage-induced carrier depletion in phase shifter diode results in phase shift of light

hole density at **0V bias**



hole density at **-3V bias**



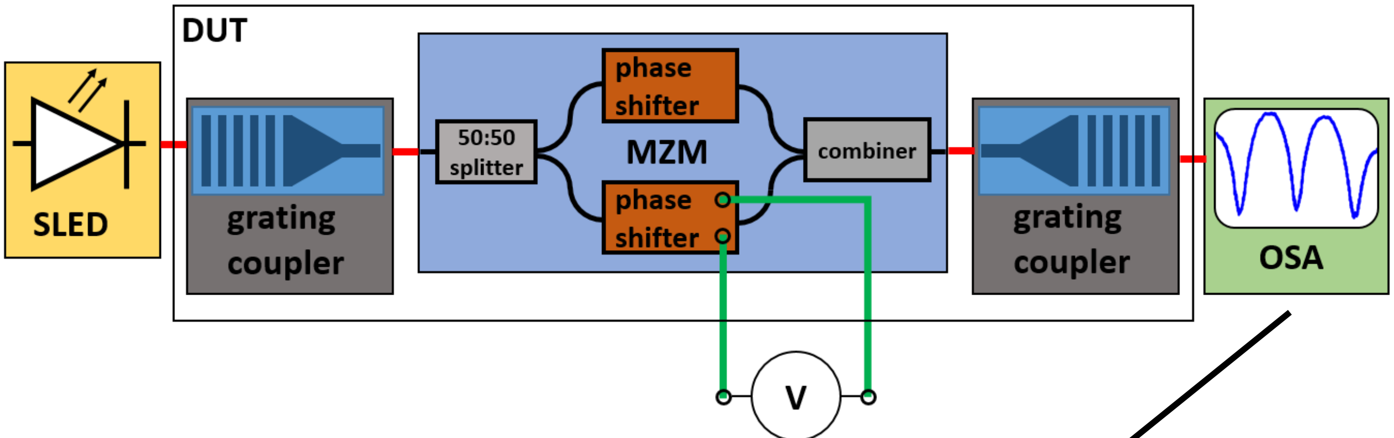
Carrier density change leads to change in material's refractive index (Plasma Dispersion Effect).

Guided mode sees a change in its effective refractive index n_{eff}.

Accumulated phase shift of light after traveling through phase shifter of length L:

$$\Delta\phi = \frac{2\pi \Delta n_{eff} L}{\lambda}$$

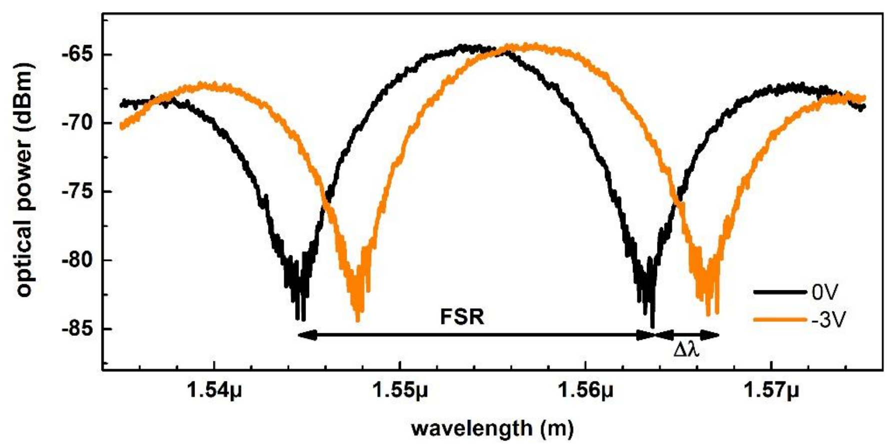
Phase shift can be determined by measuring MZMs’ transmission spectra



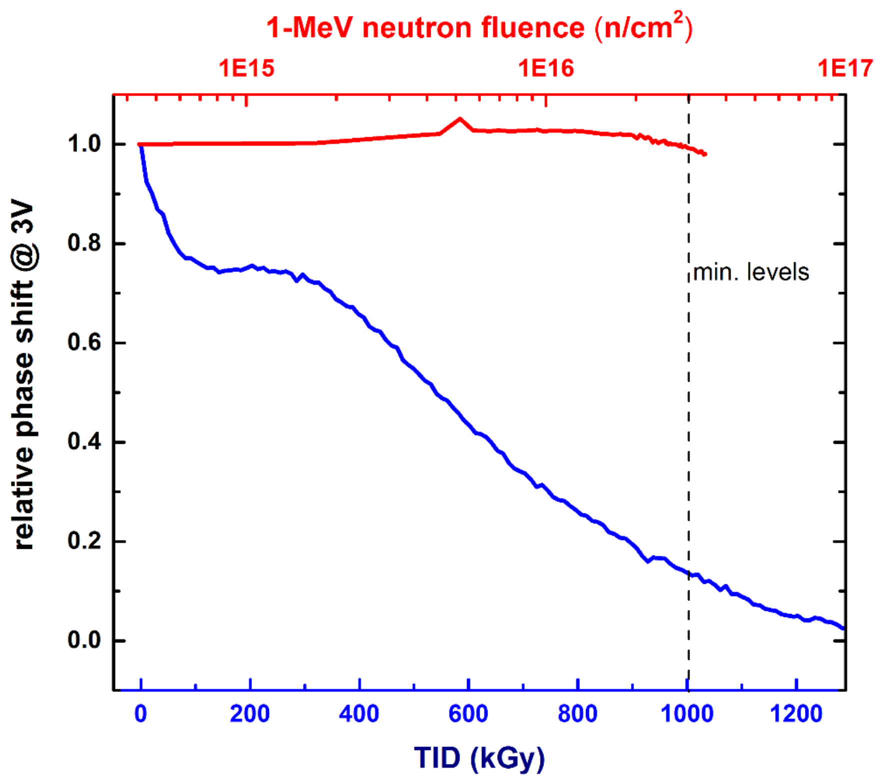
phase shift given by

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

➔ the larger the phase shifter the more efficient the device



SiPh MZMs show high resistance against displacement damage



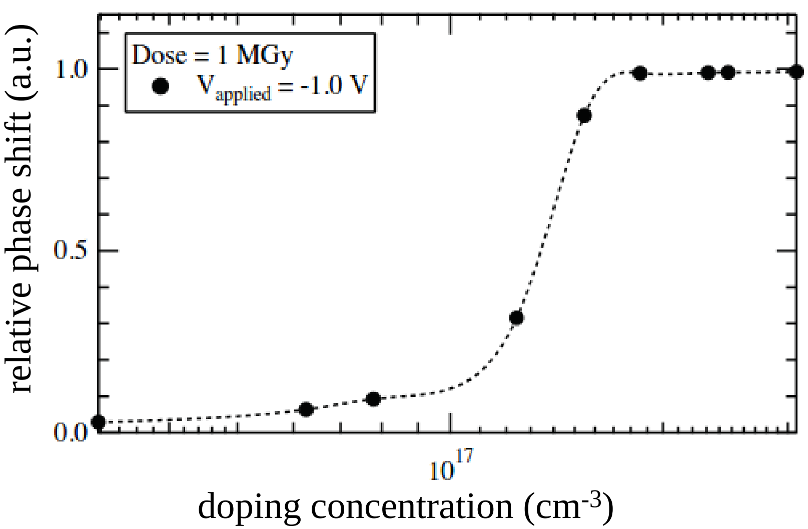
Silicon Photonic (SiPh) Mach-Zehnder Modulators (MZMs) show **no significant performance degradation due to displacement damage.**

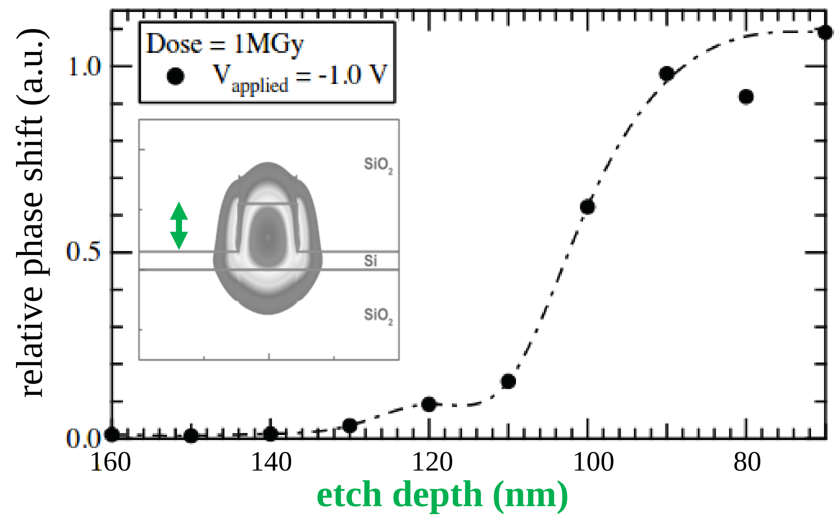
But: devices are very **sensitive to ionizing radiation** [3].

➔ Can MZM design be improved to increase resistance to ionizing radiation?

Simulations indicate that changes to MZM design can improve resistance against ionizing radiation

MZM's failure mechanism can be attributed to large density of positive trapped charge in SiO_2 which pinches-off holes in waveguide from contact [4].



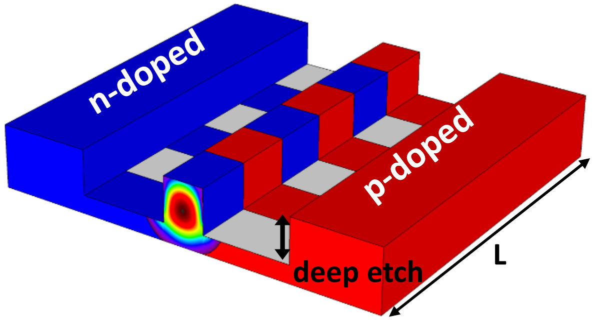


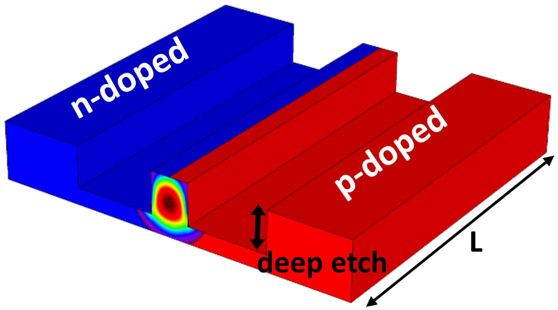
Higher doping levels in MZM can mitigate effect of ionizing radiation.

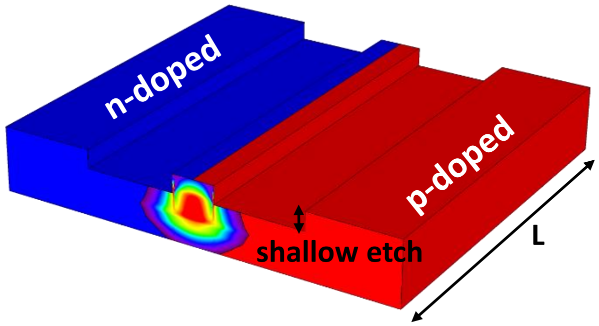
Lower etch depth can delay carrier pinch-off.

3 types of phase shifter diodes were evaluated for their radiation hardness

interleaved pn-junctions deep etch depth L=0.5mm, 1.0mm, 1.5mm	lateral pn-junctions deep etch depth L=1.9mm	lateral pn-junctions shallow etch depth L=1.9mm







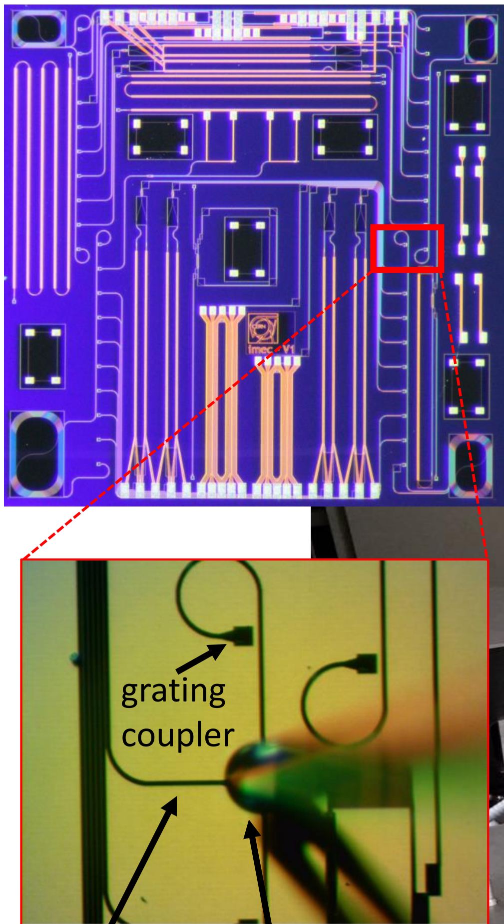
+ highest modulation efficiency - lowest modulation bandwidth	• medium modulation efficiency • medium modulation bandwidth	+ highest modulation bandwidth - lowest modulation efficiency

In addition: Samples with two different p- and n-doping concentration in the waveguide were fabricated in 2015 by imec [5]

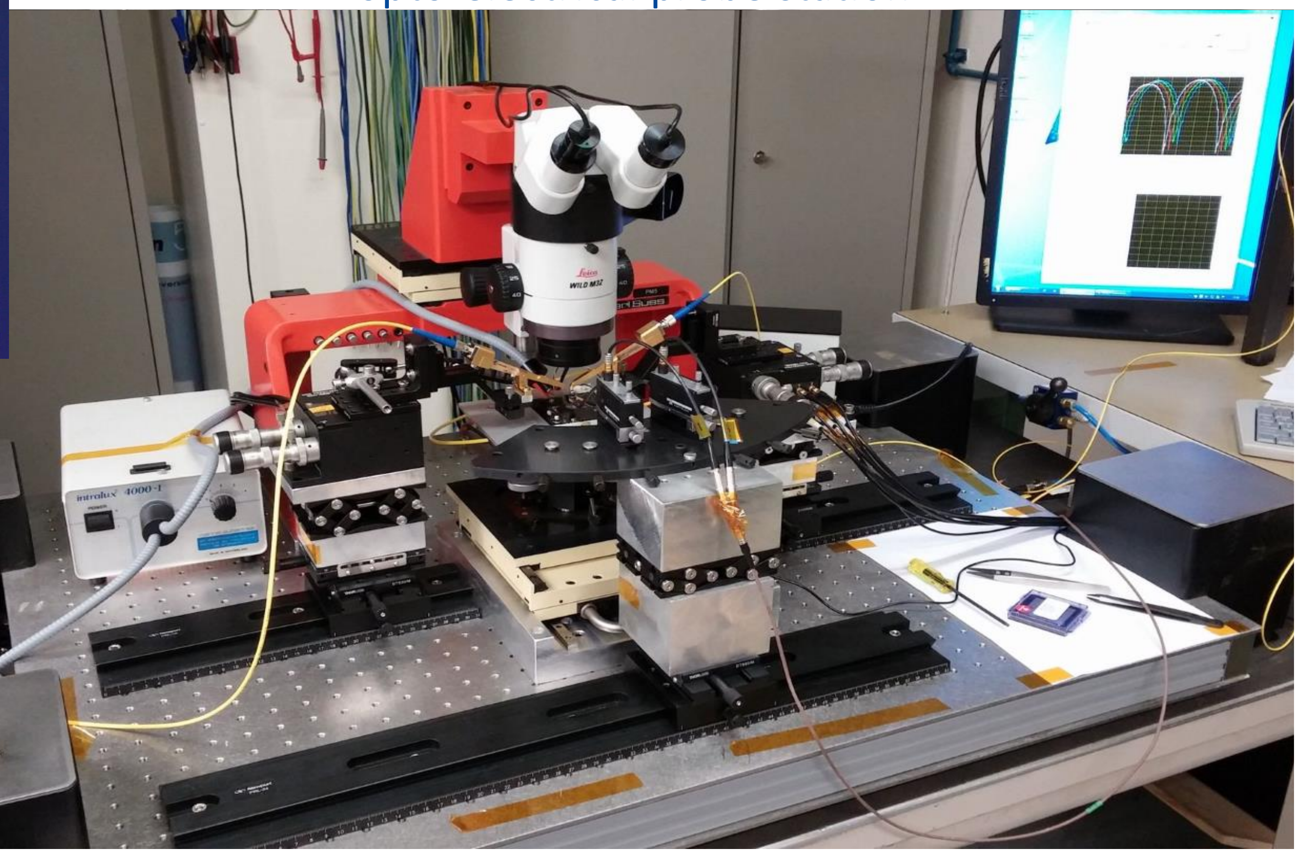
- nominal doping
- 2x nominal doping

All measurements were done at die-level on a probe-station

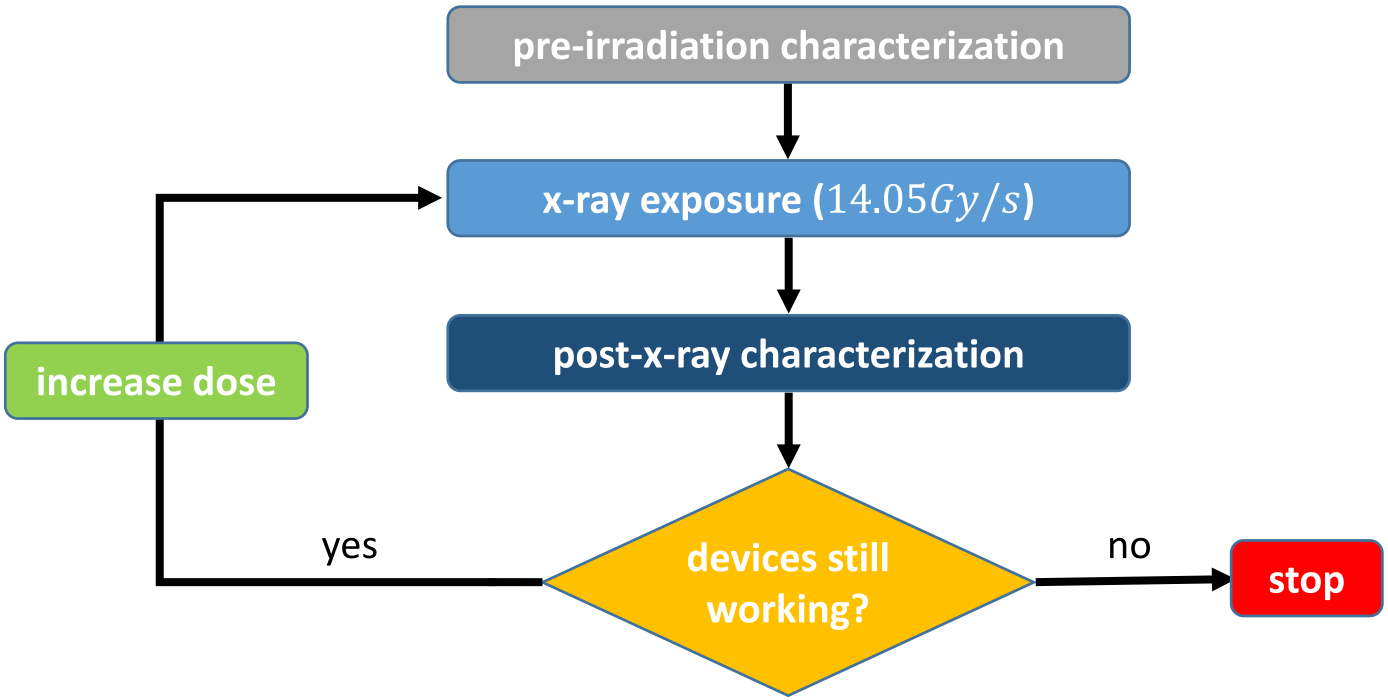
die: 5 x 5 mm^2



opto-electrical probe station



MZM samples were exposed to increasing TID and characterized after each dose-step

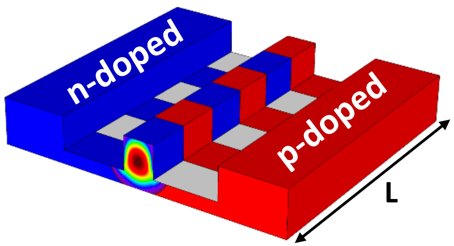


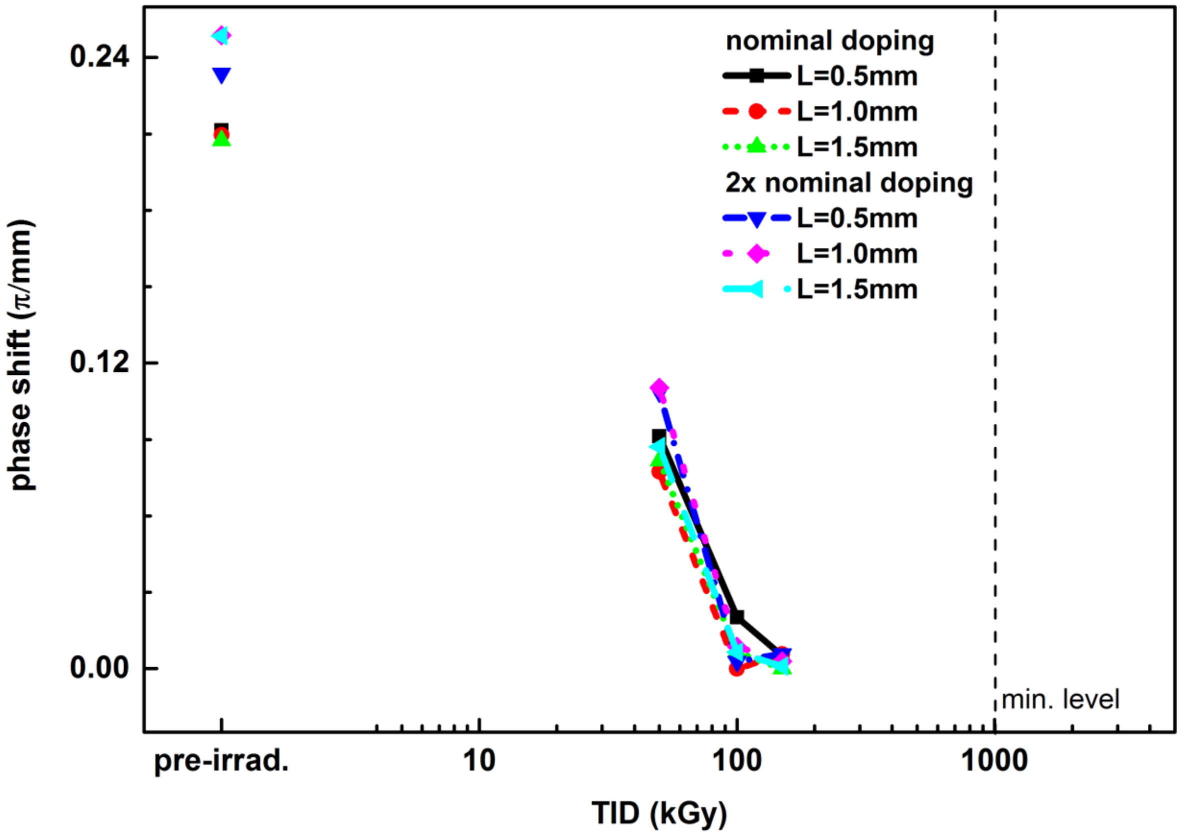
Dice were not bonded to PCB ➔ not biased during irradiation

No annealing between and after irradiation steps

Irradiation and measurements at room temperature

Phase shift of MZMs with interleaved junctions vanishes around 100kGy



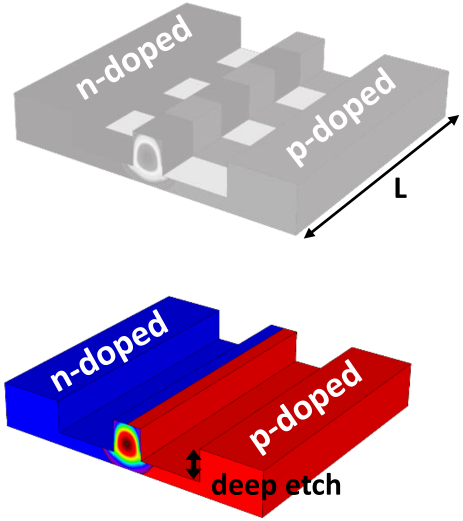


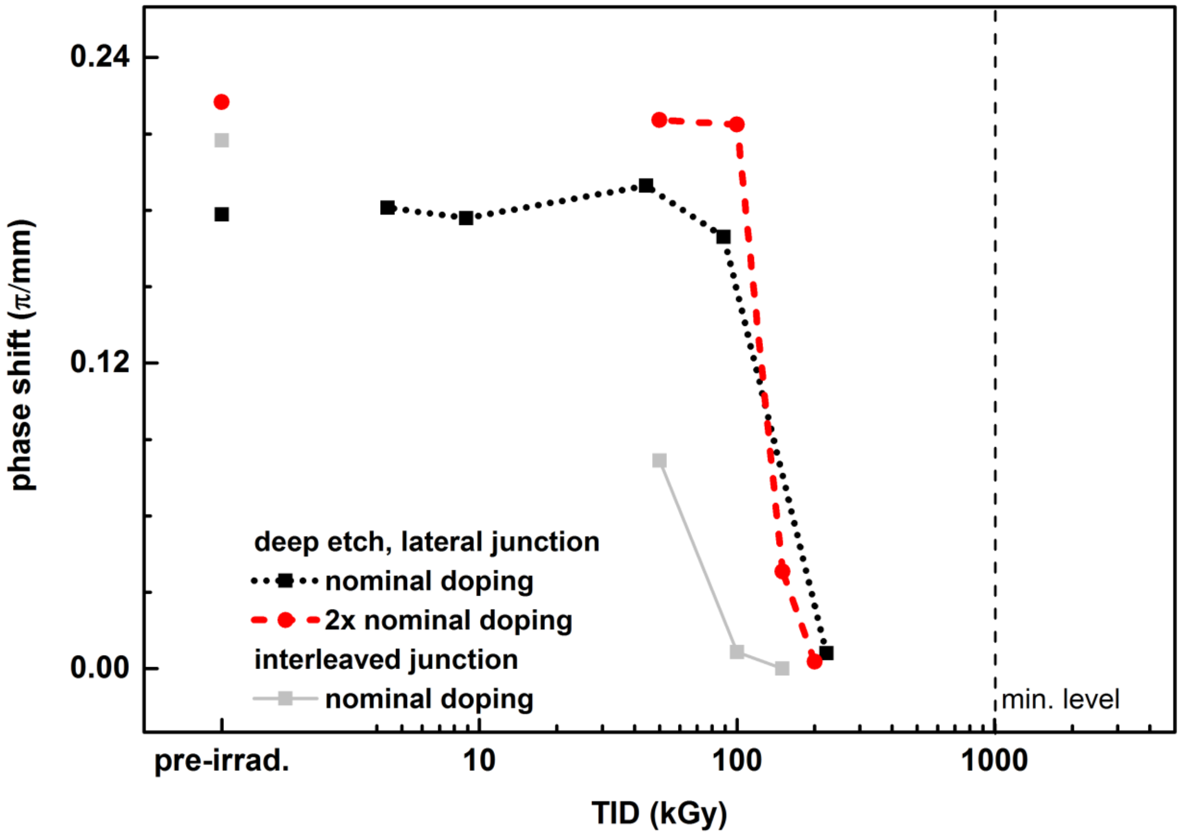
Independent of MZM length and doping concentration

- only 50% phase shift remains at $50kGy$
- No phase shift measurable for TID levels $> 150kGy$

➔ **design not of interest to HEP applications**

MZMs with lateral junction withstand higher TID despite having the same etch depth



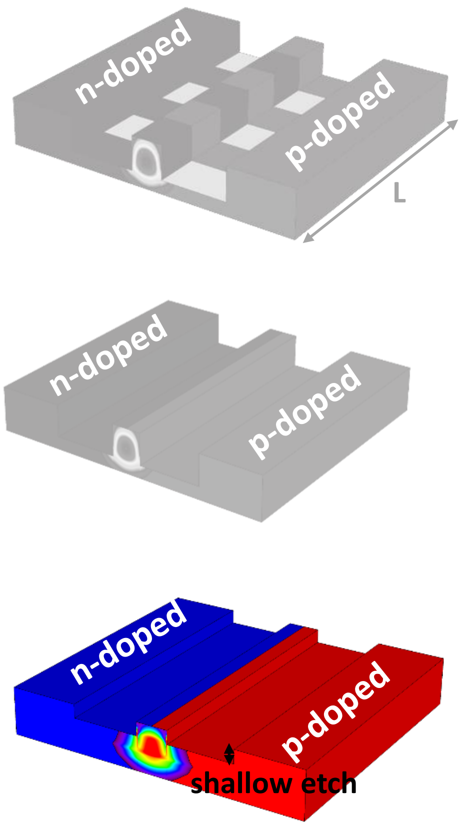


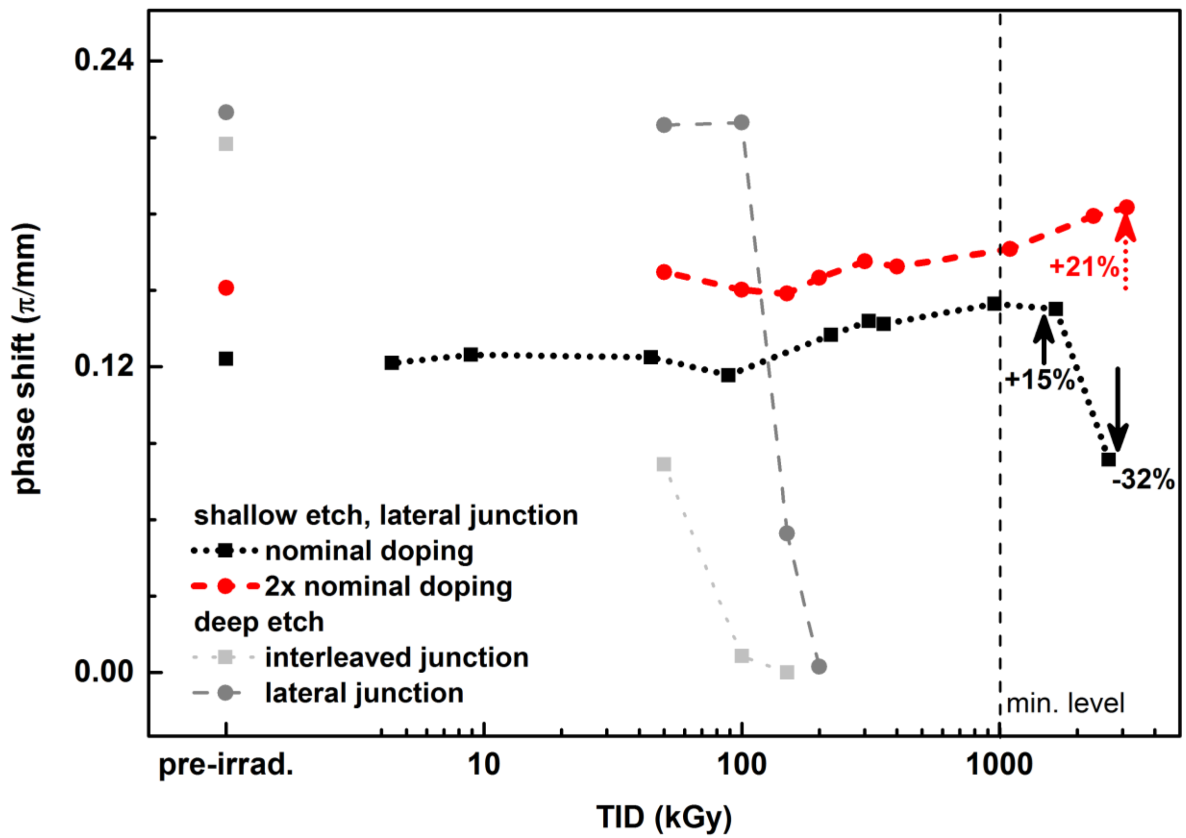
Independent of w_{Dop} and doping concentration

- No significant phase shift degradation up to $100kGy$
- No phase shift measurable for TID levels $> 200kGy$

➔ **slightly better than MZMs with interleaved junction but still degrade too fast**

Reducing the etch depth greatly improves the radiation hardness

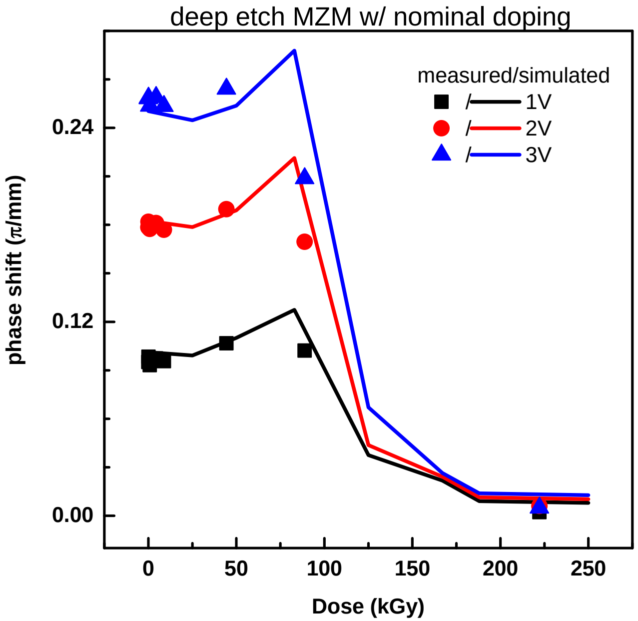


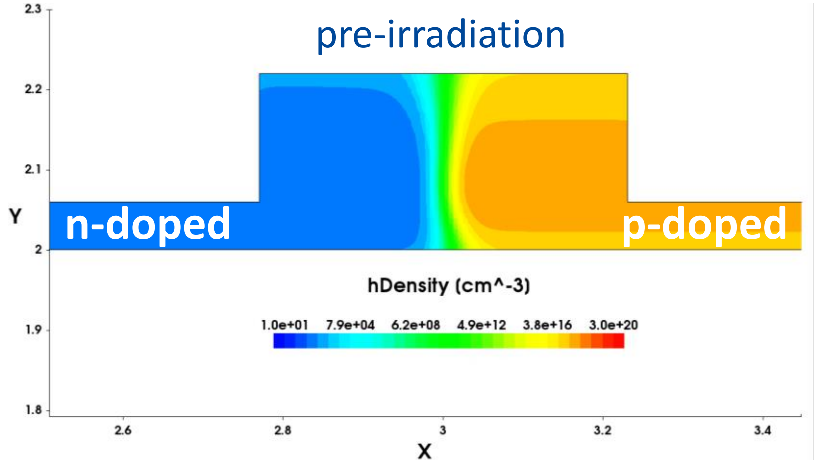


- No degradation until $2000 kGy$ but at higher TID for samples with nominal doping
- No degradation up to $3100 kGy$ for samples with 2x nominal doping
- Phase shift enhancement before samples start to degrade

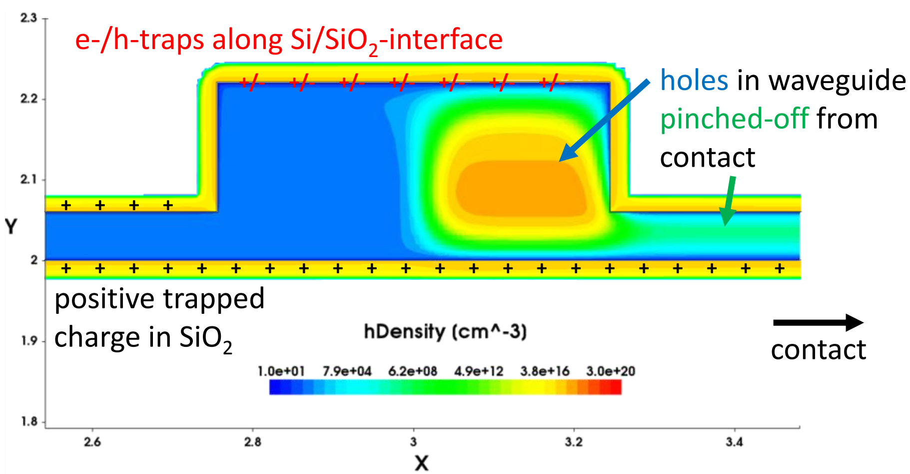
➔ **Shallow etch depth and high doping concentration increases resistant against ionizing radiation significantly; candidate devices for application in HL-LHC**

Simulations show that pinch-off of holes causes phase shift degradation





after 250kGy



Simulation performed for deep etch MZM w/ nominal doping according to model proposed in [4].

Parameter fitting for shallow etch MZM and MZMs with 2x nominal doping is ongoing work.

Summary

- LHC luminosity upgrades will require new optical transceivers with improved radiation hardness
- SiPh MZMs are therefore investigated as alternative to VCSELs because these cannot be employed in harshest radiation regions
- Simulation results indicate that the doping concentration and the etch depth affect the radiation hardness of MZMs
- SiPh test chip was designed and tested before, during and after x-ray irradiation (un-biased)
  - work on irradiation test with biased devices is in progress
- Experimental results confirm the simulation results
- MZMs with a deep etch waveguide show generally low radiation hardness
- **MZMs with a shallow etch waveguide and high doping concentrations are much harder against TID (>2MGy) than other designs**
  - can reach detector regions where VCSELs cannot be installed
  - For these devices an increase in phase shift could be observed before degradation starts

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] 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.

[5] 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.

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