Radiation-hard silicon photonics for high energy physics and beyond

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14/09/2016

ICE-DIP workshop

work package 1

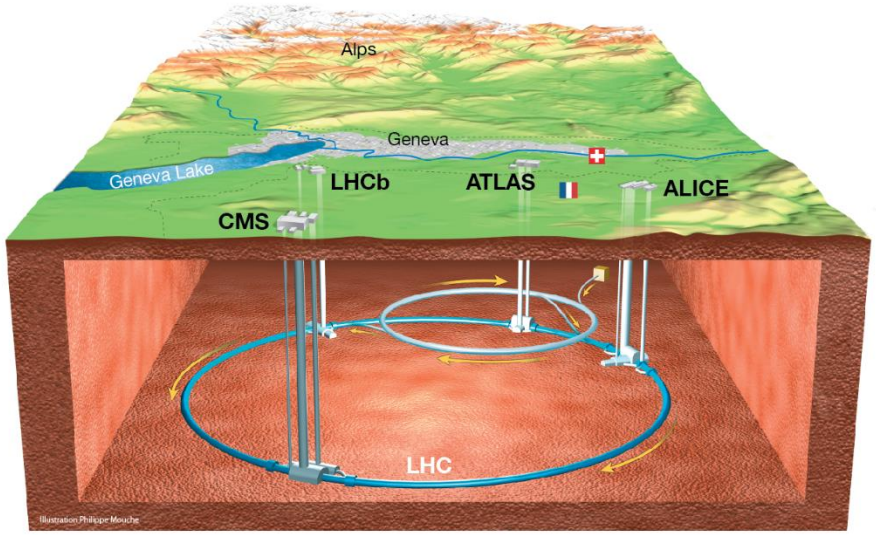
ICE-DIP is a European Industrial Doctorate project funded by the European Commission's 7th Framework programme Marie Curie Actions under grant PITN-GA-2012-316596

CERN openlab

Outline

- Motivation
- Introduction
- Results
- Conclusion

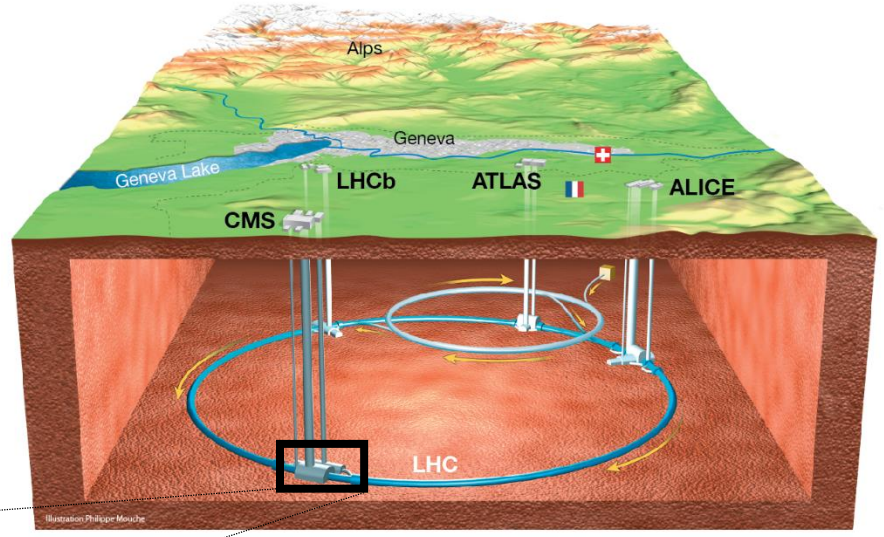
CERN conducts research to find answers to fundamental questions about our universe

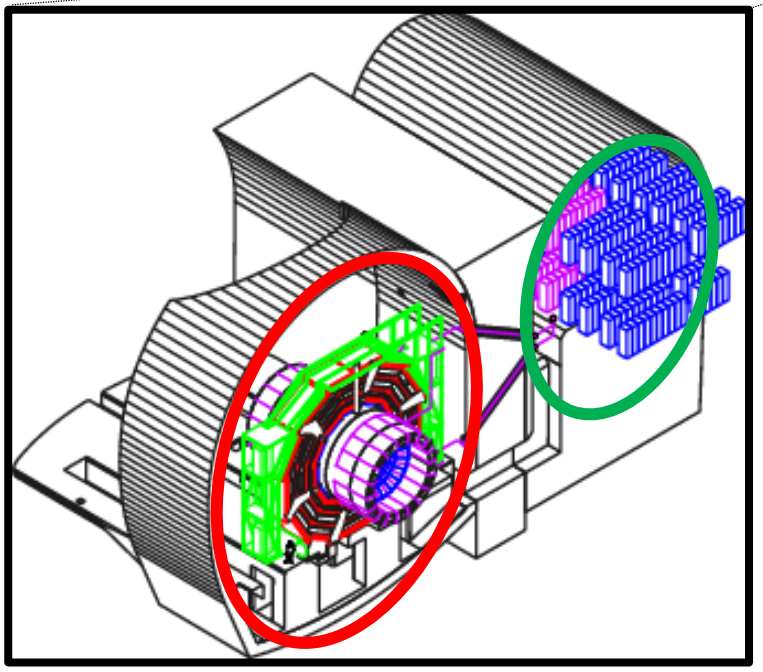


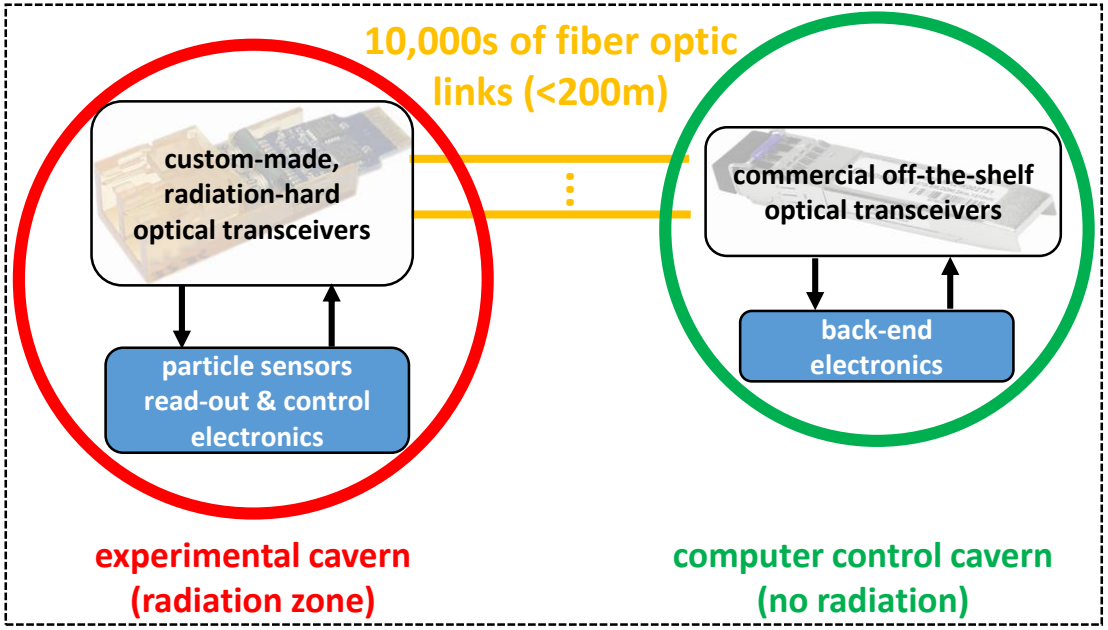
For that purpose, CERN

- 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

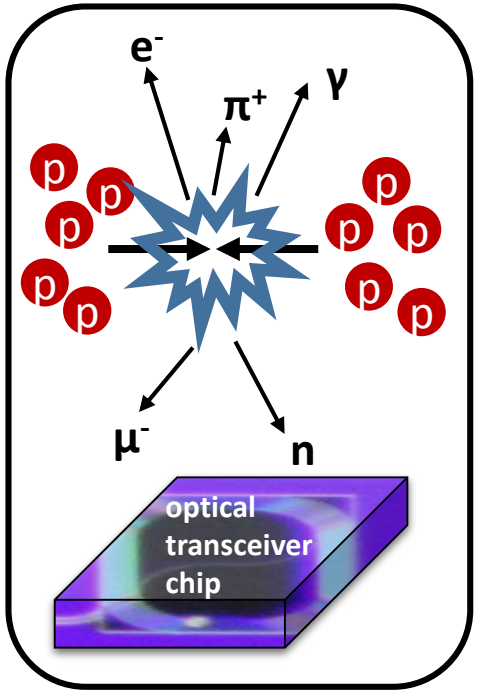




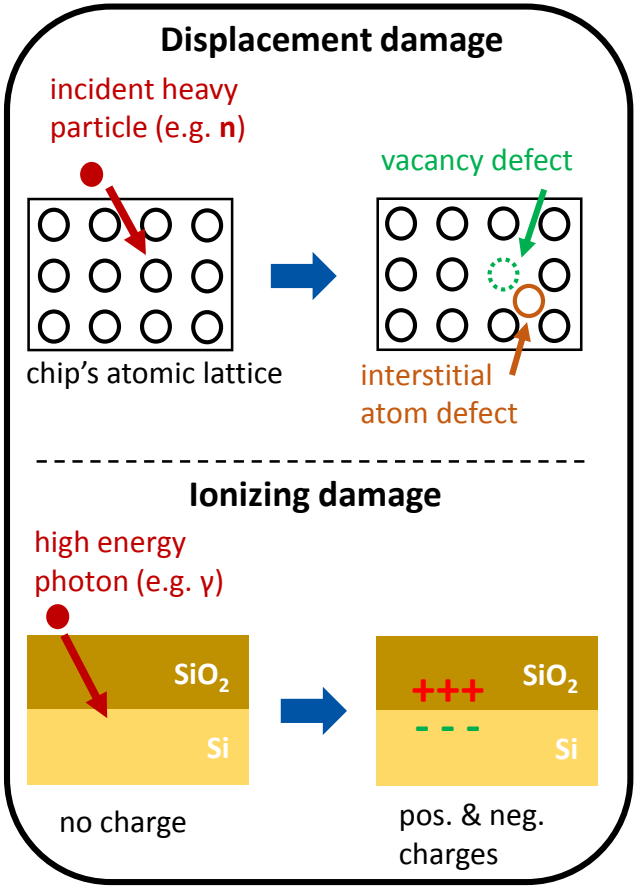


Radiation inside detectors induces damage in chips and degrades their performance

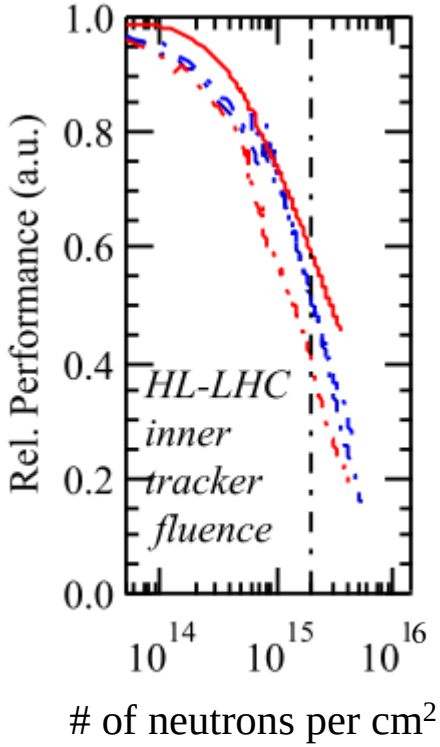
proton-proton collisions create sub-particles



sub-particles create 2 kinds of microscopic changes in transceivers' material



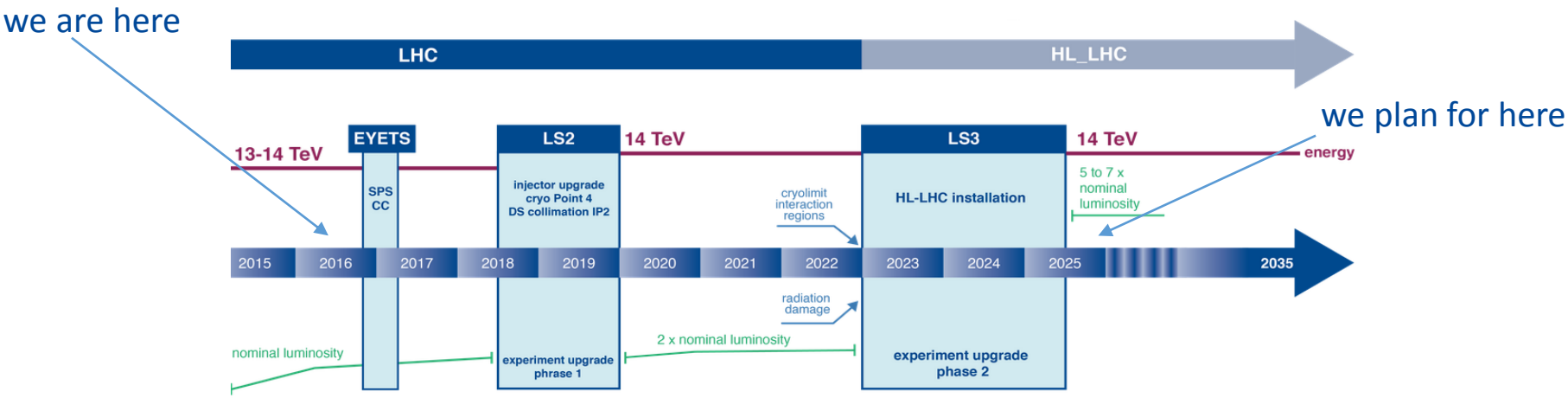
(VCSEL/pin) transceivers eventually stop working



➔ **Effect of radiation on optical transceivers needs to be mitigated**

HL-LHC luminosity upgrades will entail even more particle collisions

LHC/HL-LHC upgrade plan



5x higher levels of radiation in innermost detector regions

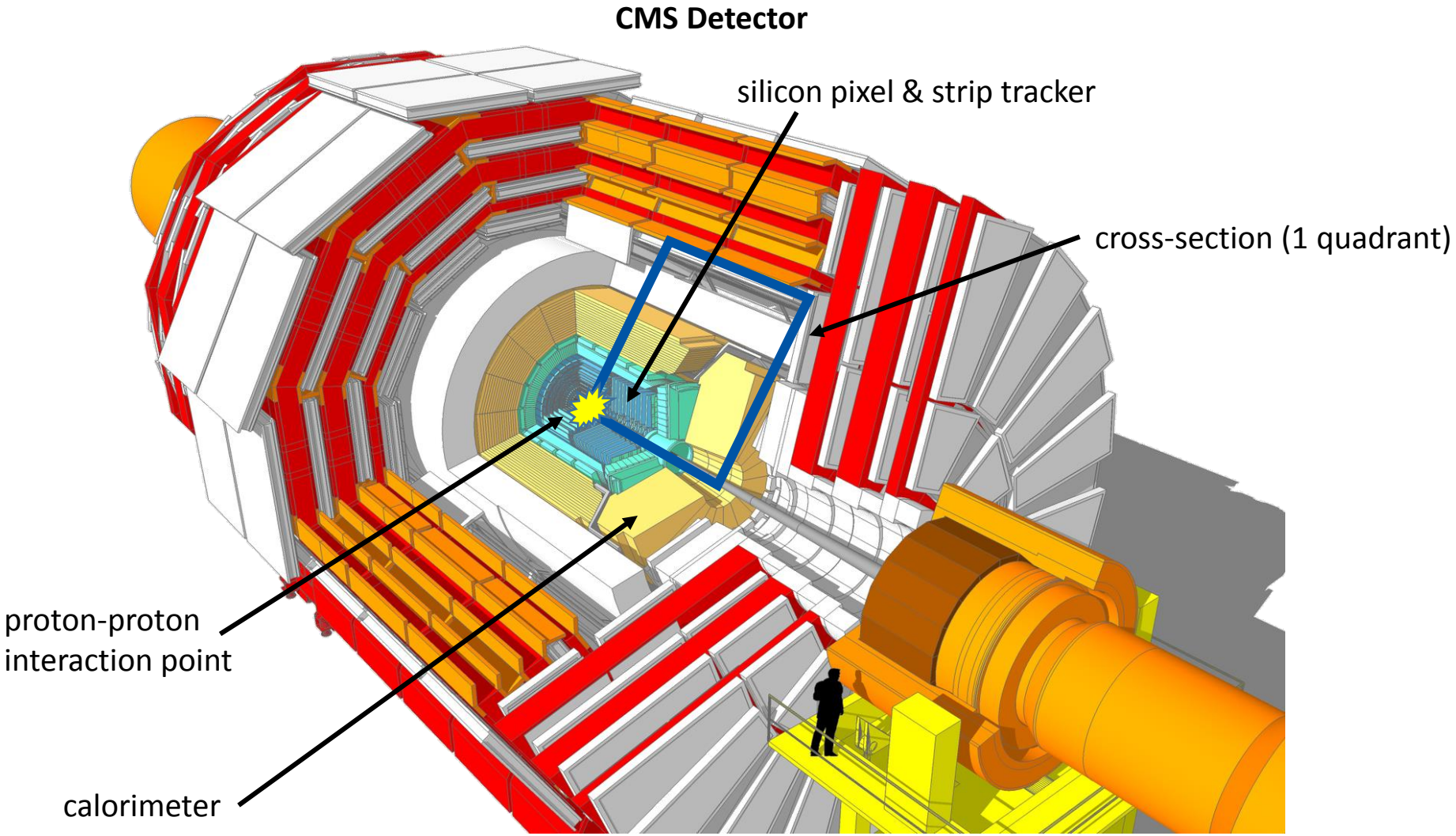
- 1-MeV neutron fluence up to $3 \times 10^{16} n/cm^2$
- Total Ionizing Dose (TID) of at least $1 MGy$

} during 10-year operational lifetime

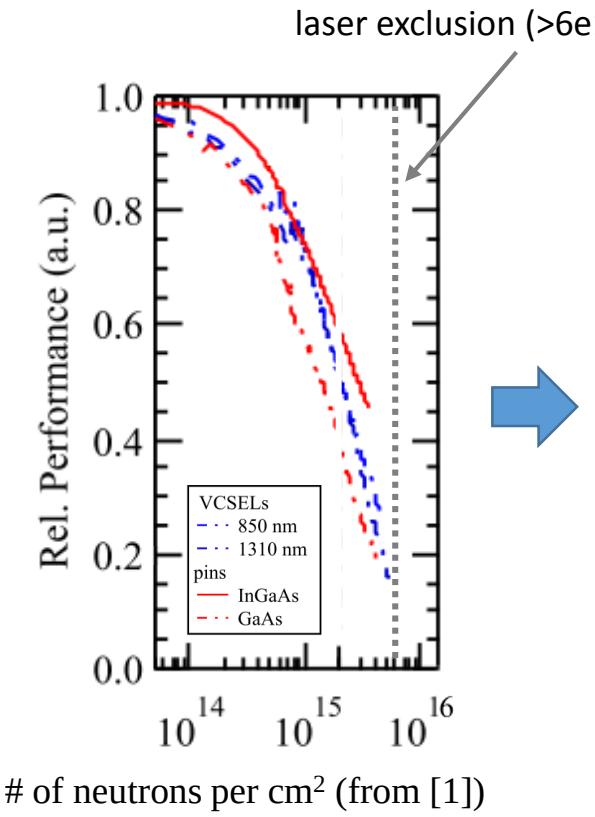
larger amounts of data to be carried by optical links

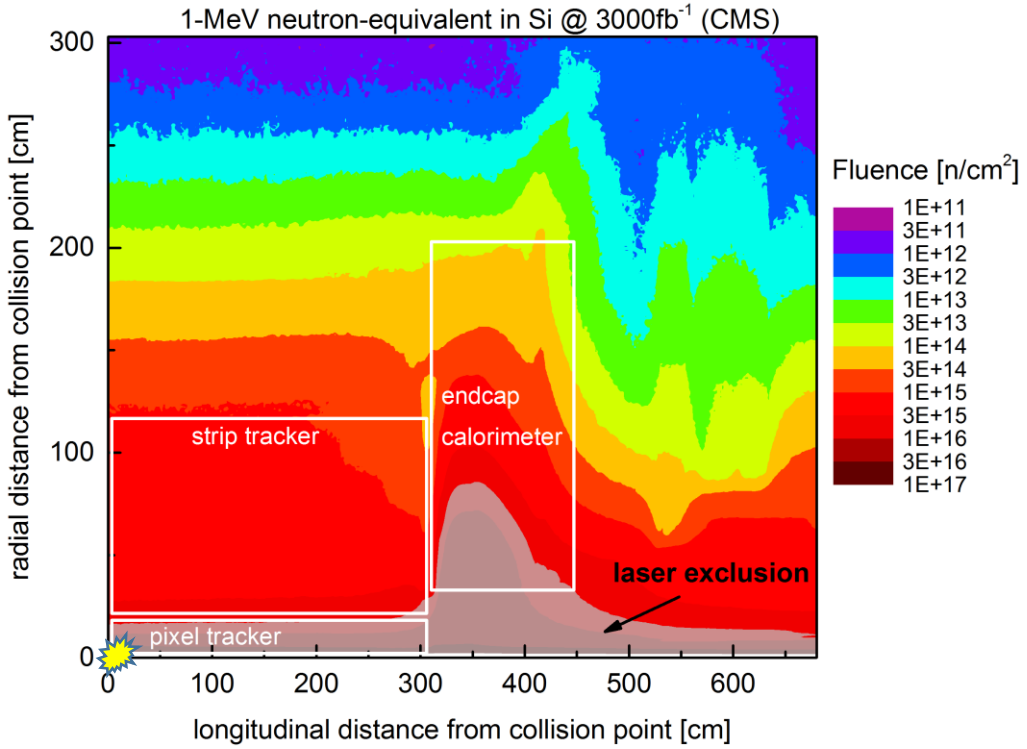
- bit-rates of >10Gb/s per channel

What does this mean e.g. for CMS?



Current technology cannot be used in innermost detector regions

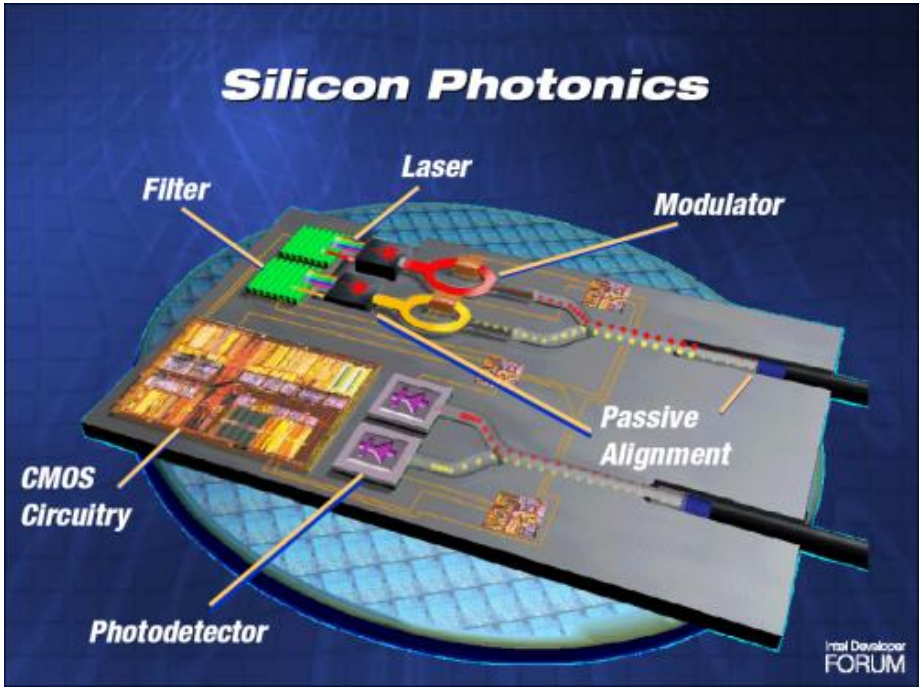




Lasers degrade too fast and thus cannot be used for tightly integrated read-out modules in harshest radiation environments in CMS.

➔ ICE-DIP's work package 1: **radiation-hard Silicon Photonics (SiPh) for data intensive communication links**

Silicon Photonics: CMOS-compatible electro-optic integrated circuits



from https://ic.tweakimg.net/ext/i.dsp/1109883395.png

Idea:

Fabrication of photonic devices in silicon in existing and mature CMOS infrastructure

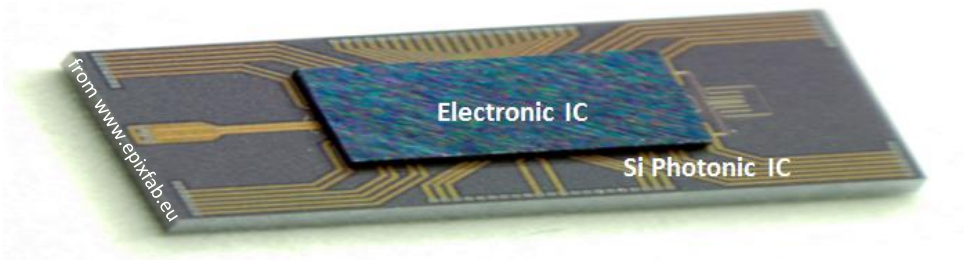
Promise:

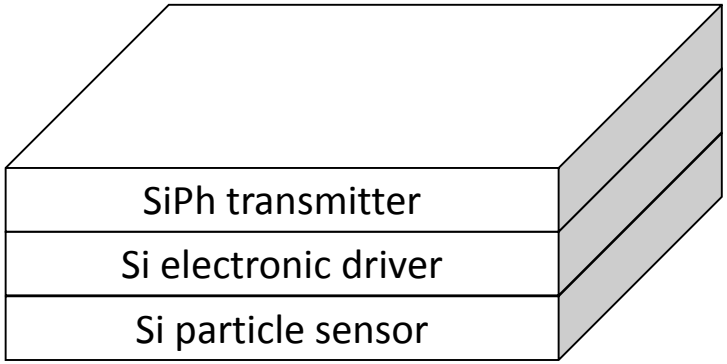
Production of chips with increased functionality, reduced power consumption at lower cost

Our hope:

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

Easier integration with electronics could open up new paths for read-out systems



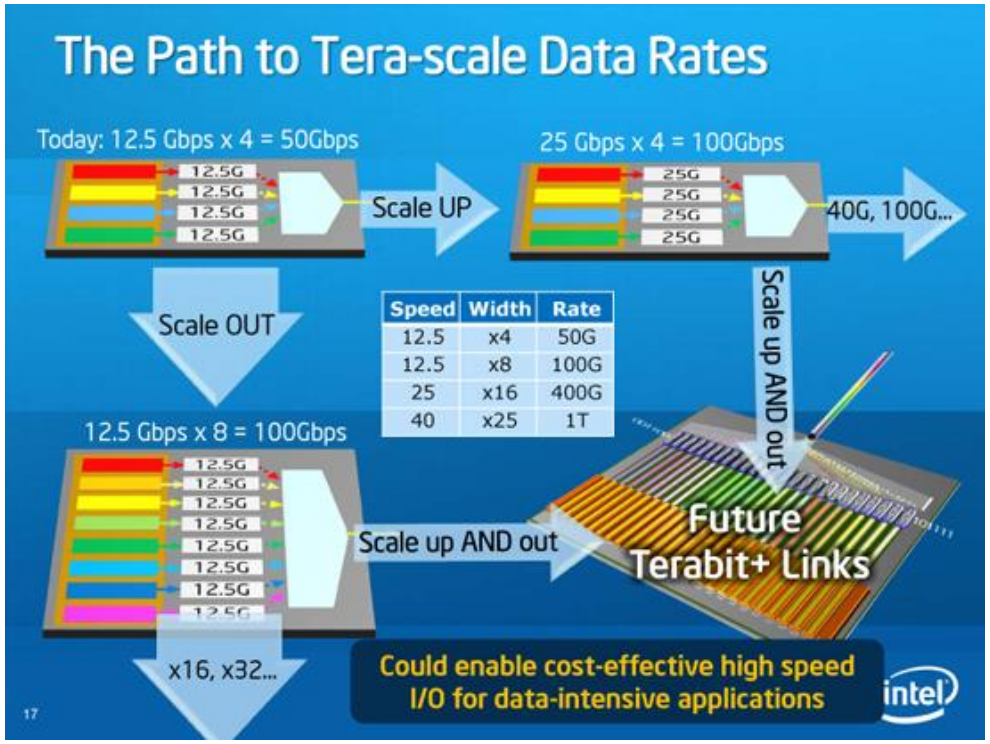


Module with reduced mass and volume

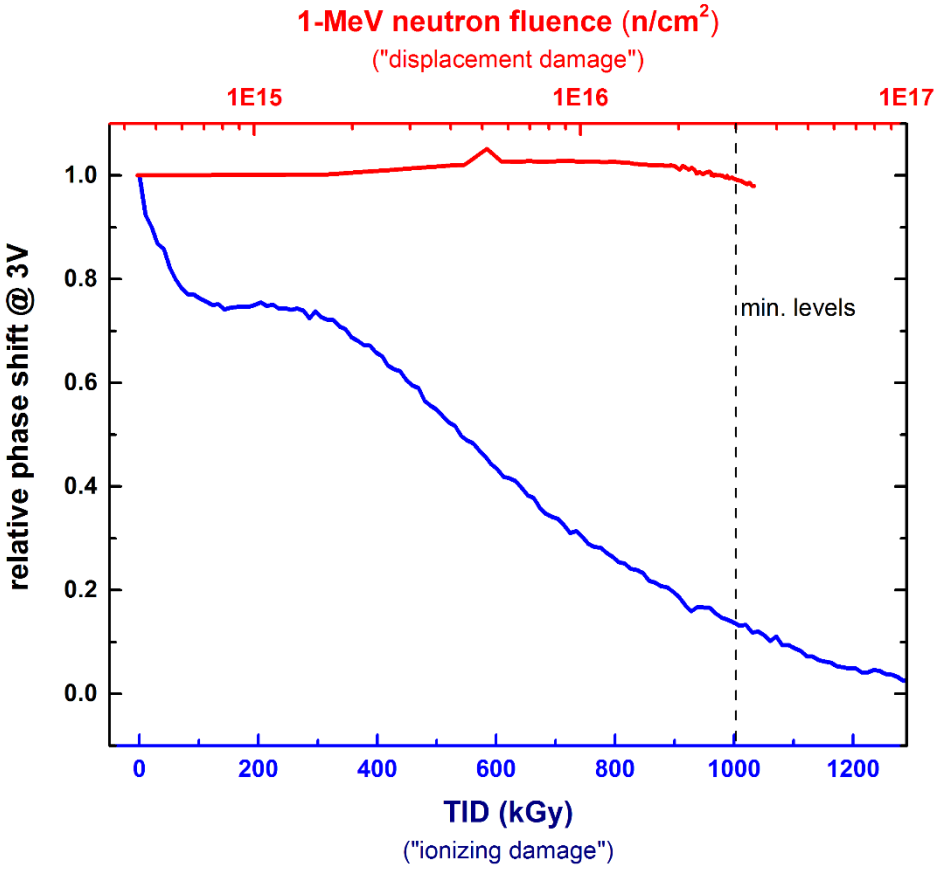
Less material in detector ➔ higher precision physics measurements

SiPh would also offer further advantages over current technology

- Single-channel data rates 10–50Gb/s have been demonstrated.
  - 5-14Gb/s for current technology
- Multiplexing of multiple channels into one fiber offers way to increase bandwidth w/o need for new fiber installation.
  - not possible w/ current technology
- Transmission distances of up to 2km.
  - 200m for current technology



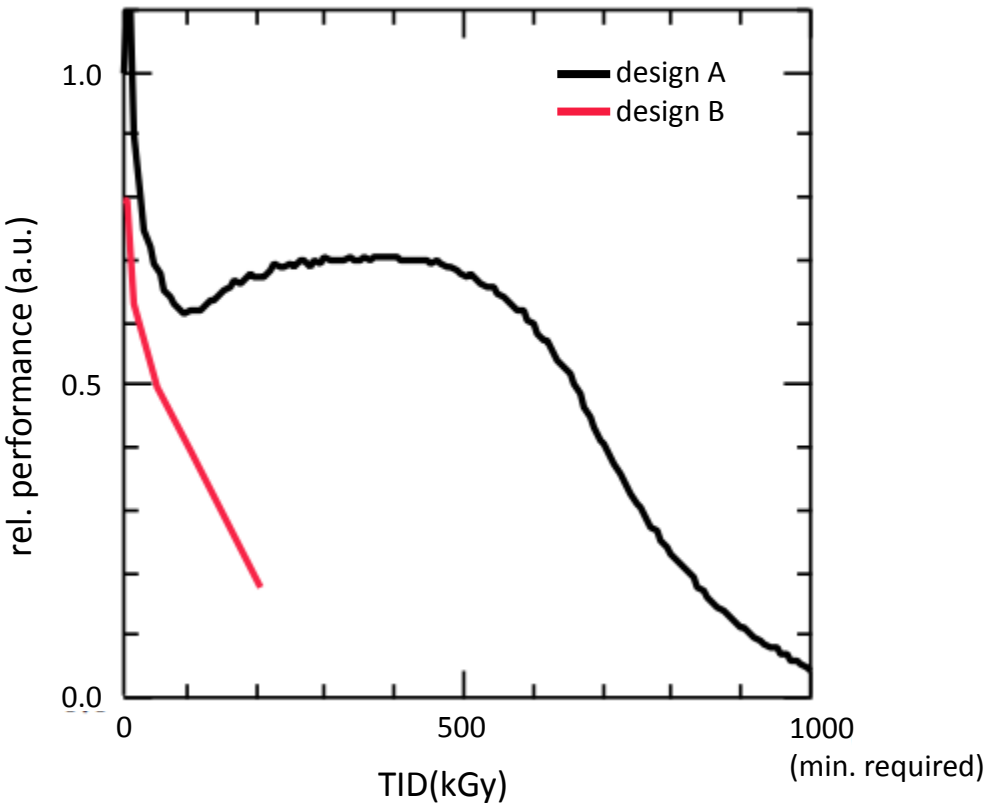
First tests showed promising results for radiation hardness of SiPh



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

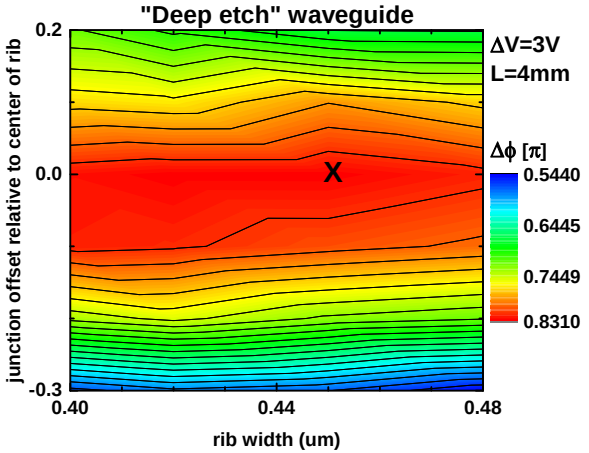
But: devices are very **sensitive to Total Ionizing Dose (TID)** damage**.**

Device design directly affects performance degradation



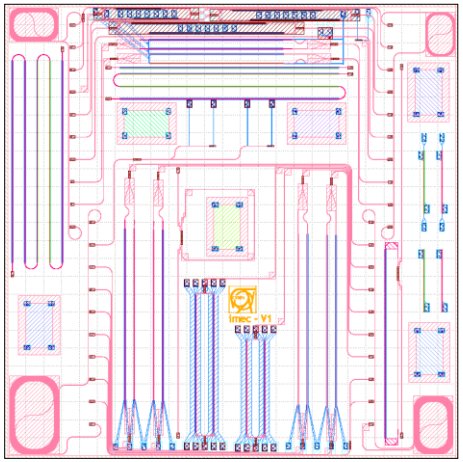
➔ Can MZM design be changed to increase resistance against ionizing radiation?

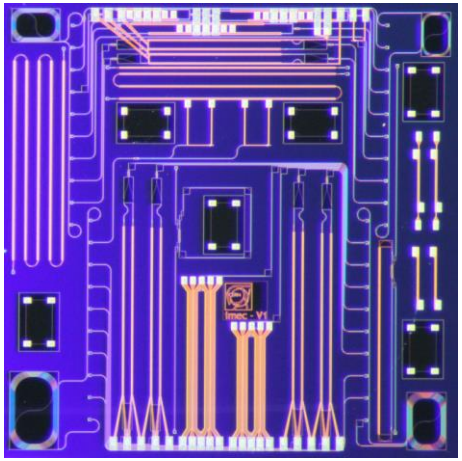
SiPh chip with different designs has been devised and tested



performance prediction from simulations

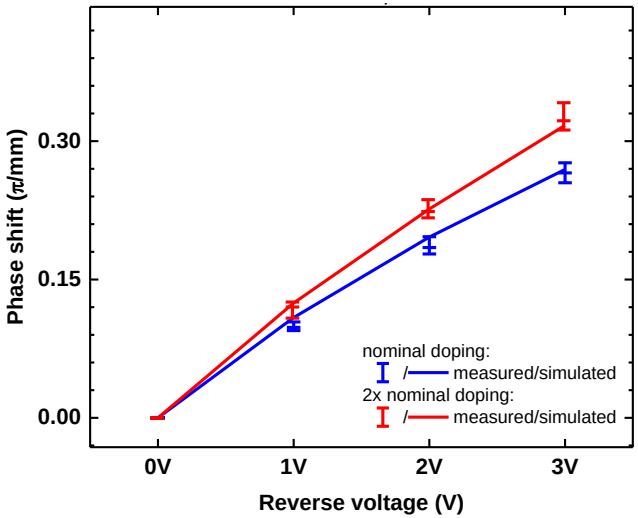
chip design



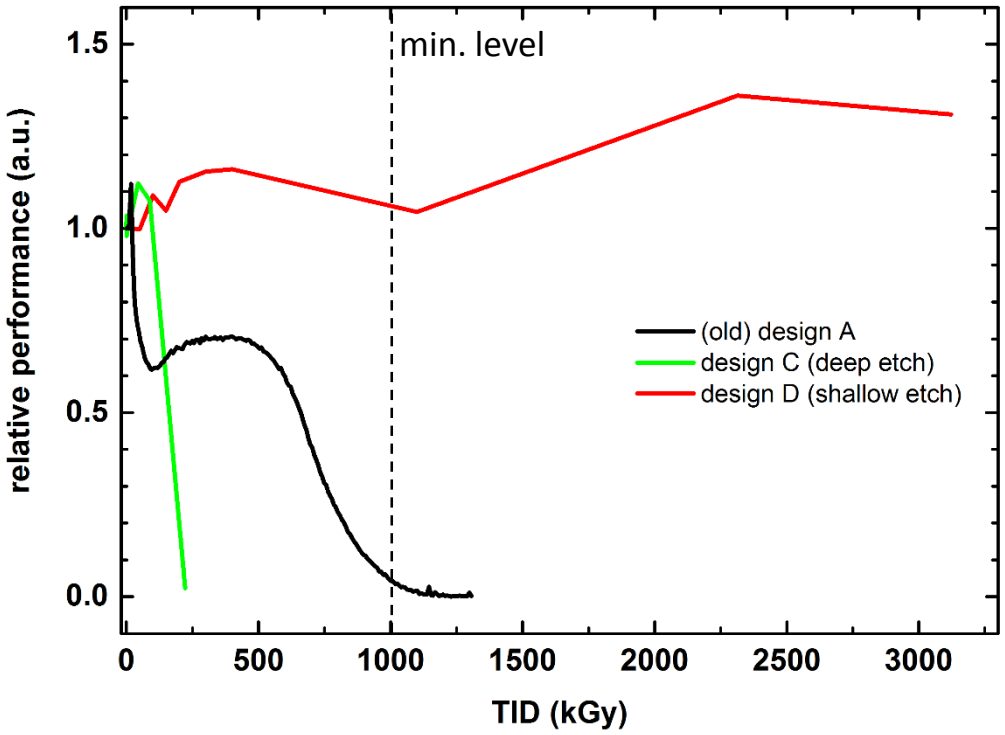


chip fabrication (by imec)

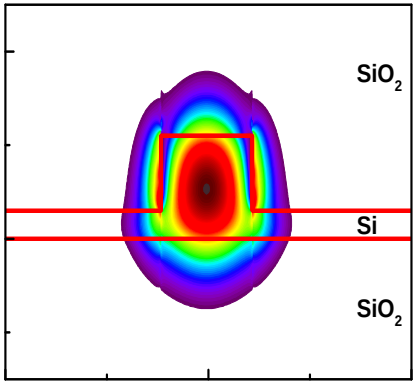
successful pre-testing and agreement with predictions



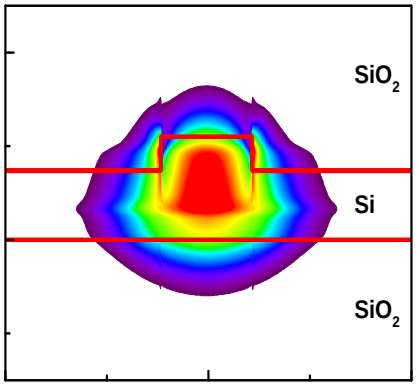
SiPh transmitter with a 5x higher radiation-hardness could be identified



"deep etch"
low radiation hardness



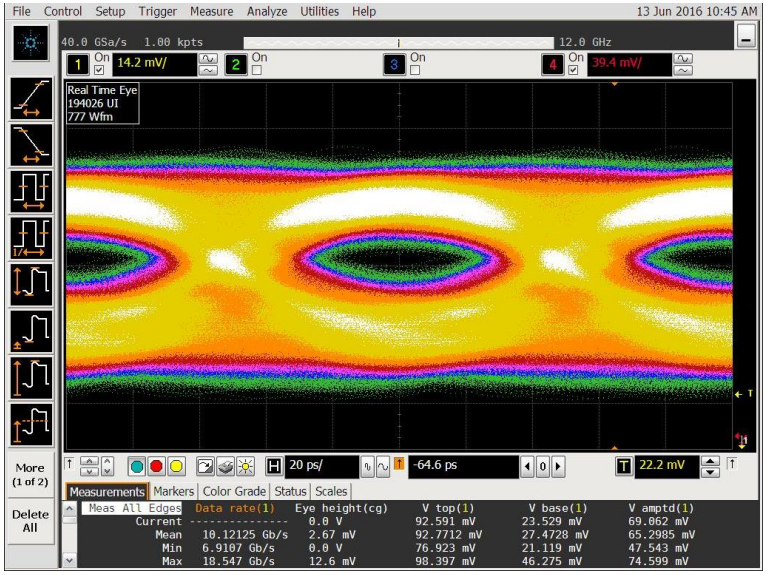
"shallow etch"
high radiation hardness



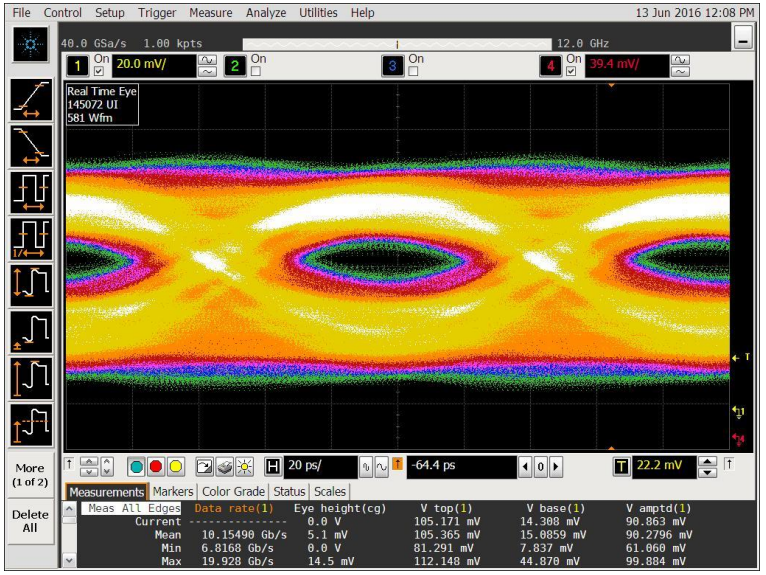
➔improved radiation hardness for SiPh transmitters with shallow etch depth

Data transmission quality of SiPh transmitter is not impaired by ionizing radiation

before irradiation



after TID of 2655kGy



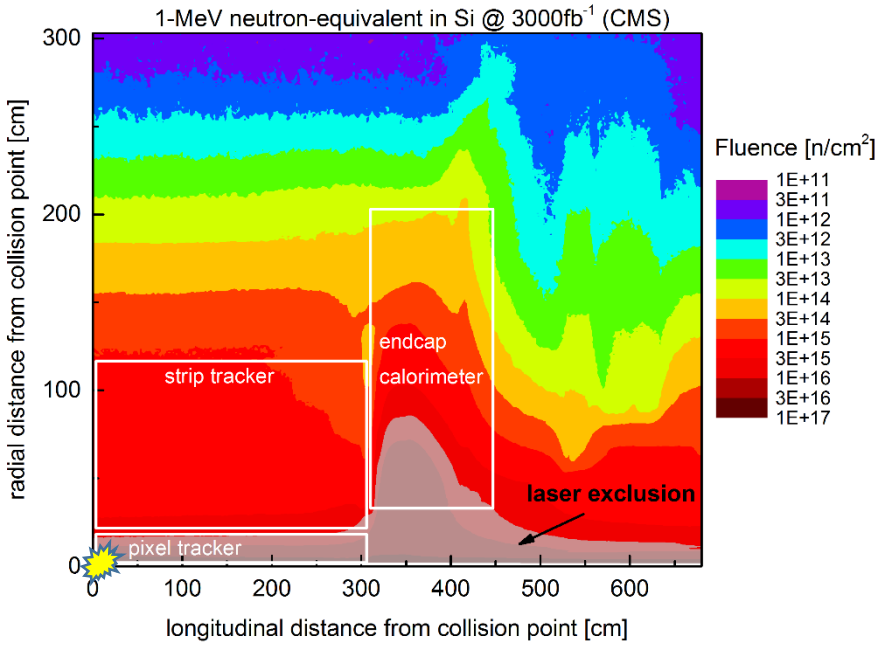
Data transmission tests made at 10Gb/s don't show degradation of transmitted signal after irradiation.

➔ **Demand for high bit-rate and radiation-hard transmitters can be met by SiPh**

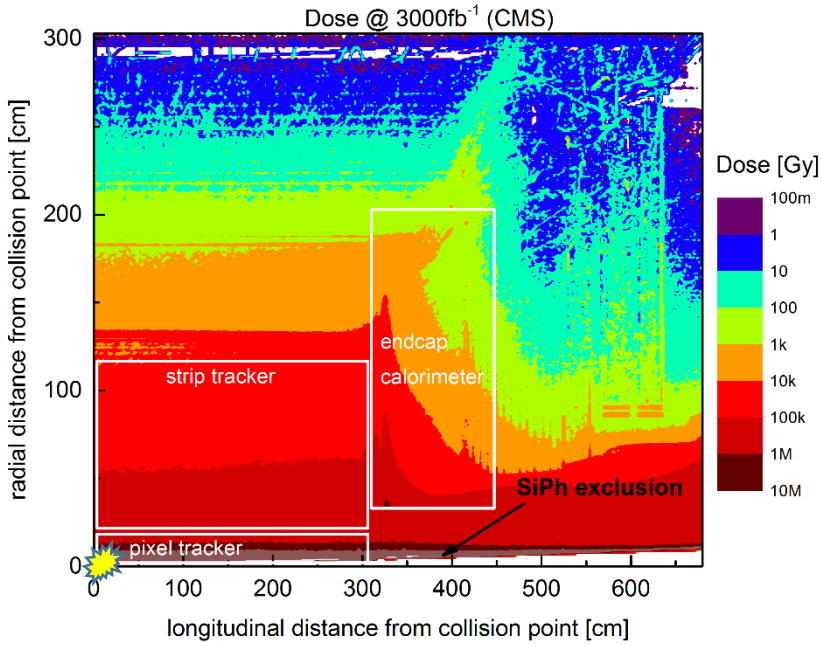
➔ **SiPh technology could be adapted to CERN's needs!**

Regions that were inaccessible for optical links before could now be reached with SiPh

laser based technology



SiPh transmitters

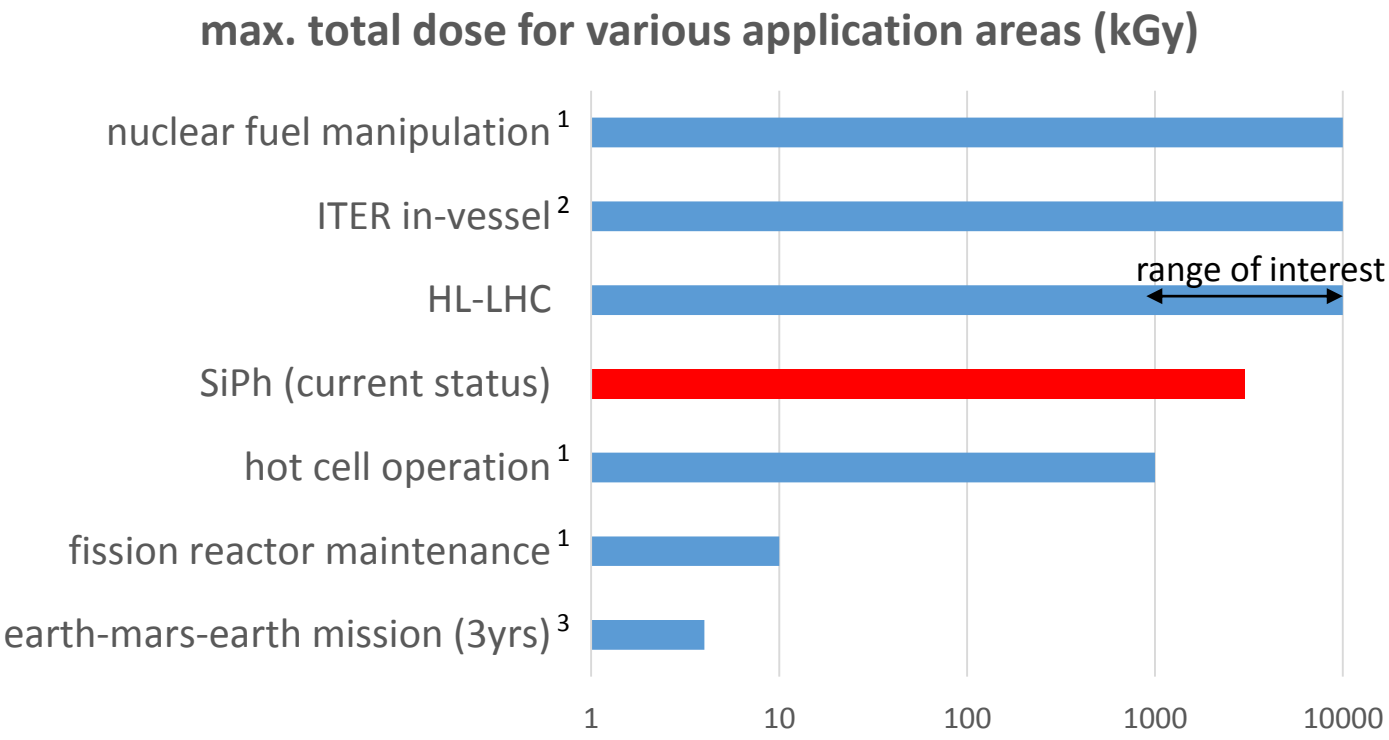


Currently used bulky copper wiring could be removed to access innermost sensors in detector.

➔ less material in detector

➔ possibility to read-out large amounts of collision data from innermost detector via optical links tightly integrated with particle sensors

Application of SiPh could be extended to other radiation sensitive fields



Possible fields of application

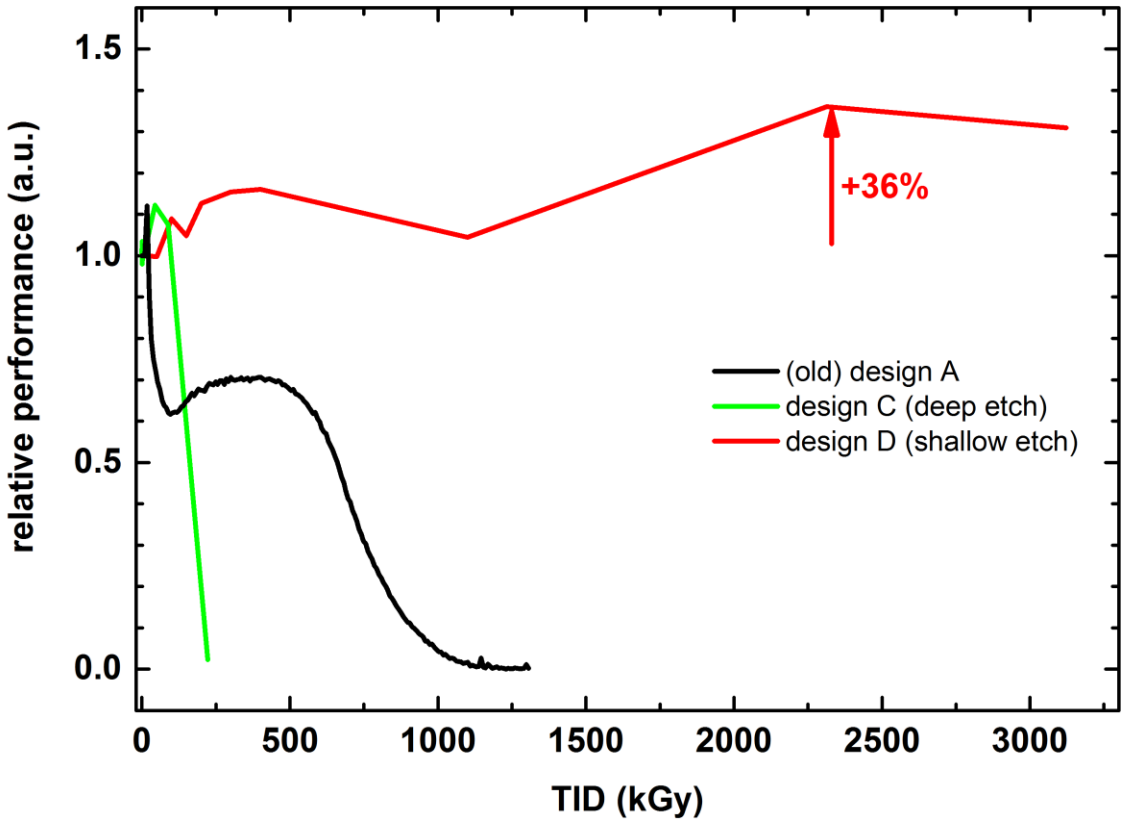
➔Civil nuclear industry

➔Medical applications

➔Air & space

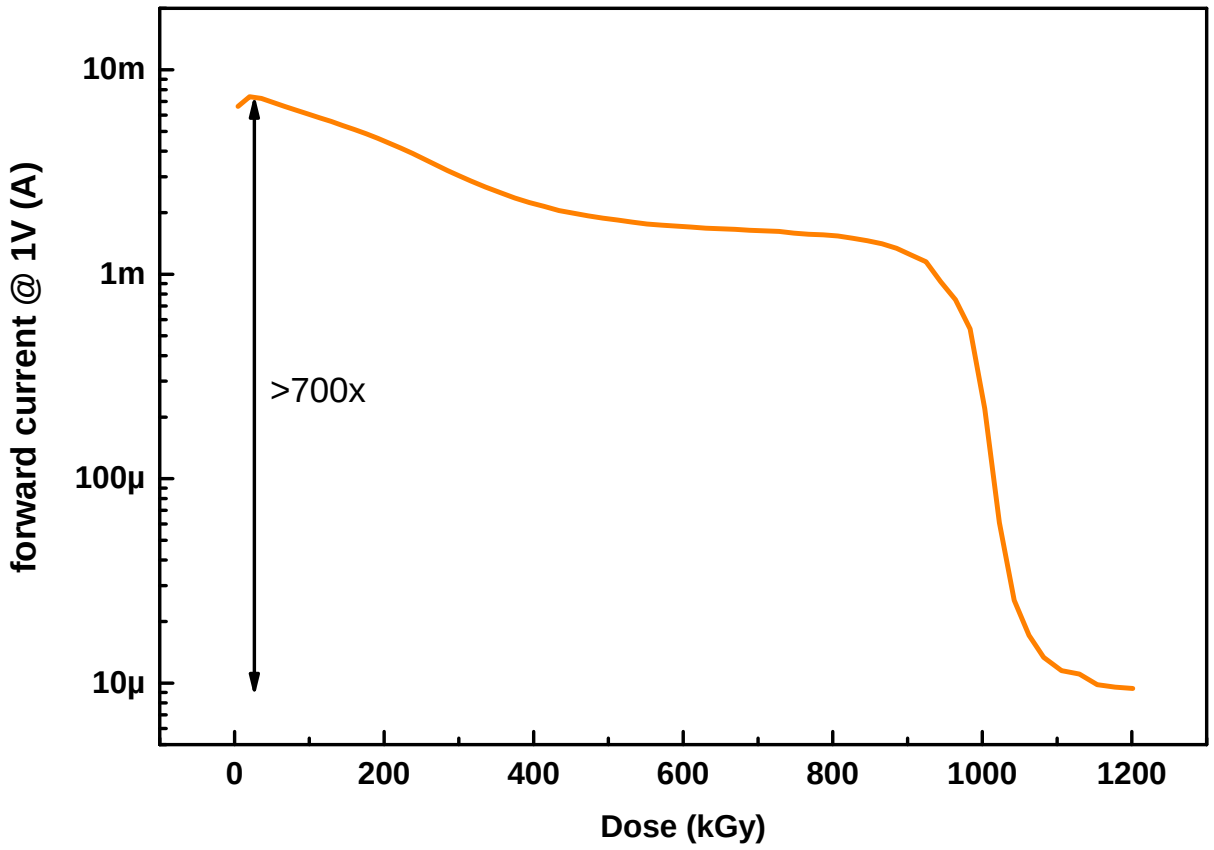
1) F. Berghmans et al., "An Introduction to Radiation Effects on Optical Components and Fiber Optic Sensors," in *Optical Waveguide Sensing and Imaging SE - 6*, 2008
2) M. Van Uffelen, L. Mont Casellas, "Radiation damage studies at F4E for ITER - from policies to case studies", in *22/05/2014 – RadWG @ CERN*
3) N. V. Kuznetsov et al., "Estimates of radiation effect for a spacecraft on the Earth-Mars-Earth route," *Advances in Space Research*, vol. 30, no. 4, pp. 985–988, 2002.

Performance of SiPh transmitters can be enhanced through ionizing radiation



➔ Could potentially be used to generally enhance performance of commercial SiPh transmitters

Changes in device's electrical characteristics could be exploited for radiation sensing



➔ Electro-optical sensor for ionizing radiation

Summary

Radiation-hardened, high bit-rate optical transceivers are required for future CERN experiments.

Silicon photonics (SiPh) technology was investigated because high bit-rate transmitters had already been demonstrated and a high radiation tolerance was expected.

SiPh test chip was designed and tested.

A SiPh transmitter design showing **5x higher radiation hardness** over other designs could be identified and is candidate for deployment in HEP experiments.

- SiPh allows transmission over longer distances & channel-multiplexing

Improvements made could open up new design paths for optical read-out systems at CERN enabled through **integrated modules** that could be in innermost detector regions.

- Research on SiPh will be continued after ICE-DIP by EP-ESE-BE Opto-Team.

Such SiPh transmitters could also be used in radiation sensitive **applications in air & space and civil nuclear industry or for radiation sensors**.

Outreach & Dissemination

Conferences:

- 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," in Topical Workshop On Electronics For Particle Physics (TWEPP), 2015.
- 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) (accepted for publication), 2016.
- M. Zeiler, S. Detraz, L. Olantera, C. Sigaud, J. Troska, and F. Vasey, "A system-level model for high-speed, radiation-hard optical links in HEP experiments based on silicon Mach-Zehnder modulators," in Topical Workshop On Electronics For Particle Physics (TWEPP) (accepted for publication), 2016.
- M. Zeiler, S. Detraz, L. Olantera, C. Sigaud, C. Soos, J. Troska, and F. Vasey, "Comparison of the Radiation Hardness of Silicon Mach-Zehnder Modulators for Different DC Bias Voltages," in IEEE Nuclear Science Symposium/Medical Imaging Conference (NSS/MIC) (accepted for publication), 2016.

Journal papers:

- 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.

Seminars:

- M. Zeiler, "Simulation and Design of Si-Photonic Mach-Zehnder Modulators for radiation hardness testing," EP-ESE-BE Student Seminar, 03/06/2015
- M. Zeiler, S. Seif El Nasr-Storey, "Radiation Hard Silicon Photonics Devices for Future High Speed Optical Links," EP-ESE Group Seminar, 09/02/2016

Magazine articles:

- M. Zeiler, "Silicon photonics explored for data links at CERN's LHC," *SPIE Professional*, pp. 10–11, 2015.
- M. Zeiler, "Data Acquisition at CERN: A Future Challenge," *IEEE Potentials*, pp. 36–39, 2016.
- M. Zeiler, "Silicon Photonic Components for Optical Data Links in High Energy Physics Experiments," *Europractice Activity Report*, pp. 28–29, 2015.

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