Geant4 quartz fiber simulations as part of luminometer development for CMS

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Abstract. Measurements of luminosity are required to be exceedingly accurate for the new upcoming era of the LHC with higher energies and a more complex structure of the beam (HL-LHC). A new device is being developed for the CMS experiment to fulfill demands of being stand-alone and precise. The paper describes the design, main components and physics behind the new quartz fiber based luminometer (QFL). Via simulations of a single quartz fiber, we were able to calculate an average number of photons reaching the end of the fiber after a single particle hit.

1. Introduction
The new quartz fiber luminometer takes its inspiration from the HF – the Hadronic Forward calorimeter [1] that operates at CMS (CERN). However, the new era of the LHC places additional requirements on the detectors. We strive to address all of them by introducing a new device which will be robust and stand-alone. It will also provide bunch-by-bunch measurements of luminosity with uncertainty of not more than 1%.

1.1. Luminosity
Luminosity (L) measured in m$^{-2}$ s$^{-1}$ is the coefficient of proportionality between the cross-section of an event ($\sigma_p$) and the rate of such events [2, 3]:

$$\frac{dN_p}{dt} = \sigma_p \cdot L$$  \hspace{1cm} (1)

Luminosity is an important factor when considering the collider’s performance. Most collider experiments seek methods to push the limits of luminosity, since the increase in the statistical significance of rare events corresponds to the increase in the number of observed events.

If we integrate luminosity with respect to time, we’ll get another factor, called integrated luminosity. It is measured in fb$^{1}$ and also plays a role of a proportionality coefficient. The total number of events with a specific signature (e.g. the process of a particle production under investigation) can be calculated as follows:
\[ N_p = \sigma_p \cdot L_{\text{int}} \]  

(2)

The new era of the LHC is the high luminosity era, or HL-LHC. Its main objective is to increase luminosity up to \(5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}\) and integrated luminosity up to 250 fb\(^{-1}\) per year (3000 fb\(^{-1}\) in total) [4].

Collider experiments aim to test the predictions of established theories of physics and explore new ones. That is why observation of rare events and measuring their cross-sections become the priority. Due to the connection between cross-section and luminosity, the latter contributes to the large margin of error of the former. The errors in cross-section measurements that represent luminosity value accuracy are one of the biggest among all the uncertainties. That is why it is crucial to measure luminosity to the highest degree of certainty in order to eliminate those errors. The required uncertainty of integrated luminosity measurements of 1% allows to decrease the luminosity errors to almost negligible.

1.2. Time structure of the beam

Another important aspect of the collider is the beam, the beam time structure in particular. Hostettler (2018) provides a filling scheme of the LHC. The nominal filling scheme of the LHC is demonstrated in figure 1.

![Figure 1. The nominal filling scheme of the LHC](image)

The beam has a complex time structure consisting of periods of time with bunches (72 in each) spaced out by periods with various amounts of bunches missing. It is one of the objectives of the HL-LHC stand-alone luminometers to measure luminosity every bunch crossing (bunch-by-bunch) when beams of such structure collide.
The revolutionary frequency of the bunches of 11 kHz and the 25 ns spacing between individual bunches place limits on possible photodetectors and electronics when developing a stand-alone bunch-by-bunch precision luminometer.

2. Design of QFL
The QFL consists of detecting channels and readout electronics. Eight detecting channels are to be installed at the CASTOR table area (−5.2 > η > −6.6) of the CMS in a ring fashion around the beam pipe at the radius of 20 cm. A detecting channel is made up of a W/Cu block, which is called a converter, a quartz fiber bundle and a photodetector.

2.1. Converter
The converter is made of a W/Cu alloy and has a shape of a block with the dimensions of 2×2×6 cm³. The purpose of a converter, which will be placed in front of the quartz fiber bundle, is to multiply the signal from primary particles, thus providing a strong localized Cherenkov signal in the bundle. The signal is multiplied via the electromagnetic shower induced in the converter when a particle hits it creating a chain of electron, positron and photon production and multiplication.

2.2. Quartz fiber bundle
After passing through the converter, particles enter fibers collected in a bundle. When a charged particle (e.g. an electron or a positron) enters fiber material, Cherenkov radiation is produced. In order for photons to be produced, a particle needs to move through the medium with the speed higher than the speed of light in said medium. If that condition is met, photons are emitted on the surface of a cone with the angle θ:

\[ \cos \theta = \frac{1}{n\beta}, \]  

where \( n \) is the refractive index of the medium; \( \beta = \frac{v}{c} \), where \( v \) is the velocity of a traversing particle and \( c \) is the speed of light in vacuum.  

Cherenkov spectrum, or the number of photons generated per track length can be calculated as follows [5]:

\[ \frac{dN}{dx}(\lambda_1, \lambda_2) = \frac{2\pi z^2}{137} \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \sin^2\theta, \]  

where \( \lambda_1 \) and \( \lambda_2 \) represent the wavelength range in which the refractive index is assumed to be constant, \( z \) is the charge of an incident particle.

The purpose of the fiber bundle is twofold. Besides production of radiation, fibers are intended to transport [6] photons to a photodetector, which can be placed outside of the most damaging area. Quartz is chosen to be the core material for the fibers due to its status of one of the most radiation-hardened materials. It can withstand large amounts of radiation and thus will be used to distance the photodetector from the active zone.

2.3. Photodetector
There are a few possible options for a photodetector. They are SiPMs, PMTs and MCP-PMTs. We are currently investigating SiPMs, as they are considered ‘a “nearly ideal” photon detector’ [7]. Along with their response to the incoming Cherenkov photons, their radiation hardness is under investigation [8] so that they are able to withstand harsh new conditions of the HL-LHC. Other photodetectors are being researched and simulated as well. However, the choice of the photodetector
will not be made just after obtaining simulation results. Testing of several prototypes with a test beam is also required.

3. Geant4 simulation of single fiber
A single quartz fiber is the basis of the QFL. That is why it is important to have a complete and accurate model of the production and transportation of Cherenkov radiation before optimizations of any kind. For that purpose, a Monte-Carlo simulation was performed using C++ based simulation toolkit Geant4 [9, 10].

3.1. Geometry and materials
In the simulation a quartz fiber consists of three physical volumes, which are buffer, cladding and core. The volumes have cylinder form and are nested one inside each other. They form a fiber structure in a layered manner.

The fiber that was simulated is the Quartz-PolyClad fiber produced by Molex with the outermost diameter of 800 μm, which is where the buffer ends. Another layer is the cladding with the diameter of 630 μm. The last one is the core, which is 600 μm thick (figure 2). A physical structure with glass properties was added to the end of the fiber to be used as a detector.

![Figure 2](image)

**Figure 2.** Cross-section of the fiber (blue – core, green – cladding (clad), yellow – buffer)

Each layer has its own optical and material properties. The information about SiO$_2$ for the core, Polyethylene for the cladding and C$_4$H$_8$F$_4$ for the buffer was obtained from the manufacturer. Optical properties such as refractive indices and absorption lengths were added to Geant4 as well, thus, creating a complete and comprehensive Geant4 model of optical behavior in a fiber.

3.2. Simulation results
In order to obtain a distribution of the number of photons reaching the end of the fiber after a single incident particle, a simulation was run using the created model. A visualization of a single event of an electron hitting the fiber is shown in figures 3 and 4.
Figure 3. Event visualization. Red track (a) electron, green tracks (b) optical photons.

Figure 4. Event visualization. End of the fiber with a detecting volume (red (c) active area of the detecting volume.

A ‘particle gun’ was used to create $10^5$ events of electrons with the energy of 100 GeV hitting the fiber with momentum at the angle of 45 degrees relative to the axis of the fiber. All the data obtained using Geant4 and a few custom written methods were forwarded to and processed by ROOT. The result of that simulation run is shown in figure 5.

![Distribution of the number of photons that reached the end of the fiber](image)

Using the presented results, we can calculate that $18.41 \pm 0.02$ photons reach the end of the fiber on average.

4. Conclusion
A new quartz fiber based luminometer for CMS was introduced with detailed explanation of the physics behind its operation. The purpose of each component was described: the importance of shower multiplication of the signal from incident particles in the converter and the dual aim of the fiber bundle. Cherenkov radiation as one of the main components of signal creation was extensively...
explained. The simulation of a single fiber, which resulted in a number of photons reaching the end of the fiber per single hit, was demonstrated with a visualization. A further study with the comparisons of simulated results and experimental data will yield a comprehensive and accurate model of a fiber which will become the basis of all future simulations.

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References

[1] Penzo A and Onel Y 2009 J. Phys.: Conf. Ser. 160 012014
[2] Karacheban O 2017 Luminosity measurement at CMS CERN-THESIS-2017-246
[3] Hostettler M 2018 LHC Luminosity Performance CERN-THESIS-2018-051
[4] Apollinari G et al 2017 CERN Yellow Reports: Monographs 4/2017 CERN-2017-007-M
[5] Abramov A I, Kazansky Yu A and Matusevich E S 1985 Principles of experimental methods in nuclear physics (Moscow: ATOMIZDAT press)
[6] Ghatak A and Thyagarajan 1998 An Introduction to Fiber Optics (Cambridge: Cambridge University Press.)
[7] Vinogradov S and Popova E 2019 Nucl. Instrum. Methods Phys. Res. A 952
[8] Garutti E and Musienko Yu 2019 Nucl. Instrum. Methods Phys. Res. A 926 69
[9] Geant4 Collaboration 2019 Geant4 Physics Reference Manual
[10] Akchurin N et al 2014 Nucl. Instrum. Methods Phys. Res. A 762 100