Ripon College Undergraduate Thesis

Design and Assembly of Pulsed Low Energy Electron Gun for Use in Ultrafast Electron Microscopy

by

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Abstract

Ultrafast electron microscopy is an emerging field of interest that utilizes pulses of electrons as a tool to probe specimens, particularly to enable the study of ultrafast dynamics. We will use optical techniques to try and compress electron pulses to generate an improved temporal resolution. This will enable faster dynamics to be at the center of attention for future research. The work presented in this undergraduate thesis is a contribution to this optical technique and involves the design and operation of a pulsed electron source.

Acknowledgments

A great deal of gratitude is extended to the National Science Foundation for funding this research project. Furthermore, thank you to Dr. Brett Barwick, Dr. Christina Othon, and Ryan Anthony-Ceres in for their close collaboration in generating this work presented. A final thank you to Jim, Lisa, and Rachel Zeman; my supporting family that continues to fuel my eagerness to succeed in my academic endeavors.

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1 Introduction

Ultrafast electron microscopy has emerged as an effective technique for imaging temporally evolving dynamics and has practical uses in studying condensed matter systems, material properties, and nanoscale ultrafast dynamics. Ultrafast electron microscopes (UEM) use pulses of electrons induced by femtosecond laser pulses on an electron source. These pulses are then accelerated by electric potentials to probe and image specimens. The field of research for ultrafast dynamics is currently limited by the temporal resolution of these short duration electron pulses as the temporal resolution of electron pulses has been plagued by the kinetic energy distribution of emission source electrons. Electron pulses that have a distribution of initial kinetic energies causes the faster, higher kinetic energy electrons, to move to the front of the pulse meanwhile the slower, lower kinetic energy electrons, fall behind in the back of the pulse. This causes the short pulse to disperse over time, increasing the duration of the electron pulse and ultimately leads to diminished temporal resolution, inhibiting the resolution needed to capture ultrafast dynamics. In this thesis we seek to develop a technique that will be used to combat the dispersion of propagating electron pulses. The overarching research plan intends to use the fundamental interactions of low energy electrons and light to employ an all-optical compression of short duration electron pulses from picoseconds down to tens of femtoseconds or less, creating the temporal resolution needed to study ultrafast dynamics.

1.1 Optical Standing Waves

The technique that we wish to employ depends on the creation of intense optical standing waves; a phenomenon that can be created by spatiotemporally overlapping short duration laser pulses. The importance of optical standing waves that we seek to create involves the stationary nodes and antinodes, or the locations of deconstructive and constructive interference of light amplitude, respectively. These nodes and antinodes create an interference pattern of light intensity. With a proper optical setup, the spacing of the interference pattern can be calculated and verified experimentally. There are various previous works that have been published that elaborate on the experimental setups that are required to achieve an optical standing wave [1,2]. These various optical setups often include the use of transmission diffraction grating to split an incident pulse of light into multiple orders which can then be recombined, or overlapped, in space and time. The popularity of the use of a transmission grating is due to the simplicity of the apparatus set up as less components are needed. Spherical mirrors, all-reflective objectives, and lens telescopes are all feasible options for diffracted order recombination [1]. During summer research in 2018 with Dr. Barwick, we were able to verify the theoretical and experimental interference pattern spacing using a diode laser at various wavelengths as well as a 1030nm femtosecond pulsed laser using both the simple lens telescope and the all-reflective objective as the method of overlap.

Another trivial combination technique includes aligning two identical counter propagating light sources; this technique requires a more difficult apparatus setup and is less practical. We will likely employ the use of an all-reflective objective in combination with a spatial light modulator (SLM). The use of a SLM creates an advantage for this optical apparatus as it can be used to generate singular diffracted orders, which eliminates the need to block unwanted lower intensity diffracted orders, and ease of control over the interference pattern spacing. The SLM is also versatile for other possible research opportunities including studying the exchange of orbital angular momentum (OAM) from photons to electrons which involves an identical optical setup. The various capabilities that a SLM presents for phase modulation has been documented in literature as well [3].

Current uses of optical standing waves vary from the demonstration of the Kapitza-Dirac effect [4,5] to photon-induced near-field microscopy [6]. The closest related research that has been published on electron compression [5,7,8,9] involve traveling optical standing waves and rely on the ponderomotive potential to selectively accelerate electrons, resulting in the optical compression of an electron pulse. The scope of this research differs from the techniques above as we plan to use a stationary optical standing wave to spatiotemporally overlap a propagating low energy electron pulse with the pulsed standing wave. By doing so, we then plan to use the fundamental interactions of light and electrons to selectively accelerate electrons, resulting in an optical compression of the electron pulses.

1.2 Electron Pulse Compression

When an electron interacts with an electromagnetic wave, or optical standing wave as in this case, the oscillating electric field of the electromagnetic wave imparts a force on it. As mentioned, we plan to subject the lower kinetic energy electrons to a force in the direction of propagation by overlapping an antinode, the location of high intensity electric field in the pulsed optical standing wave. Ideally, we also wish to overlap the higher kinetic energy electrons in the nodes of the interference pattern, or the location of low to no presence of electric field. This will result in an isolated acceleration of the electrons in the back of the pulse, effectively resulting in a compression of a dispersed electron pulse. We plan to accomplish the spatiotemporal overlap of the electron pulse with respect to the pulsed interference pattern’s nodes and antinodes with our ability to control the spacing of the interference pattern with the SLM and the MATLAB simulations of the propagation of the electron pulses and the interactions they experience in the overlap region given their initial conditions. The simulation will allow us to fine tune our apparatus parameters to achieve the best possible theoretical overlap.

There have been other numerous approaches used to combat electron pulse dispersion. Some tactics include radio frequency fields [10], terahertz fields [11], and visible/infrared laser pulses [7,12]. These tactics operate with electrons in the high energy range of tens to hundreds of keV. We plan to use low energy electrons of ~1 keV as they provide various advantages for compression techniques including the reduced difficulty in apparatus setup as well as increased photon-electron interaction.

1.3 Electron Source

One of the major components to this research plan includes the creation of an electron source that allows femtosecond pulses of light to create a femtosecond electron pulses using the photoelectric effect. This electron source is also required to be vacuum compatible and be able to apply variable potentials to accelerate the electrons to the desired kinetic energy as well as steer the direction of propagation of the electron pulse. This component is at the center of attention as it is responsible for the electron pulses that will propagate to eventually meet up with the overlapping femtosecond laser pulses and interact with the nodes and antinodes of the interference pattern generated by the standing wave.

1.4 Current Research Project Progress

The progress of this research plan is currently in the first year towards completion. The efforts towards accomplishing the goal of an all-optical compression of electron pulses is a collaborative project in which the efforts of two individual students (Ryan Anthony-Ceres and Jared Zeman) are working towards providing the foundational work for future students to continue and complete the research objective. This collaborative research project includes two separate tasks towards the research objective; a computational and experimental research emphasis. The computational task includes constructing the MATLAB simulation that was referenced earlier to aid in the experimental overlap of pulses and electron pulses [13] while the experimental task includes the design and construction of an operating pulsed electron source, as presented in this undergraduate thesis. The scope of future research opportunities will be discussed in Conclusion and Future Direction.

2 Materials and Methods

2.1 Electron Source Design

The key components in an electron source, or electron gun, includes the following: a cathode, an electrostatic lens to focus the electrons, and vertical/horizontal deflection to steer the propagation of the electrons. The design of this electron gun was based on being vacuum compatible, having electrically isolated components, and being able to create pulses of electrons. The design and alignment of all components used in this gun was developed using Autodesk Fusion 360.

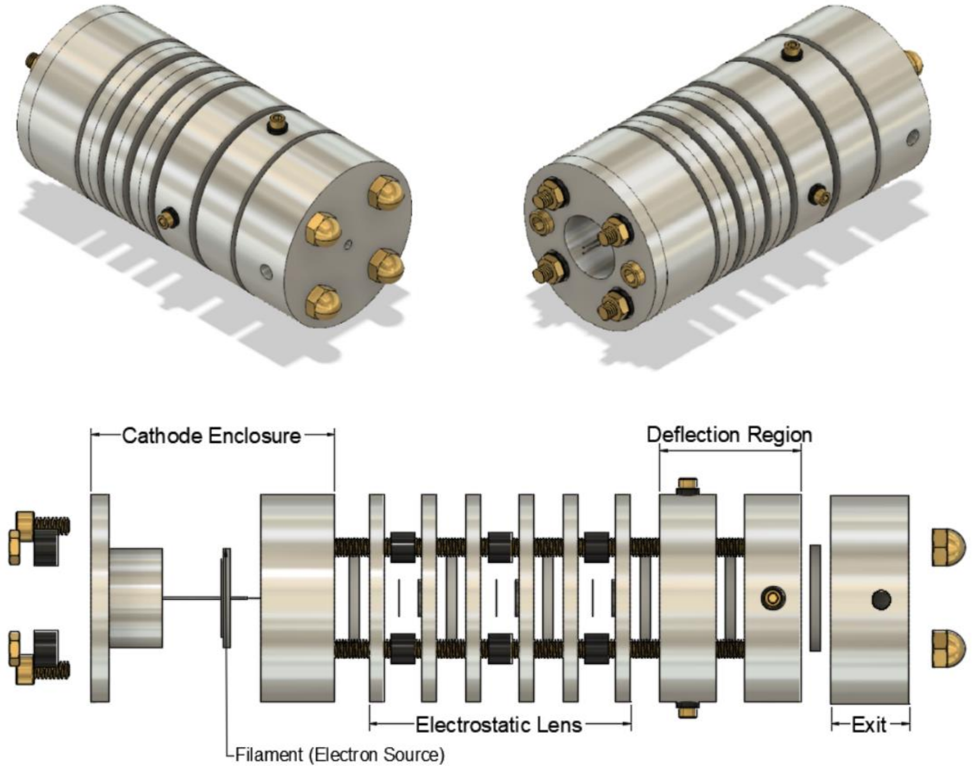


Figure 1: **Electron Gun Component Layout.** The image above is a horizontally stretched layout of the electron and its components. The gun includes a cathode and its securing enclosure, an electrostatic lens, horizontal/vertical deflection plates, and an exit.

This gun features a self-aligning design as four threaded rods pass through each component in a circular arrangement. Located on the threaded rods there are Garolite and ceramic spacers to not only ensure a snug fit but also insulate the threaded rods from each conductive component in the gun that has an electrostatic potential applied to it. The material used has no relevance to performance but rather based on spacer size availability as both serve as an electrical insulator. Additionally, ceramic spacers are located between each conductive component to insulate charged components that contain a potential. The entire assembly is snug fit with cap nuts on the threaded rods at the exit and hex nuts fastened at the cathode enclosure.

Material	Component(s)	Conductor/Insulator
Aluminum (6061-T6)	Cathode Enclosure, Aperture plates, Deflection Plates Exit	Conductor
Brass	Cap nuts, hex nuts, socket screws, threaded rods	Conductor
Ceramic	Washers (spacers) Insulator spacers	Insulator
Garolite	Insulator spacers	Insulator
Teflon	Deflection Plate insulators	Insulator

Table 1: **Component Classification.** The table above lists all materials used, the purposes they serve, and whether they are a conductive or insulative material.

The table above displays the component materials used and their respective specifications. Each component material was carefully selected for its insulative and vacuum compatibility properties. The functioning roles of every component in the design will be discussed in the following component breakdown sections.

2.1.1 Cathode Enclosure

The cathode enclosure is composed of two machined aluminum components; the cathode housing and the cathode cap, as well as its insulating spacers and fasteners. The cathode enclosure was designed to allow the cathode to be exchanged or removed without disassembling the entire gun in the event of a burned-out cathode.

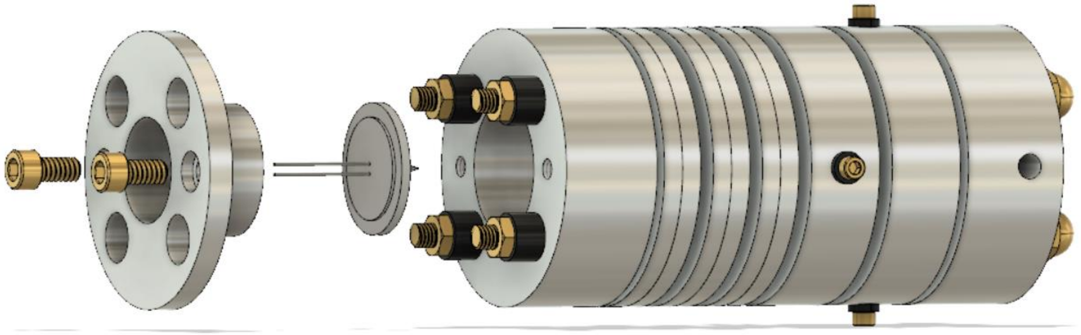


Figure 2: **Cathode Exchange.** The figure above demonstrates the simple removal of two fasteners to remove the cathode cap to expose the cathode.

There are no potentials applied to the cathode enclosure. The cathode enclosure is insulated from the electrostatic lens with a ceramic spacer placed between them. For electron experimentation using thermionic emission, applying a current through the two cathode posts will result in an electron source. For pulsed electron sources, a current will not be used. This method of operation will be discussed in further detail in Electron Gun Operation.

2.1.2 Electrostatic Lens

An electrostatic lens (EL) is an electron focusing technique that uses the electric fields generated by a series of electric potentials applied to symmetrical regions of conductive metal i.e. cylinders, plates, and apertures are commonly employed symmetrical EL's. This feature is imperative for the electron gun as it creates a focal point in the electron beam where the electrons are high populated. The EL for this gun includes three aperture assemblies with ceramic spacers placed between them to isolate the potentials from each other. Each aperture assembly in comprised of two machined aluminum plates, a 1mm aperture, and four insulating Garolite spacers. Each aperture assembly features a male/female mating design where the aperture rests in the female contact on one plate and the male contact on the other plate sandwiches and centers the aperture in place.

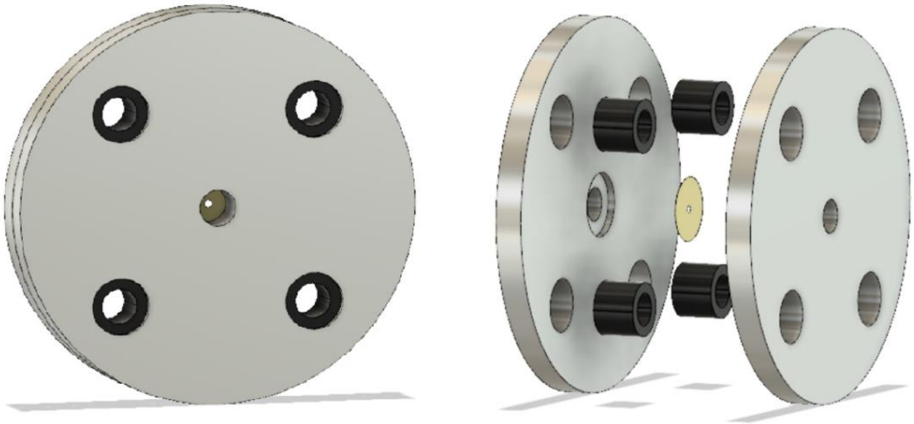


Figure 3: **Aperture Assembly.** The figure above displays a single aperture assembly and how it sandwiches the small aperture in the center of the plates. To apply a potential to the assembly, an electrical lead is simply sandwiched between the aperture plates.

To effectively focus the electron source, we would like to make an Einzel Lens. An Einzel Lens is a three-aperture system that has the first and third apertures that electrons encounter grounded while the center aperture has either a positive or negative voltage applied to it.

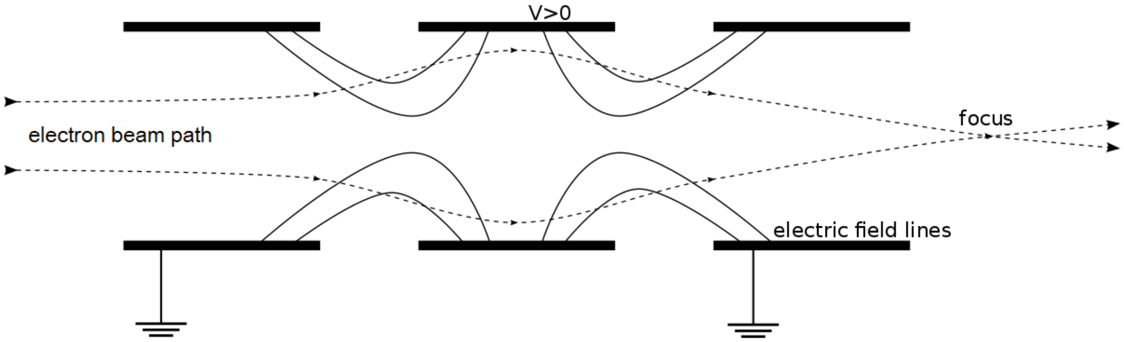


Figure 4: **Einzel Lens Schematic.** The figure above presents the focusing scheme behind the Einzel Lens. In this gun's design, the parallel plates in the figure represent the aperture assemblies. Lensing also occurs with a negative potential applied to the center aperture, which we plan to employ. Image downloaded and modified from https://commons.wikimedia.org/wiki/File:Einzel_lens_schematic_drawing.svg.

2.1.3 Deflection

The deflection region in this gun design incorporates two deflection assemblies orientated perpendicular to each other to provide a vertical and horizontal deflection region for the propagating electron source. The deflection region provides the ability to fine tune the direction of the propagating electrons by establishing an electric field perpendicular to the parallel deflection plates. Each deflection assembly is comprised of a centering ring, two semi-circular “plates”, two socket screws, and six insulating Garolite spacers, and insulating sheets of laboratory grade PTFE Teflon.

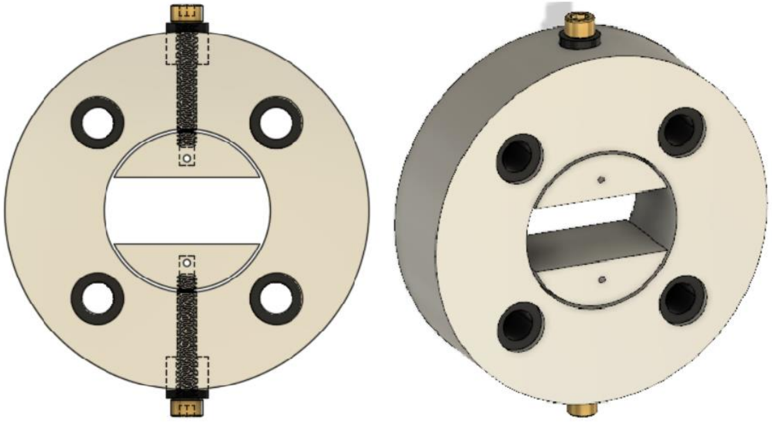


Figure 5: **Deflection Assembly.** The figure above depicts a deflection assembly. The deflection plates are secured, or pulled tight to, the centering ring by the socket screws. Teflon sheets are sandwiched between plates and the ring to insulate the ring from the potentials applied to the plates. To apply a potential to each plate, an electrical lead is secured to the head of the socket screw that is screwed into the plate. The outer edge of the ring is isolated from the socket screws by ceramic spacers that are used to center the socket screw in a larger diameter hole and space the head of the screw away from the outer edge of the ring.

The deflection assemblies are isolated from the EL, the exit, and each other with ceramic spacers placed between each component. To effectively create an electric field perpendicular to the planar faces of the deflection plates, a positive voltage needs to be applied to one plate and a negative voltage of the same value needs to be applied to the opposing plate. The direction of deflection is determined by the orientation of the electric field between the plates.

2.1.4 Exit

The exit, despite its apparent simple purpose, plays an incredibly important role in the creation of pulsed electrons. The exit contains a right-angle mirror aligned with the port on the side of the exit. The mirror provides means to reflect femtosecond laser pulses down into the gun towards and eventually striking the cathode, creating a femtosecond pulse of electrons as theorized in the Electron Source section.

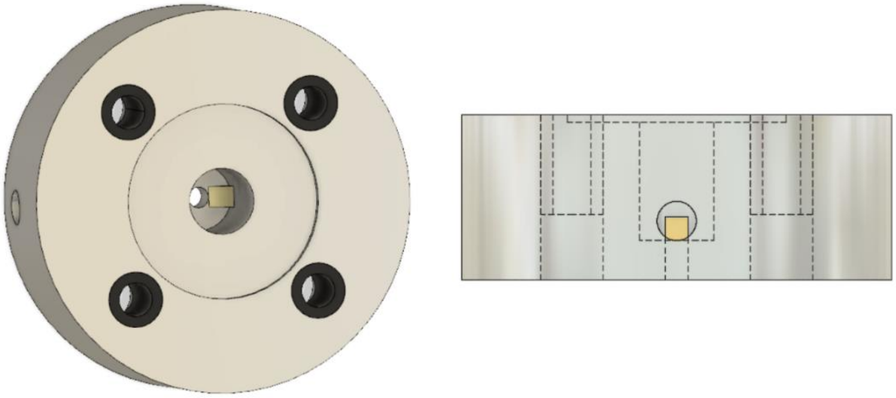


Figure 6: **Exit.** The figure above depicts the exit or end piece to the electron gun. The exit is a machined aluminum component that contains a right-angle UV enhanced aluminum coated mirror aligned with the port on the side of the exit and four Garolite insulating spacers.

The implementation of the mirror in the exit to create pulsed electrons will be discussed in further detail in Electron Gun Operation.

2.2 Electron Source Power Supply

The power supply unit used to administer the electric potentials needed for this electron gun design is a Kimball Physics Electron Gun Power Supply (EGPS) (Model #: EPGS 12B). This supply is designed to be operated with a Kimball Physics electron gun, which is also in possession of the Department of Physics at Ripon College. This gun and its electrical connections are specific to the Kimball Physics EGPS, making operating a self-designed electron gun without these specific connectors not feasible. This created a need to reverse engineer the connections and the purposes that they served in the Kimball Physics gun to be compatible with the designed electron gun. The Kimball Physics EGPS utilizes three Amphenol female contact circular plug connectors that serve three different outputs: deflection, focus, and main supply. The deflection plug supplies the potentials applied to the deflection region (four in total) and two grounded connections. The focus plug supplies a single potential administered through a coaxial connection. The main supply supplies four high voltage connections, two of which, when connected in series with a cathode, provide an electron source through thermionic emission. The other two connections include the cathode grid, which is manually adjusted on the EGPS unit and an additional high voltage connection that is directly proportional to the energy of the electron. The corresponding Amphenol male mating plugs were purchased along with 9-conductor 18 AWG shielded power cable and RG-8/U coaxial cable to distribute the electric potentials to a circular multi-pin feedthrough.

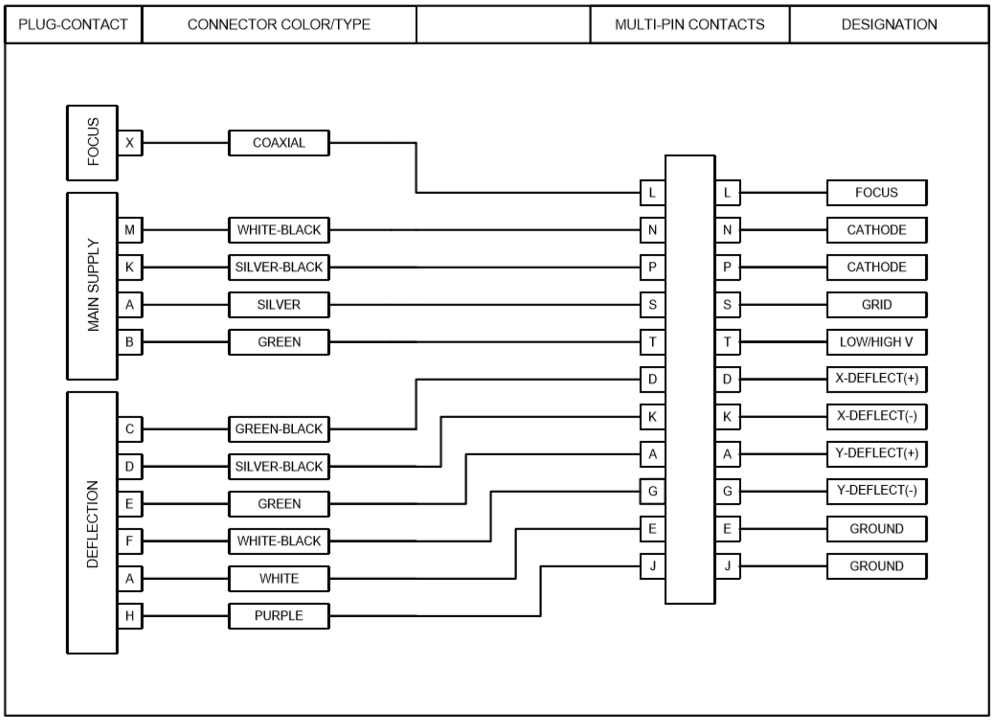


Figure 7: **Schematic Diagram of Electrical Connections from EGPS to Vacuum System.** The diagram above illustrates the electrical connections made between the EGPS and the multi-pin feedthrough and their respective purposes. The specific solder/pin contacts for each connector/flange feedthrough are labeled in squares.

2.3 Electron Gun Operation

From the multi-pin feedthrough, connections are made to the electron gun inside the vacuum system using AccuGlass TFE Teflon insulated 18 AWG conductors. These leads include a male pin and female socket quick-disconnect feature near the connections to the gun. This allows for the ease of removal and reinsertion of the gun into the vacuum system without tampering with the connections of the electrical leads to the multi-pin feedthrough.

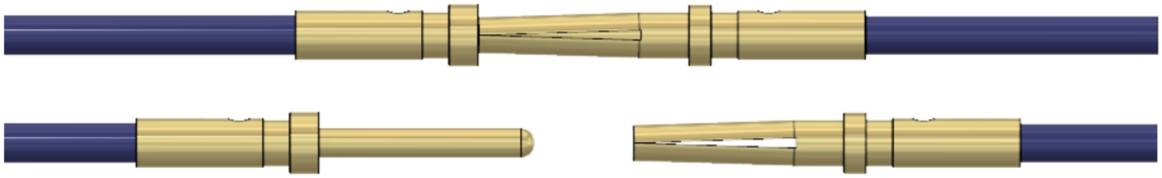


Figure 8: **Quick-Disconnect.** The figure above depicts the quick-disconnects that are located on the insulated conductors that make connections between the feedthrough and the gun. The disconnect feature includes a male pin and female socket that coincide when connected.

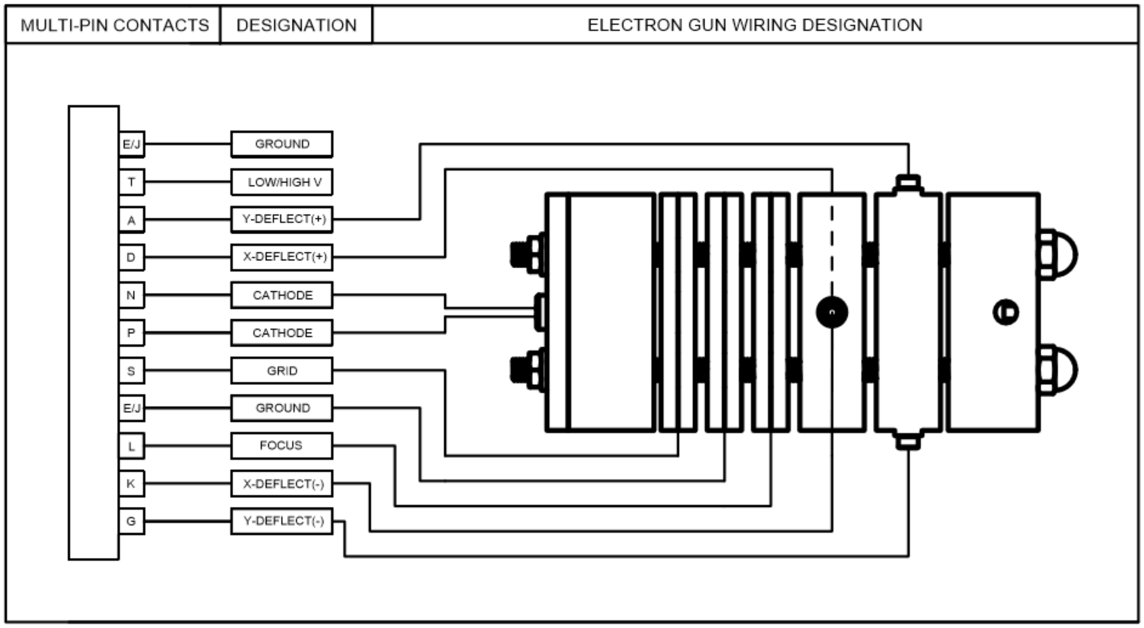
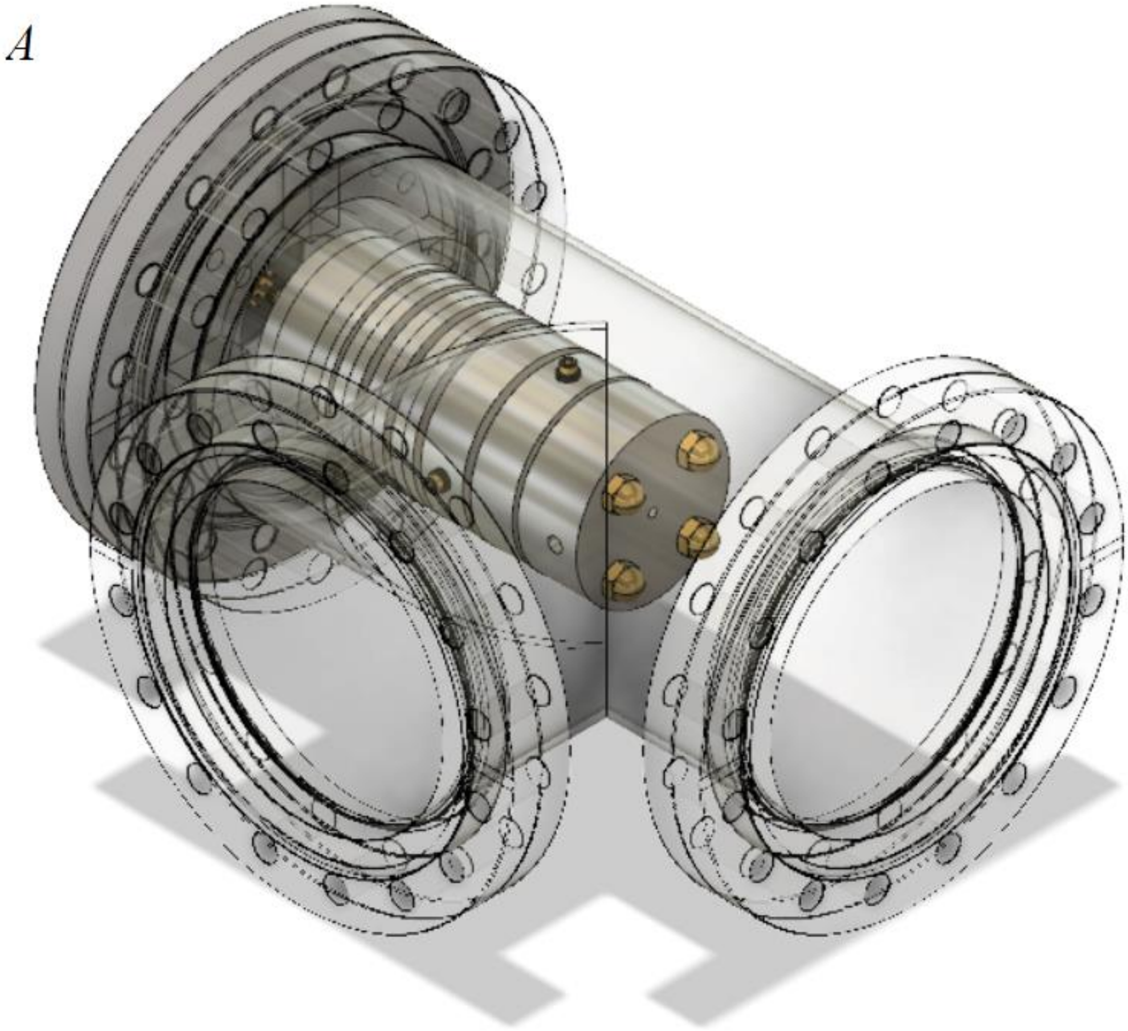


Figure 9: **Schematic Diagram of Up to Date Electrical Connections from Multi-Pin Feedthrough to Electron Gun.** The diagram above illustrates the electrical connections made between the multi-pin feedthrough and the electron gun along with the connection designation. The specific contacts for the multi-pin feedthrough are labeled in squares.

To operate the gun to produce an electron source via thermionic emission, a current is applied to the cathode, causing the cathode to heat up and glow. After the electrons pass through and focus in the EL, they then pass through the deflection region where voltages can be applied to the horizontal and vertical deflection plates to steer the path of propagation of the electron source through the exit. After exiting the gun, electrons will then propagate through vacuum to phosphorescent coated viewport, where a green glow denotes the presence of electrons bombarding the viewport.



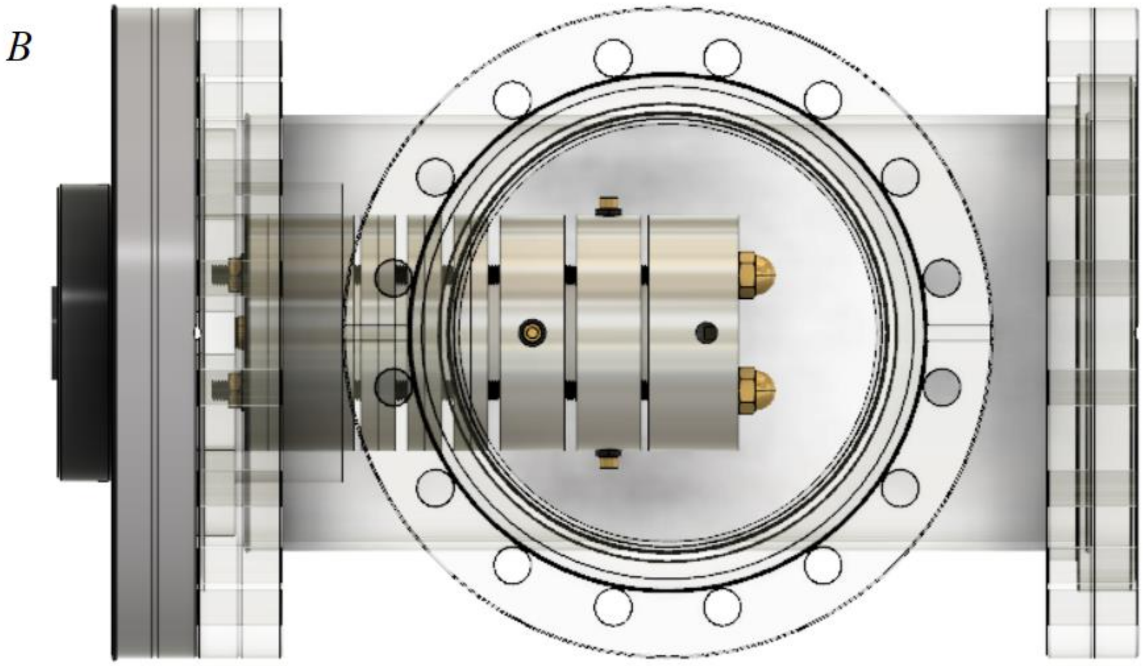


Figure 10: **Electron Gun Inside ConFlat Tee Vacuum Chamber.** In the images above, the electron gun, ConFlat Tee (clear), multi-pin feedthrough (black), and 6” flange (gray) are visible. *A* and *B* illustrate the electron gun inside the vacuum chamber and *B* provides an alternate view of the gun inside the chamber and its exit port alignment with the flange opening. The ConFlat Tee appearance has been altered to see the gun inside the chamber.

The method of creating a pulsed electron source involves abandoning passing a current through the cathode to create electrons via thermionic emission. Instead, the electrons will be created by the photoelectric effect when a pulsed laser light strikes the cathode. To achieve this, pulsed laser light will enter the vacuum system through a viewport, which will be placed on the flange perpendicular to the orientation of the gun, as seen in Figure 10, and enter the port on the exit of the gun to reflect off the mirror. The reflected pulse will then travel through the gun towards the cathode, passing through the deflection region and the EL where it will strike the cathode, creating a pulse of electrons. After verification of electrons on the phosphor screen for both the thermionic emission and pulsed method, we plan to place specimens in the ray path of the electrons and view the resultant images on the phosphor screen.

3 Results and Discussion

3.1 Operating the Electron Gun

After successfully converting all outputs from the EGPS to be compatible with the electron gun, all the ordered and manufactured components of the electron gun were cleaned in a methanol bath and then were assembled and placed in vacuum as seen in Figure 10. The electron gun's first test fire resulted in a successful viewing of electrons on the phosphor screen. The electron source was visible for a wide range of operating parameters however the source image was distorted, off-center, and did not respond as anticipated regarding focusing the source. After confirming that the electron gun was able to produce an electron beam that propagated out of the gun onto the screen, the remaining time spent experimenting with the gun involved trying to clean up distortions in the electron source image and successfully focus the beam.

3.1.1 Electrostatic Lens

As seen by the wiring configuration in Figure 9, we created a slightly modified EL than the true Einzel lens as planned. This EL features the first lens (grid) acting as a Wehnelt; a common component used in electron guns to focus and control the flow of electrons. The grid is floated at the same high voltage, V, as the current source making the voltage applied to the grid through the EGPS act as a small ΔV to the electrons that emit from the cathode. In comparison, V is three orders of magnitude larger than ΔV for the operating parameters that we experimented with (>10 V). The grid operated as expected and restricted the flow of the electrons propagating through the gun. As the grid voltage increased in negative value, the electron source would dim and eventually fade away as it was deflecting all thermionic emission electrons from entering the EL. We applied the focus, which operates on a separate high voltage, to the third aperture and grounded the second aperture. This aperture operated at ~1KV to exhibit a focus of the electron source.

3.1.2 Deflection

The deflection plates performed as expected and as we were able to successfully steer the electron source both vertically and horizontally. This was a trivial yet promising result as it was useful for steering the path of electron beam propagation to align it with specimens for imaging purposes. While experimenting with this function, we found that the deflection plates operated in a range of 0-30 V to walk the electron source image on the phosphor screen. This will be a useful operating function for further experimentation as it provides an additional means of electron source manipulation.

3.2 Viewing Electrons

To successfully view electrons on the screen, we first tuned the energy of the electrons to the expected 1-2 KeV by floating the energy output at approximately 1-2 KV. No experimentation took place past 2 KV. Next, the current source was coarsely tuned until an emission current was registered on the EGPS. The current was then fine-tuned until an electron source was visible. If a source was not found while fine tuning, the deflection was used to discover the source. The glow of hot cathode would also appear very dim on the phosphor screen, a good precursor to finding the electron source shortly after the correct conditions were met. Once the source was positioned, focusing attempts took place using the grid and focus outputs.

Figure 11: **Electron Beam on Phosphor Screen.** The electron beam unaltered out of the gun onto the phosphor screen (left) and a specimen, in this case a post on linear motion feedthrough with a hole drilled in it, dropped down in the path of the electron beam (right). In both images, the electron beam is not focused.

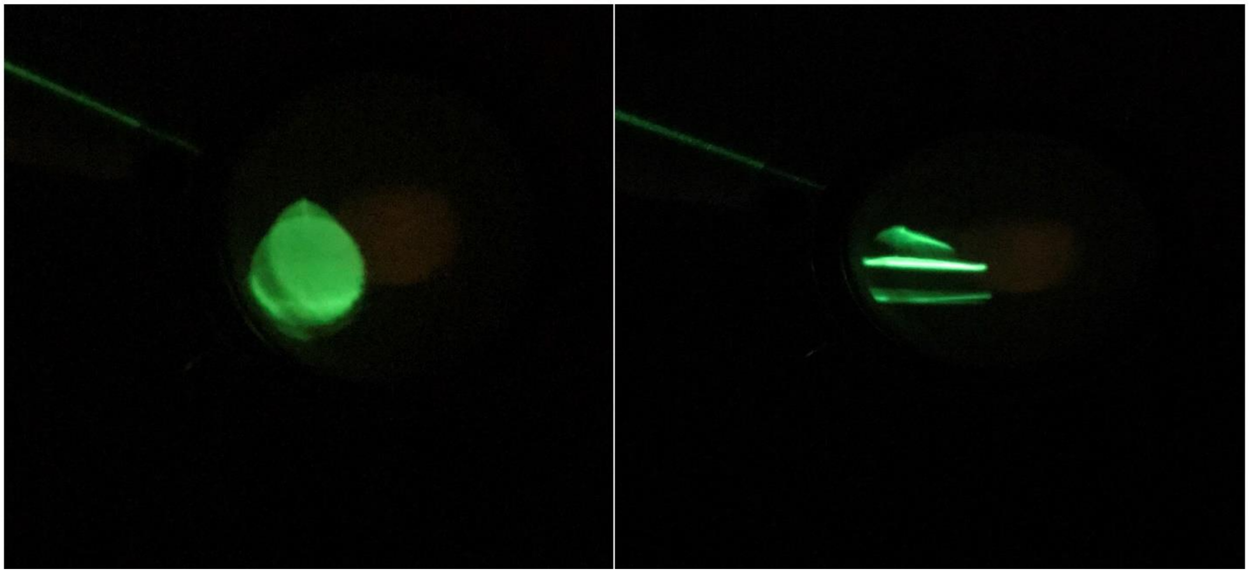


Figure 12: **Focusing the Electron Beam on the Phosphor Screen.** The electron beam unaltered out of the gun onto the phosphor screen (left) and the beam focused onto the phosphor screen (right). The stray line in the upper left corner of both images is stray light in the lab.

The focused image in Figure 12 is comprised of three horizontal stripes. The centered stripe is the main electron beam seen on the left being focused vertically into a line. The lines above and below the center line are stray electron sources that appeared while focusing. The origination of these stray sources and why they do not focus with the main beam is unknown currently.

3.3 Discussion

There were a variety of tough obstacles that were faced in this experimental electron gun design. One of the main difficulties faced in the duration of this research project was the conversion of the EGPS to be compatible with the electron gun design. As mentioned, the outputs on the EPGS and connectors were specific to a separate Kimball Physics electron gun. This made for a challenging conversion as the connectors to three separate outputs needed to be completely rebuilt by purchasing the corresponding male mating plugs and soldering all conductor connections. In fact, one Amphenol mating plug (deflection output) used in the EGPS was specially manufactured for the EGPS, meaning purchasing the corresponding mating male plug impossible as it was not available for individual sale. This mating pair was replaced with a similar Amphenol 8-pin mating pair and had to be rewired in the EGPS. The Kimball Physics connectors were designed to handle very high voltage which made trying to figure out what contacts were connected to from the EGPS very difficult as the connections were well enclosed and not accessible. This required testing each output contact to isolate and verify what contacts in each output from the EGPS did with respect to the operating controls to be able to properly connect the output from the EGPS to the electron gun.

Another large difficulty faced in this research project was the discovery that the original electrical isolating spacers purchased for the electron gun were not totally electrically isolative. The original components purchased were made of polyether ether ketone (PEEK) which were described to be vacuum safe and presumably isolating since polymers are not good electrical conductors. However, the components purchased were PEEK sleeve bearings. Sleeve bearing are designed for mechanical processes to facilitate linear motion by reducing vibrations and noise by absorbing friction between moving parts. For this reason, we believe the components included trace amounts of a conductive material, such as graphite, to strengthen the sleeve bearing, compromising the electrical isolating property of PEEK. This resulted in a complete reorder of new electrical isolating components which included the ceramic and Garolite spacers.

Another issue faced in operating the electron gun was a peculiar emission current signal on the EGPS. Without even applying a current to the cathode, the emission current signal would register a current as the energy of the electrons, or the voltage floated on the cathode, was increased. The emission current signal is created by current, in this case electrons that are propagating, that passes through the potential field created by the grid. We theorized that the grid aperture was too close to the cathode, causing the faulty readings. To combat this, we simply moved the grid aperture further away from the cathode. An additional theory that may implicate faulty emission current readings includes the possibility of a short in the electrical connections. The contacts that contain the current source, grid, and an additional voltage output are all capable of being floated at very high voltage. When at high voltage, if the contacts are close enough such that the path of least resistance to a nearby pin is possible, arcing occurs to alleviate the buildup of excess charge. This arcing could also cause faulty readings which could explain random spikes in emission current and other erratic behavior that we have observed. To mitigate this possibility, we removed the additional high voltage contact (T) that was not in use, as seen in Figure 9. This contact was wired in the early progress of the EGPS conversion just in case it was needed further down the line in experimentation. Since it is floated at the same high voltage as the other contacts with no use, its buildup of excess charge could be arcing to nearby pins or grounded sources. As planned, this fixed our signal and the gun was able to operate at higher voltages without the electron beam flickering, a sign that it was shorting.

The first test fire of the electron gun resulted in a distorted electron source image and the electron source did not respond to any focusing attempts. The result of a confirmed electron beam created by the electron gun was promising, however any useful utilization of this electron beam requires the ability to focus the electrons into a tight, highly populated electron beam. The inability to focus was due to the original ordering of the EL which had the ground and focus apertures swapped. The first variation we made to resolve our lensing issues included placing the center aperture at ground and applying the focus to the third aperture. This resulted in a cylindrical lens effect, as seen in Figure 12, which focused the beam only in the vertical direction. A true spherical lensing would focus in both directions, creating a focused point. Future attempts to resolve this focusing issue would include adding a fourth aperture plate to the electron gun assembly and try and create a true Einzel lens that follows the Wehnelt as the first aperture. The length of the gun is a limiting factor in this gun design as the mirror in the exit needs to align with the viewport to successfully create a pulsed source. If adding a lens compromises this design feature, a secondary solution will need to be conceived.

4 Conclusion and Future Direction

Despite a successful viewing of electrons out of the self-designed electron gun, there is still a lot of progress that will be continued to be made during the remainder of the semester and for future students. Currently, we have an electron source that focuses but not to a fine point as desired. This task, including any needs to redesign or recreate elements of the gun to perfect the method of creating an electron source via thermionic emission, will be the center of attention after the completion of this undergraduate thesis. Once fully operational and well behaved, the next step in the direction of this project is to create a pulsing electron source. This will involve the implementation of the right-angle mirror and laser light to enter through the view port and into the exit on the gun as seen in Figure 10. Hopefully, with all operating functions working properly in the gun, controlling the electron beam should be trivial as it will hopefully behave like the electron source generated in the thermionic emission source. Before any pulsing can be done, the right-angle mirror needs to be coated in aluminum with the sputter coater in the laboratory. The biggest roadblock facing getting this electron gun to pulse requires the task of aligning the gun, viewport, and mirror properly. Once a fully functioning pulsed electron source is created, along with the aid of computer simulations [13], the beginning stages of electron pulse compression can take place. This will provide ample research opportunities for future students and will hopefully lead to a successful completion of the research goal.

References

1. Kozma, I.Z. and J. Hebling, *Comparative analysis of optical setups for excitation of dynamic gratings by ultrashort light pulses.* Optics Communications, 2001. **199**(5-6): p. 407-415.
2. Maznev, A.A., T.F. Crimmins, and K.A. Nelson, *How to make femtosecond pulses overlap*. Optics Letters, 1998. **23**(17): p. 1378-1380.
3. Long, Z. and Wang, J., *Arbitrary manipulation of spatial amplitude and phase using phase-only spatial light modulators*. Scientific Reports, 2014. **4**(7441).
4. Handali, J., P. Shakya, and B. Barwick, *Creating electron vortex beams with light.* Optics Express, 2015. **23**(4): p.5236-5243.
5. Kozák, M., Eckstein, T., N. Schönenberger and Hommelhoff, P., *Inelastic ponderomotive scattering of electrons at a high-intensity optical travelling wave in a vacuum.* Nature Physics, 2018. **14**: pg. 121–125.
6. Barwick, B., D. Flannigan, and A.H. Zewail, *Photon Induced Near-Field Electron Microscopy.* Nature, 2009. **469**: p. 902-906.
7. Baum, P. and A.H. Zewail, *Attosecond electron pulses for 4D diffraction and microscopy.* Proc. Natl. Acad. Sci. U. S. A., 2007. **104**: p. 18409-18414.
8. Kozák, M., Schönenberger, N. and Hommelhoff, P. *Pondermotive Generation and Detection of Attosecond Free-Electron Pulse Trains.* Phys. Rev. Lett. **120**(10): p. 103203-103209
9. Feist, A., K.E. Echternkamp, J. Schauss, S.V. Yalunin, S. Schafer, and C. Ropers, *Quantum Coherent optical phase modulation in an ultrafast transmission electron microscope.* Nature, 2015. **521**(7551): p. 200-203.
10. Gliserin, A., A. Apolonski, F. Krausz, and P. Baum, *Compression of single-electron pulses with a microwave cavity.* New Journal of Physics, 2012. **14**(7): p. 073005
11. Kealhofer, C., W. Schneider, D. Ehberger, A. Ryabov, F. Krausz, and P. Buam, *All-optical control and metrology of electron pulses.* Science, 2016. **352**(6284): p. 429-433.
12. Hilbert, S.A., C. Uiterwaal, B. Barwick, H. Batelaan, and A.H. Zewail, *Temporal lenses for attosecond and femtosecond electron pulses.* Proc. Natl. Acad. Sci. U. S. A., 2009. **106**: p. 10558-10563.
13. Anthony-Ceres, Ryan. *Numerical Simulation of Low Energy Free Electron Interaction with Femtosecond Optical Standing Waves for Use in Ultrafast Electron Microscopy.* BA Thesis. Ripon College, 2019