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CERN's LHC explores silicon photonics for data links

Next-generation optical components for the LHC must be faster and more resistance to radiation

By Marcel Zeiler

Big data is of the highest interest to CERN, the European Organization for Nuclear Research.

The 2012 discovery of the Higgs boson by the ATLAS and CMS particle detectors at CERN's Large Hadron Collider (LHC) was possible only because scientists could transmit, store, and analyze all the relevant data from the two experiments.

The four main particle detectors at CERN produce approximately 25 petabytes of data each year, taking up as much storage space as would a 175-year-long HD video file.

Before the detectors' raw measurement data can be analyzed for interesting and rare physics, it has to be sent approximately 150 meters from the particle detectors to their control rooms.

For this purpose, LHC currently has more than 100,000 optical links. Some of those are used to send timing and control signals to the accelerator and its subsystems. The majority of the links, however, provide the required bandwidth to read out the raw data of the particle collisions from the detectors.

Although fiber-optic links are widely deployed throughout the world, commercial, off-the-shelf optical data-transmission components usually cannot be used inside LHC's particle detectors because they must be small and lightweight and consume a minimum amount of electricity.

In addition to these packaging and power demands, the components must be designed to address the physical challenges imposed by the harsh environments such as the very strong magnetic fields (3.8 Tesla inside the CMS detector) and enormous levels of radiation.

OPTICAL COMPONENTS DAMAGED FROM RADIATION

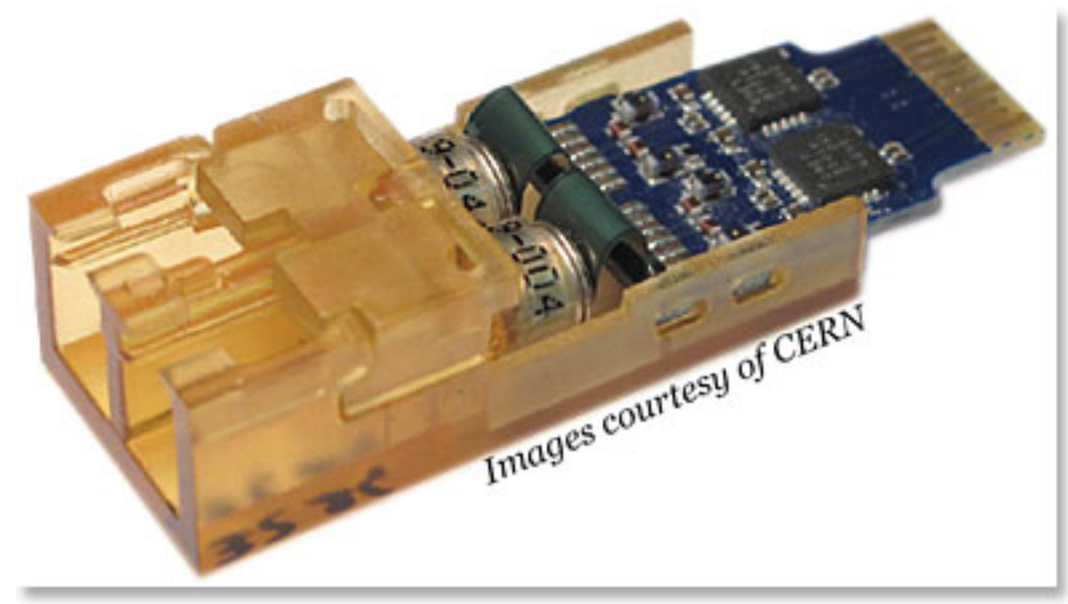
Among the various physical effects that can damage the optical components, radiation is typically the biggest concern.

Displacement damage caused by nucleons impinging on optical components, for example, creates atomic lattice defects that can introduce changes to fundamental material properties, thus impacting device performance.

Another concern is damage from incident high-energy photons, such as x-ray or gamma radiation, that lead to charge creation and trapping in the components. This trapped charge causes alterations of the electric field inside the components and also affects the component's operation.

VERSATILE OPTICAL LINKS

To mitigate these effects and meet the demands for the upgraded super LHC (to be called SLHC), scientists at CERN have developed so-called "versatile-link" optical components for LHC applications, based on III-V semiconductor materials. These versatile-link optical components are designed to withstand total ionizing doses (TID) of up to 10 kilo Gray. That's approximately 10,000 times higher than the dose to which the electronic components were exposed during NASA's Apollo missions.



A Versatile Twin-Transmitter (VTTx) developed at CERN and used at the Large Hadron Collider comprises two commercial, off-the-shelf, multi-mode, VCSEL laser diodes that have been qualified for radiation resistance and two laser drivers.

Versatile-link optical components must also be resistant against a fluence of up to 500 trillion (5e14) neutrons per square centimeter (about 50,000 times more than the fluence during the Apollo missions). The dose and fluence limits are defined such that the components' data-transmission quality will be kept above a predefined threshold during its 10-year life span.

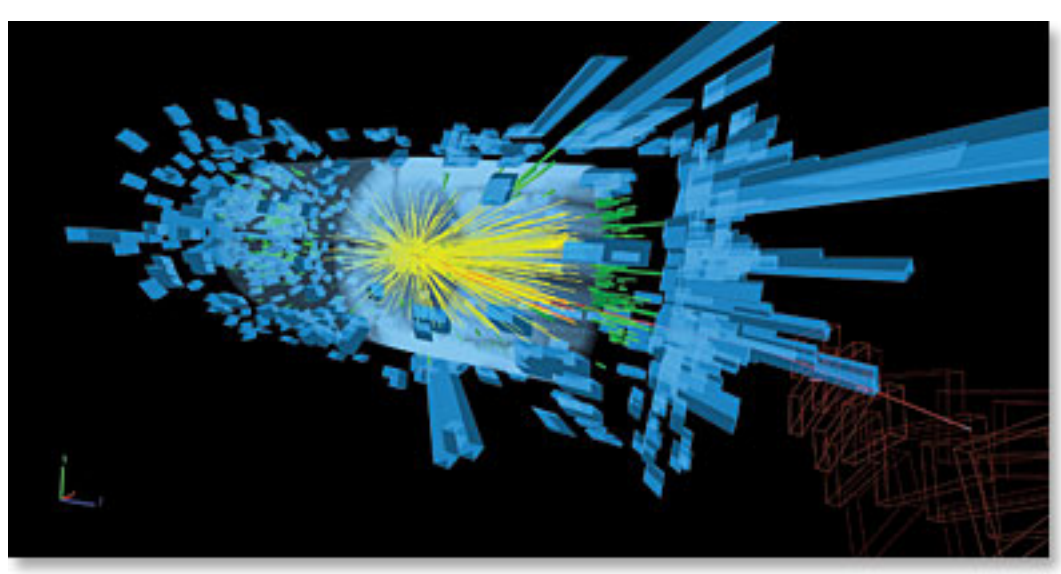
This is especially important since the high radiation levels inside LHC mean the optical components cannot easily be replaced during operation.

NEXT-GENERATION COMPONENTS FOR LHC

Even as these versatile-link optical components are to be installed in a 2018-2020 shutdown, it is already evident that next-generation optical components will be needed in 10 years when the high-luminosity-LHC (HL-LHC) starts its operation. The HL-LHC is an upgraded version of the SLHC, providing more particles for each collision and leading to even higher radiation levels as well as more measurement data.

So, the next-generation optical components must provide higher data rates and be much more radiation hard.

While current versatile-link optical components are composed of as many off-the-shelf parts as possible to keep manufacturing costs low, such parts cannot be used for the next-generation optical components. Thus, CERN is investigating custom optical components for HL-LHC use, with an emphasis on silicon photonics.



A proton-proton collision leaves multiple tracks in the different layers of the CMS detector after the restart of the LHC in July.

LHC EXPLORES SILICON PHOTONICS TECHNOLOGY

As part of the Intel-CERN European Doctorate Industrial Programme (ICE-DIP), our group chose to investigate silicon photonics technology because of its compatibility with CMOS fabrication, its possibility for integration with electronics, and because radiation-hard electronic components have been fabricated in silicon for a long time.

We made an initial assessment of the radiation hardness of silicon photonics with irradiation tests of silicon photonic interferometric modulators (see **dx.doi.org/10.1109/TNS.2015.2388546**). The modulators are based on a Mach-Zehnder design in which incoming light is split equally into two waveguides.

The optical path length, and thus the phase of the optical signal, in one waveguide is modulated by applying a voltage to a pn-junction incorporated into this waveguide. After recombining the light from both waveguides, phase modulation translates into an amplitude modulation.

The irradiation results show that the pn-junction's current leakage increases with neutron fluence and TID.

While the modulator's phase modulation efficiency does not significantly degrade during neutron irradiation, these initial results show that it falls to below 50% of its pre-irradiation value when the modulators are exposed to x-ray doses expected in HL-LHC.

These early findings indicate that additional research is necessary before silicon photonics components can be applied to LHC's environment. If the radiation hardness can be increased enough, silicon photonics could open up a new application area and contribute to future breakthroughs in particle physics at CERN.

The next step is to identify design parameters of Mach-Zehnder modulators that can be tailored in a way that the radiation hardness, particularly with respect to total ionizing dose, improves.

We are pursuing this work and are currently fabricating custom silicon-photonics Mach-Zehnder modulators. After those samples have been tested for radiation hardness, the research team will make a thorough assessment of silicon photonics for HL-LHC applications.

FACTS ON THE LARGE HADRON COLLIDER

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. It began operations in September 2008 and remains the latest addition to the accelerator complex at CERN, the European Organization for Nuclear Research.

The LHC consists of a 27-kilometer ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along a tunnel beneath the Franco-Swiss border near Geneva.

More than 10,000 scientists and engineers from 100 countries collaborated on the project.

- **March 2010 to February 2013:** First research run.
- **2012:** Higgs boson discovered.
- **February 2013 – July 2015:** LHC shut down for maintenance and upgrading.
- **July 2015:** LHC restarted for research "Run 2."
- **2018-2020:** LHC to be shut down for maintenance and upgrading, including installation of versatile-link optical components under the name Super LHC (SLHC).
- **2021:** SLHC expected to restart for "Run 3"
- **2023 or 2024:** SLHC to be shut down for upgrades, including radiation-hard components, for what will be called the High Luminosity LHC (HL-LHC).
- **2025 or 2026:** HL-LHC expected to restart operations.

–Marcel Zeiler is a PhD student at Dublin City University and a Marie Curie Fellow working on the ICE-DIP project. His research focuses on radiation-hard silicon-photonics components and their potential use in the harsh environments at the LHC. He has a BSc and MSc in physics and previously conducted research on directly modulated diode lasers for optical data communications at Fraunhofer Heinrich Hertz Institute for Telecommunications in Berlin.

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