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Geant4 simulation as part of luminometer development for CMS at HL-LHC

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ABSTRACT

Luminosity is one of the main characteristics of an accelerator. It determines the number of colliding particle (e.g. protons) interactions in a bunch crossing. The task of luminosity measurements in two-beam experiments is challenging. It becomes harder with the LHC upgrade – High-Luminosity LHC – with even higher energies, luminosity and a complex time structure of the beam. The proposed luminometer is being designed to perform online bunch-by-bunch luminosity measurements with the frequency of 25 ns, the accuracy of 1% and the ability to withstand high radiation. The proposed for this task radiation hard quartz fibers are simulated using Geant4: the physics, geometry and optical parameters are varied to optimize the accuracy of the processes of emission, capturing and transportation of Cherenkov light.

PRINCIPAL OF OPERATION

There are two main components in the proposed luminometer: an absorber made of a dense material (e.g. copper, lead, tungsten) and quartz fibers imbedded in it. An incident particle creates electro-magnetic showers inside the absorber that produce Cherenkov photons inside the fibers. Created photons get transported by the fibers and registered by a photodetector (e.g. PMT, SiPM). A version of the detector is shown in figure 1.

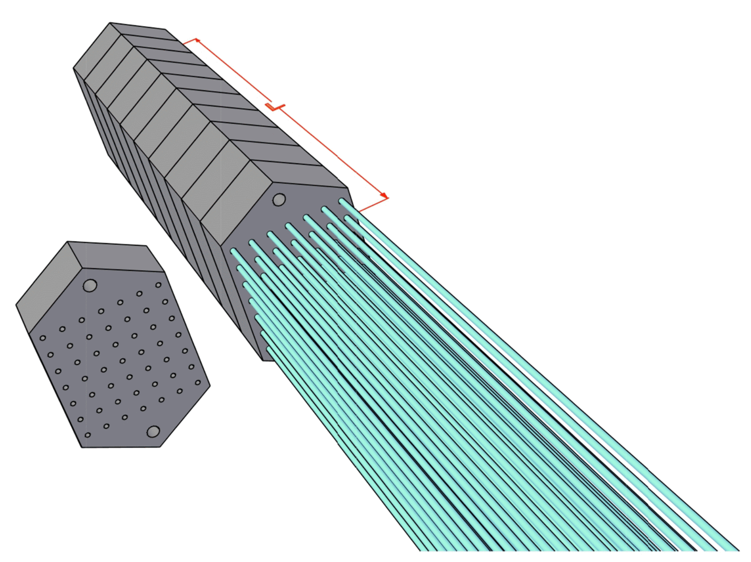


Figure 1. A version of the luminometer. Grey – an absorber, blue – quartz fibers.

Such a detector has a lot of advantages: quartz – is one of the most radiation hard materials, also due to the nature of all of the components, its response is very fast (under 25 nsec) and it can be compact. Everything mentioned above fulfils the requirements for the luminometer: it needs to withstand high radiation conditions of the HL-LHC, provide online measurements of the luminosity in order to control beam accuracy or even initialize a shut down in the event of the emergency [1, 2].

CHERENKOV LIGHT

Cherenkov photons are produced when a charged particle traverses a medium with its speed higher then the velocity of light in that medium. The photons are emitted in the surface of a cone with angle θ,

$$v > \frac{c}{n} \qquad \cos\theta = \frac{1}{n\beta} \qquad \beta = \frac{v}{c}$$

Where c is the speed of light, n – the refractive index of the medium and v – the velocity of the traversing particle.

Cherenkov photons are produced when a charged particle traverses a medium with its speed higher then the velocity of light in that medium. The photons are emitted in the surface of a cone with angle θ with respect to the direction of the particle. The number of photons generated per track length can be calculated:

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

where λ1 , λ2 – wavelength range for the calculation, since the index of refraction is dependant on it, z – charge of the incident particle. [3, 4]

GEANT4 MODEL

The simulation is carried out using Geant4. First, the testing setup is simulated. It consists of a Sr-90 β-radioactive source, a single quartz fiber from from Polymicro/Molex (600630800). The fibers have a 600 µm diameter fused-silica core, 630 µm with the polymer hard-clad, and 800 µm with protective acrylate buffer. Two scintillation triggers made of PMMA (2 x 2 x 2 mm) are placed underneath the quartz fiber, one after the other. PMTs are connected to both sides of the fiber. Trigger and PMT signals are recorded by the oscilloscope.

The Geant4 model has a fused silica core and Methyl 2-fluoroacrylate (C4H5FO2) cladding (2 m long). Two counting volumes are placed on both sides of the fiber. Two triggers are placed underneath the fiber. The source is simulated by emitting 1 MeV electrons from a circle with the diameter of 1 mm. The placement of the source (and the direction of electrons) an be changed.

A schematic of the Geant4 model is shown in figure 2. The sizes are not in proportion to each other.

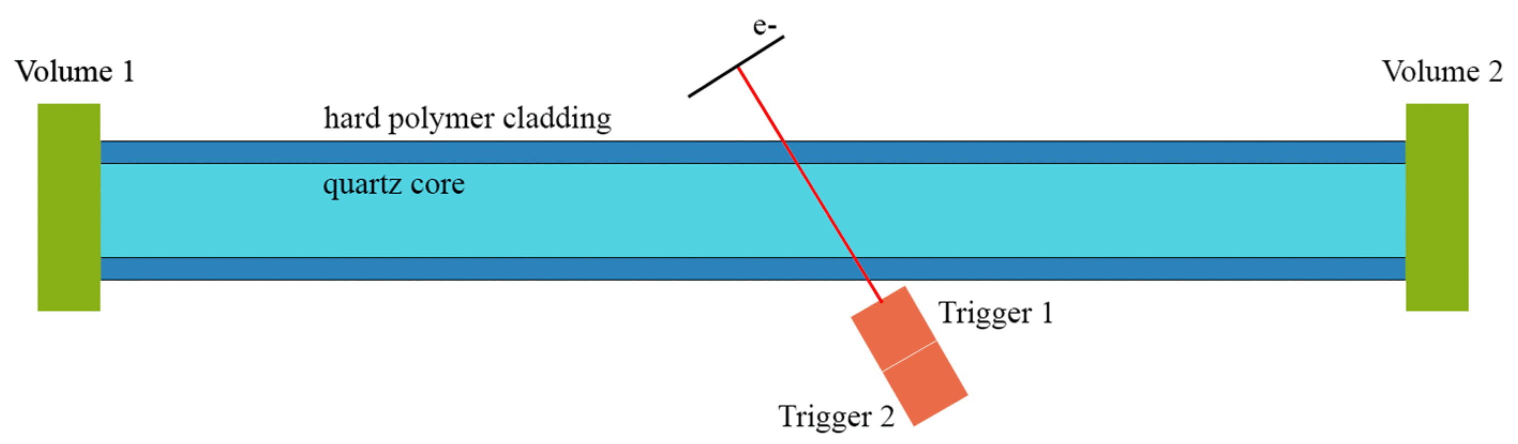
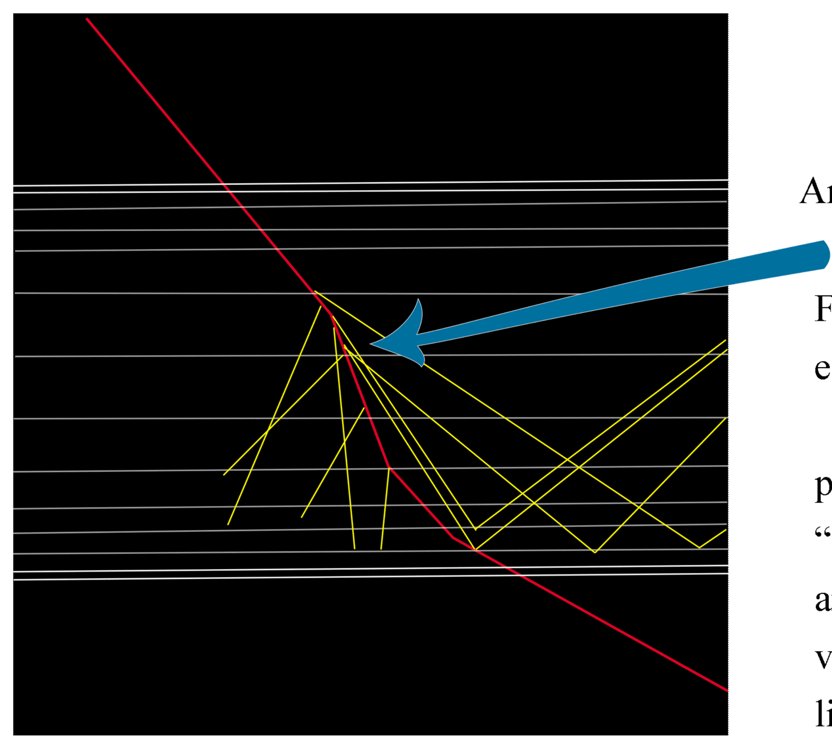


Figure 2. A schematic of the Geant4 simulation. Green – counting volumes 1 (left) and 2 (right), light blue – quartz core, dark blue – hard polymer cladding, orange – triggers 1 (up) and 2 (down), black – an electron source, red – electron momentum direction

Electrons are emitted and if they traverse the fiber, Cherenkov radiation is produced. Created photons (if their angle of emission is larger than the critical angle of the fiber ~ 75°) are reflected and transported to counting volumes,



Angle θ – angle of emission of Cherenkov photons

Figure 3. Visualization of a single event. Red – electron track, yellow – photon tracks.

Due to the electron incident angle fewer photons that are emitted (at the angle θ) on the "left" side of the track get captured in the critical angle of the fiber, therefore fewer of them get to volume 1. On the other side photons are more likely to be transported to the counting volume 2.

RESULTS

The results were obtained by simulating 5000 events of monoenergetic 1 MeV electrons emitted from the source. The angle of thei direction is 40 degrees relative to the vertical. Energy deposition in both triggers and the fiber was tracked and number of photons in both counting volumes 1 and 2 was counted. The resulting histograms of number of photons in the counting volumes are shown in figure 4. Energy deposition inside both triggers is shown in figure 5.

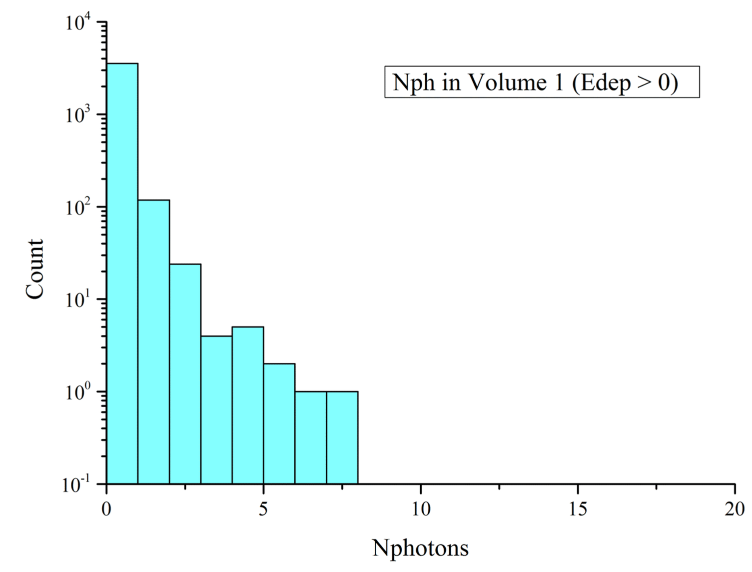


Figure 4a. N photons in volume 1 (Edep in fiber > 0)

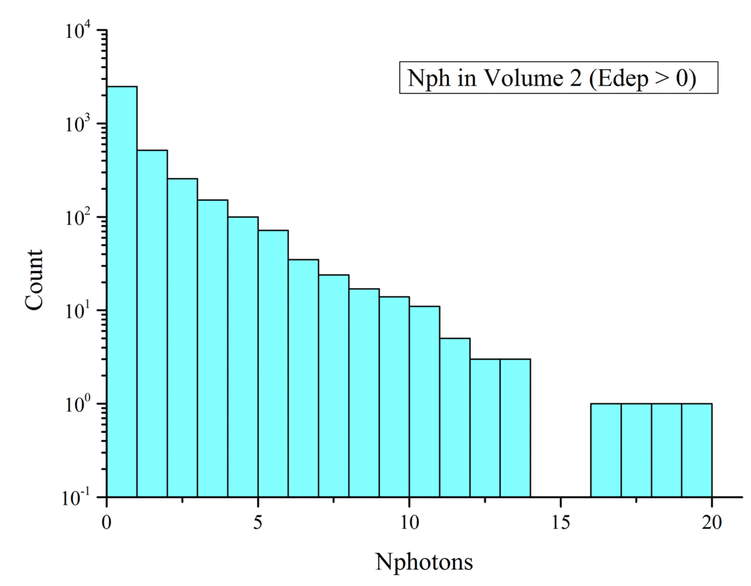


Figure 4b. N photons in volume 2 (Edep in fiber > 0)

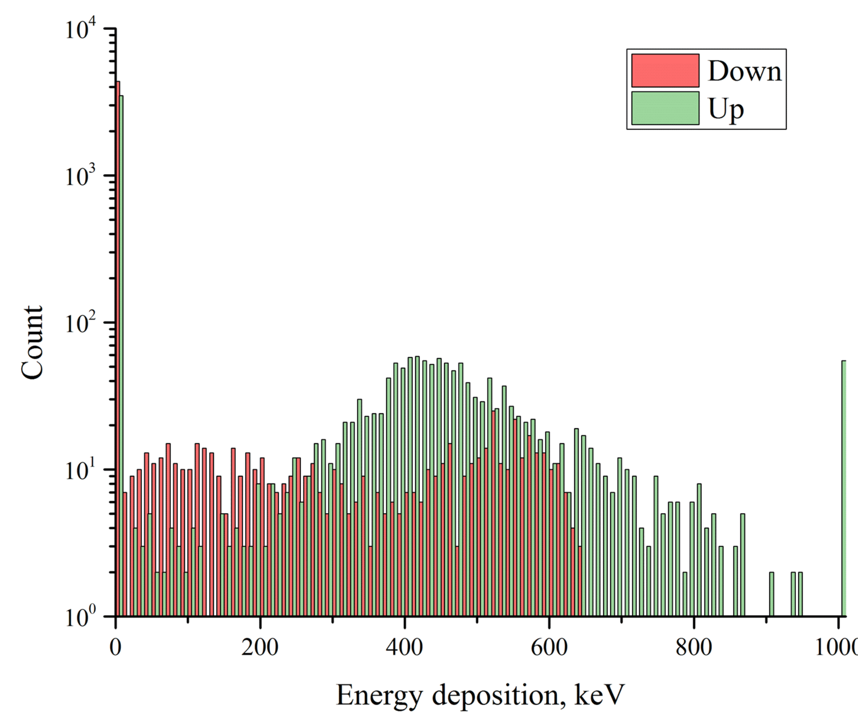


Figure 5. Energy deposition in up (green) and down (pink) triggers

CONCLUSION

Simulation is one of the key aspects in the development of new equipment. An accurate model (that which is tested against experimental results) can provide insight into new ways of detector construction.

Geant4 model was developed to simulate experimental testing of the fibers and photodetectors proposed for the luminometer. Cherenkov light production was simulated and the number of produced photons was calculated. Both experimental and simulation results show a need of further development and testing. The dependence of the signal on the angle of incident particle is to be simulated.

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