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CORDLESS POWER SUPPLY FOR ENCASED PHOTO MULTIPLIER TUBES

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Abstract

Neutrinos are produced by a variety of sources, such as supernovae, solar fission, and nuclear reactors, and can be measured using Cherenkov radiation. WATCHMAN is a water Cherenkov detector that is being built to detect whether or not a nearby reactor is on. Cherenkov radiation can be measured by Photo-Multiplier Tubes (PMTs) to determine a neutrino's energy, direction, and flavor. However, these PMTs may be encased in acrylic shells to make them more pressure resistant. Having a cordless power supply will make the shells more pressure resistant. The basis of the design for the cordless power supply is two solenoids, with one inside of the other; the inner with a set AC current running through it which induces a current in the outer coil due to the changing magnetic field, which was simulated in COMSOL Multiphysics. PMTs are extremely sensitive to magnetic fields, so the power supply needs to be shielded. Introducing an iron core increases the magnetic field, as well as the current, voltage, and power for the outer coil, and the voltage and power for the inner coil. Increasing the amount of turns for the inner coil, as well as increasing the radius of the inner coil's wire, increases the current, voltage, and power for the outer coil, and the voltage and power for the inner coil. Conversely, increasing the amount of turns for the outer coil, as well as increasing the radius of the outer coil's wire, decreases the current, voltage, and power for the outer coil, and the voltage and power for the inner coil. The Mu-Metal shielding works as expected for small thicknesses, but as the thickness increases, the shielding works less. The final design has an iron core, with the inner coil with a wire radius of 1 mm, and twenty turns, and an outer coil with a wire radius of 1.25 mm, and twenty turns. The mu-metal works best with a thickness of 0.5 mm. The inner coil has an AC current with a peak value of 1.65 Amps, and the outer coil has a resistor attached to it of 5 Ω.

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Acknowledgements

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I would finally like to thank my parents, for pushing me outside of my comfort zone, and my family for all of their love and support.

Chapter 1

Background

1.1 Neutrinos

Neutrinos were first proposed by Wolfgang Pauli, in 1930, and were shortly later proposed by Enrico Fermi, as a solution to the problem of three body beta decay in 1933 [1]. At the time what was seen for beta decay of a neutron was only the proton and the electron (otherwise known as a beta particle), but they could not detect the anti-neutrino:

$$n^0 \rightarrow \beta^- + p^+ + \overline{\nu}_e$$

They knew that the conservation of energy, as well as conservation of both linear and angular momentum, had to hold, but they had less energy coming out than what was going into the reaction [2]. The proposal of a neutrino, a small neutral particle (to conserve charge) allowed for the theory to match what was being observed [2].

The neutrino was purely theoretical until 1956 when Clyde Cowan and Fredrick Reines observed the particle [3]. They knew from Hanford's experiments in 1953 that a large reactor was likely to have neutrinos. They used a detector filled with a scintillating liquid, a material that emits light when a charged particle interacts within it, which then can be detected, to measure the parent neutrinos. They compared their measurements with the predicted values for neutrinos and found that they were consistent with the neutrino hypothesis [3].

Neutrinos are very interesting particles. They have a spin of ½, no charge and exist in three different "flavors", electron, muon, and tau (ν_e, ν_μ, ν_τ). Neutrinos also have antiparticles, called antineutrinos, which have the same flavors as neutrinos ($\overline{\nu}_e$, $\overline{\nu}_\mu$, $\overline{\nu}_\tau$). The masses of these particles are very small. They have three mass eigenstates, commonly known as ν_1, ν_2, and ν_3, that are linear combinations of the flavor eigenstates. The exact masses of the eigenstates are not known; however, it is known that 2 is heavier than 1, but it is unknown how heavy 3 is relative to the other two. If 3 is heavier than 2, it is called the normal hierarchy, however if 3 is lighter than 2, then it is called the inverted hierarchy [4]. Neutrinos can also oscillate between flavors. A particle may be created as an electron neutrino and then travel a distance. Within the time it takes for the neutrino to travel that distance it may oscillate to a new flavor, or between different flavors, such as tau or muon.

Neutrinos can be produced from many different events. They can be produced from supernovae, which occurs when either when a white dwarf star in a binary star system explodes, or a massive enough star collapses in on itself, which are known as Type I and Type II supernova respectively [5]. However neutrinos are only produced for a Type II supernova, and are generated when the core of the star collapses in on itself [5].

They can also be produced in solar fusion during proton-proton chain reactions [5]. Four protons combine to produce a Helium atom, two positrons, and two electron neutrinos [5].

$$4\text{p}^+ \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$$

Solar neutrinos provide data on what the solar core is doing in real time [6]. In comparison, the data we get from the surface of the sun via light and heat gives us information about the solar core from about a hundred thousand years ago [6]. However there appears to be fewer solar neutrinos than there should be, and it has been determined that the lack of solar neutrinos was due to neutrino oscillation [6].

Anti-neutrinos are produced in nuclear reactors, generally as a product of radioactive decay. For instance, Uranium-238 undergoes fission by interacting with an electron, changing it to Uranium-239. Then Uranium-239 undergoes beta decay twice, which produces an electron and an anti-neutrino twice, and the Uranium-239 becomes Plutonium-239.

1.2 Cherenkov Radiation and WATCHMAN

Cherenkov radiation occurs when a charged particle moves through a medium at a speed greater than the speed of light within that medium, and the physics behind it is similar to that of a sonic boom. A sonic boom occurs when an object is travelling faster than the speed of sound in air. The object is traveling faster than the sound it makes, so the sound is built up in a shockwave, usually in a conical geometry. An observer will hear nothing as the object passes until the shockwave hits their position, creating the sonic boom. Cherenkov radiation is similar to a sonic boom, just using light instead of sound.

The speed of light within medium is slower than the speed of light in vacuum. A particle can move through the material at a speed faster than light can move through that material. If the charged particle was moving slower than the speed of light in that medium, it would still produce light, but it would not create a shockwave like Cherenkov radiation.

As the particle moves through the medium, light is radiated by the particle. One of the more important parts of Cherenkov radiation is the fact that the particle that is moving through the medium is a charged particle and that the material is a dielectric. The particle itself does not radiate the light, rather, since the particle is charged, the electrons of the atoms of the dielectric are accelerated by the passing of the particle [7]. The electrons then emit radiation within the visible light spectrum, which is known as Cherenkov radiation.

The particle's velocity is faster than the speed of the light in the medium, thus it moves quicker than the radiated light, creating a shape like a cone (see Figure 1.1 below). The light moves in a sphere shape, propagating out, however, the particle moves faster than the light. So, as the particle moves, the light continues to propagate at a speed slower than the particle, forming a cone.

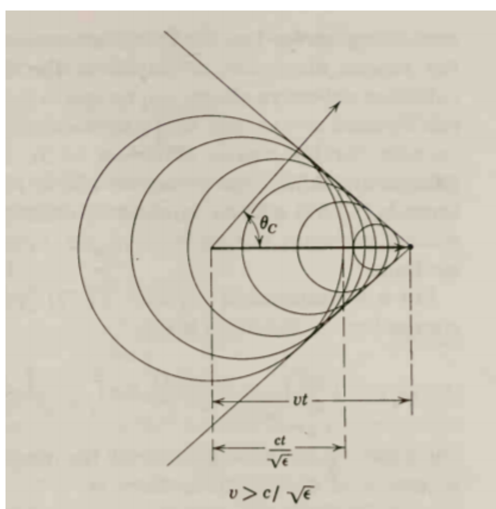

Figure 1.1: A picture showing a particle moving with a velocity, v, faster than the speed of light within that medium. Circles of light propagate slower than the particle, forming a cone with the angle θ_c pointing into the direction of propagation of the light. [8]

Cherenkov detectors use Cherenkov radiation to determine neutrino energy, direction, and flavor. A neutrino interacts with an electron, proton, or neutron. The charged particles that are created produce Cherenkov radiation. This light can be traced back to where it began, to give useful information about the neutrino.

The Water Cherenkov Monitor for Antineutrinos (WATCHMAN) is to be built in Boulby Mine in England. It is to be a kiloton-scale tank with gadolinium laced water and several thousand Photo-Multiplier Tubes that may be encased in protective acrylic spheres [9]. WATCHMAN is a neutrino detector that is not only being built as a neutrino observatory but also to detect whether or not a nearby reactor is on [10]. When a reactor is on, it produces neutrinos due to nuclear fission, however when it is off it does not produce neutrinos. This means that when the reactor is on, the amount of neutrinos a detector measures will increase. It is therefore possible to tell, from a distance, whether or not a reactor is on. Detectors like WATCHMAN can be placed near borders and, depending on the distance, be able to tell if there are undeclared nuclear reactors in use. If there are hidden or unknown nuclear reactors that are being used to try and create nuclear weapons, a detector like WATCHMAN may be able to detect them.

1.3 Photo-multiplier Tubes

Photo-multiplier tubes (PMTs) are instruments that are used to detect charged particles. They consist of a photoemissive cathode, an anode, and several dynodes, all within a sealed transparent container in vacuum [11]. The cathode, if struck by a photon, produces an amount of electrons relative to the intensity of the photon [11]. These electrons will head towards a dynode, that is positively charged relative to the cathode, which in turn produces more electrons, that will head to another dynode [11]. This will create a cascade effect that continues until it reaches the anode, which receives the electrons and collects a signal proportional to the intensity of the initial light pulse [11]. Arrays of PMTs can be used to determine where the charged particle producing the light occurred and in what direction it was heading (See Figure 1.2).

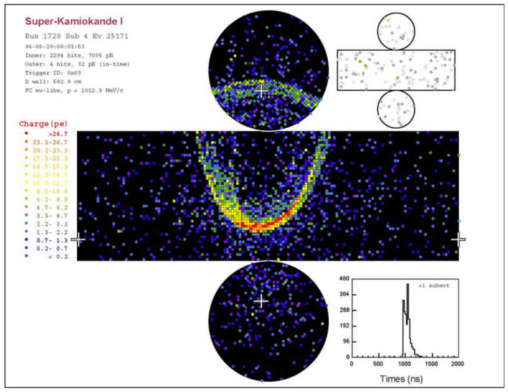

Figure 1.2: A picture showing the Cherenkov radiation measured from a muon neutrino event from Super Kamiokande [12].

The PMTs within WATCHMAN may be placed within acrylic vessels that contain both the PMTs, and the electronics needed to process and transmit the data. Not only does the acrylic vessel help to keep the pressure of the water off of the PMTs, it also prevents any issues in one PMT from affecting others. In 2001, one of the PMTs in Super Kamiokande, a neutrino detector similar to WATCHMAN in Japan, imploded. It caused the PMTs around it to implode as well, as the force of the implosion cracked their casings, which then in turn caused others to implode. This chain reaction effect ended up damaging 6,779 of the PMTs [13]. With acrylic shells, if one PMT implodes, the shell will prevent it from affecting other PMTs.

Chapter 2

Providing Power to Encased PMTs

2.1 The Problem of Power

The basis of this thesis is that the PMT housing, in order to make it maximally waterproof and pressure resistant, would be best served by having a cordless power supply, rather than a corded one. A power supply that depends on cords would make the housing less water resistant, seeing as it would have to have a hole in it to fit the cord for the power supply, and it would be difficult to deal with thousands of such power cords. However, it is possible to achieve a cordless power supply by using two solenoids to induce a current to provide power to the capsule, similar to how a cordless electric toothbrush is charged.

One problem with using this type of cordless power supply with PMTs is that PMTs are not only highly sensitive to UV and visible radiation; they are also sensitive to magnetic fields, to such a degree that the Earth's intrinsic magnetic field can affect them. The proposed solenoid creates a changing magnetic field with the changing current to induce a current in the other solenoid to provide power to the PMT and associated electronics. In order for the cordless power supply to work in conjunction with the PMT, it must be covered in a material that blocks magnetic fields. In this case we decided to use mu-metal as it is a good absorber of magnetic fields. Depending on how it was produced, the relative permeability of the mu-metal may be different than the values chosen. We used values from Magnetic Shield Corporation, which not only gave us the relative permeability but also an idea of how thin the mu-metal could be [14]. According to the Magnetic Shield Corporation's data sheet, for alternating current, the relative permeability is 65,000, and mu-metal foil can be as small as 0.05 mm thick [15, 14].

Chapter 3

Simulation

3.1 Setting Up the Simulation

We used COMSOL Multiphysics in order to simulate the designs without actually physically building them. We used COMSOL's built in materials and given values for said materials.

We first started with two coils, an inner coil which has current flowing through it, and an outer coil which has induced current flowing through it. The outer coil is the one to supply power to the PMT, while the inner coil is the source for the cordless power supply. The outer coil is made up of a copper wire with a radius of 1.25 mm, and with 20 turns. The inner coil is also a copper wire, but with a radius of 1 mm, and with 10 turns. The inner coil is positioned 2.1 cm away from the center, while the outer coil is 4.3 cm away from the center. See Figure 3.1. The coils are separated to emulate the shell between the two coils. The inner coil is given a current of 1.5 Amps that had a frequency of 60 Hz, while the outer coil has an attached resistor with a resistance of 1 Ω.

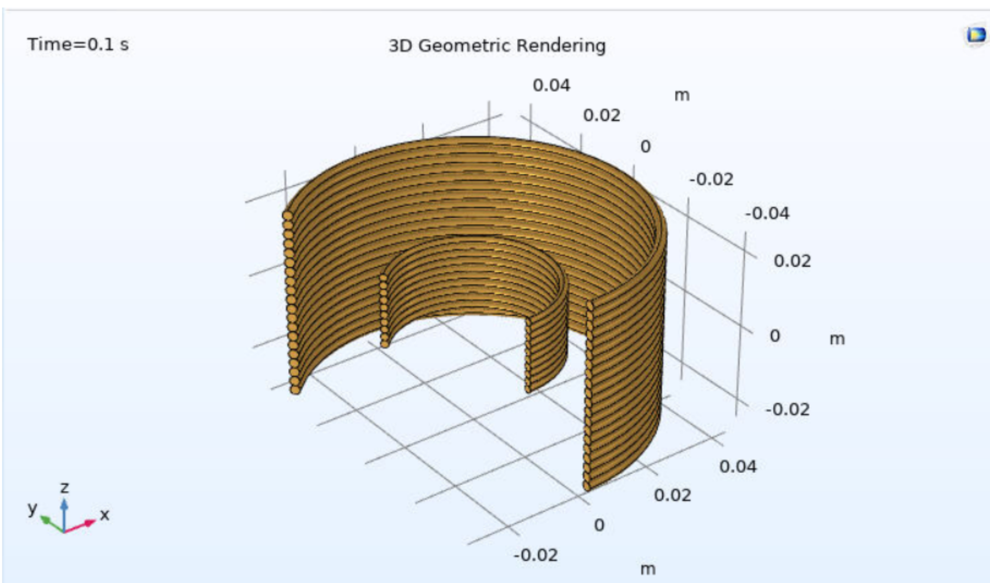

Figure 3.1: An image of two coils with one around the other. The outer coil has 20 turns and the inner coil has 10 turns. They are centered around the same point.

Chapter 4

Results

4.1 Introduction of the Iron Core

The magnetic fields with just the two coils were not strong enough to induce a large enough current in the outer coil. Due to this we introduced an iron core within the inner coil to focus the magnetic fields, similar to a transformer (See Figure 4.1).

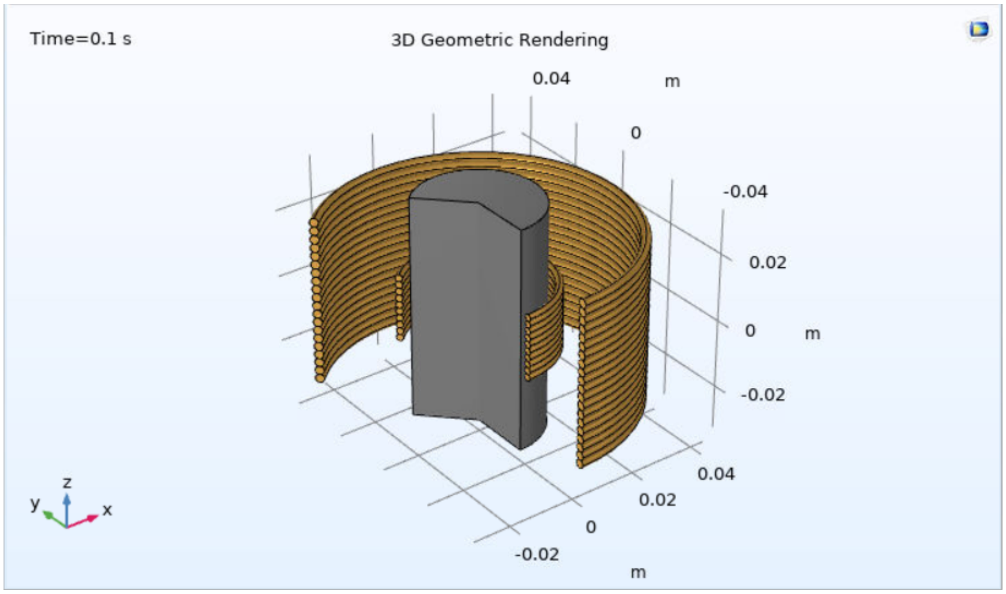

Figure 4.1: An image of two coils with one around the other. The outer coil has 20 turns and the inner coil has 10 turns. They are centered around an iron cylinder.

Table 4.1: Current, Voltage, and Power for Coils

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.147
Peak Voltage (V)	1.126	0.147
Peak Power Difference (W)	1.056	0.022

Table 4.2: Current, Voltage, and Power for Coils and Iron Core

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.511
Peak Voltage (V)	2.835	0.511
Peak Power Difference (W)	1.835	0.262

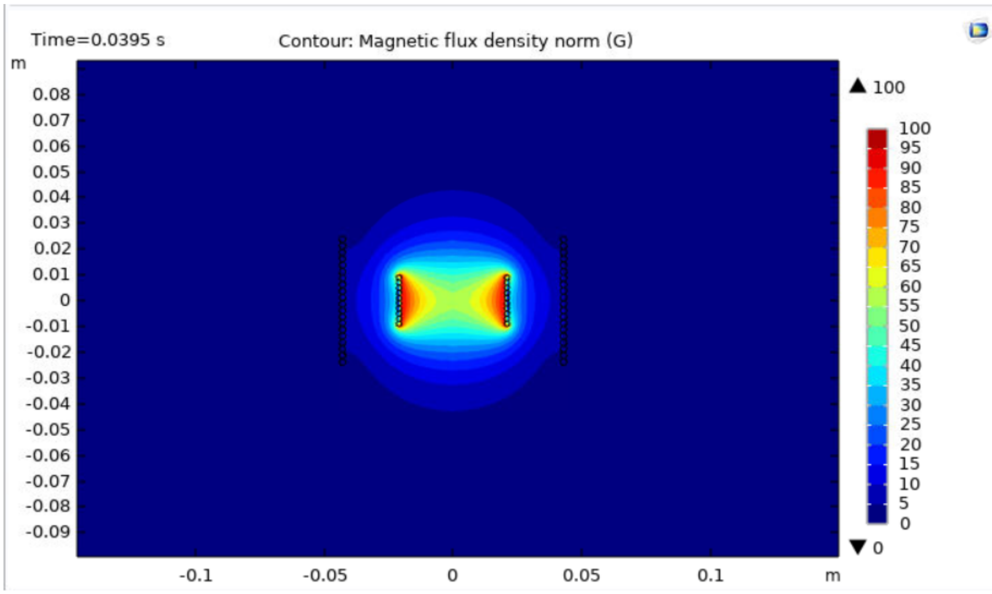

Figure 4.2: An cross sectional image of the magnetic fields of the two solenoids. The scale goes from 100 Gauss in red to 0 Gauss in dark blue.

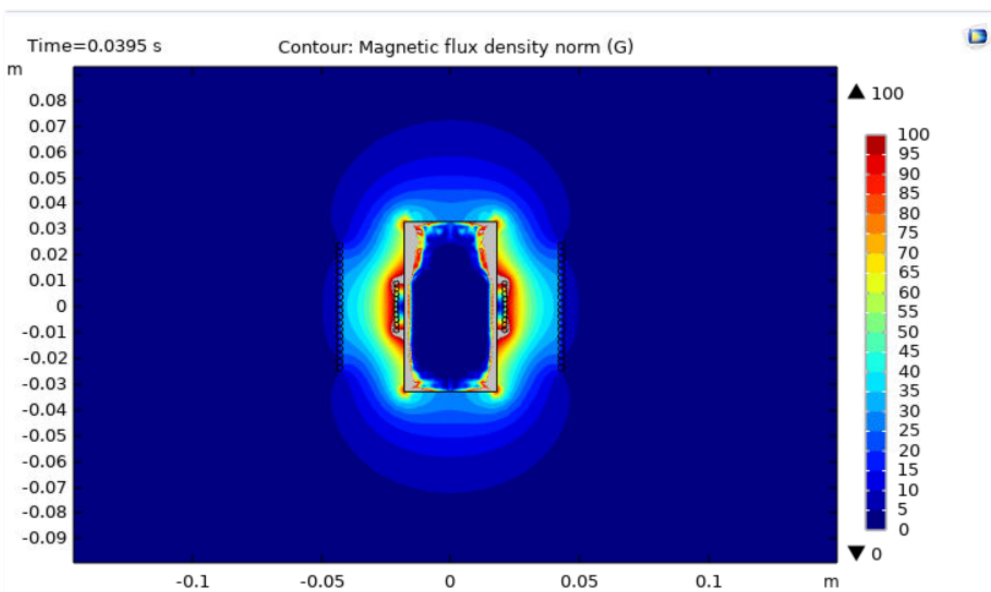

Figure 4.3: An cross sectional image of the magnetic fields of the two solenoids and iron core. The scale goes from 100 Gauss in red to 0 Gauss in dark blue.The grey sections are where the fields are greater than 100 Gauss.

As you can see from Figure 4.2 and Figure 4.3, when the iron core is introduced the magnetic fields are greatly strengthened by the presence of the iron core. The amount of current in the outer coil, as well as the voltage and the power for both coils increase. The increase in the outer coil comes from a stronger changing magnetic field, which induces a stronger current within the outer coil. The current for the inner coil stays the same, since it is a controlled current source, however the voltage and power both increase due to the iron core. The iron core helps to make sure that current, voltage, and power that we are running through the solenoids is reasonable, and not too large.

4.2 Varying the Coil Parameters

After adding the iron core, we then varied how many columns and rows each coil had, as well as the size of the wire for each coil and how each change affected the amount of current, voltage, and power that flows through each coil.

Table 4.3: Control for Coil Variations

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.511
Peak Voltage (V)	2.835	0.511
Peak Power Difference (W)	1.835	0.262

Table 4.4: Coil Variations - Inner Coil - 20 turns over 1 column

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.915
Peak Voltage (V)	7.412	0.915
Peak Power Difference (W)	4.884	0.935

Table 4.5: Coil Variations - Inner Coil - 20 turns over 2 columns

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	1.028
Peak Voltage (V)	10.314	1.028
Peak Power Difference (W)	5.415	1.066

Table 4.6: Coil Variations - Outer Coil - 40 turns over 1 column

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.318
Peak Voltage (V)	2.787	0.318
Peak Power Difference (W)	1.538	0.103

Table 4.7: Coil Variations - Outer Coil - 40 turns over 2 columns

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.262
Peak Voltage (V)	2.639	0.262
Peak Power Difference (W)	1.415	0.068

Adding more turns to the inner coil, whether they were columns or rows, did as one might expect; it increased the voltage and power for both coils, and also increased the current for the outer coil. When there are more turns in the inner coil, it strengthens the magnetic field, which then induces a stronger current in the outer coil. Thus, the voltage and power for the outer coil increases, and then the inner coil's voltage and power increases as well. However, when more turns are added to the outer coil, no matter whether they are added as columns or rows, the voltage and power decreased for both coils and the current in the outer coil decreased as well. This is most likely due to the fact that there are more coils for the magnetic field to induce a current into, so the amount of current is reduced, and similarly, so is the voltage and power for the outer coil.

Table 4.8: Coil Variations - Inner Coil - 2 mm radius

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.483
Peak Voltage (V)	2.186	0.483
Peak Power Difference (W)	1.714	0.234

Table 4.9: Coil Variations - Outer Coil - 2.5 mm radius

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	0.574
Peak Voltage (V)	3.125	0.574
Peak Power Difference (W)	2.042	0.329

Changing the wire size produced surprising results. When the inner coil's radius was increased, the voltage and power for both wires decreased, as well as the current for the outer coil. In contrast when the outer coil's radius was increased, the voltage and power for both wires increased, as well as the current for the outer coil. So, in order to have a larger magnetic field, as well as greater power and voltage induced, it is better to have a smaller radius for the inner coil and a larger radius for the outer coil. We determined that the best design for the coils is for the inner coil to have a radius of 1 mm and twenty turns in a single column, and the outer coil to have a radius of 1.25 mm and also twenty turns in a single column (See Figure 4.4). This gave data for in Table 4.12, and Figure 4.5.

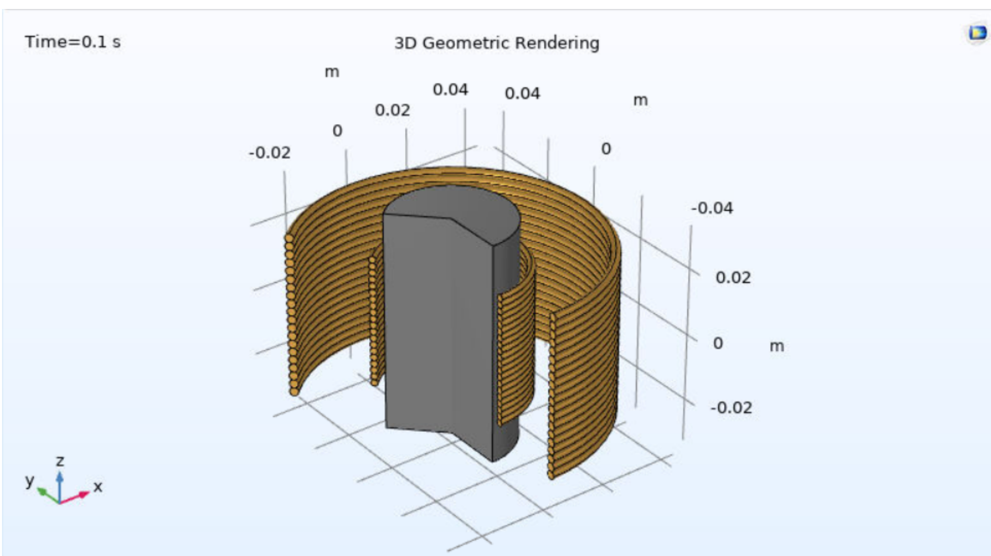

Figure 4.4: An image of two coils with one around the other. The outer coil has 20 turns and the inner coil has 20 turns. They are centered around an iron cylinder.

Table 4.10: Final Design of Coils and Iron Core

	Inner Coil	Outer Coil
Peak Current (A)	1.500	0.967
Peak Voltage (V)	8.190	0.967
Peak Power Difference (W)	4.884	0.944

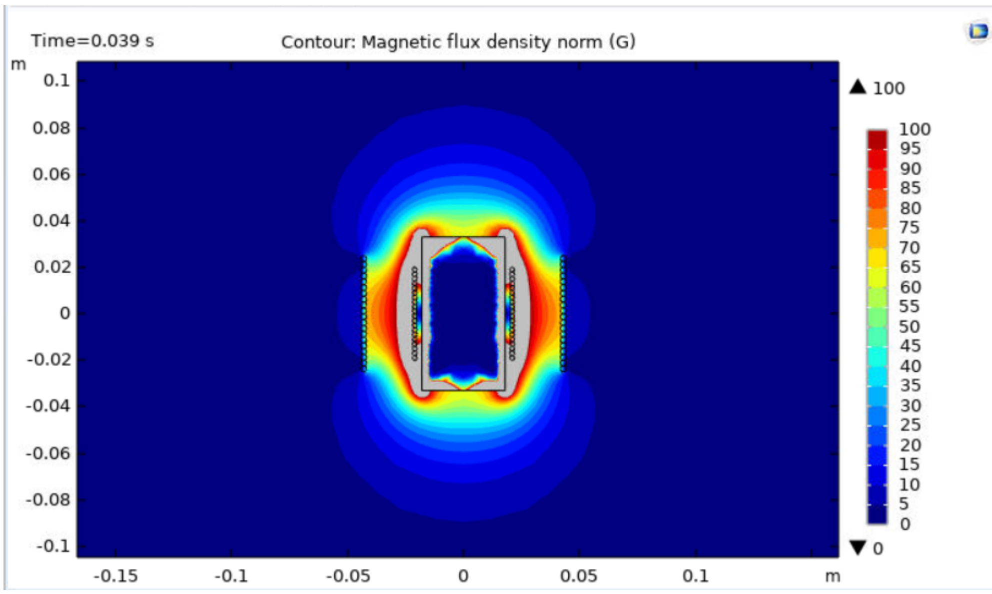

Figure 4.5: An cross sectional image of the magnetic fields of the two solenoids and iron core. The scale goes from 100 Gauss in red to 0 Gauss in dark blue.The grey sections are where the fields are greater than 100 Gauss.

4.3 Thickness of the Mu-Metal

Next, we varied the thickness of the mu-metal to determine what thickness best shielded the PMT from the magnetic fields. The data in Figure 4.6, was measured by varying the thickness of the mu-metal and measuring the magnetic field at 5 cm away from the mu-metal.

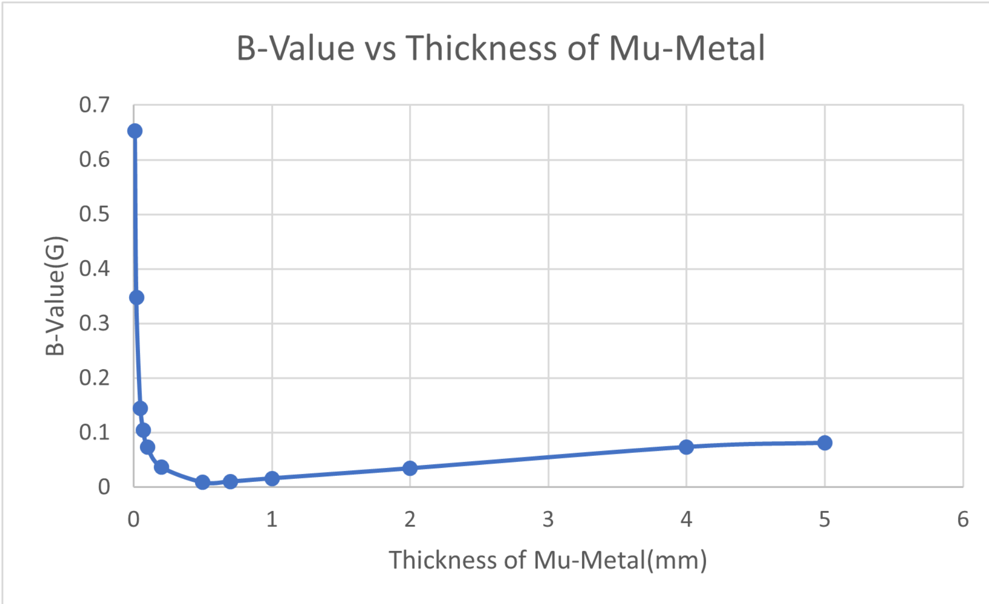

Figure 4.6: A graph showing the thickness of the mu-metal vs the magnetic field value. The magnetic field is measured in Gauss and the mu-metal thickness is measured in mm.

As expected, as the thickness of the mu-metal increased, the magnetic field decreased. However, as the mu-metal thickness increased past 0.05 mm, the magnetic field value increased as well. This is most likely due to induced magnetic fields within the mu-metal itself, which can be seen in Figure 4.7, where the mu-metal thickness is 5 mm. In comparison Figure 4.8, where the thickness of the mu-metal is 0.5 mm, any induced magnetic fields do not produce a pronounced effect on the magnetic fields outside of the mu-metal. There are still induced magnetic fields in the mu-metal, however the mu-metal does its job and contains the magnetic field. In order to reduce the effect of the magnetic fields, we chose to use the 0.5 mm thickness for the mu-metal, because it reduces the magnetic fields to the smallest they can be, which can be seen in Figure 4.6. At 5 cm away from the mu-metal shield, the magnetic field is 0.0088 Gauss; in comparison the magnetic field of the Earth can be anywhere between 0.2 and 0.6 Gauss.

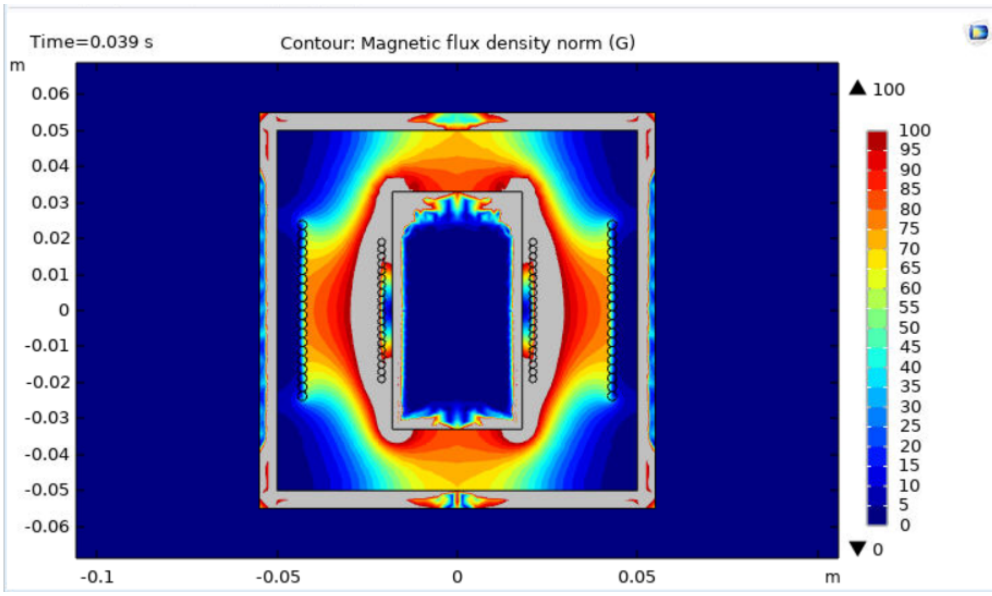

Figure 4.7: An cross sectional image of the magnetic fields of the two solenoids and iron core. The solenoids and the iron core are enclosed by 5 mm of Mu-Metal. The scale goes from 100 Gauss in red to 0 Gauss in dark blue.The grey sections are where the fields are greater than 100 Gauss.

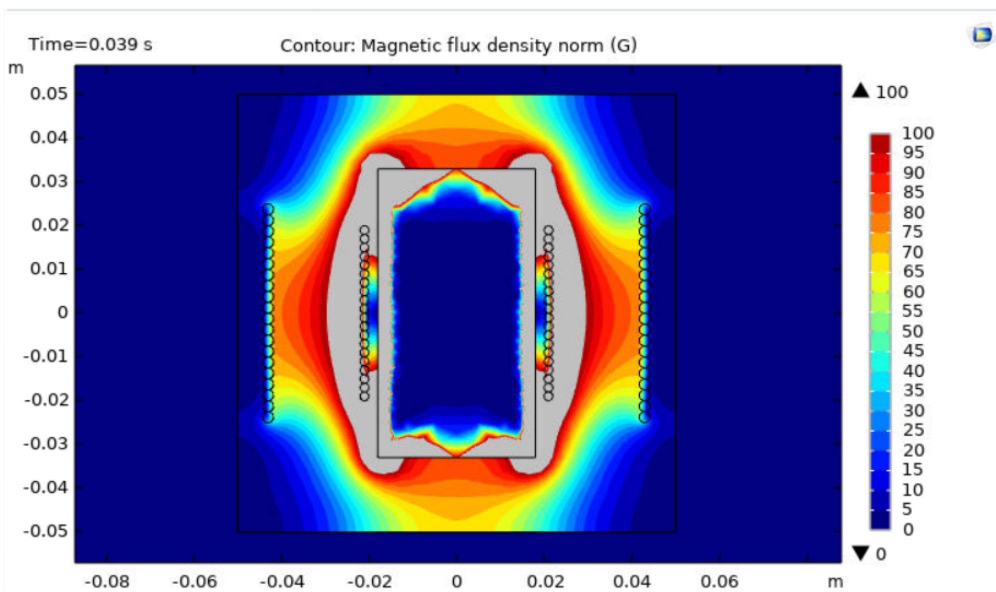

Figure 4.8: An cross sectional image of the magnetic fields of the two solenoids and iron core. The solenoids and the iron core are enclosed by 0.5 mm of Mu-Metal. The scale goes from 100 Gauss in red to 0 Gauss in dark blue.The grey sections are where the fields are greater than 100 Gauss.

The final iteration of this design can be seen below in Figure 4.8, and the values of current, voltage and power in Table 4.11. To reiterate, the inner coil has twenty turns and is a copper wire of 1 mm radius. The outer coil has twenty turns as well, and is a copper wire of 1.25 mm radius. The mu-metal is 0.5 mm thick, and encloses the entirety of the coils.

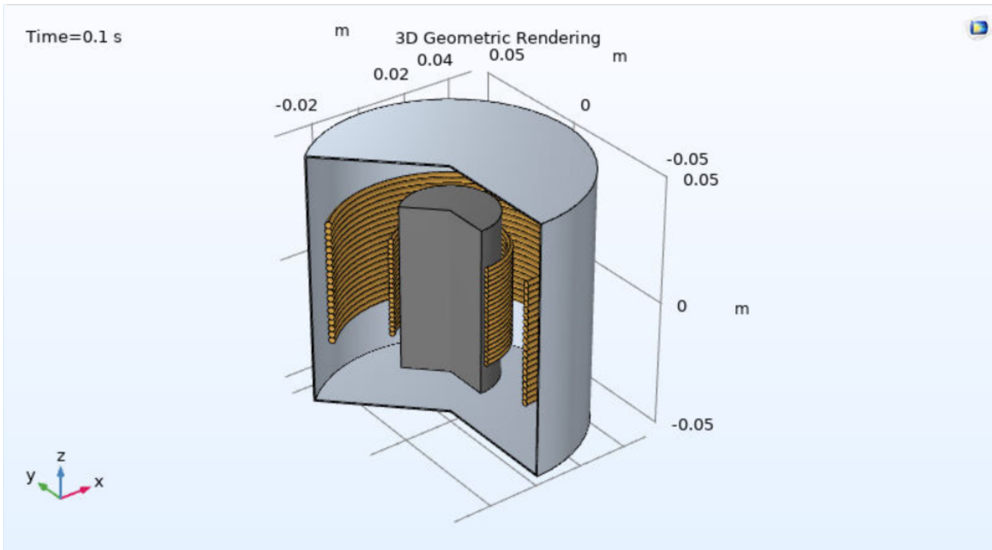

Figure 4.9: A 3D rendering of the two solenoids, iron core, and mu-metal. The outer coil has 20 turns and the inner coil has 20 turns. They are centered around an iron cylinder. Mu-Metal encloses the entire structure.

Table 4.11: Final Design of Coils, Iron Core, and Mu-Metal

	Inner Coil	**Outer Coil**
Peak Current (A)	1.500	1.037
Peak Voltage (V)	8.297	1.037
Peak Power Difference (W)	5.313	1.074

4.4 Setting Current and Resistance

Finally, we determined the values of the current for the inner coil and the resistor of the outer coil. We could not accurately determine what those values were until we knew the thickness of the mu-metal. This is because of the induced magnetic fields from the mu-metal that affected the coils. We wanted the current induced in the outer coil to be equal to 1 Amp. This is because if the current is 1 Amp, we can set the resistance to be 5 Ω, and, using Ohm's Law, easily get the power and voltage in the outer coil equal to 5 Watts and 5 Volts respectively. By increasing the current running through the inner coil to 1.65 Amps, we get a current of 1 Amp running through the outer coil. The values of current, voltage, and power for the final design can be seen in Table 4.12 and the magnetic field of the final design in Figure 4.10.

Table 4.12: Final Design

	Inner Coil	**Outer Coil**
Peak Current (A)	1.650	1.000
Peak Voltage (V)	11.703	4.999
Peak Power Difference (W)	9.898	4.993

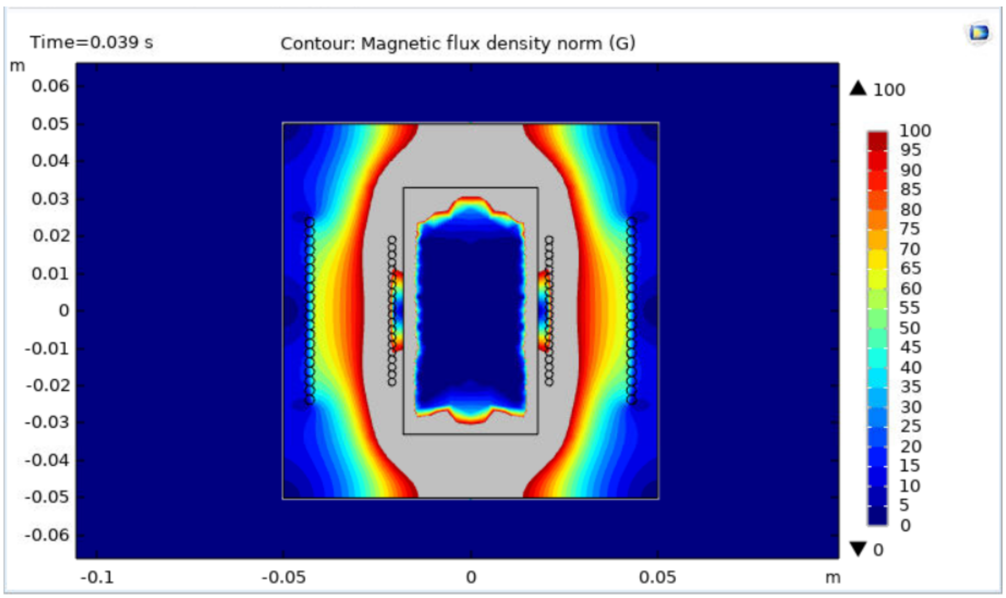

Figure 4.10: An cross sectional image of the magnetic fields of the two solenoids and iron core. The solenoids and the iron core are enclosed by 0.05 mm of Mu-Metal. The scale goes from 100 Gauss in red to 0 Gauss in dark blue.The grey sections are where the fields are greater than 100 Gauss.

Chapter 5

Conclusion

5.1 Conclusion

To reiterate, the PMTs need a power supply that can be cordless, to allow the acrylic shells to be more pressure and water resistant. Utilizing two solenoids and a changing magnetic field to induce a current will work. We set up a simulation following the design laid out in Simulation, and added an iron core, and varied the coil parameters. We also evaluated the thickness of the mu-metal and determined the best current and resistance to give the values we needed.

Adding an iron core to the center of the coils helped to increase the strength of the magnetic fields, and similarly increased the current, voltage, and power, of the outer coil, as well as the voltage and power of the inner coil (whose current is held constant). By increasing the amount of coils for the inner coil, whether the addition increased the number of columns or rows, or increasing the radius of the inner coil, the voltage and power of the inner coil increased and so did the current, voltage, and power of the outer coil. Conversely, increasing the amount of turns for the outer coil, no matter whether the columns or rows increased, or increasing the radius of the wire for the outer coil, decreased the current, voltage, and power induced in the outer coil, as well as the voltage, and power of the inner coil. The mu-metal worked as expected for small thicknesses, however at higher thicknesses, the induced magnetic fields in the mu-metal began to affect the strength of the shielding. We then finally determined the best current for the inner coil, and the best resistance for the resistor of the outer coil. We needed the best values that would allow for the inner coil to have reasonable values for current, voltage, and power, and for the outer coil to have 5 Volts of voltage and 5 Watts of power, to power the PMT and associated electronics. The final design has the inner coil with a copper wire radius of 1 mm, and twenty turns, and the outer coil, also a copper wire with twenty turns, but a radius of 1.25 mm. There is an iron core in the center and mu-metal surrounds the entire design with a thickness of 0.5 mm. The current running through the inner coil is 1.65 Amps, and the resistor on the outer coil is 5 Ω.

5.2 Recommendations

This design was proof of concept, and an idealized version at that. There may be numerous other designs that may work just as well as the one presented in this paper. Our recommendations include not only evaluating other designs for use, but also testing of how changing the length and position of the iron core affects the magnetic fields, as well as changing the position of the coils in respect to one another. We also recommend further evaluation of how this design and others work within the context of the acrylic shell, as well as how having gaps in the mu-metal might affect the strength of the shielding and how to overcome the issues that gaps may bring.

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