THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF PHYSICS

DESIGN AND IMPLEMENTATION OF RADIATION CURING UVLED ARRAY FOR USE IN RHIC AT BROOKHAVEN NATIONAL LAB

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ABSTRACT

An ultraviolet LED (UVLED) array was designed and built for use on the forward meson spectrometer (FMS) of the relativistic heavy ion collider (RHIC) at Brookhaven National Lab. One component of the FMS is an array of lead glass blocks. These lead glass blocks undergo radiation damage over time that darkens them and decreases the amount of signal recorded. The UVLED array created is an array of many ultra violet LEDs that effectively soak the lead glass blocks of the detector with light, their light being an effective cure for the radiation damage. Additionally, compared to the traditional method of curing the detector cells the UVLED is both easier and much more effective. The UVLED array proved to be successful, curing the residual damage of the cells preventing the buildup of additional damage.

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ACKNOWLEDGEMENTS

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Chapter 1

Introduction

1.1 Motivation

The relativistic heavy ion collider (RHIC) at Brookhaven National Lab is a very important particle accelerator as it is the only spin-polarized proton collider ever built [1]. Part of the solenoid tracker at RHIC (STAR) experiment is the Forward Meson Spectrometer (FMS). The FMS consists of electromagnetic calorimeters, which are lead glass blocks optically coupled with photomultiplier tubes (PMTs) [2]. These PMTs act as detectors by measuring optical photons that result from the electromagnetic shower of high-energy electrons and photons [3]. The amount of light that is measured is proportional to the energy of the original particle [3]. This high-energy radiation damages the blocks causing yellowing or darkening over time. More optical phonons are absorbed by the damaged glass, and some signal is lost [3]. Figure 1 shows clean cells next to damaged cells.

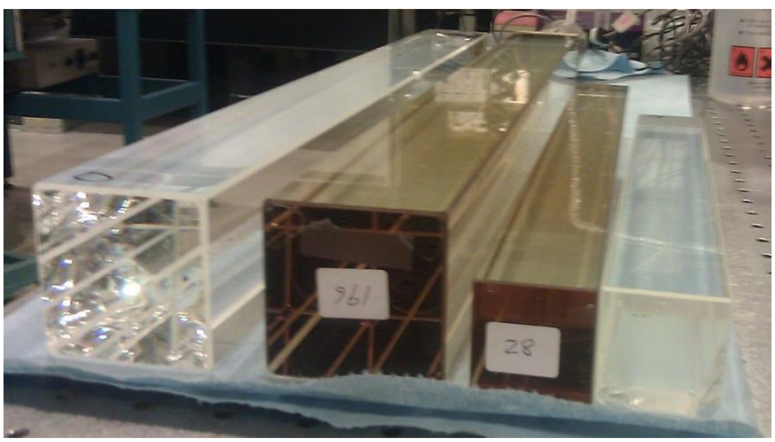


Figure 1- Damaged blocks in the middle of clean blocks.

The FMS consists of small and large cells, both pictured in Figure 1. The smaller blocks are located close to the center of the beam to increase the resolution of the detector. This radiation damage is a long-term problem must be addressed, especially since the current experiment at STAR is using much higher energy and luminosity, each of which cause more damage than previous experiments.

The traditional method of curing the lead glass blocks was to expose them to sunlight by placing them outside [4]. A few weeks outside would eventually cure the cells. This worked because sunlight consists of many different wavelengths of light, some of which cure the lead glass blocks, but it was tedious and time consuming. The UVLED array will be very beneficial to the scientists in the STAR project, curing any residual damage and preventing the build-up of additional damage. As a result, scientists can use higher energy and luminosity without fear of damaging the detector.

This project is to build an UVLED array to cure or stabilize the damage to the lead glass blocks used in the forward meson detector of the STAR project at Brookhaven National Lab. A UVLED array was chosen because it is a reliable curing method that can also fit in the limited space available given the detector design. It will cure any residual damage as well as any additional damage incurred.

1.2 Theory of Radiation Damage

Lead glass is a commonly used material in particle physics accelerators [6]. The reason that lead glass is used is that the lead has a high atomic number, thus causing more coulombic interactions, but it is also transparent. High-energy particles interact with the lead nuclei and its coulomb field and create internal showers of electrons, photons, and positrons, which are measured by the PMTs [5].

A side effect of the high-energy particles interacting and showering in the lead glass blocks is that the glass darkens and loses transparency. This is bad, as it reduces the signal that propagates to the end of the block and to the coupled PMT [3]. The mechanism of the darkening is the ionization of electrons from their associated atoms [7]. The freed electrons eventually become stuck in a new location. Glass is an insulator and very inhibitive of electron movement, so it is very difficult for any electrons to move any further and rebind with ionized atoms. These separated electrons create color centers and additional absorption bands that cause the darkening of the glass [7].

Color centers, also called f-centers, are a type of crystallographic defect in which one or more electrons take the place of an anion in the crystal. Figure 2, below, shows this phenomenon. Electrons being in different positions changes their energy and the energies that they are able to interact with [5]. This results in different and more absorption bands than clear glass. Some of these absorption bands are in the visible light spectrum, thus the glass becomes 'colored' [7]. The fact that more energies are being absorbed means less overall signal reaches the PMTs.

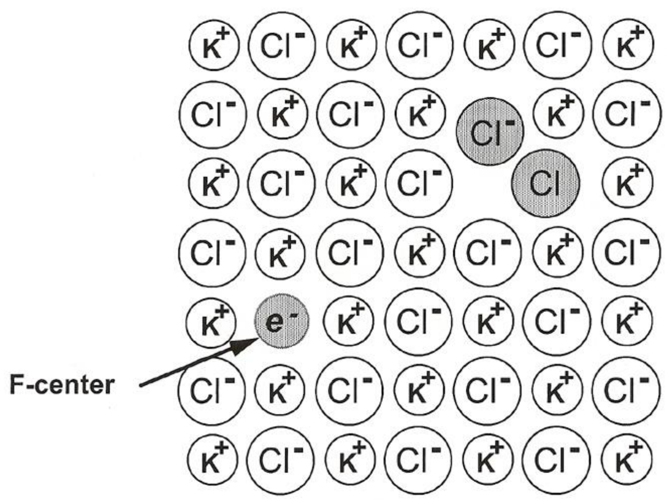


Figure 2- Color center in KCl crystal [8].

The radiation damage affects the absorption of different energies of particles differently, but by far has the largest effect on wavelength in the ultraviolet and near-visible light spectrum [9]. The shower max, the area of most damage, is about 1/3 of the length down the lead glass block. The attenuation coefficient, μ, is a characteristic of a material that relates to how easily a material can be penetrated by light, sound, or other particles. The probability of a photon surviving a specified distance, z, after being directed through a material is [9]

$$P_{Survival}(z) = e^{-\mu(\lambda)z} \quad (1)$$

The attenuation coefficient, μ, is also a function of the wavelength of incident light and can be written as

$$\mu = \frac{1}{\ell(\lambda)} \quad (2)$$

where ℓ is the characteristic length of lead glass. The attenuation length of a material is the distance that (in this case) photons will travel before only 1/e of their energy has not been absorbed. In a clean, undamaged cell, $\ell(\lambda)$ can be written as $\ell_0(\lambda)$. After radiation damage occurs, however, an extra term must be added to account for the change. This leads to an attenuation length equation of

$$\frac{1}{\ell(\lambda)} = \frac{1}{\ell_0 + g(\lambda, z)} \quad (3)$$

where $g(\lambda,z)$ is the effect of the radiation damage as a function of the different energies and the length along the cell[8]. From tests of the FMS during the current experiment the ADC count, which is proportional to the amount of signal that propagates all the way through the lead glass, drops around 20% each day for the smaller cells. This means that the probability that a photon will be affected by the radiation damage in a small cell is roughly:

$$P_{affected} = 1 - (.80)^n \quad (4)$$

In this case n is the number of days without curing the lead glass block. The larger cells will have slightly less damage, as they are farther from the center of the beam. The goal of this project is to either completely clean each cell or at least to prevent additional damage so that the variation caused by further radiation exposure is negligible.

1.2.1 Methods of Curing

Two main methods are used to cure damaged lead glass calorimeters. The idea behind both of the most common curing methods is to provide a lower and more constant energy to the material to weaken the inter-atomic bonds and allows electrons to find their way back to the ground state [7]. The energy from the LEDs is much lower than the high-energy radiation that causes the damage.

One method of curing is thermal annealing [10,11]. Heating the lead glass to its annealing temperature weakens the inter-atomic bonds and allows the electrons to fall back to the ground state when it cools and settles. This method, however, is not possible for the FMS. The PMTs that are optically coupled to the lead glass blocks are susceptible to damage from the extremely high heat that would be required [8]. Additionally, it is also very dangerous, as the lead glass blocks become very fragile and may shatter during the heating or cooling process.

The other method to cure radiation damaged lead glass blocks is to expose them to light in the UV and near visible light spectrum[4]. Previously this was done through exposure to sunlight for 2-3 weeks. The method employed in this project is to use LEDs to shine ultraviolet light on the damaged cells, which has many advantages over sunlight. An obvious advantage is that it does not require putting the lead glass blocks in sunlight. This process takes an entire summer for the FMS, so it only done rarely. Lastly, the LEDs can offer a much more intense and reliable light than the sun. All of these factors greatly reduce the exposure time required to cure the cells. Additionally, LEDs are reasonably small and safe to use in a particle accelerator. All of these factors are why the curing method chosen was a UVLED array.

Chapter 2

Systems

2.1 Project Specifications and Limitations

There were many specifications and limitations on how to build this UVLED array for Brookhaven National Lab.

For the project to work at all it had to fit in a very small area in from of the detector. The FMS detector is 2m x 2m with a .5m x .5m beam hole in the middle. The area designated for the UVLED array is the same area as the FMS, but only about 2 inches thick. The array must be put together inside of that given room. Naturally, the closer to the cells the LEDs to the lead glass detector cells the better, as there would be less light leakage and the LED light would be more direct. A schematic and picture of the available workspace are in Appendix A.

Another important consideration was the amount of material used. This array was going directly in front of the detector cells, so it should use as little material as possible in order to have the least effect possible on experimental data.

Particle accelerators work by using extremely powerful magnet fields. In order to keep the array from being ripped apart by the magnetic fields in the accelerator no magnetic material can be used in its construction. Not only would having magnetic material in the array destroy the array, but it would potentially damage many other pieces of equipment as well.

Lastly, the entire array should be mostly modular and easy to transport. The array is reassembled at Brookhaven after being built at Penn State, so this is very important. The requirement that it is modular will be very helpful if any of the components of the array should ever malfunction or break, as taking off one module to repair or replace is much less invasive than disassembling the entire array to fix a potentially small and easily fixed problem.

2.2 LED Optimization and Characterization

The first step in this project was to determine what wavelength LED would be the most optimal for curing the damaged cells. The factors taken into consideration were the power-to-light efficiency and curing efficiency of the LEDs. Several different wavelength LEDs were tested on a damaged cell by measuring the ratio of light that would pass through the damaged cell over time. This effectively allows the measurement of how fast each wavelength cures damage. The testing is explained in Appendix B. The different LED wavelengths that were tested were 420nm, 400nm, and 375nm. The LED that had the best combination of power efficiency and curing efficiency was the 375nm wavelength LED. This LED was used for the rest of the project.

Next, various characteristics of the 375nm LED had to be determined. The maximum current that the LED could sustain was tested first. If too much voltage was applied across the LED it would burn up and stop working, so it is important that the voltage is safely under that limit. It was determined that a maximal current of about 1 amp can be produced through the application of about 10.5 volts across the LED. The highest safe voltage and current possible are desirable. A current vs. voltage graph for a single

LED at both room temperature and heated are in Appendix B. The graph is important in that it shows that the LEDs are Ohmic, even when heated.

The power efficiency of the LED was characterized next. This is critically important because the LEDs become very hot after running. The efficiency is related to the amount of heat produced by the LED, since any energy used but not converted into light energy is instead converted into heat. The efficiency of the 375 nm LEDs was close to 10%. This means that for 10 watts of power over the LED 1 watt of that is converted into light energy and 9 more watts are transferred into heat. This amount of heat requires a cooling system. The cooling system is addressed in a later section.

2.3 LED Distribution

When determining the ideal distribution of LEDs the damage concentration of the various cells must be taken into account. The small cells closest to the center of the detector array sustained much more damaged than the cells towards the edge.

Each LED projects a cone of light in about a 60 degree angle from the LED. This is useful because it means that not every cell needs an LED dedicated to it. A three dimensional model of the FMS was built in mathematica. An array of LEDs and their projected light cones were created and added to the FMS model. The distribution parameters were modified until a reasonable and realistic spread of LEDs was obtained. This model contained about 1000 total LEDs. This was a proper amount of LEDs because it was not possible to pack any more LEDs in the center of the distribution and the radially decreasing distribution must be held. The Mathematica© model of the FMS and LED placement in Appendix B.

2.4 Thermal Calculations

Now that the number of LEDs and their approximate positions were determined, a cooling system was developed to deal with the heat produced. Using the efficiency mentioned before of 10%, along with the operating voltage and amperage gives an accurate measure of how much heat is produced. For 1,000 LEDs each receiving 10 watts of power, 10 kW of power are used. Nine kW of this is heat from the LEDs and one kW of it is light power that goes into the FMS detector.

The UVLED array required a cooling system to keep it from overheating. The easiest and best cooling systems were small liquid cooling panels. Nine of these panels would cover the area of one quadrant of the FMS. Not only would individual liquid cooling panels make sure that the LEDs did not become too hot and malfunction, but they also would serve to ensure that the UVLED array was modular so that any possible future repairs would be much easier to manage. An image of the cooling plate and its specifications is in Appendix D.

A 1-1 scale model of the LED and cooling plate was made in SolidWorks. The panels were then placed in their respective position that it would occupy in the FMS. Finally, a script placed LEDs according to the distribution from the Mathematica model. Since the cooling plates are not perfect and leave small areas uncovered some LEDs were shifted until all of them were over a cooling plate.

The densest plate had about 60 LEDs on it. This means that the most heat that a cooling panel would have to relieve would be about 54 kW. Using the datasheet for the cooling panel shows that 1 gallon/min of water flow would only result in an increase of about 5 Kelvin, which is well within reason. 1 gallon/min of water flow is very possible given the utilities available at Brookhaven National Lab.

2.5 Structural Layout

The next important part of the project was to determine how to mount the panels with LEDs onto the preexisting FMS frame. The best material to use would be aluminum since it is strong, light, and nonmagnetic. An aluminum frame was modeled in Solidworks to hold all of the panels together. Each panel would screw into the aluminum frame to stay in place.

It was important to make sure that the final frame design was somewhat flexible because the exact dimensions of the preexisting FMS frame were not known. The design accounted for this by placing the plates about the center and leaving extra material on the top and side. Appendix E shows both the aluminum frame design and how the panels were mounted.

2.6 Electrical Planning

The electrical design of the panels was the last major thing that needed planning. The power supplies that Brookhaven would provide were tested to see how much power they could actually supply to our LEDs. The test panel was a replica of the densest plate. The power source provided 42.5 Volts spread over 12 strings of LEDs. Each string of contained 4 LEDs, so the very dense panels would require more than one power source. The voltage drop over each LED in the string was the same to within 1%. This is important because it is necessary for each LED to have the same power to ensure uniform curing.

The LED placements on the panels were then adjusted again on the panels to group the LEDs into strings of 4. This would make it so that each power source would provide power to 12 strings of 4 LEDs. In order to accomplish this while keeping each panel a separate module a few LEDs had to be shifted to nearby panels until each panel contained a multiple of 4. Next, the LEDs were rotated to group all of the ground and source ends together and facilitate wiring. Wiring schematics drawn in Solidworks added to the final shifted LED positions to use for reference when soldering wire connections. These can be seen in Appendix F.

In order to further increase the safety and decrease the possible damage from any failure, fuse blocks were to be included on both the source and drain of each LED chain.

2.7 Cooling Panel Construction

The Solidworks files for the final LED positions were converted to the appropriate format for use with the CNC machine and holes were drilled.

The SolidWorks model was used to measure and cut the frame parts to the appropriate size. The aluminum frame was constructed first. Then the panels were placed in their respective positions. The frame and panels were both marked with drilling locations and everything was taken apart again to drill using a drill press. 6 holes were put in each panel along the edge where there were no circulation pipes. Once everything was drilled the panels were manually tapped and then everything was reassembled. Holes were modified or enlarged until everything fit well.

Next, the panels were removed and LEDs were attached. There were two screw holes for each LED. Thermal paste was applied to the bottom of the LEDs before they were screwed on. The wiring schematic made in Solidworks was used to ensure that the LEDs were attached with the correct orientation.

Once the LEDs were all attached to the cooling panels they needed to be wired. Again, the wiring design from Solidworks was referenced. Each contact of the LED was soldered to the wire and was then covered with heat shrink wrap to protect the circuit from shorting. The wire at either end of the chains of four was left 3 to 4 feet to give enough leeway for connection to the fuse blocks and actual installation at the accelerator.

Once the LEDs were all wired, the heat shrink-wrap was shrunk with hot air from a hair dryer and the end wires were bundled together. All of the connections were tested one last time to make sure there all LEDs were connected correctly. The panels were reinstalled one last time to ensure they still fit. The panels with

LEDs on them are pictured in the Appendix F. Once all of that was completed, everything was taken apart and transported to Brookhaven to be installed.

Once at Brookhaven, everything was again reassembled around the detector. The ends of the circulating plumbing tubes were connected to one another and to a water source and drain. The free ends of the wires were cut to length and soldered to fuse blocks, which were then connected to the power supplies. Images of the installation process and final installed array can be seen in the Appendix F.

Chapter 3

Results

3.1 Temperature

After installation the UVLED array was turned on and tested. Over several hours of testing the water temperature coming out of the array was less than 3 Kelvin higher than the supply water. This is enough cooling and proves the liquid cooling panels effective.

3.2 Curing

In order to determine how effective the LEDs were at curing the detector cells, a sweep of different wavelengths of light through a transverse slice of a lead glass block was done for a damaged cell. Three slices were taken in the front, middle, and back of the cell and for a large and small cell. The UVLED array was then turned on and the new transmission amplitude was recorded after 15 and 40 hours. This was also done with a completely cured cell. The data taken was plotted and can be seen in Figure 3. Additional curing data is in Appendix G.

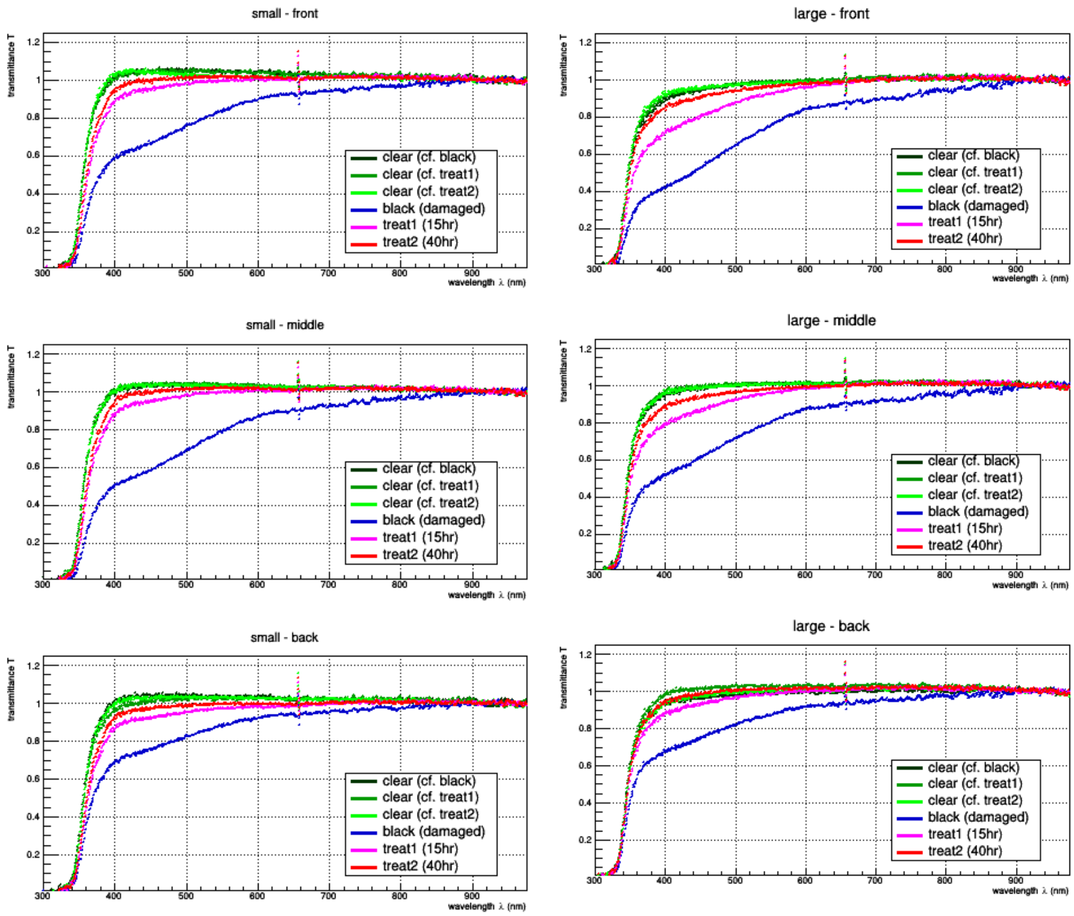


Figure 3-ADC count transmitted transversely through the cells at the front, middle, and back for small (left) and large (right) cells as a function of wavelength and time under a UV soak from the UVLED array.

As can be seen in Figure 3, the UVLED array worked very well. It did a good job of curing the damage in the lower wavelength range where the most damage occurred. It was determined that the scientists at Brookhaven will just run the UVLED array for 3-4 hours every night in order to cure the cells. The UV soak will be enough to stabilize the damage cells from high energy experiments over the day.

Chapter 4

Conclusion

4.1 Conclusion

A UVLED array was designed and built in order to cure radiation damage to the FMS at Brookhaven National Lab. The UVLED array was designed and built from scratch, starting with characterizing and optimizing the LEDs used. The layout of the LEDs was determined by fitting the LEDs as densely as possible in the center and radially decreasing the density. Next, the thermal output of the LEDs was derived from their efficiency. This heat was taken care of with liquid cooling panels. The panels also helped to make the UVLED array modular to make future changes easier. The power sources were tested to determine how many LEDs they could supply power to. From there, the wiring of the LEDs, which would be mounted on the cooling panels was planned out. An aluminum frame was designed to fit the panels and cover the FMS. LEDs were installed on the panels, and the frame was constructed at Penn State to make sure the panels fit. The array was taken apart and reassemble at Brookhaven National Lab.

Future work that can be conducted for the UVLED is to perform more tests on how well they cure the FMS detector cells. The damage to the cells can modeled and taken into account in simulation software used to model interactions in the FMS. The UVLED array will require maintenance if any LEDs burn out or connections break. This will be relatively easy to fix, as the modular design with the cooling panels means it will be possible to only replace or work on a single panel.

Appendix A

Project Space Available

The dimensions of the available workspace for the UVLED array is below in Figure 3 along with an actual picture of the space. The presented images are for the right half of the FMS. The distance from the frame to the lead-glass blocks is about 2 inches.

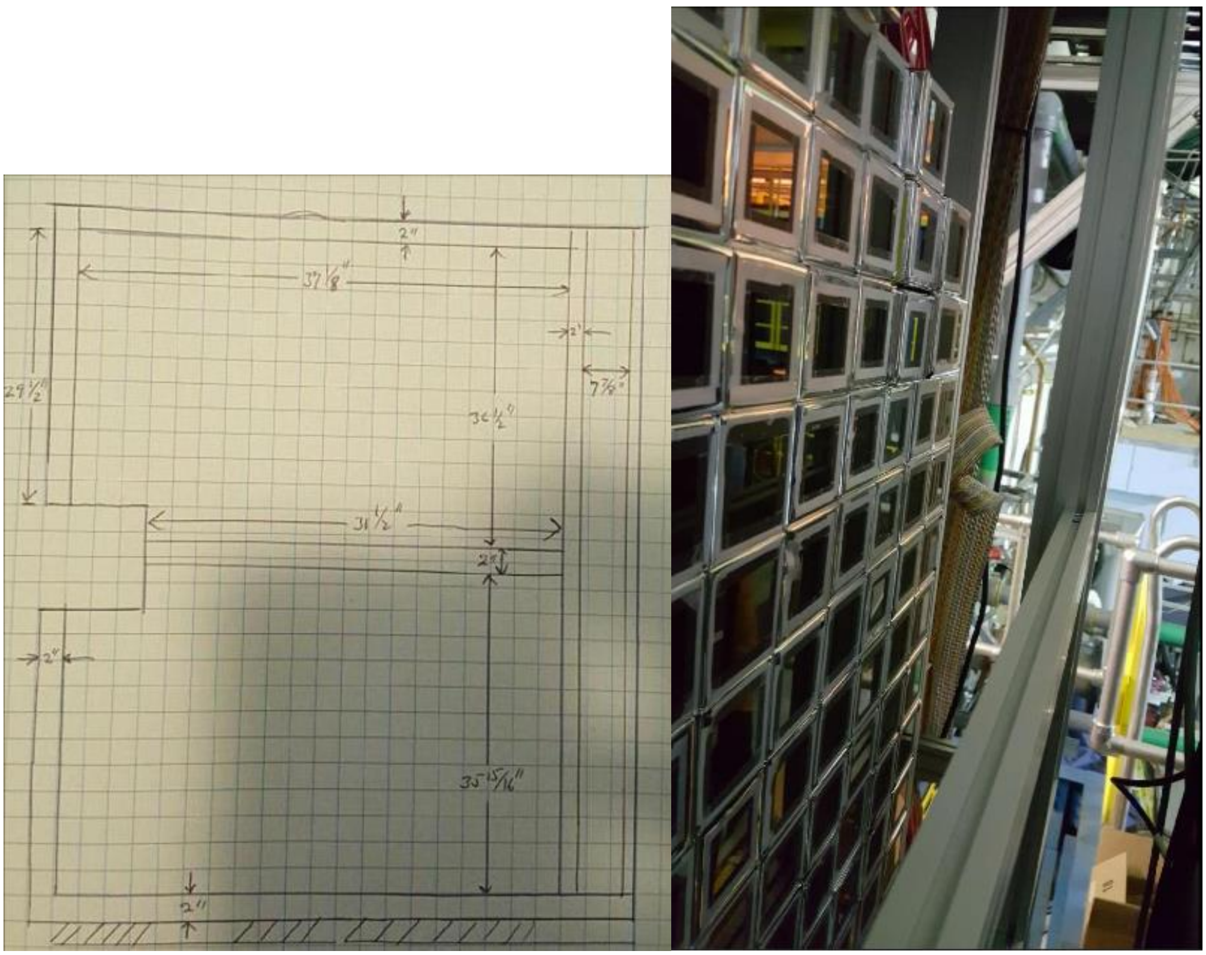


Figure 4- Dimensions of available workspace (left) and image of workspace (right).

Appendix B

LED Optimization and Characterization

A schematic of the experimental setup used to test and determine the optimal LED Wavelength to use is below in Figure 5.

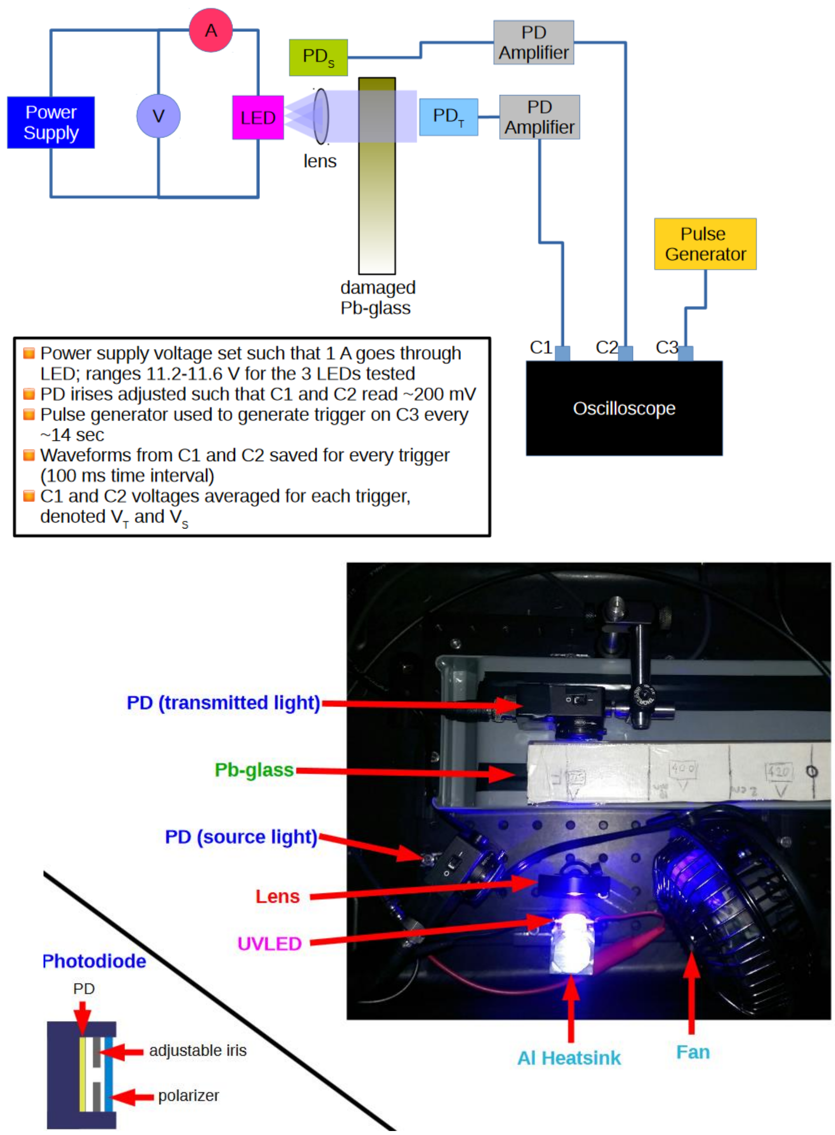


Figure 5-Schematic of LED wavelength optimization setup (top) with an image of the actual setup (bottom).

The assumptions used for calculating the fit equation for the shape of the voltage ratio (curing percent) vs time graph of the data obtain were that:

1. The rate of f-center removal is proportional to the number of f-centers.
2. The number of f-centers removed is proportional to the ratio of the voltages between transmitted and initial.

These assumptions grant the differential equation

$$\frac{df}{dt} = \frac{1}{\tau}(a - f) \tag{5}$$

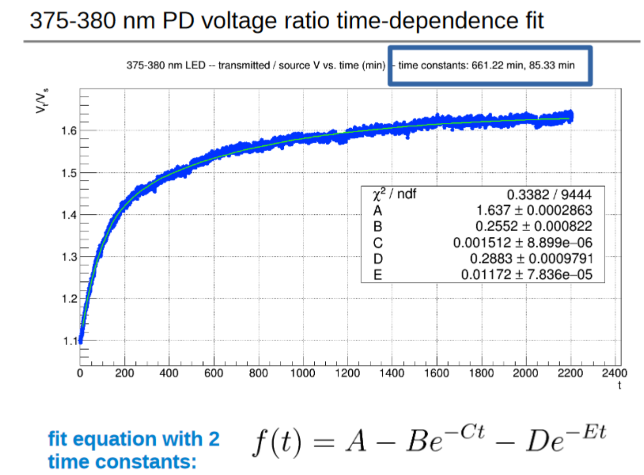
where τ is the time constant where a 1-1/e fraction of f-centers are removed and ‘a’ is the constant for a completely clean cell. Solving the differential equation leads to the following:

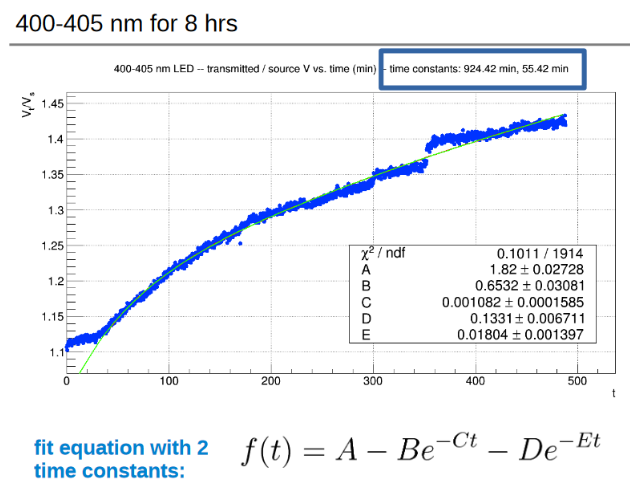
$$f(t) = A - Be^{-\frac{t}{\tau}} \tag{6}$$

This equation did not quite fit the collected data, so the hypothesis that there are instead two linear processes, one fast and the other slow. This leads to the fit equation below.

$$f(t) = A - Be^{-\frac{t}{\tau_1}} - Ce^{-\frac{t}{\tau_2}} \tag{7}$$

The plots for 420, 400, and 375 nm along with the corresponding fits are below in Figure 6.





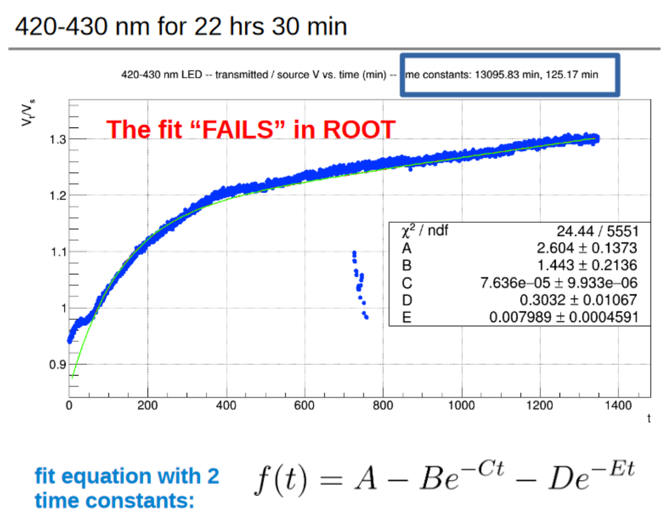


Figure 6- Transmission ratio curve for 375 nm (top), 400 nm (middle), and 420 nm (bottom) and associated fit parameters.

The time constants are the important pieces of information to take from these graphs. The time constant is the time it takes for all but 1/e of the radiation damage to be cured. The fit for the 420 nm LED was not very good and the time constant was large. The time constants for the 400 nm LED were 924.42 mins and 55.42 mins and the time constants for the 375 nm LED were 661.22 mins and 85.33 mins. The time constants for both the 375 and 400 nm LEDs were comparable, but overall the 375 nm LED seemed to cure the cells faster in most cases.

The power efficiency of the LEDs was plotted as a function of wavelength. That plot is shown below in Figure 7.

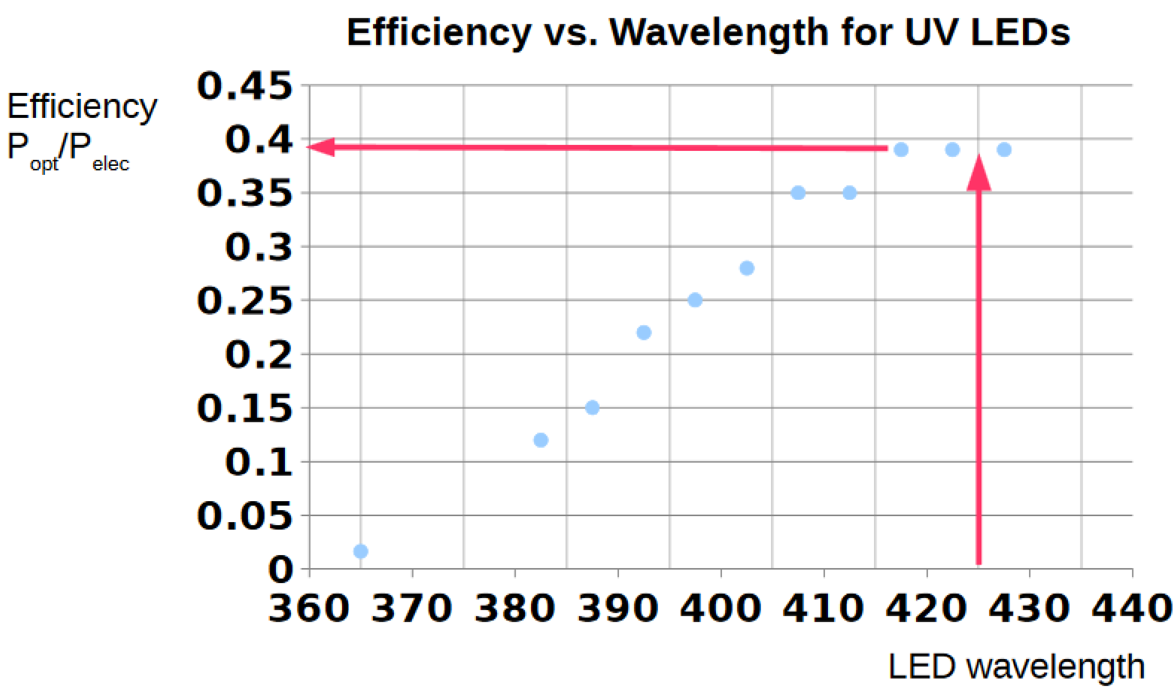


Figure 7- Efficiency vs Wavelength for different LEDs.

The trend shows that the lower the wavelength of the led the lower the optical power it outputs is vs the electrical power it takes in. This means that they give off more heat at lower wavelengths. Overall, the decision was between lower wavelength and hotter LEDs vs higher higher wavelength, but cooler, LEDs. Lower wavelength LEDs were chosen because they cleaned the cells quicker and more consistently and the heat difference would not mean a whole lot since a cooling system would have to be implemented in both cases.

The current vs voltage for a single LED is shown below in Figure 8. This is important because it shows that the LEDs are Ohmic devices. This means that the follow the equation:

$$V = IR$$

Where V is the voltage across the LED, I is the current and R is the resistance of the LED. The fact that it is ohmic will be used when wiring many LEDs together to know how much voltage is required to produce the desired amperage.

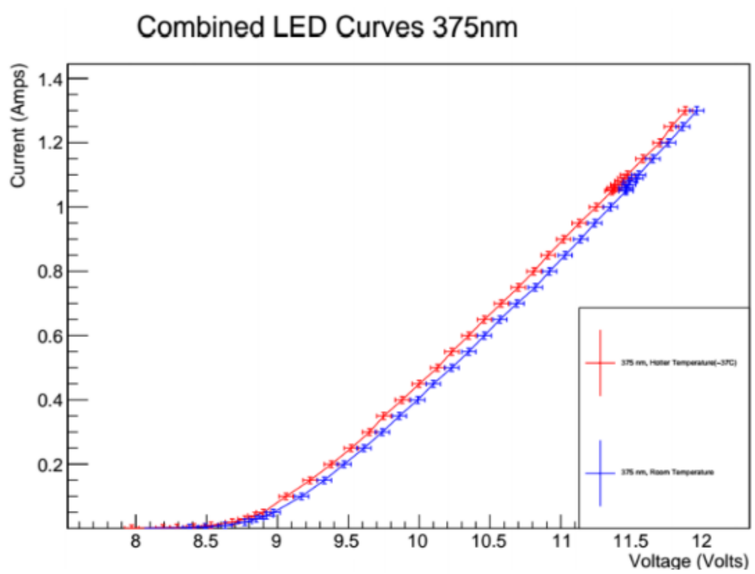
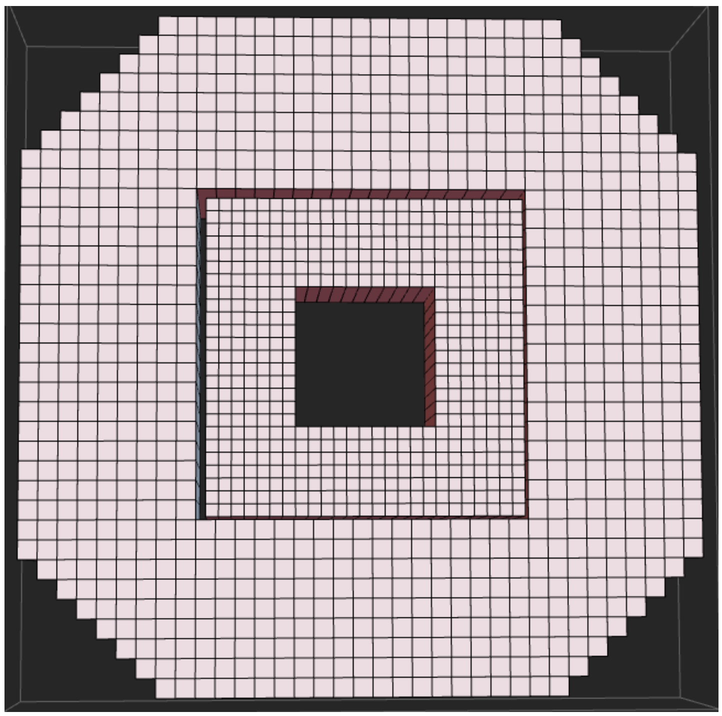


Figure 8- Current vs voltage curve for 375 nm LED. The linear relationship means the LEDs are ohmic.

Appendix C

FMS Model and LED Distribution

A 3D model of the FMS constructed in Mathematica is shown in Figure 9. The locations of the LEDs and the distribution and light cones covered from each LED for one quarter of the FMS are also included. This pattern was mirrored for each quadrant.



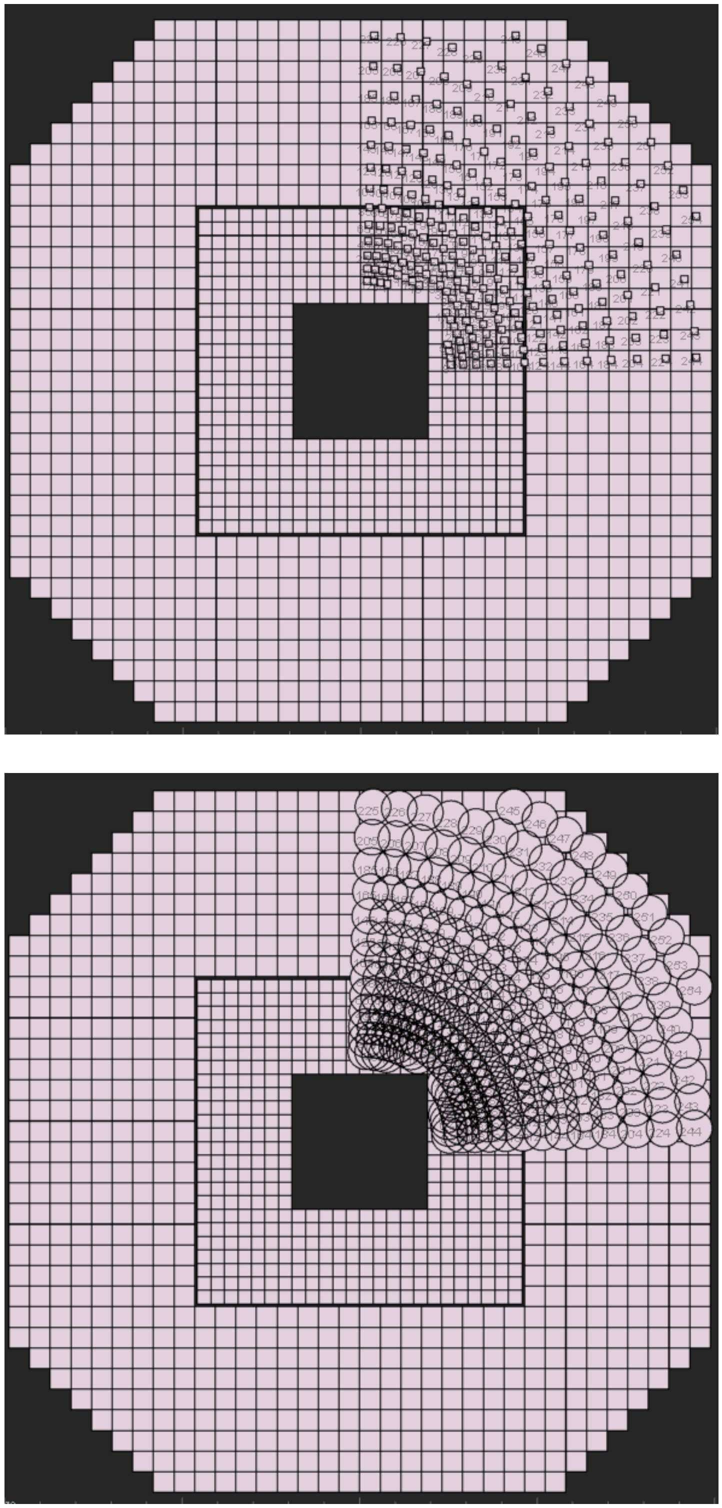


Figure 9- Mathematica model of the detector cells (top). Led Placements (middle). Light cones from LEDs (bottom)

Appendix D

Cooling Panels

The cooling panels used were from the Aavid Thermalloy company. A picture and the associated datasheet are in Figure 10 below.

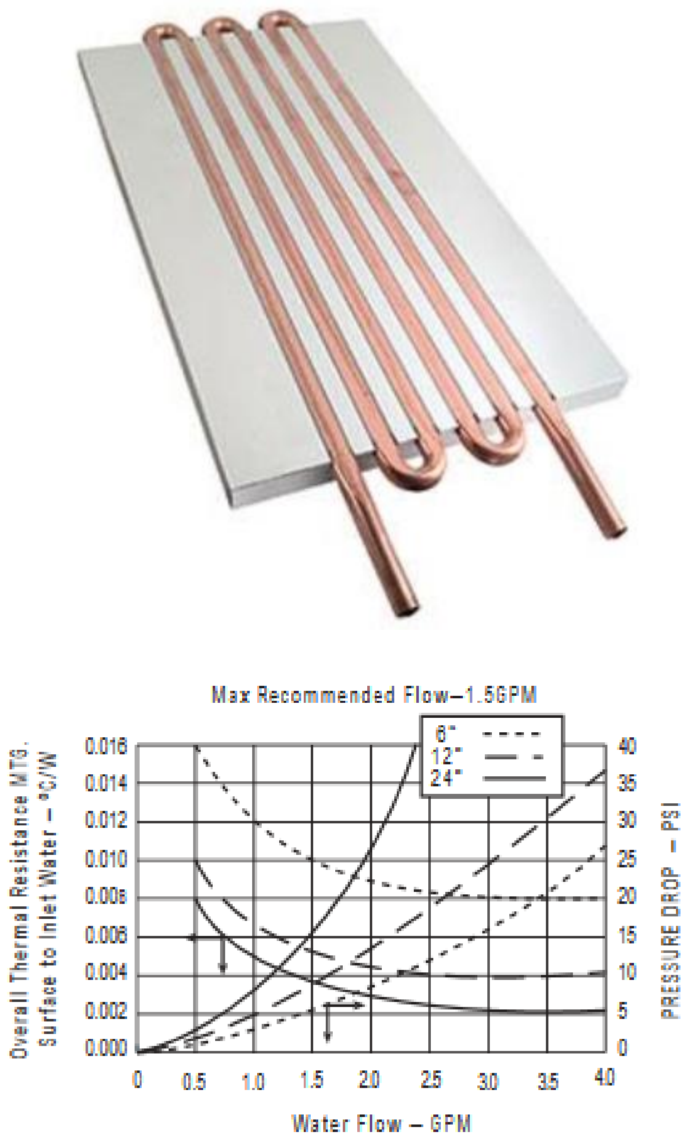


Figure 10- Image of liquid cooling panels used (top) and datasheet for cooling plate (bottom).

Appendix E

SolidWorks Models

Figure 11 contains an image of the actual LED used and the model LED created in SolidWorks.

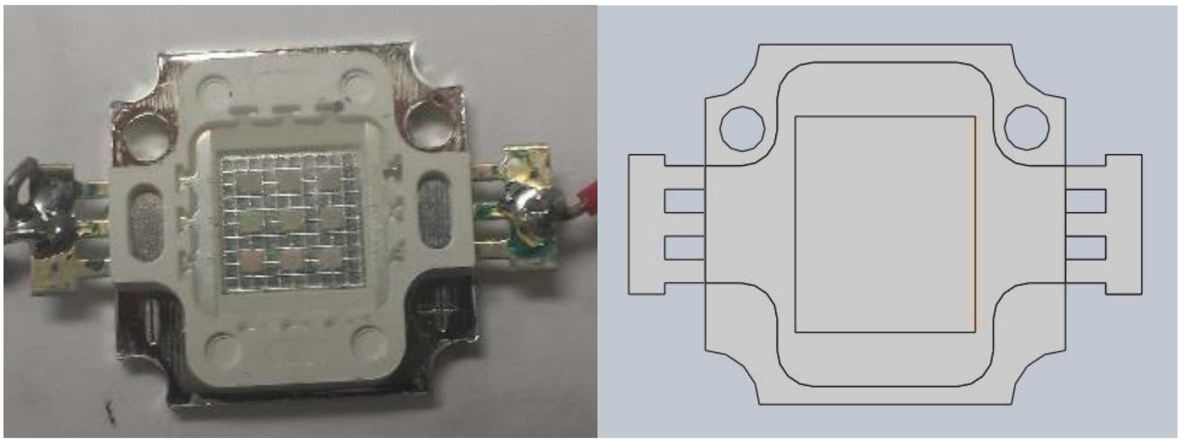


Figure 11- Image of the LED used (left) and Solidworks model of the LED (right).

Next, Figure 12 is a model of the cooling panel and last is a picture of the LEDs on the cooling panels for one quadrant of the FMS, with the LEDs following the proper radially decreasing distribution. Figure 13 is a model of the cooling panels in the aluminum frame.

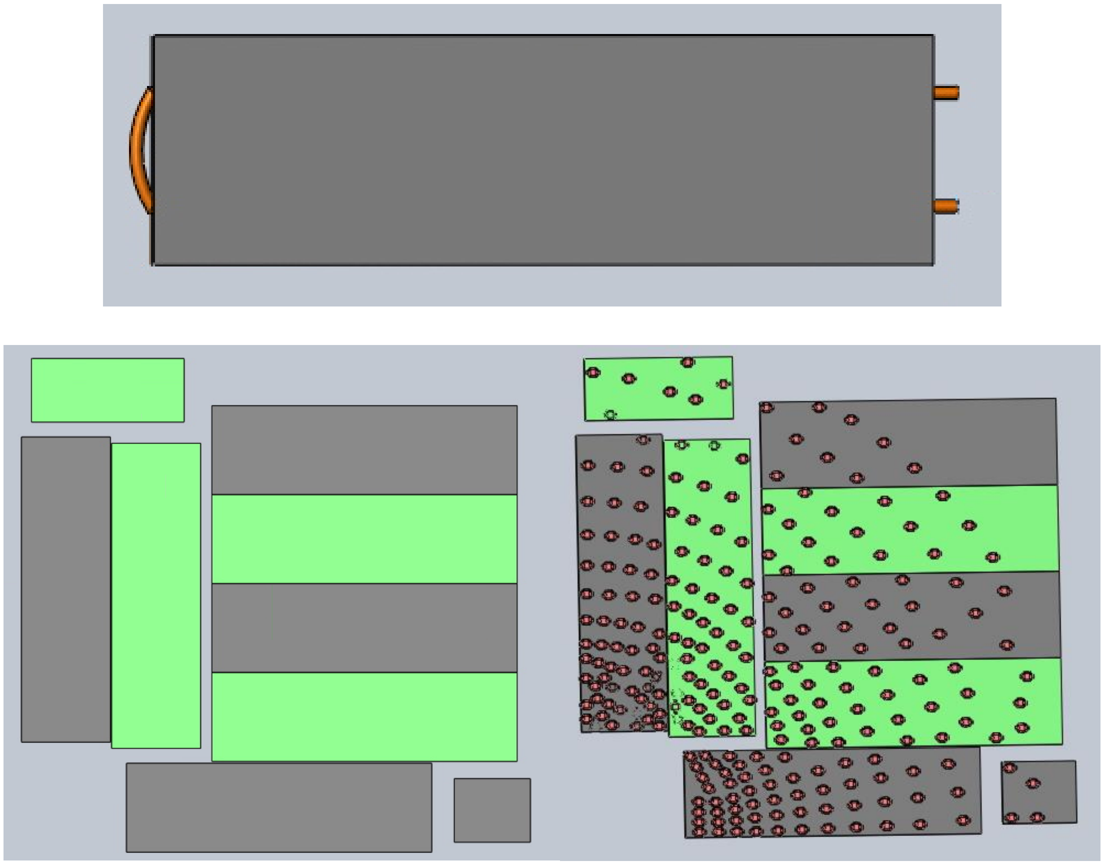


Figure 12- Solidworks models of the liquid cooling plate (top), plate placement for one quadrant of the detector (bottom left), and LED placement on the plates for one quadrant (bottom right).

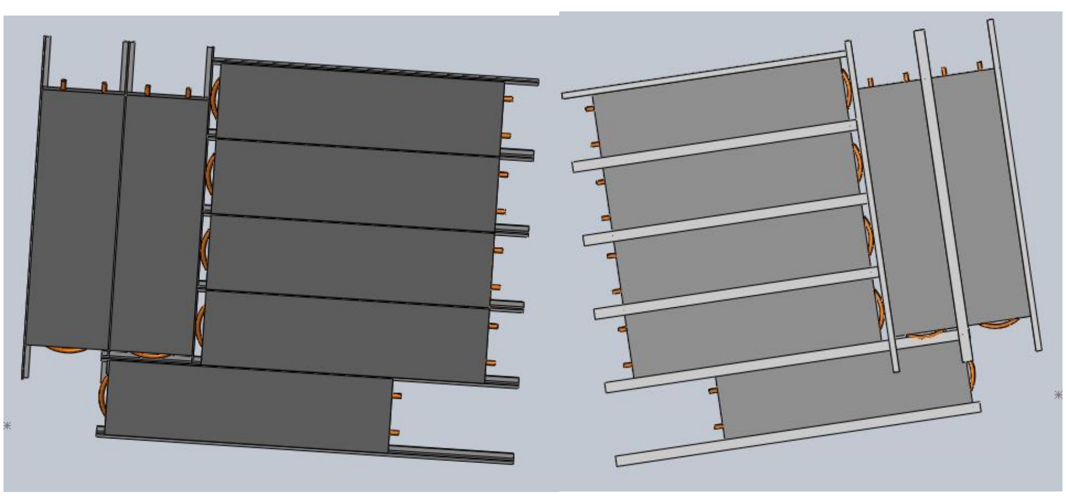


Figure 13- Frame with Cooling Panels SolidWorks Model.

Appendix F

Construction

Figure 14 is a picture of the frame put together with the cooling panels on it. This is after the holes have been drilled by the CNC machine. This step is to make sure that everything will fit later when the LEDs are added.

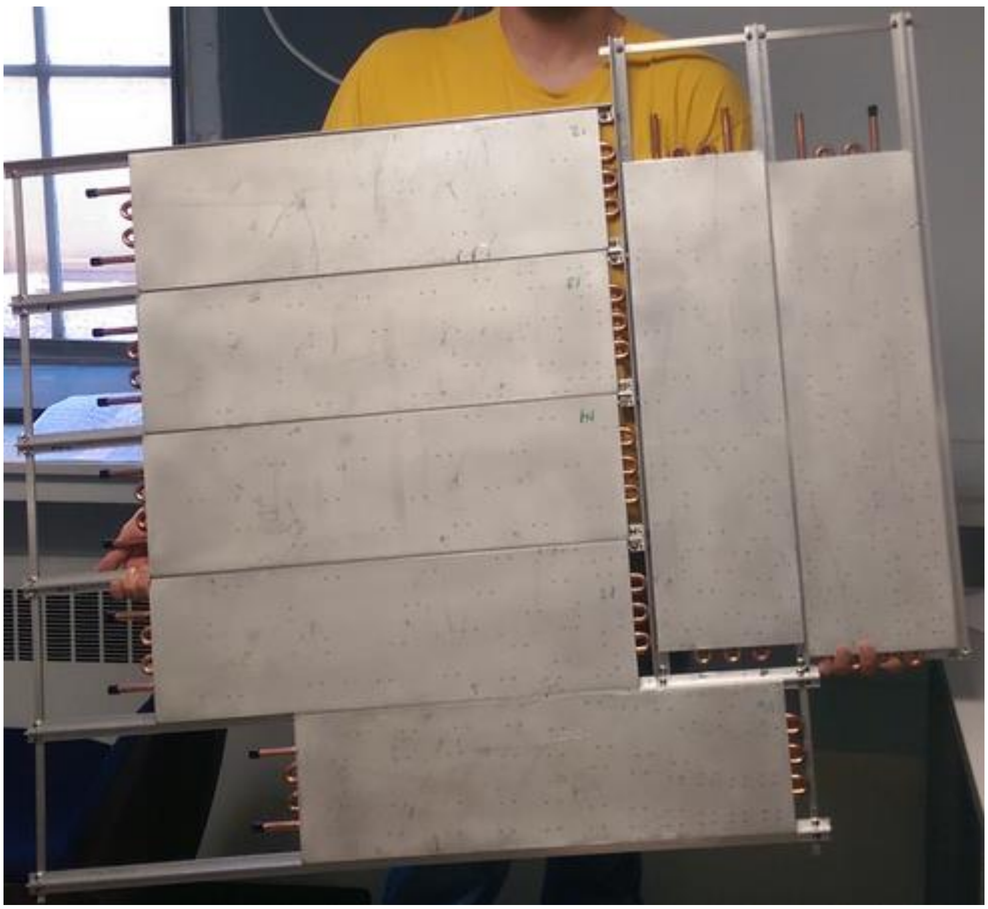


Figure 14- Cooling panels on aluminum frame before LEDs are attached.

An image of the cooling panels under construction is included in Figure 15.

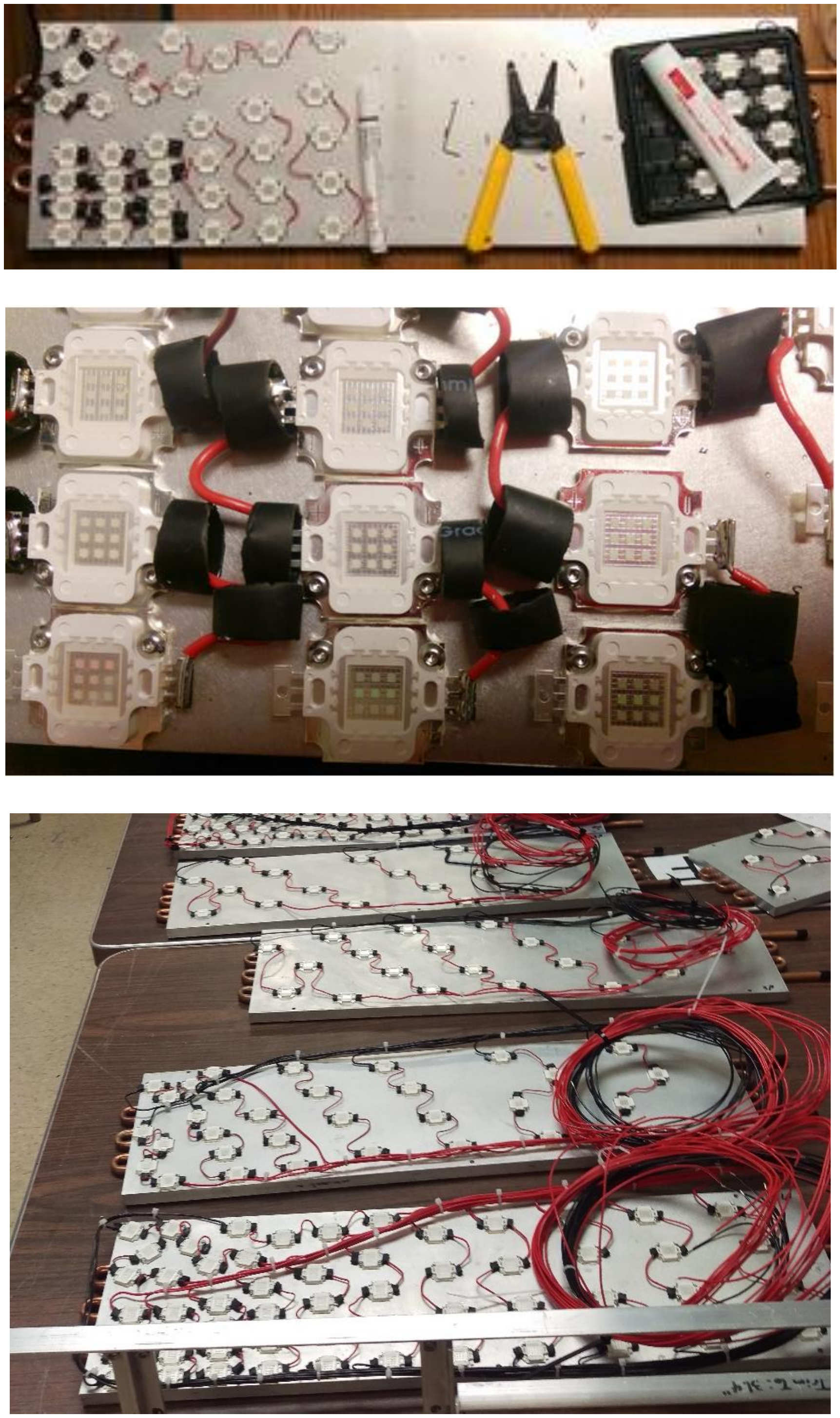


Figure 15-Construction of liquid cooling panels. Top is panel in progress. Middle is a close up view of the heat shrink-wrap. Bottom is a few finished plates.

Figure 16 shows the installation of the panels at Brookhaven National Lab.

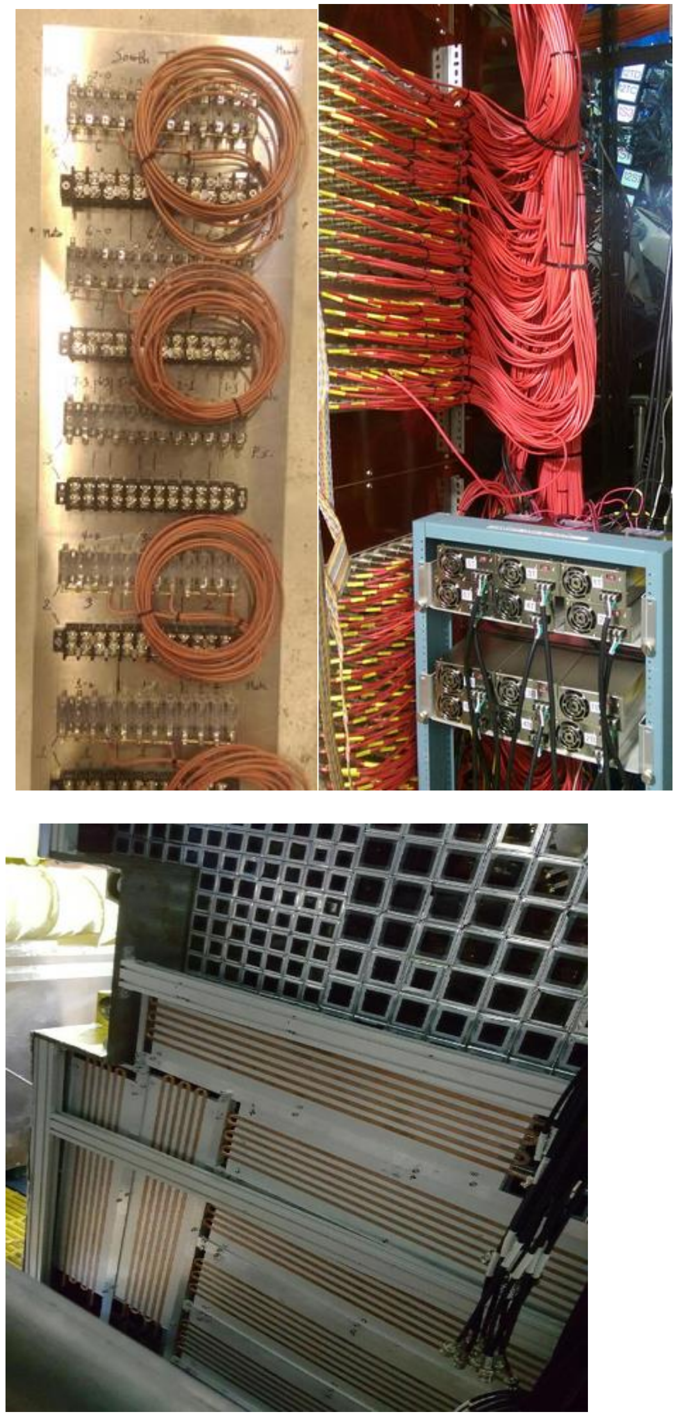


Figure 16- Fuse blocks prepared (top left). The source and drain wires to the LED chains (top right). One quadrant of panels in place in front of detector (bottom).

Appendix G

Curing

Figure 17 contains an image of the UVLED array in action.

Figure 17- Curing in action.

The curing worked very well. A graphical representation of the curing can be seen in Figure 18, which shows how the event ratios from the LEDs changed after an initial 8 hours of curing. The LED ADC ratio in the plot corresponds to the ratio of LED signal through the detector before and after the soak. Eta is called pseudorapidity. In the case of the detector, it can be related to the angle relative to the beam axis. An Eta of 4 corresponds to the cells closest to the center and an Eta of 0 corresponds to 90 degrees from the beam axis.

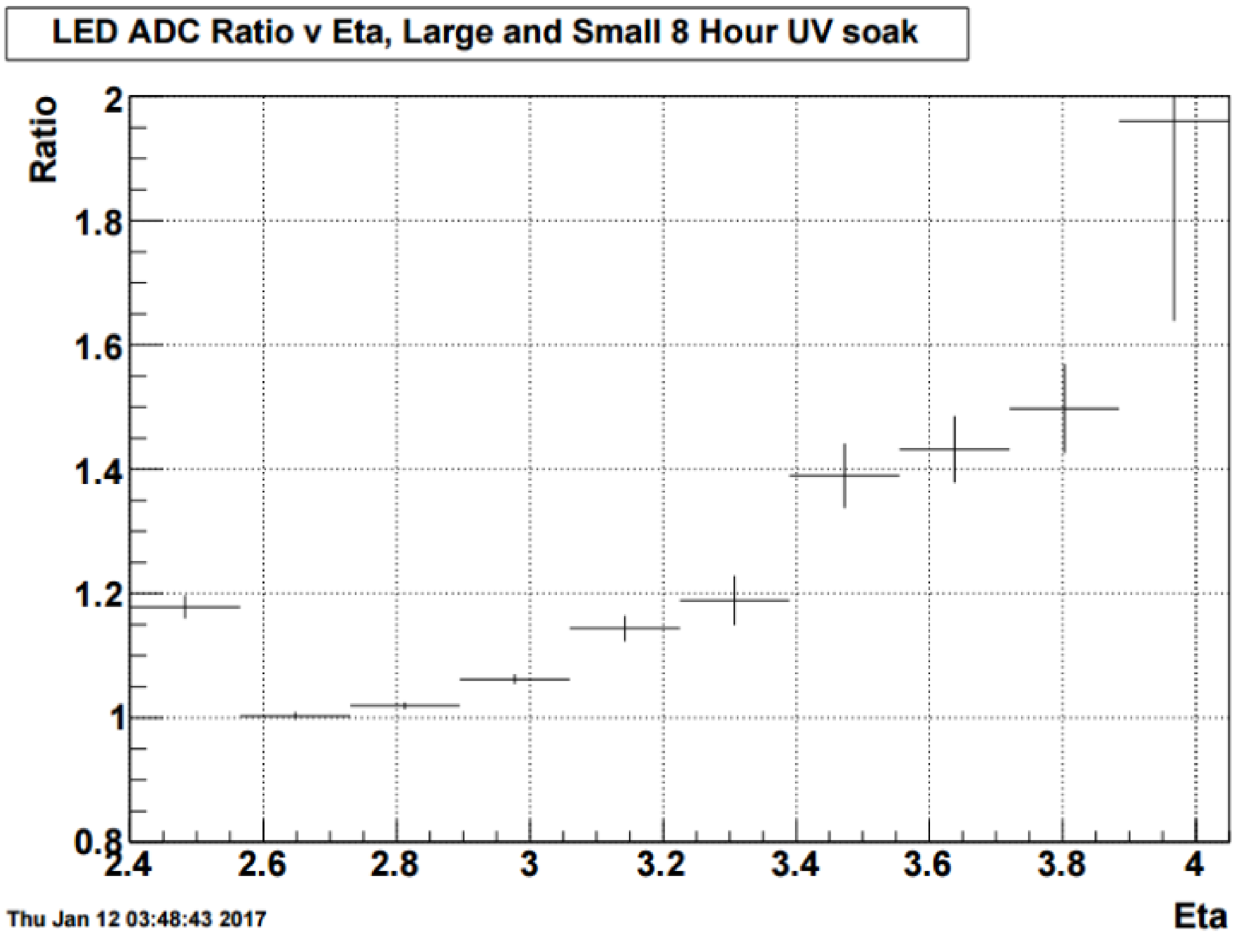


Figure 18- LED ADC ratio before and after an inital 8 hour UV soak vs Eta.

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