ZDC Light Guide Optimization

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Contents

1 Abstract

The "Zero Degree Calorimeter" (ZDC) is a high energy particle detector, used extensively across various experiments at the Large Hadron Collider at CERN. Designed to measure energy, the ZDC was originally proposed as part of the ATLAS and CMS experiments for use in heavy ion collisions (Pb-Pb collisions) . There, two beams of lead-208 ions are accelerated in opposite directions. With that many nucleons, each ion is not a pointlike particle- but an object with finite size. Upon colliding, the ions are often not perfectly aligned; and the impact parameter b is defined to be the distance between the (parallel) axes of motion. It turns out that outside the overlap region, nucleons are unaffected by the collision- some of them neutrons. These "spectator" neutrons keep traveling in a straight line, unimpeded by the electric and magnetic fields of the accelerator- hitting the "zero degree" calorimeter head on. The energy measured from these spectator neutrons in the ZDC, is proportional to the number of neutrons that were outside the overlap region, which is related to the impact parameter. Since being used for counting neutrons, the ZDC's have found other roles- even in proton-proton collisions, and are also used to measure photons.

Generally speaking, the ZDC is composed of tungsten plates, quartz fibers and a photomultiplier tube (PMT). Incoming particles induce a "shower" in the tungsten plates. The secondary particles move faster than the phase velocity of light in this medium, resulting in Cherenkov radiation being emitted. The emitted light is guided through the quartz fibers, and into the PMT. At that point, the light is converted to an electric signal which we can read and interpret.

Zvi's group is working on improving current models of the ZDC, for the ATLAS and CMS experiments at LHC. In my project, I'm concerned with guiding the Cherenkov photons from the quartz fiber, and into the PMT. I will attempt to better the current reflector, responsible for ~ 100 quartz fibers- by optimizing its geometry in a computer simulation.

2 Introduction

2.1 The problem

My project is centered around the light-guide structure; I was only concerned with the path of the photons, after they had left the quartz fibers ("rods")- and until they had reached the PMT (or not). We'll call the symmetry axis of the light guide 'z'.

In current versions of the ZDC, one PMT (at $z = h$) is in charge of collecting light from around ~ 100 rods, sitting in a structured grid at the $z = 0$ plane. The rods are roughly point-wise sources, with respect to the dimensions of the system. The light guide in use today, reflects the photons off of a planar surface ("trapezoid" reflector).

In testing, is a new light guide curved like a parabola ("Winston cone" reflector) - which would be ideal, if the photons had traveled in parallel to the z-axis. **A paraboloid reflects all light rays, incoming parallel to the z-axis: to the focus point**:

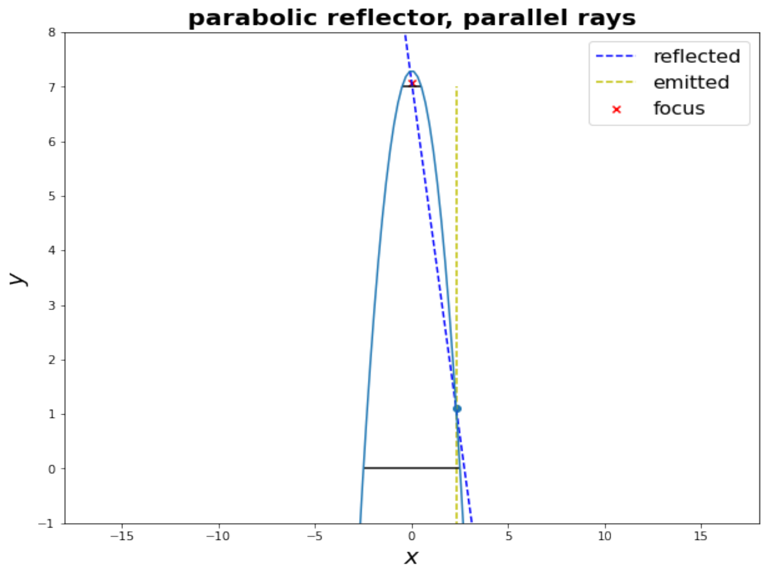

Figure 1: Parallel rays converge to the focus

The problem I was presented with, is that most photons exit the rods at a $\sim 45°$angle with respect to the z-axis:

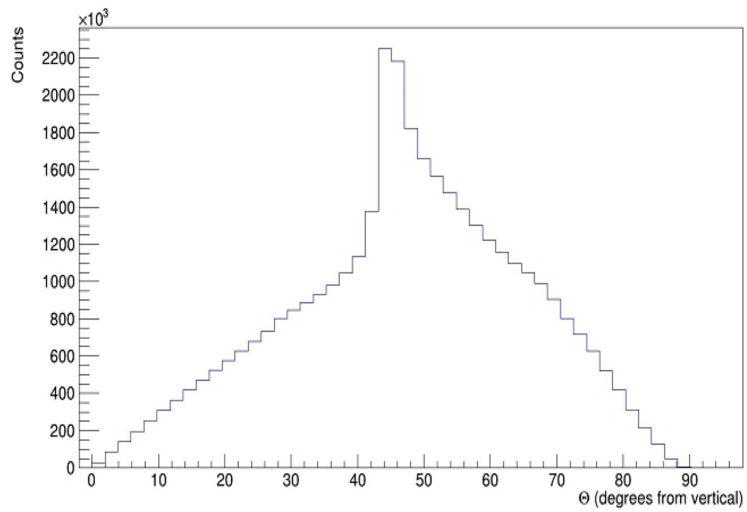

Figure 2: Angular distribution, from detector simulations (Yuval Bashan)

Which means they frequently miss the PMT :

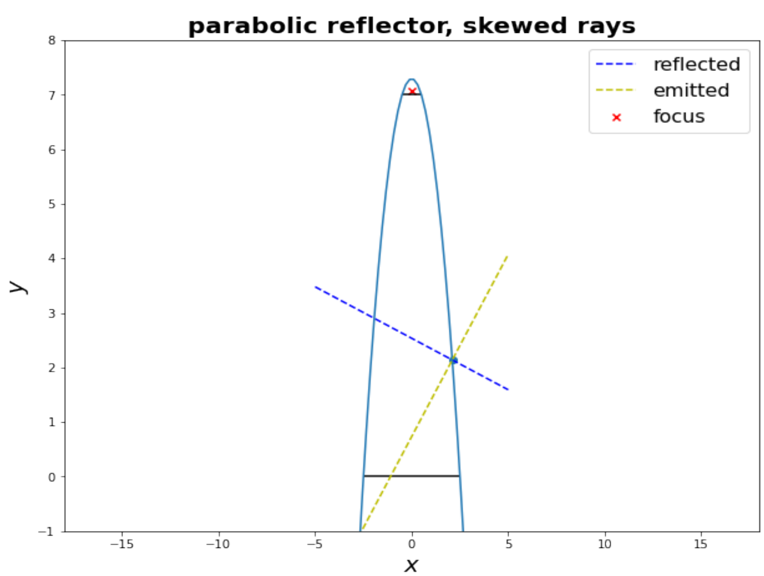

Figure 3: A $\sim 45°$photon missing the mark

In my computer model of the system (3.2) I estimated only about 1% of the photons make their way into the PMT. I was given the following task: replace the parabola, with any other shape that could do a better job at collecting the photons.

2.2 The boundary conditions

The detector is always in the presence of powerful radiation. Consequently, not all materials are fit to be used- for example, mirrors and lenses would quickly be damaged, and need to be replaced.

The Cherenkov photons are in the middle-UV region, about 200nm. There are no diffraction effects- geometrical optics is sufficient to describe the behavior of the system. There are rigid requirements for the dimensions of the system:

Dimension	Notation	Value
Height	h	$\sim 7_{cm}$
Rod diameter	r_f	$\sim 0.15_{cm}$
Rod per row	N_y	25
# of rows	N_x	5
Grid width	$2y_0$	$\sim 4.3_{cm}$
Grid length	$2x_0$	$\sim 2.8_{cm}$
PMT width	$2y_p$	$\sim 1.16_{cm}$
PMT length	$2x_p$	$\sim 1.00_{cm}$

Table 1: Dimensions of the system

3 Finding a new shape

3.1 Commercial software

I'd spent a few days searching for existing products, that were designed to simulate and optimize optical systems. In particular I used "TracePro"[1] by Lambda Research Corporation. After playing around with a trial version for about a week, I finished assembling a model of the system- but the couldn't get the optimization feature to work properly. At that point I moved on to my own algorithm.

3.2 My own code

My code is available on GitHub [2] The repository **project-lightguide** contains 3 python notebook files:

- The first notebook, **light_guide**, contains the code for ray tracing, and optimization of the light guide.

[1] https://lambdares.com/tracepro/
[2] https://github.com/orenir49/project-lightguide

- The second notebook, **user_guide**, introduces 'light_guide' step by step, and explains how to run simulations- as well as test (relatively) simple changes to the system.

- The third notebook, **programmer_guide**, is a more detailed documentation, that also explores the basic building blocks of the existing simulation tools.

3.2.1 Features

The program has the current dimensions (table (1)) of the system built in as default, and a parabolic light-guide is set up with the PMT at the focus point. The basis of the program is a ray-tracing code, that relies on very basic geometrical optics to follow photons inside a 3D model of the system.

It's possible to plot the path of the photons (up to one reflection off of the system boundary); however, some functions can account for multiple reflections. Each photon comes out of a rod, picked at random. There are two default choices for the angular distribution of the light- one is a narrow Gaussian around 45°that resembles figure (2), and the other has only photons exactly parallel to the z-axis.

The main features in the program are:

- Efficiency test- the user specifies the light guide shape- a level surface $f(x, y, z) = 0$, that should encapsulate the system. The program simulates photons with the chosen angular distribution, and traces them up to a specified number of reflections off of $f(x, y, z) = 0$. The function counts how many photons hit the PMT, and prints out statistics about the light guide performance.

- Optimization- this function takes a brute-force approach toward finding a better (and axially symmetric $\rho = \sqrt{x^2 + y^2}$) shape for the light guide $f(\rho, z) = 0$. The function takes an existing shape, and a functional form ($f(\rho, z) = a_0 z^2 + a_1 \rho^2$ or $f(\rho, z) = a_0 z + a_1 \rho$ for instance)- and over several iterations, tries to better its choice of the parameters a_i based on heuristic arguments. The output contains useful statistics, about the optimization process: firstly, an efficiency charts for comparison between the different shapes. Next, a convergence plot for the parameters of the light guide shape a_i is shown. Finally, the most efficient shape is displayed.

- Dog cones- this option will be described in (4).

- CMOS projection- at the lab, we used a CMOS to observe light coming out of the rods in various experimental configurations. This function predicts the image we should expect on the sensor, provided the angular distribution of the light and the distance from the source. I used this feature to learn about the set up we had in the lab.

3.2.2 More on brute force optimization

I shall try to be more precise about the process of optimization: An initial shape is chosen, and a Monte Carlo simulation begins. A photon is generated- which hits the light guide at some point. The algorithm figures out the required orientation at that point, for the photon to hit the PMT.

The process continues, as the function gathers data for $\frac{dz}{d\rho}$ ("slope" or orientation) at different points on the surface. Finally, with enough data, a new shape is chosen: the function $\frac{dz}{d\rho}$ is determined from a χ^2 regression. This is an attempt to "patch together" different pieces of the surface, each one guiding a single photon to the PMT- if all goes well, we should expect improvement in the efficiency. However, one such iteration is not sufficient: suppose the orientation at point (x, y, z) was chosen to guide some photons to the PMT. It's very unlikely for the new shape to pass through (x, y, z) again, because it's practically impossible to change the orientation at different points on the initial surface, without changing their spatial coordinates (while keeping the surface continuous). Consequently, the same photon that we wanted to guide; will now reflect off of a different point in space $(\tilde{x}, \tilde{y}, \tilde{z})$ and the orientation we once chose may not be appropriate anymore.

By the implicit function theorem, $\frac{dz}{d\rho} = -\frac{\partial_\rho f}{\partial_z f}$. The specified functional form of $f(\rho, z)_{a_i}$ can be used to find a functional form of $\frac{dz}{d\rho}$, which is then used as input for the regression algorithm. In this manner, we can find all coefficients a_i, directly from the regression- except for one, which is obtained by requiring the lightguide to pass through a reference point (default- light guide touches the PMT).

A pretty good analog is a Youtube video[3] about a basketball backboard, which was designed much the same way: different points on the surface, were oriented to guide the most probable incoming shots into the hoop.

This is not a rigorous optimization algorithm. For that reason we call it "heuristic" or "brute-force". This is also not the most general method- who's to say the best shape has an analytic functional form $f(x, y, z) = 0$? If there is, who can guarantee the best solution has radial symmetry, and is a smooth function $f(\rho, z) = 0$? Moreover, what if the said functional form is not easy to guess? Even convergence of the algorithm was not certain, initially. Possibly, the shape could just bounce around forever- torn between its obligation to help different photons, coming at different angles from various places.

The considerations above were certainly in the back of my mind, while waiting for the code to do its work. But there are a few compelling arguments in favor of this method, as a useful tool in this problem:

- Even the "conventional" optimization methods (that I know of) are susceptible to the so called "functional form problem". One would still need to guess beforehand.

[3] https://youtu.be/vtN4tkvcBMA

- High precision in the parameters of $f(\rho, z)$ is overkill- the final design will nevertheless only be inspired by the results of the algorithm, since perfect radial symmetry is impossible due to restricted space. Hence all we asked of the code, is to give us a step in the right direction.
- For reasonable initial conditions, and with photons coming in parallel- I have found this function converges to a paraboloid shape pretty often! Not only did it converge, but it also found the best (in this case, analytical) solution.
- It's conceivable, that if the algorithm doesn't converge- it could still find a better choice than the initial condition. The user can always pick the most efficient surface for further testing.

3.2.3 Some results of optimization

In my eyes, the 'proof of principle' for this optimization method is the result for parallel light. Here I'll show one of (many) examples, in which reasonable initial conditions led to convergence on the expected optimal shape: the paraboloid (abbreviated 'wc' for 'winston cone' in the graph):

Figure 4: Efficiency at each iteration ($\frac{\#\text{photons detected}}{\#\text{photons simulated}}$), parallel light

In this case, the optimal shape has 100% efficiency. We used a functional form of $f(\rho, z) = a_1 z^2 + a_2\rho^2 + z + a_3\rho + a_4 = 0$. Here I'll show the parameter values for each iteration, and we'll see that they converge to the winston cone values (dashed lines)- where $a_2, a_4 \neq 0$ and $a_1, a_3 = 0$:

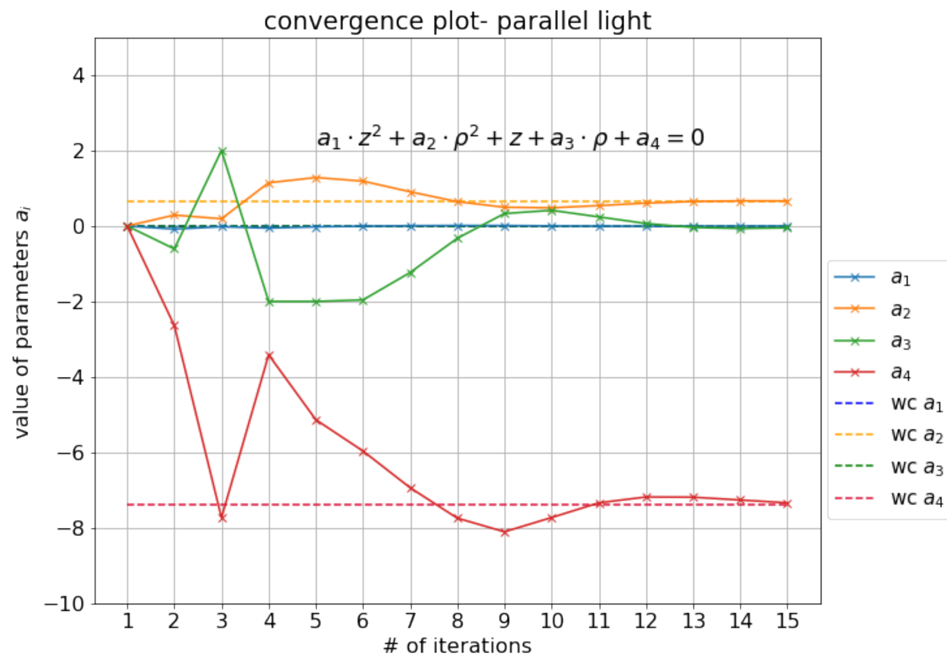

Figure 5: Convergence of regression parameters, parallel light

For non-parallel light, it's more difficult to get the algorithm to converge on a surface. In fact, I could only get it to converge in the original 2D model; In 3D convergence is more tricky. It may take a lot of 'massaging' (changing initial conditions, number of parameters, functional forms) to make it work. Personally, I had only explored for a few days (not enough)- since I'd already moved on from this method by the time the 3D model was ready. It was common for the code to bounce back and forth between 'better' shapes and 'worse' shapes, with the efficiency alternating between rising and falling:

Figure 6: Efficiency at each iteration

I could also show the parameter paths (like in figure (5)), but they are not very interesting- the parameters just bounce around randomly.

3.3 Conclusions

After playing around with the brute force optimization method for a few weeks- using various functional forms and initial conditions, testing different numbers of iterations, different number of photons per iterations; and even after changing parts of the code (the original version was less general and less efficient than the one I presented): I haven't stumbled upon any satisfactory solutions.

I attribute the shortcomings of this method, to a flaw more fundamental than those considered in (3.2.2). Namely, to further pursue this method- one has to assume that a good solution exists. Who's to say there exists a shape that could accommodate all 100 different light sources at once?

It's conceivable that if the PMT is "too far away", and the light "too diverge", no single geometrical shape could focus enough light into the desired small area. Instead of waiting for a lucky break, I decided to try a different route.

4 Dog Cones

4.1 The idea

The simplest approach would be to use existing tools to solve our problem. We've only discussed one tool- a basic property:

A parabola reflects 100% of incoming parallel light, to the focus point.

We could only use this to our advantage, had the photons come out of the rods parallel to the z-axis. Thankfully, in geometrical optics light rays have reversible paths. So the following statement is also a property of parabolas:

A parabola reflects 100% of light going out of the focus point, in parallel.

Theoretically, using two parabolic reflectors- we can focus light from one point-wise source, onto a point-wise detector, with 100% efficiency:

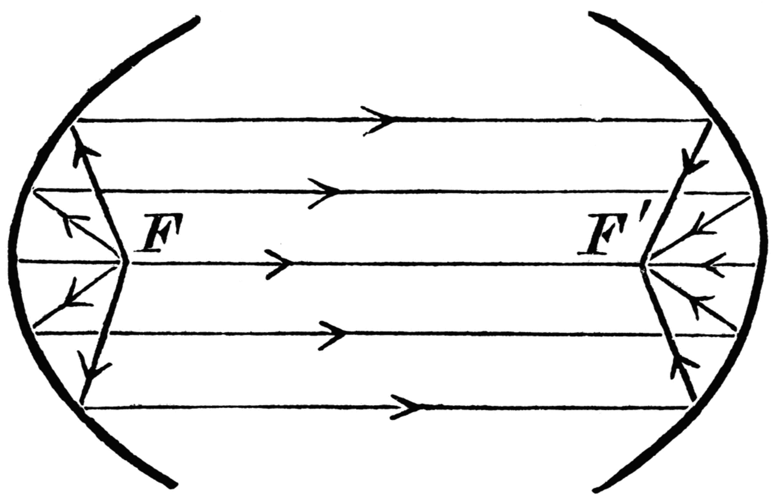

Figure 7: Focusing light from point-wise source F onto pointwise detector F'

If a quartz fiber was the point-wise source at point F, and the light guide an ideal reflector: this would be a perfect analytical solution, to the problem of getting the photons to their destination F'.

Despite the fact that our rods <u>are not point-wise sources</u>, they are very small relative to the system- and I thought this idea was worth a shot. After all, it's very simple and should be easily applicable even if the design of the system is changed; contrary to the light guide shape from the optimization process, which would've been sensitive to any changes in the design (table (1)).

Tiny rods, and tight spacing- call for very small parabolic reflectors. I concluded that paraboloids of this size are probably not practical: they are not easy to make accurately, finding the focus is a challenge, and aiming them at the right spot is hard. The closest shape would probably be just a straight, truncated cone sitting at the top of each rod; a bit like the collars we put on a dog to prevent it from scratching a wound.

Figure 8: Illustration- dog cone

Ideally, the dog cone could also get photons to travel parallel to the z-axis: so we can guide them into the PMT with the big parabolic light guide.

4.2 The design

I designed the cone based on simple considerations, without trying to optimize its performance. Unlike the parabola, the cone won't reflect all light rays in parallel to the z-axis. Hopefully, photons deviating slightly from parallel could still hit near the paraboloid's focus; if they hit near enough, they will get detected at the PMT.

The tilt of the cone shifts the angular distribution of the light, by a constant angle. I chose the tilt of the cone to shift the center of the distribution, to 0°. It follows from a little geometry, that the reflected photon will make an angle β_{new} with the vertical; that depends on α the tilt of the cone (from the horizontal) and β_{old} the angle of the original photon (from the vertical):

$$\beta_{new} = 2\alpha + \beta_{old} - \pi$$

By this reasoning, I chose $\alpha = 67.5^{\circ}$. It takes the center of the photon distribution to parallel! To choose the radii of the dog cone, and its height, I had to find a compromise: between fitting more cones in a tight space, and catching more photons.

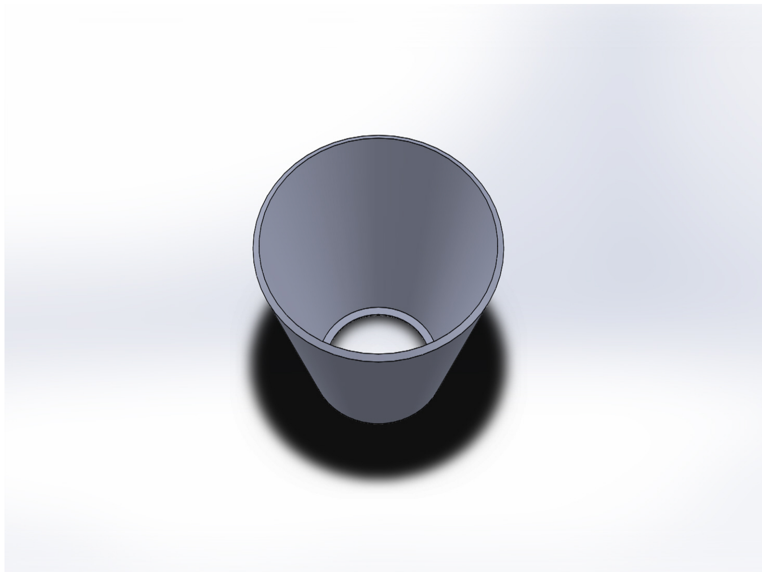

Figure 9: Solidworks design of the dog cone

4.3 Simulations

The next stage was to implement and test the idea using my computer model (3.2.1). I added to the code the option to "attach" a cone, or a paraboloid reflector to specified rods on the grid. Then I could compare the efficiency of the model in the different scenarios:

Scenario	$\frac{\#photons-detected}{\#photon-simulated}$
Original model	$1.6 \pm 0.1\%$
Cones	$30.0 \pm 0.4\%$
Paraboloids	$44.9 \pm 0.6\%$

Table 2: Simulation results

The simulations shoot the photons uniformly from all the rods. It's reasonable to take the average efficiency from the table above, and attribute it to the effect of a single dog cone on a single light source:

We expect a light source with a dog cone to be about 20 times more efficient.

Although the cones are not as good as the parabolas, they still improve the current performance of the light guide remarkably. Satisfied with the result, we decided to push the idea forward. The next step: Is it possible to manufacture reflectors this small?

4.4 Fabrication

A useful dog cone would have to:

- Be made out of a “radiation hard” metal (traditionally- aluminum).
- Be polished very well on the inside- non smooth surfaces scatter light instead of properly reflecting it.
- Be robust enough to withstand polishing without breaking down.
- Have the correct dimensions to a very high precision.
- As a rule of thumb- manufacturing time is proportional to the price (for one unit). A real ZDC would contain hundreds of dog cones, so I prefered methods with faster work rates.

I tried to understand the pros and cons of different methods, by reading online and speaking with professionals. I put together a rough comparsion:

Method	Precision	Surface quality	Work rate	Product strength
3D printing[4]	Very high	Low	Average	May not withstand polishing
Sheet metal die and stamp[5]	Low	Very good	Fast	Average
Casting	Very high	Low	Slow	Very robust
Electrical discharge machining[6]	High	High	Above average	Robust

Table 3: Different fabrication methods

I finally decided to contact workshops that implement the “die and stamp” method. Only one workshop replied: Hi-Cut 85' ltd[7].

They suggested to me the “electrical discharge machining” method, also known as “spark erosion”- which I learned was more suitable for the task. In this method, a very small needle produces an electric spark near a solid block of metal. These sparks can melt and even vaporize very small portions of the metal, momentarily. Point by point, the needle creates sinks in the block- and the liquid metal is cleaned off quickly (usually with water). Using a computer program, the operator can control the needle and the sparks- and mold the initial block of metal, to pretty much any shape with very good accuracy. Smaller needles and faster sparks can be used to achieve a very good surface quality. The final product will be strong enough to withstand post-production polishing.

Also at the manufacturer’s suggestion, we decided to make the dog cones out of stainless-steel, instead of aluminum: it would be easier to work with, and stronger- making polishing easier, while not being overly compromised by radiation.

4.5 Other open questions

Question: Where would we put the cones, if there is such little space between the rods?
Answer: Currently, it’s only possible to put a dog cone on every other rod- we only need

[4] https://iim.technion.ac.il/additive-manufacturing-3-d-printing-center/
[5] https://www.youtube.com/watch?v=5CuJjSk4U38
[6] https://en.wikipedia.org/wiki/Electrical_discharge_machining#Die-sink_EDM
[7] https://www.hicut.com/#hero

to make those rods slightly longer. We'll still get relative improvement.
Question: How would we attach a cone to the smooth, brittle quartz?
Answer: The spark erosion method allows for excellent precision in the dimensions of the cone. In fact, the small diameter of the cone can be made to fit the diameter of the rod, up to only a few micrometers. This tailoring greatly restricts the movement of the dog cone, so it doesn't tilt or slip easily. In addition, an O-ring can be used for additional security against slipping.
Question: Is the computer model missing important effects, that could overshadow the efficiency improvement? (like absorption of light in the cone)
Answer: We have to test a physical model to be sure.

5 Testing in the lab

5.1 Goals

The dog cones were designed with one purpose: shift the angular distribution of the light, such that the center moves from $\sim 45^{\circ}$ to $\sim 0^{\circ}$. So the basic way to test the cones:

Measure the exit angle of a narrow beam, that entered the cone at 45°

There's a second method to test the cones. For that, we'd need to assemble a partial prototype of the ZDC and irradiate it for duration T. Much like the computer simulations, the bottom line is:

Compare # of detected photons with and without dog cones

5.2 Setup

For the time being, we settled on the (seemingly) simpler approach- the first one. Beaming light directly into the cone proved to be a challenge (since it's so small), so we decided to use a middleman: a quartz fiber.

From our efforts we concluded, that this method is not suitable for the task of testing the cones. **For this reason, I won't be pedantic in my description of the setup and the results- the main conclusion is independent of fine details**.

Roughly, the setup was composed of:

- LED or laser as a light source.
- Adjustable mount, free to rotate along the arc of a circle (marked angles).
- Quartz fiber.
- Camera without lens (CMOS exposed).

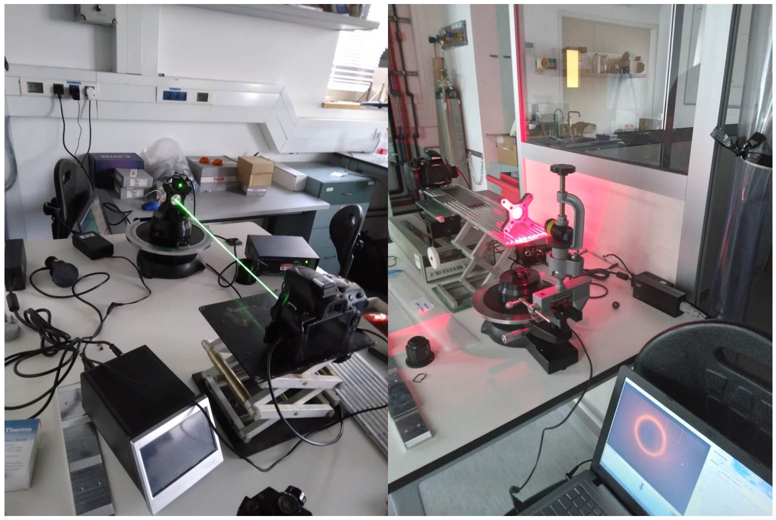

Figure 10: The setup (left- laser, right-LED)

We tried to make the incoming light beam as narrow as possible- for example using a lens to focus the LED, and by covering up as much of the rod as possible (leaving only the very edge exposed to the beam). We put black tape on the front of the camera, with a very small hole allowing the rod to go through- that way, there's very good contrast between the signal (light from the rod) and the noise (light from the room) was.

With and without a dog cone, we varied two parameters:

- Angle of incoming light
- Distance between rod and CMOS

We tested the resulting picture on the CMOS.

5.3 Predictions

5.3.1 Light in the rod

Typically in quartz $n \approx 1.5$- the index of refraction is similar to glass. Let's assume the rod is a perfect cylinder, and denote the symmetry axis by $\hat{z}$. We focus the laser or the LED on one base of the rod, at an angle θ_{in} with respect to $\hat{z}$. By Snell's law, the light transmitted from the air ($n_{air} \approx 1$), into the fiber will now travel at an angle $sin(\alpha) = \frac{sin(\theta_{in})}{n} \approx \frac{2}{3} sin(\theta_{in})$ with respect to $\hat{z}$. In this simple analysis, we assume the light propagates through the fiber- by total internal reflection off of the surface. In a perfect cylinder, that means the light will bounce back and forth, without changing the angle it makes with the $\hat{z}$ axis- α:

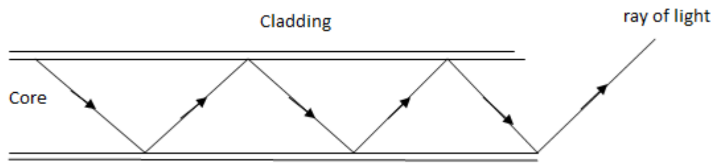

Figure 11: The total internal reflection picture

That happens until the light crosses the length of the cylinder, hitting the second base- again at an angle α. By Snell's law, $n \cdot sin(\alpha) = sin(\theta_{out}) \equiv sin(\theta_{in})$. For this reason, if **we shine light at θ_{in} on one end; we expect it to come out of the other end with $\theta_{out} = \theta_{in}$.**

But could we do this for any θ_{in} we want? The angle α with the $\hat{z}$ axis, requires the light ray to hit the surface of the cylinder at an angle $\beta = \frac{\pi}{2} - \alpha$. There's a condition on β for total internal reflection to happen:

$$n \cdot sin(\beta) \geq 1$$

Using $sin(\beta) = cos(\frac{\pi}{2} - \beta) = cos(\alpha)$ we get a condition for α:

$$cos(\alpha) \geq \frac{1}{n}$$

We can translate this to a condition on θ_{in}:

$$cos(\alpha) = \sqrt{1 - sin^2(\alpha)} = \sqrt{1 - \left(\frac{sin(\theta_{in})}{n}\right)^2} \geq \frac{1}{n}$$

Squaring both sides and rearranging:

$$sin^2(\theta_{in}) \leq n^2 - 1 \approx 1.25$$

The condition hold for all θ_{in}.

5.3.2 Light on the CMOS

The tip of a fiber is approximately a point-wise source, provided that the detector is far enough from it. I've stated this before- and now this assumption comes into play once again. Assume all our photons leave the tip of the fiber, tilted at an angle θ_{out} from the $\hat{z}$ axis. All the photons travel along straight lines, and then hit the CMOS detector (placed at a distance d) where we can observe them. The path of the light can be mapped onto a cone: the combination of all straight lines tilted by θ, that come out of a single, point-wise source. The intersection of the cone, with the CMOS, gives the expected picture:

Without dog cones, we expect to get circles with radius $\mathbf{r} = \mathbf{d} \cdot \mathbf{tan}(\theta_{\mathbf{out}})$

I went to the computer simulation (3.2.1) to test out this idea. Indeed, when d is large enough, and when our light beam is narrowly distributed around θ_{out}- we get a circle on the CMOS:

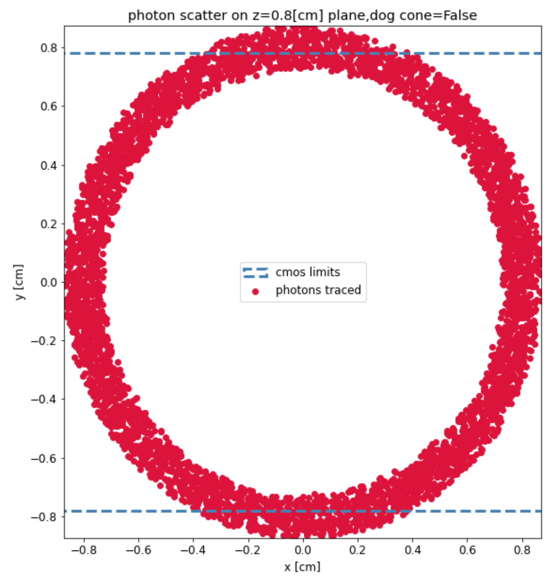

Figure 12: Expected picture on the CMOS $d = 0.8[cm], \theta_{out} = 45^{\circ}$

Running the simulation for different θ_{out} and different d (denoted by z on the graphs), we see a very good agreement with our expected $r = d \cdot tan(\theta_{out})$ behavior. In the next figures, the uncertainty in r comes from the width of the circle, in the image. I chose r to be radius of maximum intensity, approximating the uncertainty using the full width half maximum. The uncertainty in $tan\theta$ stems from $\delta\theta$, the width of the angular distribution I used in this simulation. The uncertainty in d is arbitrary, because distances are exact in the simulation. However, it won't effect the conclusion (obviously the fit is nearly perfect):

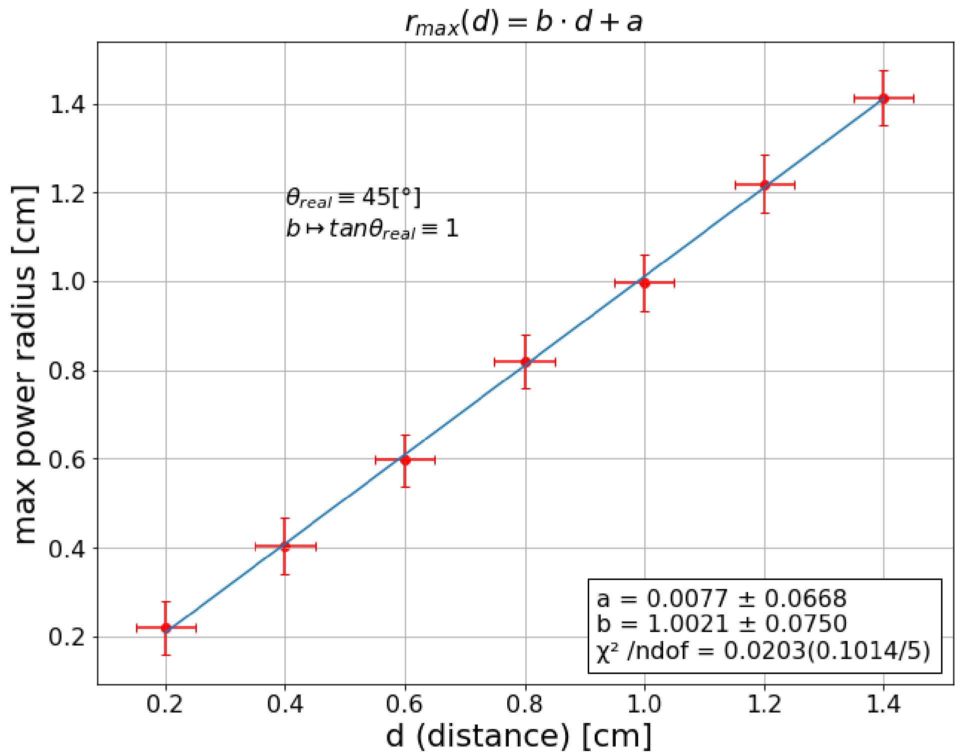

Figure 13: Circle radius vs. distance ($\theta_{out} = 45^{\circ}$), simulation

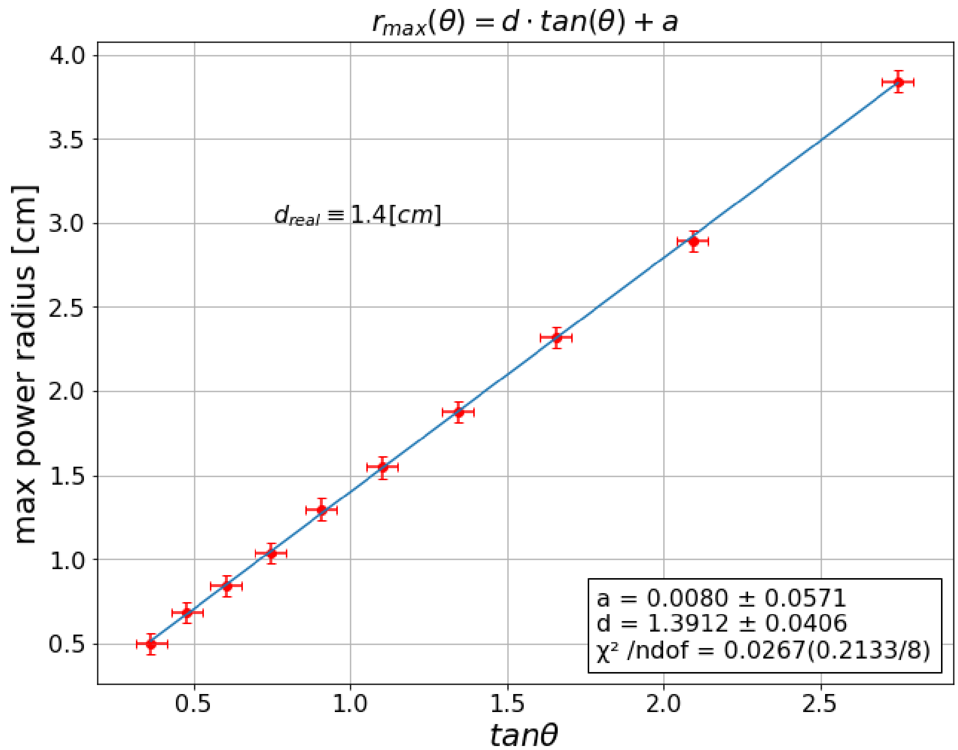

Figure 14: Circle radius vs. tilt ($d = 1.4[cm]$), simulation

These results are nice, but we haven't considered dog cones yet. I'd realized the point-wise source approximation may not transfer over to the cones, since they reflect the light from an area larger than the tip of the fiber. As it turned out, the latter statement is correct- and in the simulations I observed some new behavior:

- We don't usually get a very thin ring- the light is more spread out on the sensor.
- The dependence on the tilt is more complicated than before.
- The distance d has to be even larger than before, to get a good sense of the distribution.

In any case, the dog cones were designed to reflect $\theta_{out} = 45^{\circ}$ light, parallel to the $\hat{z}$ axis. I predicted that the circle "drawn" by parallel light on the sensor, will have constant radius as we vary the distance d:

With dog cones, we expect r independent of d

So at larger distances, I obtained the radius of the circles r from the simulations and saw that it's reasonably constant in d:

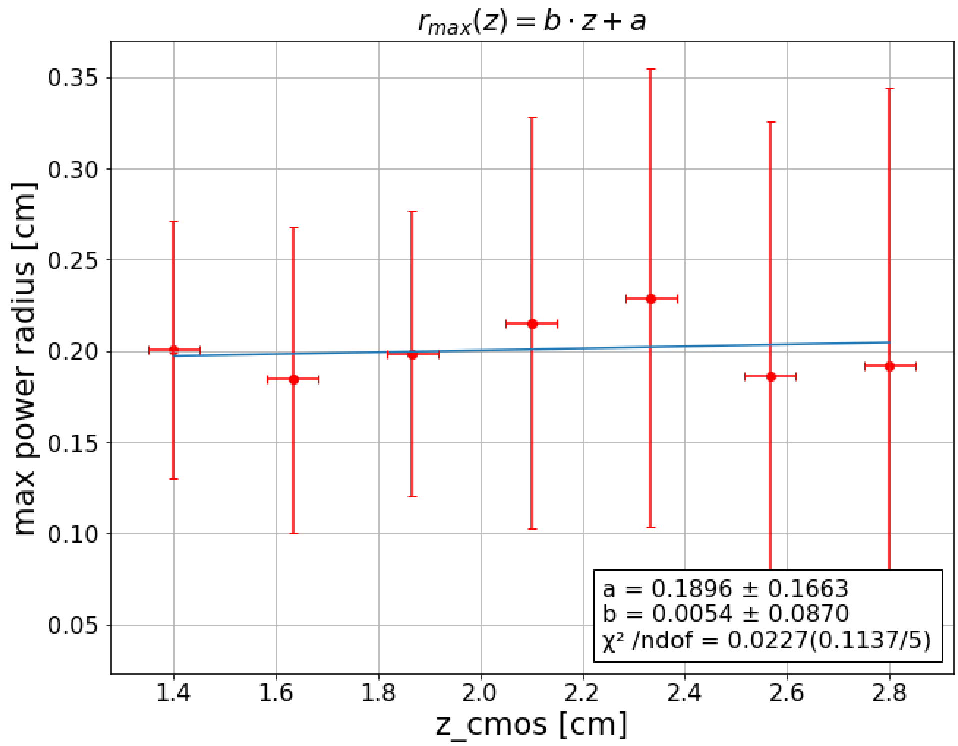

Figure 15: Circle radius vs. distance ($\theta_{out} = 45^{\circ}$), with dog cone, simulation

5.4 Results

By shining light through the quartz fiber, and analyzing the picture for different d, θ_{in}- I could count pixels and estimate the radius of the circle with maximal intensity, with uncertainty determined by the FWHM. The dominant uncertainty in my measurements was the distance of the CMOS from the tip of the fiber. I used a reference distance d_0, and measured all distances with respect to it. In that way, I eliminated the systematic error (d_0 is a constant in our regression)- and remained with the measuring device uncertainty, which was pretty significant at around 10%.

Without dog cones, I was able to confirm our prediction for the relation $r_{max} = d \cdot tan(\theta_{out})$ from figures (13),(14):

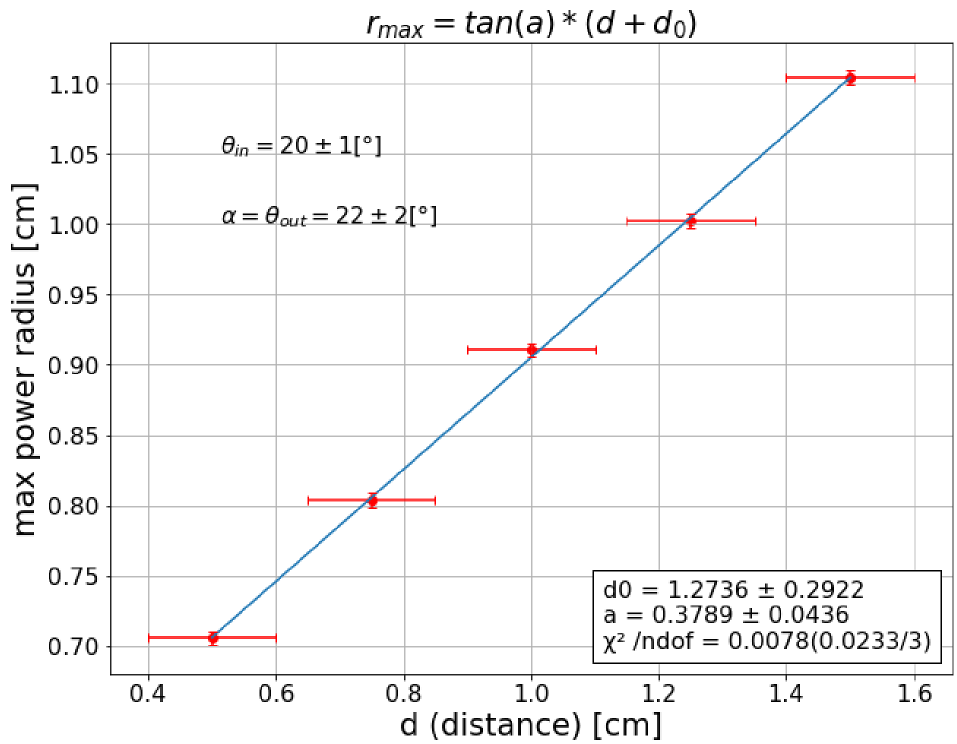

Figure 16: Circle radius vs. distance,$\theta_{in} \approx 20^{\circ}$,lab

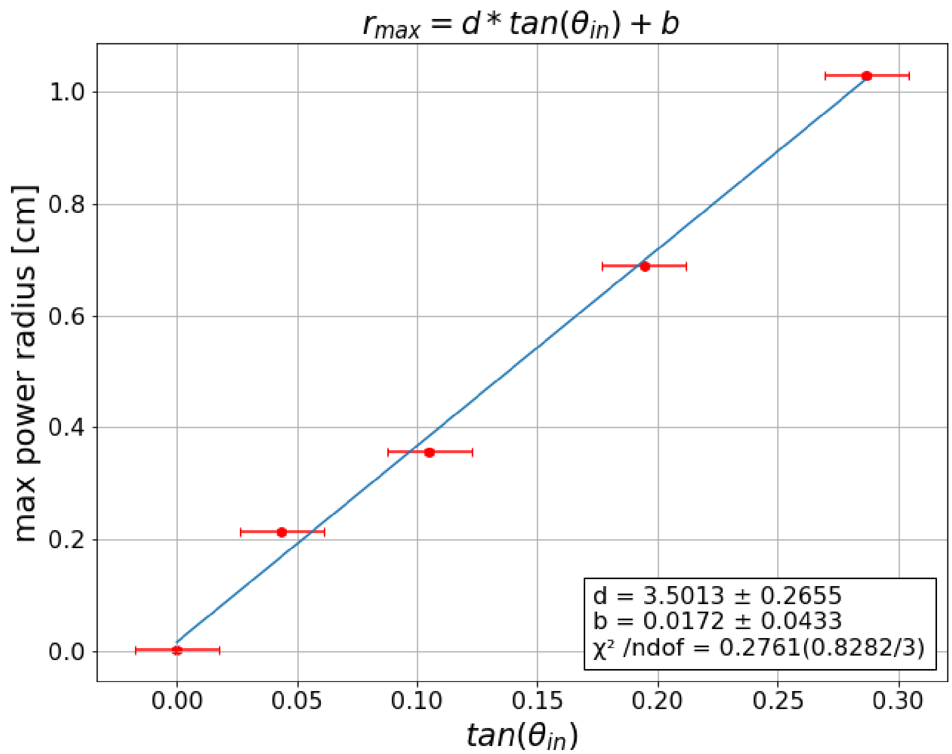

Figure 17: Circle radius vs. tilt, lab

Note- we wrote down the relation for $r(d, \theta_{out})$, but in our fit we used data for $r(d, \theta_{in})$. In this way, I tested the prediction from (5.3.1); that $\theta_{in} = \theta_{out}$. I estimated $tan(\theta_{out})$ from the slope of $r_{max}(d)$ in figure (16), and **indeed our estimates of** $\theta_{in} = (20 \pm 1)^{\circ}, \theta_{out} = (22 \pm 2)^{\circ}$ **overlap.**

For smaller angles, we observed a thin ring on the CMOS- that resemble the simulation (figure (12)):

Figure 18: Picture on the CMOS,$\theta_{in} = (6 \pm 1)^{\circ}$

As we slowly increased the angle, the ring continuously grew in size (as expected). However, at $\theta_{in} \approx 20^{\circ}$ the ring started to “smear”; though the max intensity circle was still identifiable:

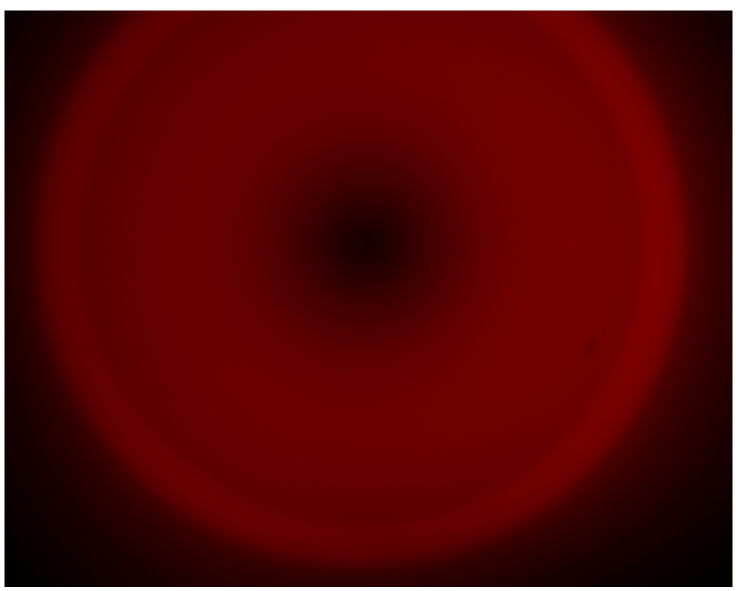

Figure 19: Picture on the CMOS,$\theta_{in} = (20 \pm 1)^{\circ}$

At $\theta_{in} > 20^{\circ}$, it was no longer possible to discern the ring which corresponds to $r_{max} = d \cdot tan(\theta)$- from the rest of the picture. In other words: **At large angles,**

there's too much noise to identify the signal. In the 'Conclusions' subsection, I discuss possible effects that could explain the increase in noise and damping of the signal .

I hadn't bothered to make any measurements with the dog cone, since at $\theta \approx 20^{\circ}$ light is not deflected from it. In addition, varying d accurately is much more challenging with the dog cone, and I haven't found a good way to get around this problem with the current setup.

5.5 Conclusions

I started out the discussion about the setup of the system by stating the main conclusion:

This setup is not appropriate for testing the dog cone.

The method I suggested, relied on our ability to measure the deflection of 45°light by the cone, however:

With 45°light, the signal is unreadable from the data.

I'll discuss effects that exacerbate the signal-to-noise ratio, and our attempts at eliminating them.

- Light from the environment- we hadn't put our system in a dark room, so light could enter the camera either directly or through the fiber. This didn't turn out to be a huge problem- turning off the lights, covering the front of the camera with tape, increasing LED power, and decreasing exposure time all allowed very good contrast. I believe it's evident from figures (18)-(19), that the noise comes from the LED- it has the same color and pattern as the signal.
- Faulty fibers- we switched out the fibers a few times, to make sure that noise wasn't a result of internal defects in the quartz. It's apparent in figure (10) that the green laser light is not propagating with ideal total internal reflection, as we assumed before. If it were, we wouldn't be able to see the fiber lighting up in green. This may contribute to noise in our data- if the angle between the $\hat{z}$ axis and the light isn't fully conserved (if it were, there should be TIR), it's expected that we won't get a picture of a perfect ring even for the narrowest of incoming light beams. In any case, I don't believe this is the most dominant effect.
- LED from the side- in figure (10) it's clear the red LED isn't lighting only the tip of the fiber, as we would want. That indeed induces noise in most conditions, either when the LED hits the camera directly, or enters the fiber from the sides. To counter this, we focused the light with a lens, and covered up the sides to make sure light hits only the very tip of the fiber.
- Width of the beam- when making our predictions, we pictured the propagation of light in the rods by visualizing a single light ray. However, no light source can produce beams that travel with a single well defined direction. If light enters the rod with a wide range of θ_{in} values, it's expected that we'll observe a smeared

circle instead of a thin ring. This obviously contributes to the noise, but it doesn't seem to be an overwhelming effect. Firstly, the tip of the fiber is very tiny, and at a large enough distance from the source- the incoming light should be approximately parallel (like we on earth observe light from the sun as approximately parallel). Moreover, this effect is not evident when θ_{in} is small. Lastly, using a lens, and even a laser- didn't greatly improve the picture at $\theta_{in} > 20^{\circ}$, even though we would expect significant improvement for "more parallel" light.

- Back reflection- also called optical return loss. Each detected light ray, passes from air to quartz, and back to air. The transmission and reflection coefficients for each event, are given by the Fresnel equations. I won't show the calculation here, but it turns out that as θ_{in} increases: the transmission decreases. I estimate only around 80% power of $\theta_{in} = 45^{\circ}$ light is fully transmitted, while for $\theta_{in} = 30^{\circ}$ it's closer to 90%. This shouldn't have a great impact on it's own; but combined with some of the other effects, this only amplifies the noise from light traveling at unwanted angles. This is an intrinsic property of passing light through the fibers- we can't get rid of it.

- Spreading out[8]- light with bigger θ, corresponds to rings with bigger $r = d \cdot tan(\theta)$.The signal is relatively weaker for big θ, because it's spread out over more area on the sensor (a bigger ring)- less photons hit each pixel, making the signal harder to read relative to smaller radii. This, just as the previous effect, only decreases the signal to noise ratio when noise is present. The only way to counteract, is to take pictures at smaller d- where the radii of the rings are the smallest, and the picture less spread out; but we haven't seen much improvement.

From this lengthy discussion, I hope it's clear why we chose to abandon this method. It has some intrinsic flaws that amplify noise and damp the signal. We played around with it for a few weeks, and haven't found a satisfactory solution to some of the problems above; neither a way to bypass those difficulties. In addition, it's possible that I don't fully understand the propagation of light in the quartz fibers, and am missing a way to make it work.

6 Future experiments

I'll give a brief description of the setup we intend to use, to implement the second method (5.1) of testing the dog cones. We shall build a partial prototype of the ZDC in the lab, roughly composed of:

- Radiation source- cosmic rays induce particle showers in earth's atmospheres. Some of those particles are muons which we can detect in the lab.

- Two "triggers"- from all the muons coming in at random directions, these secondary detectors will help us single out those particles with the desired orientation.

[8] I thank Itay Gelber for bringing this point to my attention

- Tungsten plates.
- $10-20$ Quartz fibers in a designated chamber.
- $10-20$ dog cones.
- 1 parabolic light guide ("Winston cone").
- PMT.

The muons should hit the tungsten plates and induce particle cascades. Those secondary particles should emit Cherenkov radiation upon passing through the quartz fibers. The angle of emission depends on their energy, the quartz index of refraction, and the angle at which the particles travel in the fiber. We'll try to set up the system, such that the photons mainly come out of the fibers at $\theta_{out} \approx 45^{\circ}$. The main goal, as we've stated:

Compare # of detected photons with and without dog cones.

Hopefully I'll continue this part of the project in the near future.

7 Acknowledgments

I'd like to express my gratitude to my adviser Zvi Citron, for giving me a very interesting project to work on; for guiding me along the way, supporting my ideas and steering me in the right direction.

I'd also like to give my special thanks to Itay Gelber, who had an equal part in planning, building, and conducting the experiments described in (5.1).