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Study on Geant4 Simulation of Cherenkov Photons Generation and Propagation in Quartz Core Fibers

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Abstract

In today's world, quartz-core fibers are extensively used in scientific studies due to their high radiation resistance. Thanks to the quartz core's ability to generate Cherenkov photons and propagate these photons, as well as those entering the fiber from outside, it is frequently studied in the context of high-energy and nuclear physics for detector designs. In this paper, a detailed simulation was developed using the Geant4 simulation application, focusing on the photon production and propagation capabilities of quartz-core fibers. Molex's recently developed FBP (FBP600660710) broadband quartz-core fibers were integrated in the simulation environment. The production and propagation of Cherenkov photons were tested by having a charged particle pass through a specific impact point and angle on a quartz-core fiber. Based on the obtained data, reflectors were integrated onto the open end surface of the fiber to reduce photon losses, and tests were conducted again. The effects of fiber length on the photon-carrying capacity of the fiber were also tested.

Keywords: Quartz fibers, Cherenkov photons, photon propagation, geant4 framework.

Kuvars Çekirdekli Fiberlerde Cherenkov Fotonlarının Üretimi ve İletimi Üzerine Geant4 Simülasyon Çalışması

Öz

Günümüzde kuvars çekirdekli fiberler hem iletişim hem de yüksek radyasyon dirençleri sayesinde bilimsel çalışmalarda yoğunlukla kullanılmaktadır. Fiberin kuvars çekirdeği Çerenkov fotonu üretebilme ve üretilen bu fotonları yada dışarıdan fiber içerisine giren fotonları iletebilme kabiliyeti sayesinde yüksek enerji fiziği ve nükleer fizik alanlarında dedektör tasarımlarında sıklıkla kullanılmaktadır. Bu çalışmada, kuvars çekirdekli fiberlerin foton üretimi ve iletimi üzerine Geant4 simülasyon uygulaması kullanılarak detaylı bir simülasyon geliştirilmiştir. Geant4 simülasyon ortamında Molex firmasının son dönemlerde geliştirmiş olduğu FBP(FBP600660710) geniş bant kuvars çekirdekli fiberleri kullanılmıştır. Bir kuvars çekirdekli fiber üzerine belirli çarpma açılarında ve fiber üzerindeki belirli çarpma noktalarına yüklü parçacıklar gönderilerek, fiberin Çerenkov fotonları üretimi ve iletimi incelenmiştir. Elde edilen verilere dayanarak, foton kayıplarını azaltmak amacıyla fiberin açık ucuna yansıtıcı entegre edilerek testler tekrar gerçekleştirilmiştir. Fiber uzunluğunun fiberin foton taşıma kapasitesi üzerine etkileri de incelenmiştir.

Anahtar Kelimeler: Kuvars çekirdekli fiber, Çerenkov fotonları, foton üretimi ve iletimi, geant4 simülasyon uygulaması.

INTRODUCTION

Quartz-core fibers are used in global communications infrastructures that can transmit data over photons with minimal loss. Figure 1 illustrates the improvement of photon transmission in optical fibers over the years. Quartz-core fibers are not only used in communication infrastructure but are also widely applied in scientific research. As shown in Figure 1, the photon transmission capability of Quartz-core fibers has improved over the years, making them more suitable for scientific research (Wandel, 2005). These fibers are used in high-energy

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physics for both detector development and data transmission.

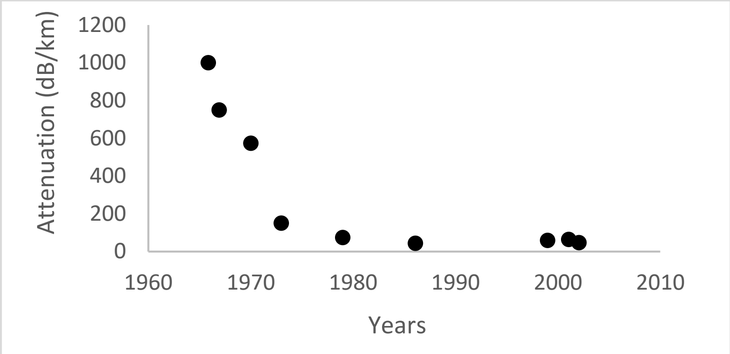

Figure 1. Evolution of optical fiber loss reduction over the past decades, starting from 1965 (Wandel, 2005)

In addition to its use in high-energy and nuclear physics, another important factor in the use of Quartz-core fibers is their high resistance to radiation (Cankocak et al., 2019; Girard et al., 2019; Hagopian, 1999; Kharzheev, 2019; Thomas, 2024). The Large Hadron Collider (LHC) is engineered to achieve a center-of-mass energy of 14 TeV in proton-proton collisions every 25 ns. However, now the LHC is being upgraded to High Luminosity Large Hadron Collider (HL-LHC), which will operate at 5 times higher luminosity ($L = 5 \cdot 10^{34} cm^{-2} \cdot s^{-1}$) and is likely to reach ($L = 7.5 \cdot 10^{34} cm^{-2} \cdot s^{-1}$) , enabling new physical discoveries. With the advent of HL-LHC, detectors operating at higher luminosity values and the currently used wavelength shifter (WLS), and other fibers will be exposed to higher radiation. Their high radiation resistance will make Quartz-core fibers more suitable for use in detectors and devices at HL-LHC that operate at higher luminosities. We have extensively discussed the development and optimization of Geant4 simulations for the geometry of a tungsten quartz fiber luminometer designed for application in the CMS experiment during the HL-LHC era (Selivanova et al., 2020; Sunar Cerci et al., 2023).

When relativistic charged particles pass through the Quartz-core fibers, they generate Cherenkov radiation and propagate the photons. Quartz-core fibers are valuable in detector designs for detecting charged particles in the environment. The fibers are usually used so that one end is integrated into a converter plate or scintillator in the detector and the other end is connected to a photodetector for photon readout. Not only for the propagation of photons but also for the generation and capture of Cherenkov photons, the impact angles, and locations of charged particles on the fibers are of critical importance. These impact angles and impact points of charged particles on Quartz-core fibers determine the number of photons the fiber generates and propagates. Similarly, the refractive indices and the dimensions of the core and cladding of the fiber determine the number of photons generated and propagated.

In this study, investigations of the generation and propagation of Cherenkov radiation in Quartz-core fibers were performed using the Geant4 simulation toolkit. As the impact angles and impact points of charged particles on Quartz-core fibers change, the number of photons generated and propagated by the fiber, as well as their motions within the fiber, were studied and analyzed.

MATERIAL AND METHODS

Properties of Quartz Fibers

Quartz-core fibers are manufactured worldwide for various purposes. Molex is one of the companies that manufacture various fibers, and the fiber used in this study is the Quartz-core FBP broadband fiber (FBP600660710) manufactured by Molex.

The quartz core fiber used in this study has a core diameter of 600 micrometers, a cladding diameter of 660 micrometers, and a buffer diameter of 710 micrometers (Figure 2). Due to the low content of OH in its structure, it exhibits high radiation resistance. The wavelength range of photon transmission is between 275 nm and 2100 nm as shown in Figure 3. It can successfully transmit photons in the UV and NIR regions. The core is made of quartz material with

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a chemical structure of SiO_2, while the cladding is made of doped silica. These fibers can operate at temperatures between -65 and +300 degrees Celsius.

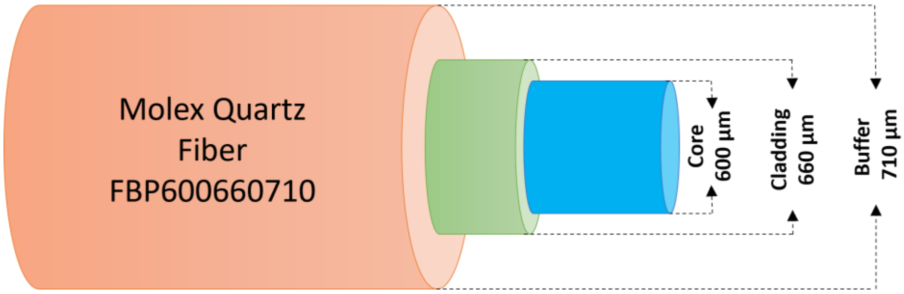

Figure 2. Cross-section of the FBP fiber (the core is blue, the cladding is green, and the buffer area is orange.) (Polymicro Molex, 2023)

The numerical aperture between the cladding and the core is 0.22 (Polymicro Molex, 2023).

Cherenkov Photon Production and Propagation in Fiber

The refractive indices of the core and cladding of the fiber are crucial for photons to propagate in the fiber. A photon entered the fiber from outside or generated inside the fiber propagates inside the fiber by hitting the cladding at certain angles. In this study, the propagation of Cherenkov radiation generated inside the quartz-core fiber was investigated. Cherenkov radiation forms at a certain angle in a cone shape.

There is a relationship between the refractive index and this angle called the Cherenkov relation (Béjar et al. 2020; Polymicro Molex, 2023). The opening angle of the Cherenkov cone is defined as:

$$\theta = \frac{1}{\beta n}, \quad \beta = \frac{v}{c}$$

where θ is the Cherenkov angle as shown in Figure 4, β is the rate constant, and n is the refractive index of the medium

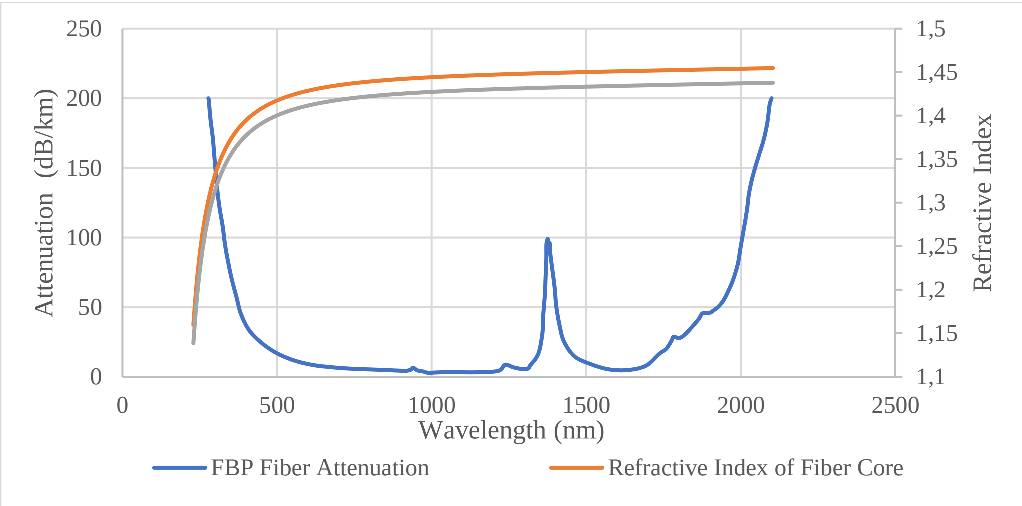

Figure 3. Wavelength-dependent properties of the FBP600660710 Quartz-core fiber are detailed in the graph. The orange curve represents the refractive index of the fiber core (Malitson, 1965), the gray curve indicates the refractive index of the fiber cladding (Malitson, 1965), and the blue curve outlines the fiber's attenuation (Polymicro Molex, 2023)

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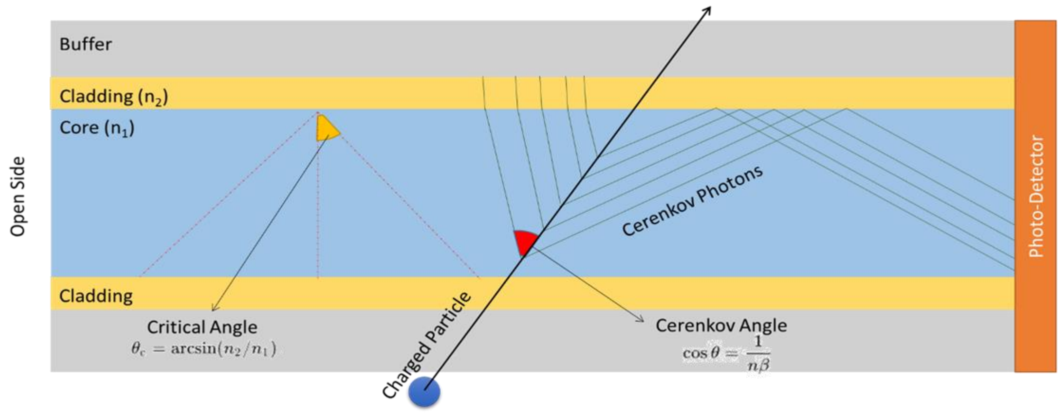

Figure 4. Side cross-sectional view of a three-layered Quartz-core fiber. When a charged particle passes through the fiber, it produces Cherenkov photons, whose movement is shown within the fiber

The Cherenkov angle, at which the Cherenkov photons are produced, depends on the refractive index of the medium within the fiber. The refractive indices as a function of wavelength for quartz material are shown in Figure 3. After the Cherenkov photons are generated in the fiber, they must exceed the critical angle (Bahaa and Malvin, 1991).

For a Cherenkov photon to propagate inside a quartz-core fiber, both the critical angle and the Cherenkov angle are significant and interrelated (Wolfenden et al., 2023). In Figure 4, the Cherenkov and critical angles are shown on a plane. However, the Cherenkov angle has a conical structure, and the fiber has a cylindrical shape. The variation of refractive indices with wavelength, the changes in the Cherenkov and critical angles depending on the refractive indices, and the photon propagation tunnel in the cylindrical structure of the fiber make the calculation process of photon transmission quite complex. Therefore, tests can be conducted through a simulation tool, and the photon transmission capabilities of the fiber under various impact angles can be examined. In this study, Cherenkov photons generated by a charged particle impacting at 11 different angles (15º, 30º, 45º, 60º, 75º, 90º, 105º, 120º, 135º, 150º, 165º) and impacting 7 different points on the fiber (0 µm, 50 µm, 100 µm, 150 µm, 200 µm, 250 µm, 300 µm) were investigated, as well as their propagation. Moreover, to prevent photon loss, a reflector was integrated into the open end of this fiber, and tests were conducted again.

Geometric Structures and Geant4 Simulation Details

The Geant4 Simulation toolkit, developed by the European Council for Nuclear Research (CERN), is frequently used in branches of physics such as high-energy and nuclear physics (Agostinelli, 2003; Chen, Hu, Zhong, 2022; Geant4, 2023; Geant4 Collaboration, 2023). In this study, a simulation for a Quartz-core fiber was prepared using the Geant4 simulation toolkit. The geometry was integrated into the Geant4 simulation toolkit as shown in Figure 5, and the experimental data for this geometry, presented in Figure 3, was added with their detail.

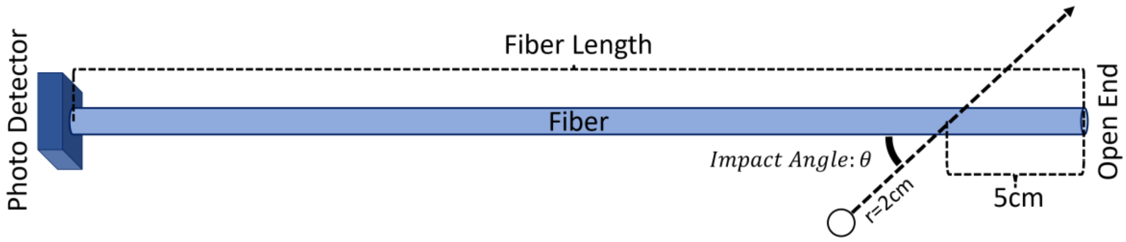

Figure 5. The design and placement geometry of a quartz-core fiber in the Geant4 simulation space is illustrated in the figure. The charged particle (beam) impacts the fiber's open end or its coated end, 5 cm before the open end of the fiber, from a distance of 2 cm and at an impact angle θ

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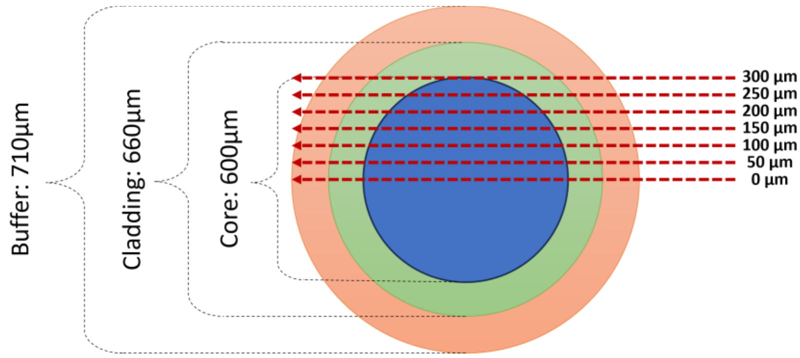

Figure 6. Cross-sectional view of a three-layered Quartz-core fiber is illustrated in the figure. Within the Geant4 simulation space, a particle is configured to impact seven different points on the fiber

The three-layered fiber structure presented in Figure 2 extends homogeneously along the fiber. One end of the fiber is connected with a photodetector, while the other end is left open (Open End). Electrons with an energy of 10GeV are directed towards the fiber at an impact angle of θ, 5 cm away from the open end. The electron is directed 2 cm from the impact point on the fiber.

As seen in Table 1, the simulation has been repeated for a total of 770 different combinations with 4 different parameters. Firstly, the open end of the fiber has been touched to the air. Due to this, some of the photons escape from the open end, while some reflect back. If a Tyvek reflector is integrated at the open end, most of the photons no longer escape and move back toward the photodetector. The second parameter is the change in the length of the fiber. The manufacturer's experimentally obtained attenuation is presented in Figure 3 has been integrated directly into the simulation. As the length of the fiber changes in the simulation, the absorption of the photons also changes. The third parameter is the angle at which the particle impacts on the fiber. The effect of the impact angle on photon generation and propagation to the photodetector can be observed with this simulation. The part where photons travel inside the fiber is the core, thus the photons generated in this section are crucial. The final parameter is the point at which the particle impacts the fiber, which is changed at regular intervals from the center of the fiber's core to its outermost part. Since the fiber has a cylindrical structure, when a particle impacts different points, the propagation of the resulting Cherenkov photons will differ due to the critical angle.

Table 1. *The setup parameters of the Geant4 simulation for a Quartz-core fiber*

Simulation Parameters		
1	End of Fiber	With Tyvek Reflector , Without Reflector
2	Length of the Fiber	5 m, 10 m, 20 m, 50 m, 100 m, 200 m, 500 m, 1 km
3	Impact Angle	15º, 30º, 45º, 60º, 75º, 90º, 105º, 120º, 135º, 150º, 165º
4	Impact Point	0 µm, 50 µm, 100 µm, 150 µm, 200 µm, 250 µm, 300 µm

RESULTS AND DISCUSSION

The Geant4 simulation for the FBP Fiber, as presented in Table 1, was conducted using varied values of four distinct parameters. Using the Geant4 Particle Generator, electrons with an energy of 10 GeV are directed towards the fiber. Upon impacting the fiber, these electrons produce Cherenkov photons, which then propagate towards both ends of the fiber. Efficiency values are determined by taking the ratio of the number of Cherenkov photons produced within the fiber to the number of photons that reach and reflect from its ends. These values are crucial for understanding the quantity of photons that successfully propagate within the fiber. Our goal is to

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understand the mechanism through which the fiber produces Cherenkov photons and transmits them. The results of this study will ensure more efficient utilization of FBP fibers in detector designs.

In detector systems, charged particles can impact any point on the fiber at any given impact angle. Figure 7 shows the distribution of the number of photons produced inside the fiber by particles impacting at 7 different points, based on their impact angles. The impact points are illustrated in Figure 6. Cross-sectional view of a three-layered Quartz-core fiber is illustrated in the figure. Within the Geant4 simulation space, a particle is configured to impact seven different points on the fiber. Tests were conducted by increasing the distance by 50 micrometers from the center of the fiber outward at each step. According to the simulation results, the highest photon production occurs at the center, and the number of photons decreases as we move outward from the center. The fewest photons were measured at the core boundary of the fiber, which is 300 micrometers. The maximum photon production for all impact points is observed at 15º and 165º. This value decreases from 15º to 90º and then increases again from 90º to 165º. The reason for this is that charged particles travel a longer distance inside the fiber at 15º and 165º. The longer a charged particle travels within the core of the fiber, the more Cherenkov photons it will produce.

Since one end of the fiber is inside the detector systems, it can be used with an open, closed, or reflective coating. When charged particles pass through the fiber, the Cherenkov photons produced move within the fiber in both directions. The Cherenkov photons produced inside the fiber, upon reaching the open end, either reflect back depending on the medium's refractive index or exit from the open end into the detector's environment. By applying a reflective coating in front of the fiber's open end, a large portion of the photons can be made to reflect back into the fiber, directed towards the photodetector. When using a reflector, if the impact angle ranges between 0º and 90º, then, due to the Cherenkov angle (as illustrated in Figure 4), the Cherenkov photons will reflect back into the fiber from the open end. Figure 8 shows the effective values of photons that reflect back into the fiber from the open end for simulations both with and without a reflector. In this graph, it is observed that the simulations using a reflector reach a maximum photon count when the impact angle is between 0º and 90º. However, in systems without a reflector, more photons leak from the open end, indicating photon loss in the system. The Cherenkov photons moving in the direction of the photodetector follow a similar trajectory.

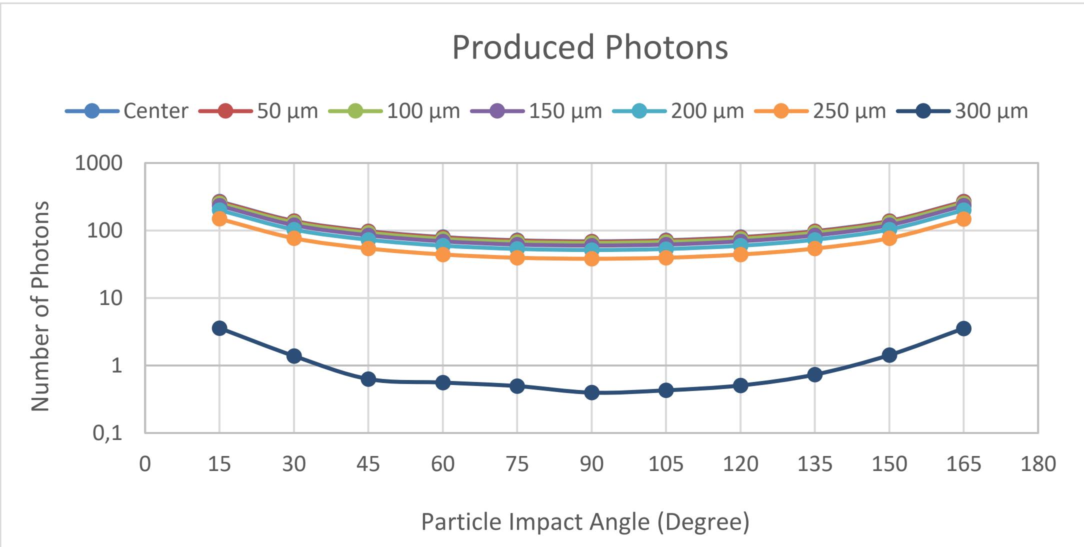

Figure 7. Number of photons plotted as a function of the particle's impact angle on the fiber, as seen in Figure 5. The graph shows simulation results for 7 different impact points on the fiber, as illustrated in Figure 6

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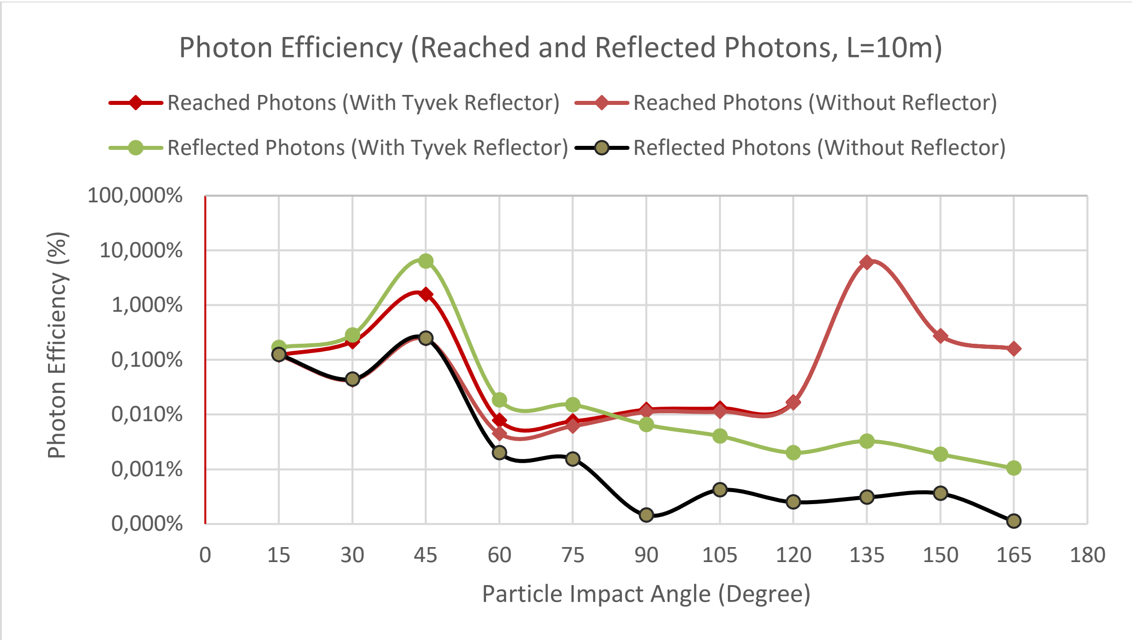

Figure 8. Distribution of Cherenkov photons generated within the fiber based on their impact angles for four different scenarios and their ratios (Photon Efficiency) reaching the photodetector and reflecting from the open end. The red and gray curves represent the photons that impact the photodetector and those reflecting from the open end within the fiber, respectively, when a reflector is used. Conversely, the orange and black curves represent the photons that impact the photodetector and those reflecting, respectively, in cases where no reflector is used

Since one end of the fiber is inside the detector systems, it can be used with an open, closed, or reflective coating. When charged particles pass through the fiber, the Cherenkov photons produced move within the fiber in both directions. The Cherenkov photons produced inside the fiber, upon reaching the open end, either reflect back depending on the medium's refractive index or exit from the open end into the detector's environment. By applying a reflective coating in front of the fiber's open end, a large portion of the photons can be made to reflect back into the fiber, directed towards the photodetector. When using a reflector, if the impact angle ranges between 0º and 90º, then, due to the Cherenkov angle (as illustrated in Figure 4), the Cherenkov photons will reflect back into the fiber from the open end. Figure 8 shows the effective values of photons that reflect back into the fiber from the open end for simulations both with and without a reflector. In this graph, it is observed that the simulations using a reflector reach a maximum photon count when the impact angle is between 0º and 90º. However, in systems without a reflector, more photons leak from the open end, indicating photon loss in the system. The Cherenkov photons moving in the direction of the photodetector follow a similar trajectory. It is evident that across all impact angles, systems using a reflector capture more photons inside the fiber compared to those without, directing them to the photodetector.

The distributions of efficiency values of photons reaching the photodetector based on their impact angles are illustrated in Figure 9 and Figure 10. In both figures, a charged particle impacting the fiber from 7 different points has been considered. It is observed that the number of photons reaching the photodetector increases around 45º for a fiber whose open end is coated with a reflector. This value has risen by over 1% around 45º for all impact points. Another noteworthy observation in these graphs is that, in the range where the impact angle is between 60º and 120º, as we move further from the center of the fiber outward, the efficiency increases. The reason for this is that, even if the charged particle travels a shorter distance inside the fiber, due to the cylindrical structure of the fiber, Cherenkov radiation can produce photons that exceed the critical angle, thereby directing more photons to the photodetector.

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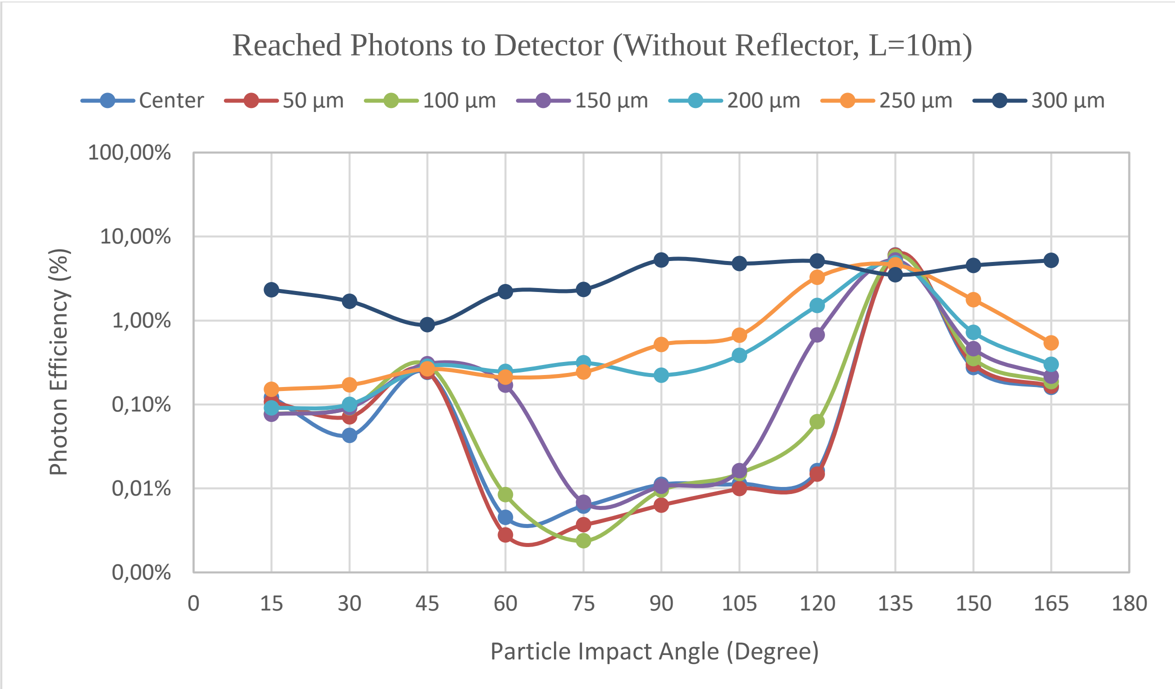

Figure 9. Distribution of the ratios of Cherenkov photons generated inside the fiber to the photons reaching the photodetector (Photon Efficiency) based on their impact angles, for a charged particle impacting 7 different points on the fiber without a reflector, as seen in Figure 6

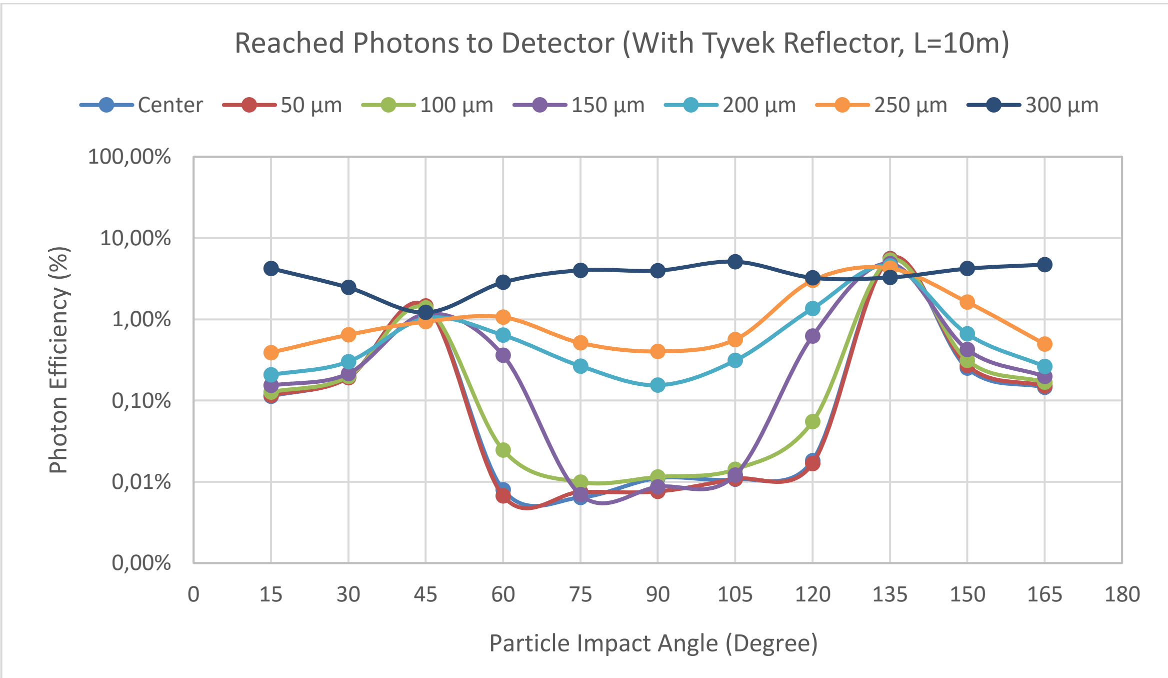

Figure 10. Distribution of the ratios of Cherenkov photons generated inside the fiber to the photons reaching the photodetector (Photon Efficiency) based on their impact angles when a charged particle impacts 7 different points on the fiber, as illustrated in Figure 6, with a reflector in use

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The distributions of efficiency values of photons reaching the photodetector based on their impact angles are illustrated in Figure 9 and Figure 10. In both figures, a charged particle impacting the fiber from 7 different points has been considered. It is observed that the number of photons reaching the photodetector increases around 45º for a fiber whose open end is coated with a reflector. This value has risen by over 1% around 45º for all impact points. Another noteworthy observation in these graphs is that, in the range where the impact angle is between 60º and 120º, as we move further from the center of the fiber outward, the efficiency increases. The reason for this is that, even if the charged particle travels a shorter distance inside the fiber, due to the cylindrical structure of the fiber, Cherenkov radiation can produce photons that exceed the critical angle, thereby directing more photons to the photodetector.

Figure 11 shows the changes in the efficiency values of photons reaching the photodetector for 8 different lengths of the fiber based on their impact angles. Since the wavelength graph corresponding to the attenuation provided in Figure 3 has been integrated into the Geant4 simulation, the geant4 simulation calculates how far the photons can travel within the fiber. This study is primarily based on the experimental data of the attenuation values (Figure 3) provided by the fiber manufacturer[8]. As shown in Figure 11 and Figure 12, in a system using reflectors, more photons reach the photodetector at a 45º impact angle compared to a system without reflectors. At 135º, that is, the angle at which the photons move toward the photodetector inside the fiber, the transmission of photons to the photodetector has decreased in both cases with and without reflectors as the length increases. The number of photons produced that reach the photodetector has fallen below 5% when a fiber longer than 20 meters is used. When fibers longer than 500 meters are used, these values have dropped below 1%.

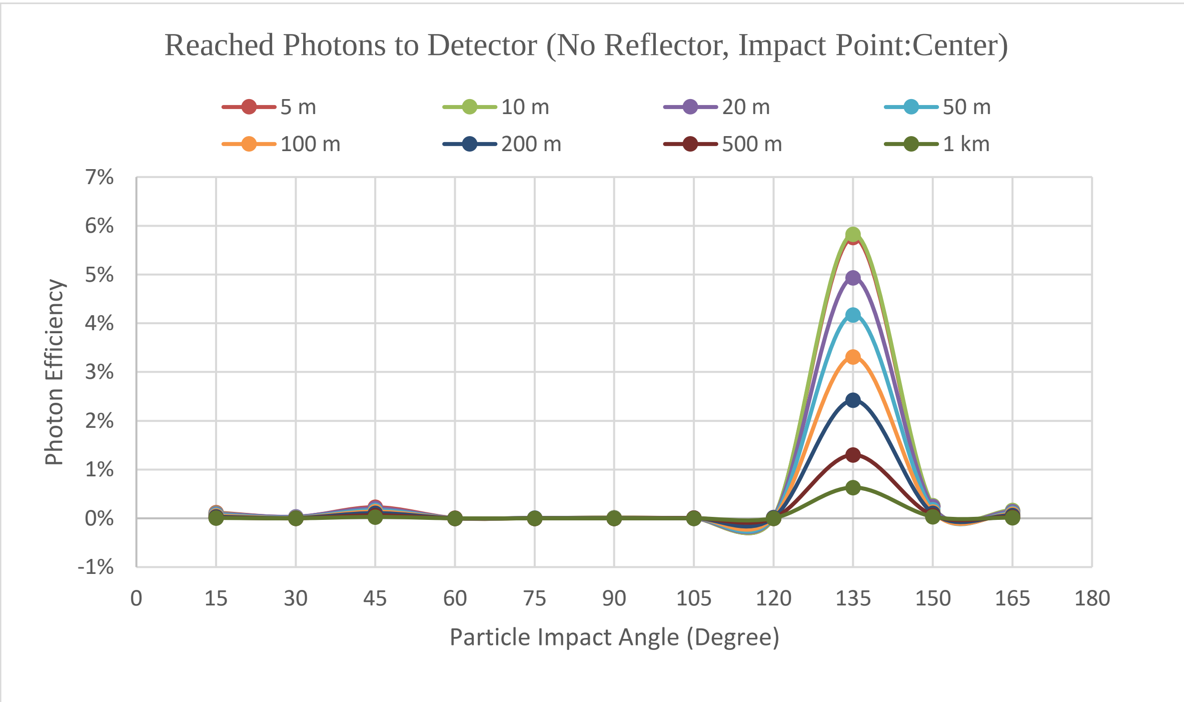

Figure 11. When a charged particle passes through the fiber with a reflector in use for 8 different fiber lengths, the figure presents the distribution of the ratios of Cherenkov photons generated inside the fiber to the photons reaching the photodetector (Photon Efficiency) based on their impact angles without a reflector in use

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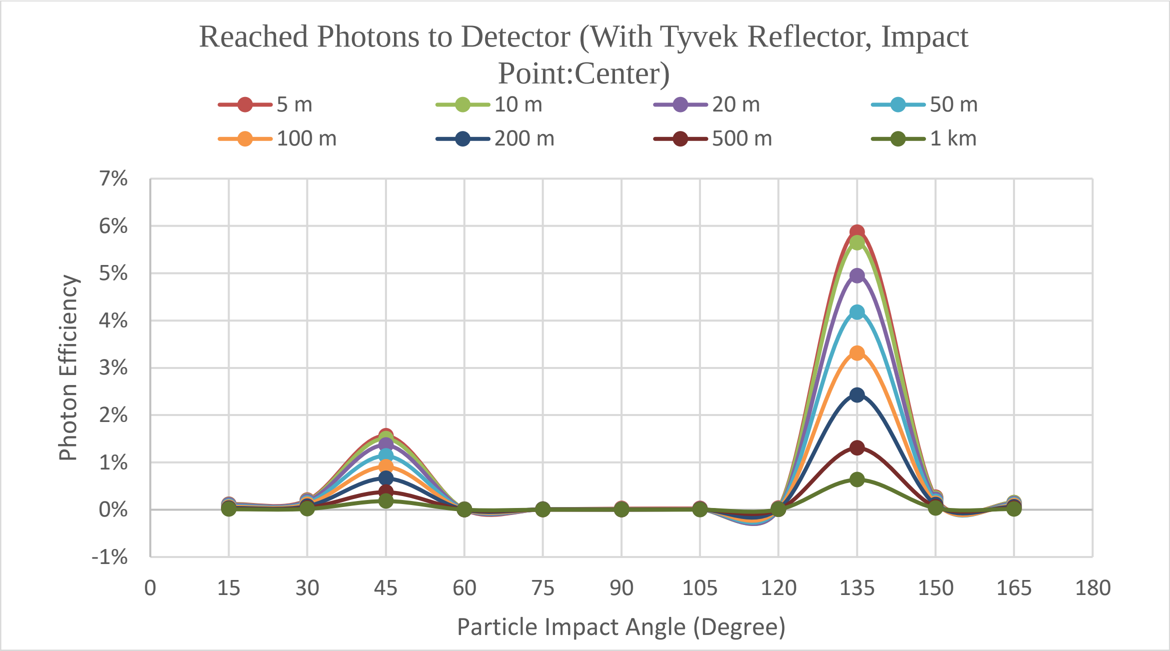

Figure 12. When a charged particle passes through the fiber with a reflector in use for 8 different fiber lengths, the figure presents the distribution of the ratios of Cherenkov photons generated inside the fiber to the photons reaching the photodetector (Photon Efficiency) based on their impact angles with a Tyvek reflector in use

CONCLUSION

In this study, the ability of the Molex FBP (FBP600660710) fiber representing Quartz core fibers to produce and transmit Cherenkov photons was tested in the Geant4 Simulation environment. Quartz core fibers, frequently used in scientific research and development areas such as high-energy physics and nuclear physics, can detect charged particles with Cherenkov photons. Simulation tests were conducted with one end of the open-ended fiber integrated into the photodetector, and the other end either left open or coated with a reflector. According to the simulation results, Cherenkov photons produced within the quartz core fiber reach the photodetector with the highest efficiency at 135º. The open end, whether a reflector is used or not, has caused some of the photons to remain captured within the fiber, and photons have reached the photodetector at impact angles of around 45º. Using a reflector also increased the number of photons reaching the photodetector at impact angles of around 45º. Charged particles pass through the fiber not only at different angles but also at different points of the fiber. Charged particles impacting the center of the fiber produce the most photons, and this value decreases as the impact point moves toward the outer coating of the fiber. One of the most crucial factors affecting the photon transmission of the fiber is the length of the used fiber. Up to a length of 20 meters, the fiber can transmit 5% of the Cherenkov photons produced within it, but as this length increases, the transmission will drop below 5%. This study shows that the fibers to be used in detector designs should be placed within the detector at specific angles and positions. The significance of the environment in which the fiber is located for the open ends of the fiber was also determined in this study.

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CONFLICT OF INTEREST

The Authors report no conflict of interest relevant to this article.

RESEARCH AND PUBLICATION ETHICS STATEMENT

The authors declare that this study complies with research and publication ethics.

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