Research on Photonic Crystals for solid state radiators for Cherenkov detection in LHCb

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Abstract
RICH is an LHCb detector used to identify the particles produced in different momentum ranges. The performance of the current gas based detector in the 1-10 GeV/c range needs a significant improvement. A new type of radiator using thin photonic crystals has been proposed as possible alternative, since these crystals are made from layers of dielectric materials resulting in having the desired effective refractive index. I have been part of the R&D team at CERN leading the efforts to build a photonic crystal Cherenkov detector, designing the improved hardware setup of the test laboratory and helping with the computational simulations that search for an optimal configuration of the PhC.

Keywords
CERN report; Summer Student; LHCb; RICH detector; Cherenkov radiation; Photonic Crystal; COMSOL model.

1 Introduction
The LHCb experiment at CERN aims to look for signals for physics beyond the standard model in particle physics, focusing in the production of b (bottom or beauty) quarks (via proton - proton collisions) which form B hadrons (mesons and baryons). The properties of this short-lived hadrons is studied through the reconstruction of the many different particles produced in the subsequent decays. Particle identification is, then, a crucial part of the analysis of data taken in LHC. The Ring Imaging Cherenkov detectors are vital instruments to obtain all the information coming from the collisions. Placed in one of the closest points to the collision (RICH-1) and one of the furthest (RICH-2), both detectors use the Cherenkov effect to identify long lived particles in different momentum ranges.

1.1 Cherenkov Radiation
The Cherenkov effect is one of the most fundamental physical mechanisms behind particle detection, mainly in high energy physics and astrophysics but also medical imaging and nuclear reactor detectors. The Cherenkov effect is the following: When particles (in our LHCb case, outgoing GeV particles from the p-p collisions) in the relativistic range of velocities (close to c) enter a dielectric material (the so-called radiator medium), their speeds fall above the relative speed of the light in the medium \( v = c/n \) (where \( n \) is the classical refractive index) and they “drive the medium to emit coherent radiation (light)” \[3\]. Cherenkov radiation is a macroscopic (the particle acts on a continuum, uniform medium) effect that produces a characteristic cone shape, defined by its angle \( \Theta \) and determined in relation to the speed of the particle \( \beta \) and the refractive index \( n \):

\[
\theta = \arccos\left(\frac{1}{n\beta}\right)
\]  

(1)

And emits little energy. According to \[5\], eq 32.45, the number of photons \( N \propto 1 - (1/\beta n)^2 \). In the LHCb setup, we are working with \( \beta, n \sim 1 \), and we get just a few dozen optical photons per particle.

\[1\]Cherenkov effect is cause of the characteristic bluish glow form a nuclear reactor’s pool
This effect is best understood as the light equivalent of the shockwave produced by a supersonic plane, since it shares the same conical geometry (see fig 1a below). Cherenkov is very different from other standard matter-particle interactions (Bremsstrahlung). In the Bremsstrahlung case, the particle interacts with the individual atoms composing the medium, emitting a lot of energy with a precise, known angular distribution.

(a) The most simple depiction of the effect. As the particle travels, in the lab frame we receive the cumulative wavefront (Blue lines) from all the previous instants, reaching now. In this picture, the particle started emitting by the red arrow and is always located at the vertex of the cone.

(b) There are two equivalent frames to study this effect: The $\theta$ frame, that describes the front facing or forward radiation cone that the particle is going to emit at the starting point and the $\eta$ frame or backwards cone, where the particle is always in the vertex, and the cone is light already emitted. The two angles are complementary, and the convention is to use the $\theta$ frame.

Once the light cone is detected, the angle can be reconstructed very easily (since it is independent of the moment you detect the light cone) and, knowing the $n$ of the material it went through, you can find out the speed. If you combine that information with a momentum measurement (like it is done in LHCb) or the energy, you can find its invariant mass and identify the type of particle it is.

However, there is a fundamental constraint: Since $\theta$ only makes physical sense between 0 and $\pi/2$ (1.57 ~ 1.6 rad), we see from eq. that $\beta \in (1/n, \sim 1.57/n)$. This is the available range of velocities to radiate light, limited below by the threshold (speed too low to produce light) and above by angle saturation (and emission with momentum over the limit, just appears at the limit angle, making impossible the particle identification, PID). If we are working with ultrarealtivistic speeds, like e.g. a pion with a rest mass of 0.14 GeV and an energy of 1 GeV (a very typical expected output), that means a speed of $\beta \gtrsim 0.99$. With $\beta \in (\sim 0.99, 1)$, we need to have a refractive index very close to 1 if we are hoping to scan the available range. For reference, a transparent solid like fused silica (pure glass) has $n = 1.458$ and a liquid like water has $n = 1.33$. This is the biggest restriction present in current high energy Cherenkov detectors, since that low value of $n$ restricts the radiator to a gas (a medium with a very low cross section, so a large volume of gas is required to increase photon yield) and even RICH1, having a $C_4F_{10}$ ($n = 1.0014$ @STP) radiator of $\sim 1$ m, is only sensible to particles with momentum higher that 9.3 GeV/c (the kaon minimum cutoff) [5].

[4] There are very low density solids like aerogel, which was present in the RICH instrument for a few years, but they do not have an effective photon yield for this energy range.
1.2 Photonic Crystals

In 1987, Eli Yablonovich [1] and Sajeev John [2] published two fundamental papers in solid-state physics, coining the term *photonic crystal* to describe the multilayered structures of dielectric materials that behaved with photons exactly like the electrons in metallic lattices, presenting dispersion bands with its associated gaps. This idea was first pioneered by Lord Rayleigh 100 years before (1887), while studying the Bragg mirror.

Photonic crystals are an arrangement of materials with a periodicity in 1, 2 or 3 dimensions:

Figure 2: Different dimensioned photonic crystal structures composed of two dielectrics (red and yellow). In our case, we are interested in fixing one of the dielectrics $n$ value to 1 (air, gas, vacuum). This would make the 1D structure become a crystal made of equispaced layers of dielectric material, the 2D version is a finite dielectric sheet full of periodic holes and the 3D version a combination of both.

Photonic crystals (PhCs) happen in nature, and they are the main responsible mechanism of iridescence of most (if not all) examples in nature, such as animal (Butterflies, peacocks) and mineral (opals). Man-made PhCs are very rare because, unlike metallic lattices, PhCs do not have a reference scale. This means that a macroscopic PhC does interact with light in the centimeter range (microwaves), and PhC that interacts with optical light (which wavelength is in the nanometer scale), requires a nanometer multilayer structure, which is difficult and expensive to produce.

15 years ago (2003), a team at MIT studied the theoretical model of a particle producing Cherenkov radiation inside a photonic crystal (PhC), and this work lied down the fundamental groundwork for our research. This extracted paragraph from it gives the key points:

CR in a photonic crystal arises from a coherent excitation of its eigenmodes by the moving charge. Its origin lies in both the transition radiation, which occurs when the charge crosses a dielectric boundary or experiences an inhomogeneous dielectric environment, and the conventional CR, in which coherence is preserved throughout the medium. [...] This CR is generated and propagates within the same crystal in the form of Bloch waves. The properties of these Bloch waves can be substantially different from waves in a uniform medium, leading to effects not previously anticipated. In one case, we can reverse the overall cone that encloses all traveling electromagnetic energy. [...] These are very general results based on direct solutions of Maxwell’s equations and should find applications in particle detection and wave production techniques.
The novel, theoretical ideas have been applied in the main reference article for this work, where LHCb members and photonic crystals experts use this revolutionary phenomenon called resonance transition radiation in order to prove the feasibility of a particle identifier a la RICH with this new method.

Textbook transition radiation implies that Cherenkov light produced inside the dielectric layers suffers total internal reflection and is dispersed sideways. The core idea behind resonance transition radiation is that, for layers of small enough width, the transition radiation, produced in the boundary between the dielectrics, does not vanish in the material but propagates in the form of Bloch waves. Light Bloch waves are modulated by the properties of the PhC, and if we finely tune the PhC, we can make that light interfere constructively in any of the air boundaries, producing a Cherenkov-like cone.

Figure 3: Example given in [7]: Radiation field from resonance transition radiation produced by a particle (forward configuration). This is not just a new way of (re)producing the same phenomena. PhC Cherenkov radiation is a new physics regime at play, able to break the classical limits mentioned before.

\[ This\ is\ the\ same\ principle\ behind\ lossless\ light\ guides\ such\ as\ fibre\ optics.\]

\[ A\ term\ borrowed\ from\ solid\ state\ physics,\ where\ all\ the\ theoretical\ framework\ for\ PhC\ comes\ from.\]
The new resonance transition radiation light cone is defined by the conservation of the planar component of the radiation wavevector \( \vec{k} \) in the air at the boundary (from the Snell-Descartes law):

\[
sin \theta = \frac{k_\perp}{\omega} = \frac{k_\perp}{k} = \frac{\sqrt{k_x^2 + k_y^2}}{\sqrt{k_x^2 + k_y^2 + k_z^2}} \tag{2}
\]

- **This formula does not depend explicitly on** \( n \). \( \vec{k} \) still depends on \( n \), but this is no longer the refractive index of the PhC dielectric components, it is an effective \( n \) coming from the PhC configuration. This means that a PhC made by solid state radiators with high \( n \) values can have a low \( n_{\text{eff}} \) and are viable candidates now, so we are no longer limited to gas radiators.

- **This formula does not depend explicitly on** \( \beta \). Resonance transition radiation also has the same speed threshold and saturation limits than the canonical Cherenkov radiation [7], but again they have lower effective threshold (see figure 4 below). There is a low energy particle range coming through RICH to which we are currently blind that could be detected though this system, but it is important to keep in mind that lower energy also implies lower photon production (see yield).

- **This formula does not depend on the particle direction.** The particle is moving so fast that is understood as a “instantaneous” excitation of the crystal modes along its path. Since the PhC is symmetric from this direction, in principle the Bloch waves do not have a preferred direction to converge. This means that the cone production can happen in the front surface of the PhC, facing the particle (Forward configuration) or on the back end of the crystal, with the forward cone following the particle’s movement (backward configuration). This is achieved by a small change in the PhC layer width or number.

![Forward and Backward Configuration Examples](image)

Figure 4: Extract from [7]. The PhC configuration for our desired the energy range shows widely different Cherenkov cones for the same particles. The new backward configuration increases the angle with the decreasing momentum.

The backward configuration seems like it could be a significant improvement in terms of resolution, and if testing supports this (not done yet), it can became the standard for all the posterior work. This new setup is possible because the RICH detectors rely on a set of parabolic mirrors to converge the light away from the beam (to avoid damaging the readout instrumentation), and another configuration just allows for new geometry designs for RICH’s focusing system.
2 Motivation

The main conclusion from [7] is that using a photonic crystal for particle identification via the resonance transition radiation is not only a plausible idea, but also that this mechanism, if working, would be far better than the canonical Cherenkov radiation for an experiment like LHCb. A redesign of the RICH detectors in a future system upgrade would allow a more effective particle detection and identification, both in quantity and quality of the particles.

A new generation of radiator would be a small sheet of PhC (≈ cm in surface and ≈ mm of thickness) placed close to the interaction point. Low atomic number elements produce less secondary particles and absorb less light, so in a working model metallic materials are discouraged in favour of complex polymers. A bigger amount of layers in the PhC would increase production of both photons and secondary particles, so there is need to increase the number of layers while reducing their width. Remember that the photons are produced between the layers, and that a layer has to be in the order of ≈ nm to interact with optical light, millions of layers can be archived in less than a centimetre.

A single photonic crystal has an optimal momentum range, so there is no single ideal photonic crystal candidate to base a whole new detector. However, this radiator would take little space in the instrument and does not necessarily increase the complexity of the focusing system, so it would even be compatible with the actual design, upgrading rather than redoing the previous work. Another improvement idea involves the combination of different PhCs, each searching for particles in its own range.

Looking for experimental confirmation of this ideas, the international team that wrote the 2018 paper built at CERN a prototype experiment using beta particles from a radioactive source (Sr-90, 0.5 MeV electrons) to trigger the effect on a 1D polymer PhC.

![Figure 5: First sketches of how would the prototype was designed. The secondary mirror gives the light the path to converge while reducing the space needed.](image-url)
Here are the first results being produced by this method:

(a) Model simulation of the expected ring signal on the detector from a 0.5 MeV electron.

(b) Reconstructed data from the experimental tests.

Figure 6: Expected vs actual detection signals from 1D PhC radiator. When a cone falls into the detector it forms a ring, and we can see that happening here, but reality is not so simple, and there is still a lot to improve before getting a working PhC detector.

There are two fundamental problems that prevents us from using any photonic crystal as a radiator:

- **Achromaticity**: Remember that, depending on the configuration, the difference between the cones produced by different particles is as small as 0.1°. If there is any distortion on the Cherenkov cone, an obtained cone cannot be uniquely identified to a $\beta$ value. Usually, the refraction index $n$ value depends with the wavelength of the light $n(\omega)$, and this introduces an aberration in the polychromatic light while propagating in the material called dispersion. Although our new mechanism produces the light cone outside of the material, we still need a radiator that introduces no dispersion in the shape of the cone (perfectly achromatic).

- **Yield**: The LHCb Cherenkov effect gives around a hundred photons per particle, but are emitted with arbitrary wavelengths (inside a optical range) and only a fraction fall inside of the detector’s scope (250 nm to 500 nm). Adding the fact we have a mirror setup, although well designed and very efficient (90%) taking some more light, we actually only detect a couple dozen (Overall efficiency of $\sim 25\%$). This problem becomes even more critical when using PhC radiators close to the low energy threshold, since that implies low production. Since we use geometrical position reconstruction (*hit map*) to obtain the cone, not only the more photons the better our resolution, but there is a necessary minimum, and below it we cannot confidently reconstruct the signal.

This problems have not a trivial solution, and probably will come from a combination of different options: Smarter geometrical arrangement, research with computational models an improved PhC configuration, better understanding of the theoretical framework of PhC on the Cherenkov regime, application of available technology (see section 5, gain materials), etc.

The CERN branch of this team, the one I joined and contributed during my Summer Student internship during June - August 2018, is in charge of designing the experimental setup upgrade; but I also got to help building new computational models to search of the best PhC configuration before acquiring them for laboratory testing.
3 Method
3.1 Experimental Setup

Right now, in the testing laboratory, we want to test the basic ideas and to gain experience with the working details of this experimental setup. Being this the first prototype, there are some shortcomings:

- The single PMT surface is roughly the same as the focused light cone, which is insufficient for full resolution of the cone, and we only get a partial signal of the possible ring.
- There is an average of 4 photons detected per incoming particle, due to the mentioned yield problems. This is not enough to have a nice reconstruction of the ring.

This means that we are working in a long time exposure configuration, where a result picture (as the one seen in figure 6b above) is not of a single event but of an average of dozens of events, taken in four different quadrants and reconstructed via software later.

This is only possible because we have a controlled, known source conditions, and even then this is far from a good result. 1D photonic crystals have negligible achromaticity, but long electron exposure introduces large, similar to achromaticity effects (see the thickness of the observed ring) from angle dependency to momentum (eq [1]) and electrons having a range of momentum from $0.2 - 0.7$ MeV.

This rings are not bad for being first results, as we can see and check some ideas with them, but this not a working solution that can be translated to LHCb. What this actually requires is a bigger detection surface, composed of at least 4 MaPMTs in a square configuration, and then a source of higher energy particles (a beam) to check for individual events and test if a single particle produces enough yield or we need another solution.
3.2 Experimental Setup Upgrade

The upgrade design is based on reusing the so-called CLARO board: A 4x4 PMT electronic readout system designed for the LHCb upgrade 2, for which there is ample supply. This required that I studied the electronics and its components, design and configuration very closely, understanding the inner mechanisms and workings of the system in order to work out a solution compatible with the two boards that were never meant to be used together. This process involved, but was not limited to:

- Gather all the needed documentation, most of which was scarce and dispersed at the beginning: images, schematics, technical files, reports, software and firmware. This required contacting components suppliers from connectors to the MAROC chips, setting up meetings and interviews with the original owners/makers of the electronics, looking at technical manuals and reading the reports of the previous users. Some of the information could not even be found, given that the Orsay board was commissioned more than ten years ago in France, and most of the people who participated in its construction were not available anymore. This presents a lot of trouble to work with and greatly hinder our progress, making us rely on assumptions and not precise knowledge.

- Produce a sketch of a prototype: This includes learning the basics of viewing and editing PCB designer programs (Cadence Allegro, Altera Designer), with constant communication and supervision from the electronics expert (Federico Cindolo). For the first two weeks different design options were considered only with spatial considerations in mind, because there was concern that there was no viable physical configuration of the components. I did manage to prove the compatibility of the sketched setup thanks to 3D CAD models, that showed comply with all the constraints and gave an approximate dimension within the experimental setup margins.

![Figure 8: Model of the first layers of the electronics, designed to prove the geometric compatibility. In principle, the CLARO board (top layers, below) can be connected to the DAQ (bottom layer) via a passive, interphase board (blue).](image-url)
Commission the prototype: After the first month, there was a good understanding of what would be needed to make the interphase board, and a bill of materials (BOM) budget approved. All the missing electronic components were then ordered and a request to the CERN workshop for the PCB construction was placed. This was far from a straightforward process, most components were outdated, and some unmarked and unnamed (like the impossible-to-find connectors) or even discontinued (MAROC2). This involved a lot of effort only on finding workarounds like careful looking into alternative suppliers or adapting newer technology (MAROC3).

After everything, not enough confidence between the different pieces was assured (Like making the electronics compatible with MAROC3), but tests of the single components in the actual setup were thought of to ensure working. The need for careful testing overlapped with the lack of personnel in summer and both the components suppliers (MAROC Chips, Readout FPGAs) and the CERN electronics workshop. Important delays postponed the manufacture of the interphase board until past my stay and the end of the summer.

Redesing and development: While the delays seem bad for the completion in the original project, this did not necessarily a bad thing per se, since it gave time for further refinement of the designs.

There was a lot of discussion about the nature of this setup configuration. The difficulty of working with old hardware limitations, the idea that the detection surface might be expanded even more in the future (When full scale testing will happen) and the idea that another future redoing of the electronic configuration will be even more costly in terms of time and money, made us think some steps forward and try to add some extra features to the interphase board that will simplify the readout for more than 4 PMTs (our original goal) while compatible with the actual conditions (plus the geometrical and design constraints).

![3D rendering.](image1.jpg)

![Actual schematics of the setup that shows the difficulty of the design, more than 400 different lines and wires had to be taken in account for.](image2.jpg)

Figure 9: Final designs of the interphase board. The system moved from a 4 PMT readout with modular design to a allow growth to a 16 PMT square array with secondary output channels to work as a standalone unit in beam testing.

More importantly, the slowness of the progress here gave me the time to switch gears and to be able to help in other aspects of the team research, acquiring more perspective about the whole experiment and the work we were doing and learning way more in depth about the physics fundamentals of the detector.
3.3 Photonic Crystal Simulation with COMSOL

Photonic crystals are very expensive to produce, so instead of commissioning a random existent configuration and lab testing its behaviour, the team is trying to model the Cherenkov light emission output of a particle inside a specific photonic crystal configuration, in order to improve the configuration design and find the optimal.

We are able to model a macroscopic effect thanks to the periodic conditions of the PhCs. We can safely ignore edge effects (Respect to the incoming particles scale, the material size is approximated to infinite) and then reduce the full simulation to a elementary, irreducible cell with periodic boundaries (called First Brillouin zone from solid state physics, where we borrow the framework).

The goal is to have a model for desired any 2D or 3D geometry, expressed by its free parameters: The characteristic scale of your PhC (the ratio between the cell and the size of the hole), the refraction index values $n$ of your materials (one value usually is set to 1 for simplicity and reference), the energy of the incoming particle and the geometry’s fundamental directions.

To be precise, we model the geometry in COMSOL, a proprietary multiphysics software based on the finite element method that solves the Maxwell equations inside the dielectrics and calculates the dispersion plot: $\omega$, the angular frequency (color) of the light vs the wavevector or momentum $\vec{k}$. Thanks to the PhC symmetries, cylindrical coordinates are used, so $\vec{k} = k_\parallel = k_z$ (direction of the incoming particle, electron in our case) + $k_\perp$ (radial direction in the elementary cell, unitary vector in the reciprocal space). The incoming electron determines the value of $k_z$: A particle can be described by a Dirac delta in space, and via the Fourier transform be defined as a superposition of plane waves in momentum space of wavevector $k_z = \omega_e/v_e$ (See [3]).

The finite element method works via meshing our geometry finely (see the figure above), and using the module called "Wave Optics", that solves the EM equations in each mesh point, obtaining the transverse eigenfrequencies $\nu_{PhC}$ (TEM values or TEM modes), the discrete solutions for the periodic conditions. Remember that this values are the ones excited by the particle, given its energy. You can also see the associated EM fields of each mode, and discard the modes that are not relevant if you want to speed up the computation. Some solutions are physical, like the combined TEM modes, but the particle excitation should be a pure TE mode. Having the eigenfrequency $\nu_{PhC}$ and $k_z$, we set up a (parametric) sweep on $k_\perp$ to find the compatible light frequency values $\omega$ for all the FBZ (between 0 and 0.5, since it is already normalized to the wavevector).

From the PhC’s dispersion relation we get the Cherenkov angle ($\theta = \arcsin(k_\perp/k)$), see eq.2.

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7The specific setup of the program comes from adapting and developing the basic square model given from COMSOL [9].
The group had just finished studying the basic square elementary cell, and I got handed a first draft of a hexagonal 2D version to start with. After getting familiar with the workings of the computer software, these were my principal contributions to the simulation models:

- **Finishing setup of 2D model**: The basic model was not using the full configuration power of COMSOL. I.e., the material refractive index $n$ was determined as a constant, where we know that the dispersion depends on the wavelength. This seems like an irrelevant effect, but we were looking to build models out of materials with lasing properties in the relevant emission range (see Future Work section), so the $n$ presented huge differences that could affect the dispersion bands. Both parametric and interpolation implementations of the non linear behaviour of the $n$ were implemented in the model, giving more realistic dispersion curves.

- **Study of 2D Hexagonal model**: 2D studies were largely unknown territory for us. There is previous literature in the topic, but our study case is for $k_z \neq 0$ and optimization for a specific size and material configuration. This is why I did dozens of searches in the free parameters of the model, to learn which are the relevant variables and how they modify the light output (dispersion plot): The spatial variables (mainly cell - hole ratio) control the wavelength (color) being emitted, increasing $n$ value suppressed the lower modes, etc.

  However, the search in the dimension variable space of the best emission conditions gave a single, unaltered result: The 2D Hexagonal model maximized both the chromaticity and the photon yield. For more info, see the relevant subsection in the results.

- **Study of 3D Square model**: While discussing the previous results, the following hypothesis formed: The 1D model ($z$ axis) produces a unique, usable cone in all available wavelengths, thus there are not enough photons in the detector’s range. The 2D model ($x$, $y$) is able to fit all the emitted light into a certain, tunable wavelength range, but the cone has no restriction. If we can assume that a 3D crystal behaves like the combination of a 1D + 2D crystals (To start with, that is perfectly possible), we might have enough degrees of freedom to be able to solve both achromaticity and photon yield.

  Trying to test that hypothesis, I built and tested a 3D square version of the models we were using, in order to repeat the previous procedure. The need for more in depth study of the model, with the increased computational demands, made it not worth he effort and it was put aside.

- **Study of 2 dielectric, 2D Hexagonal lattice**: After the 2D Hexagonal disappointing results, Gilles looked on the PhC literature for a chromatic reduction effect. In graphene-like models with 3 dielectric materials: Core + Cladding + Background (air) [4] there was a strong hint that, due to a phenomenon called "mode hybridization" in the dispersion bands, some bands could become parallel to the light line, presenting no achromaticity. While brief, the study of this model produced very preliminary but optimistic results.

- **Setup of connection to CERN computing cluster**: The full band calculation of a 2D Hexagonal model under normal conditions took aprox. 2 hours to complete on my workstation, and the 3D model is one order of magnitude more computationally demanding, with calculations taking a full day. This could only be speeded up sacrificing resolution of the model, so it was made clear that more computation power was a requirement in order to do future studies efficiently. I contacted and worked along CERN IT services to connect and use the new Linux based high performance computing cluster to solve out models.
4 Results

4.1 Photonic Crystal Simulation

4.1.1 2-Dimensional Hexagonal Lattice

(a) Dispersion (frequency in Hz vs wavevector $k_{\perp}$): The black line is the light line and all bands under it are trapped in the crystal and cannot escape into the air (total internal reflection).

(b) Associated emission from the left plot. Observe that the blue mode’s emission, the one under the light line, appears saturated at 1.57 rad (90 degrees). That light escapes from the crystal sideways.

Figure 11: 2D hexagonal solved model results from the software.

(a) Detail from [11b] above, focused on the effective search area: The RICH setup only will detect light emitted between 250 - 500 nm and under 300 mrad.

(b) Made up plot of the desired, ideal emission conditions. A particle with a fixed $\beta$ should have only a single associated angle for all colors.

Figure 12: Cherenkov emission plot for the different modes: Emitted light (in m, left or Hz, right) vs the Cherenkov angle (in radians).

We can observe points forming lines along the Cherenkov range. A point is a mode: A solution in the phase space $(\omega, k_{\perp}, k_z)$ for a single eigenvalue. A line is a band (A range of frequency/energy of the emitted light), and the different colors in the plot represent the different eigenfrequencies they come from. Flat bands in the area of interest in the graph means maximum achromaticity and maximum yield, since a particle will produce Cherenkov like cones all along the band, but all the emitted light falls into the photomultipliers (PMTs) detection range; here the emission range is optimized for PMT detection because it is tunable with the lattice size parameters. This geometry cannot be used for particle characterization.
4.1.2 3-Dimensional Square Lattice

(a) 3D elementary cell geometry. The z axis is along the cylinder, the hole in the layer of dielectric between the two half layers of air. $k_\perp$ lies on the square plane, with no preferred direction, and $\pi/2$ discrete symmetry.

(b) Dispersion plot of the 3D geometry (wavelength vs $k_\parallel$). The dispersion plot models have now controlled wavelength for all the space, since they are periodic in all $k_\parallel$, plotted here extended from the FBZ.

Figure 13: 3D relevant information: How the geometrical model is set up and how the final dispersion modes appear.

As we said before, the 3D model aims to be able to control and tune all the light emission parameters. The z axis (parallel to the particle direction) would control the single angle of emission (like the 1D model), and the perpendicular, radial direction would restrict the color of the light emitted (seen in 2D, with the small angle approximation). This means that the ideal emission plot (see [12b]) in 3D would become a single point or set of points in the dispersion plot.

However, while testing the model a problem arose: The 2D COMSOL version is able to solve the model with a frequency dependent $k_z$, but the 3D differential equation solver, while giving a set of solutions, was not accepting taking the value of $k_z$ as a fixed parameter. This could be checked by sweeping in both $\vec{k}$ and $k_z$, and then looking in the $k_\perp \sim 0.5$ plane for the intersection points with the electron line ($k_e = \omega_e/v_e$). This corrected model with the values we need, is the one seen in [13b] (above). The light emission would be produced in the intersection points with the electron line (blue), close to the light line (black).

If the first model was working, they should be the same than fixing first $k_z$ and then looking for $k_\perp$. The two set of values did not coincide, not even for $k_\perp = 0$. Since the simplified model was wrong, we could use the working model, the complete version. The problem is that, in addition to an order of magnitude bigger mesh to compute (3D), the computation time was multiplied with the two sweeps.

The computational effort, even when trying to sacrifice precision for speed (Not looking at the full bands, restricting the momentum space, etc.) and the time needed to dedicate to get a few solutions by manual search was unmanageable by us at the time, and we decided to drop the continuation of the study of this model for something easier until a solution was found.

With the express purpose of being able to continue working on this model, which viability and ideas are far from being disproved (single point solutions were found randomly during testing), by the end of my stay I managed to enable the ability to carry the models computation in the CERN high performance cluster. If combined with way to automate the computation, this will help to find the proper solution.

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8Literal problem, in the form of a warning issued by the COMSOL software.

9The second sweep happens for each step of the second sweep, not after the first one.
4.1.3 2-D Hexagonal Lattice, 3 Dielectrics

(a) 3 dielectrics elementary with dimensions and a example electric field solution. We can appreciate the periodicity of the field and the fact that is aligned with the core and modulated by the cladding.

(b) Dispersion plot of the 2 dielectric model. Worth noticing that there are 2 more fundamental modes that follow the light line.

(c) Cherenkov plot emission of this model, associated with the dispersion plot above. We can find saturation in the lower limit, producing the sought-after vertical mode. This finally looks like the solution of the achromaticity problem, thanks to the alternative geometry design. The emission at 700 and 1150 mrad (40 and 65 degrees) is not ideal but could be used with a new mirror configuration.

This result, although optimistic, is preliminary, and grounded on unstable assumptions. The hexagonal geometry used here is not the original honeycomb lattice used in the reference [4], which we did not explore because of the complexity of it primitive cell. The reference model also used metal a metal configuration, unusable by us for its light absorption properties. Switching to dielectric materials might produce an effective medium effect rather than the mode hybridization effect.

In spite of the issues, the model was shown to be perfectly compatible with the previous hexagonal one, since the dispersion plot was reduced to the earlier results where the \( n \) of the core and the cladding was made equal.

Extensive work on the feasibility of this configuration is needed.
5 Future Work

5.1 Experimental Setup phase 3: Laser pumping.

The solution to the aforementioned yield problem might have a technical solution, rather than a design one. There is nothing that prohibits that one of the two dielectric materials in the PhC is a lasing material. If we ignore the design challenges, and allow for a light source (optic fibre) to be near our PhC sheet in the detector, we could pump the material with light, induce population inversion just below the fluorescence regime (spontaneous emission), so when there is light created in the PhC, the photons provoke momentarily lasing (stimulated emission) of coherent light (should be compatible with our constructive interference), and simply increase the number of photons in the Cherenkov cone.

This is only an idea for now, but it is not an implausible idea. There has been ample research on photonic crystals and lasers, since one of the most modern ways of making a laser, and the current state of the art, is via the use of photonic crystals. During the discussion of the applicability of this idea for this research an ideal material candidate was found, GaN (and equivalents, like InGaN), because the material has the lasing peak around the violet (400 nm), close to the ideal detection range of the PMTs (350 nm).

After some tentative consulting to the laser experts at CERN, and they mentioned that the technical problems can be dealt with, i.e., the pumping light cannot interfere with the RICH PMTs, but this is doable by using light outside the effective range of our detectors or screening / filtering the scattered light. In the end, if the PhC search continues, and the yield continues to be insufficient, a laser upgrade will be necessary to the lab setup, so we can see if there is any way to increase the photon yield. Laser pumped Cherenkov effect is better than no effect.

5.2 COMSOL Simulations: Next investigation lines

– In depth examination of the 3 dielectric positive results: There is nothing we know the appearance of the vertical solutions at low angles. The only dependency studied in the brief time available was with respect of the cladding refractive index \((n_{\text{clad}})\), and it created a sort of cut-off phenomena: With increasing \(n_{\text{clad}}\), one of the modes disappeared, and with \(n_{\text{clad}} \approx n_{\text{core}}\) the second mode seems to displaced to the saturation point (1.57 rad), falling back into the regular 2D.

– Search over all the 2D configurations: There are only a few regular shapes that can tessellate the plane, and we already checked the square and the hexagonal, but other configurations are unexplored and a different geometry very well might give unexpected behaviour. The most interesting case in my opinion is the honeycomb structure (Graphene-like PhC), that we skipped before.

– Implement yield measurement within the model: The actual model does not register the necessary information to obtain a quantifiable yield of every interaction. It may need the use of the multiphysics or a the rewrite the model in another frame, but work is undergoing on how to add yield capabilities to the computer studies on the materials.

– Complete the 3D model: The hypothesis of the ideal PhC being a 3D one is not disproved yet. Maybe a new toolset might be required, but the model in COMSOL should work with some careful tweaking, specially now that the cluster computing has sped up the solving of the testing models.

– Non - perpendicular particle simulations: We need to solve the cases where the particle has no perfect perpendicular collision with the material in order to obtain a table of correction factors depending on the angle of collision. This is needed for when real beam testing will take place.

– Look for full radiation modes: In an hexagonal lattice the light has two fundamental vectors to travel thru the material \((\Gamma - M \text{ vs } \Gamma - K - M)\). For the same conditions, these two paths could be a cause of achromaticity.
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