DESIGN AND CONSTRUCTION OF A Z-PINCH APPARATUS FOR METAL-CATALYZED FUSION EXPERIMENTS

by

Shannon R. Walch

Submitted to Brigham Young University in partial fulfillment of graduation requirements for University Honors

Advisor: Steven E. Jones

Signature:________________________

Honors Representative: Brian Woodfield

Signature:_______________________

ABSTRACT

DESIGN AND CONSTRUCTION OF A Z-PINCH APPARATUS FOR METAL-CATALYZED FUSION EXPERIMENTS

Metal-catalyzed fusion, also called laboratory nuclear astrophysics, is the study of the interactions of deuterium and metals. Previous experiments in this field have focused primarily on the interactions of deuterium in metal lattices. The Alternate Energy Research Group at BYU decided to build a z-pinch device to explore the interactions of deuterium in metal plasmas. This paper describes the design and construction of a z-pinch device to be used for these experiments. A brief history of metal-catalyzed fusion and of the use of z-pinch devices in fusion experiments is included. Our reasons for choosing a z-pinch device is discussed, and our goals for the apparatus and the planned experiments. The designs and construction of the device are included, as well as those for accompanying voltage and current sensors. Our z-pinch has successfully blown up 25 micron copper wires at voltages of approximately 18 kV. Further calibration of our current sensor is required before accurate measurement of the current through the exploding wire is made. We plan to continue refining our apparatus and set up a neutron detector so that we may begin measuring the neutrons emitted from the explosion of deuterium-loaded wires for possible enhancements.

ACKNOWLEDGEMENTS

I would like to thank Dr. Jones for his help planning this project. I would also like to thank John Ellsworth for the time and effort he put into teaching me about high-voltage circuitry so I could construct this device.

TABLE OF CONTENTS

LIST OF FIGURES

I. Introduction

1.1 Discovery of Metal-Catalyzed Fusion

In the 1980s, researchers discovered that ^{3}He, a rare isotope of helium, would build up in metal containers and foils used in experiments involving deuterium [1]. Researchers in catalyzed fusion, including BYU professors Dr. Steven Jones and Dr. Paul Palmer, recognized that ^{3}He was created in the fusion of deuterium nuclei and hypothesized that the metal containers somehow catalyzed deuterium fusion. The fusion reactions were releasing ^{3}He which built up in the containers. The researchers began to experiment with the interactions between metals and deuterium. Neutrons, another product of deuterium fusion, were detected in early experiments involving palladium and titanium foils in electrolytic cells at levels several standard deviations above background noise [1]. After several repetitions of these experiments with similar results, researchers concluded they had observed cold nuclear fusion in condensed matter. Further experiments were planned to explore what exactly was occurring in the metal foils because no theory of condensed matter or atomic interactions offered an explanation for the bursts of neutrons.

1.2 Experiments Done at BYU

In order to understand these phenomena better, Dr. Steven Jones, a professor at Brigham Young University and a researcher of muon- and metal-catalyzed fusion, began working with other members of the faculty here at BYU and researchers at other institutions on three new experiments [2]-[3]. These experiments involved applying a voltage to copper foils connected in series and loaded with deuterium. The first experiment detected neutron counts significantly above the background level. The second experiment showed that large numbers of protons were being released from the foils. The third experiment placed detectors on both sides of the foil to study the dynamics of the emitted particle. As both protons and neutrons are created by the fusion of deuterons, these results strengthened the hypothesis that metals like titanium enhance the fusion of deuterium and motivated other research groups to create experiments to explore these phenomena.

1.3 Current Trends in Metal-Catalyzed Fusion

Since the early BYU experiments, other research groups have also studied particles emitted by metal foils loaded with deuterium and then stimulated in some way [4]-[11]. The most common method has been to fire beams of deuterons at metal foils. Detectors around the foils measure the energy of the emitted particles. These experiments are harder to set up than applying voltages to foils, but give experimenters control over the energy of the incident particles. Beam experiments also take less time to run and produce more particles and stronger signals. These experiments have verified the BYU team's hypothesis that the number of particles emitted due to fusion depends strongly on the material of the host foil [7],[9]. Metals produce much more energetic emissions than semiconductors and nonmetals. The number of emitted particles also varies widely for different metals; palladium, for example, releases much more energy through energetic particles than iron does [9].

1.4 Conclusions of Previous Experiments

Several experiments have verified a correlation between the metal used in these experiments and the amount of enhancement. However, a complete explanation is lacking for the correlation found between the type of metal used in these experiments and the number of particles emitted [9]. Research groups in Germany and Japan which performed these experiments and the Alternate Energy Research Group at BYU have looked for metallic characteristics that correlate the metals used and the number of particles released. However, properties such as electrical conductivity, electronegativity, and atomic number show no correlation to the measured numbers of emitted particles. This has left researchers at a loss for how to explain these phenomena, because no current theory offers any explanation for how metals could enhance d-d fusion.

1.5 Z-Pinch and Metal-Catalyzed Fusion

The lack of an explaining theory has prompted the Alternate Energy research group at BYU under the direction of Dr. Jones to design other experiments to study the interactions between deuterons and metals. One proposed experiment is to use a z-pinch device to collapse metal vapors and deuterium gas. Metal wires are loaded with deuterium gas and then vaporized by a pulse of current. The vaporized metal and deuterium then collapse under the magnetic field produced by the current, and the energy and the number of emitted particles can be measured [12]. This is another way of comparing the interactions of metals and deuterium. The benefit of this approach is that all previous experiments have used deuterons embedded in metal lattices, while a z-pinch device will hold the deuterons in a plasma of metal ions.

The Z-pinch experiment was proposed by Dr. Jones because it represents unexplored territory for metal-catalyzed fusion. By embedding the deuterium in what becomes a sea of metal ions, the z-pinch mimics conditions in the interior of the sun more closely than other metal-catalyzed fusion experiments have done. The Z-pinch apparatus will also require little time to set up for each test, allowing researchers to quickly collect data and vary the conditions of the experiment. Information obtained from these experiments could provide valuable new insights into the effect metal lattices have on the interactions of deuterons.

1.6 History of Z-Pinch Devices

A z-pinch device was first used in experiments in the late eighteenth century by Martinus van Marum; he used a large electrostatic generator to blow up wires [10]. The theoretical basis for the z-pinch was developed in the 1930s independently by W. H. Bennett and L. Tonks, but little notice was taken of the work [11]. After World War II, physicists studying controlled fusion began experimenting with z-pinch devices, when the self-constriction of the plasma was recognized as one possible way of containing fusion reactions. Experiments began in England in 1950 under A. A. Ware and in the United States in 1952 under J. L. Tuck [11].

By the time the first z-pinches were put into use, however, severe instabilities in the plasma had been predicted by M. D. Kruskal and M. Schwarzschild [12]. The first series of experiments in 1950 verified that the plasma columns produced by z-pinches rapidly become unstable and dissipate before the conditions for thermonuclear fusion are reached. Experimenters began searching for ways of stabilizing the plasmas produced, but lack of success decreased interest in z-pinches. Z-pinches fell out of use for nearly a decade until the invention of pulsed power and the discovery that arrays of wires gave better energy efficiency made z-pinches desirable for research applications [10]. For the last twenty-five years, z-pinches have been used for x-ray sources, long-distance laser guiding systems, possible fusion generators, and for studying instabilities in plasmas.

1.7 Types of Z-Pinch Devices

1.7.1 Dynamic Z-Pinches

The most common type of z-pinch used today is the dynamic z-pinch, so named because the kinetic energy of the implosion is the primary heating mechanism [13]. A high-voltage pulse is passed through a gas shell, liner, or wire array, and the material is ionized by the current. The resulting plasma collapses under the pressure of the magnetic field created by the current. Most of the energy is radiated away as extreme ultraviolet or x-ray radiation. Though initial experiments were done with gas puffs, these were found difficult to work with. Wire arrays are easier to handle and can produce greater quantities of x-rays, which has led to the dominance of wire arrays in dynamic z-pinch device. Characterized by high velocities and sizable implosions, dynamic z-pinches are used in thermonuclear fusion experiments and materials testing.

1.7.2 Equilibrium Z-Pinches

The equilibrium z-pinch uses predominantly ohmic and compressional heating to provide the plasma's energy [13]. The most common examples are exploding wires, fiber pinches, gas-embedded z-pinches, and capillary discharges. In these approaches, a high-voltage current is applied to the wire or fiber, which ionizes and explodes without imploding at high velocity. Sometimes the wires or fibers are exploded in gas chambers so the gas can provide extra stability for the resulting plasma column. These set-ups were originally used with frozen deuterium wires or other fibers and showed a surprising amount of stability for a z-pinch. However, these z-pinches never came close to achieving temperatures or pressures necessary for fusion and are now primarily used for x-ray sources. A variation on the equilibrium z-pinch is the capillary discharge. The capillary discharge applies the voltage pulse across a small hole in either a metal or polymer. Material ionizes from the sides of the hole and forms a high-density, nearly local thermodynamic equilibrium. This set-up has been used to produce pumped ultraviolet lasers.

1.7.3 Dense Plasma Focuses and Plasma Arcs

The defining characteristics of the dense plasma focus are mass accretion, axial shear, and that the implosion is initiated by a surface flashover [13]. It is typically used to study instabilities in plasmas, as this set-up is prone to extreme instabilities in latter stages of the plasma's life. The plasma arc is a low voltage, low energy version of a z-pinch typically used to produce extreme ultraviolet and x-ray radiation. The plasma density is lower than that produced by a z-pinch and is characterized by different plasma kinetics. The dense plasma focus and the plasma arc are not as commonly used because they have not proved as applicable for the fusion and plasma experiments most commonly carried out with z-pinches.

II. The Z-Pinch

2.1 Goals and Preliminary Designs

The initial goal for this z-pinch device was to explode a small wire, and eventually explode wires loaded with hydrogen and deuterium. Ultimately, we hope to detect charged particles from the explosion and measure their energies. This information will allow us to determine if enhancement similar to that measured by beam experiments occurs in this set-up. The experiment will be most straight forward if we keep the device small and in the low-temperature range. A small z-pinch also requires fewer materials and emits less radiation, making it easier to shield detectors and other experiments in nearby labs. By keeping the explosion in the low-temperature range, we limit our study to energies and temperatures similar to previous metal-catalyzed fusion experiments and out of the thermonuclear fusion range.

While keeping the z-pinch low-powered, we still want the device to produce a narrow current pulse with a fast rise time; the goal is to quickly ionize the wire with the deuterium gas still inside and to avoid gas escaping during a long heating process. With these goals in mind, we concluded that a single-wire equilibrium z-pinch would best suit our goals. After reviewing available articles describing similar devices [14-16], we concluded that our z-pinch should create voltages in the 20-25 KV range with currents of approximately 5 kA and it should be able to discharge in less than 10 microsecond.

2.2 Construction of the Z-Pinch

2.2.1 The Capacitor Bank

The primary component of the z-pinch device is the capacitor bank and the electrodes that hold the wire. The z-pinch consists of two circular aluminum plates, 6 inches in diameter, separated by six 40 kV, 2700 pf capacitors. Two copper electrodes in the center of the plates hold the wire but leave one inch exposed. The capacitors are arranged radially around the wire to minimize any disparity in arrival time of the current from one capacitor over another. This arrangement was to increase the rise time of our pulse and quickly ionize the wire. Copper was chosen for the electrodes because of its high electrical conductivity. Our original plan was to build the entire device of copper, as the device itself carries current to the wire and so copper would give us the maximum conductivity of electricity. Building the device of copper would also have allowed us to build shunts to measure current and voltage directly into the device. However, copper proved too weak to create a sturdy apparatus. We instead built most of the device out of aluminum as it was stronger and easier to work with.

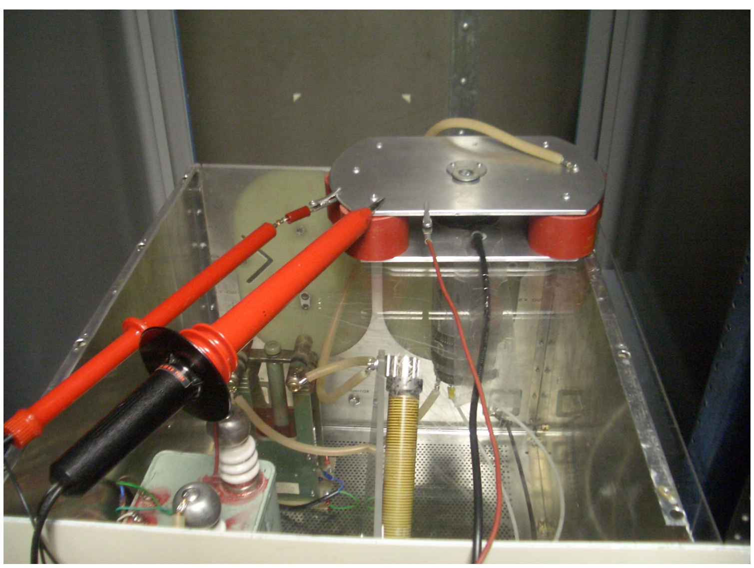


Figure 1-The capacitor bank, with voltage probes and Rogowski coil

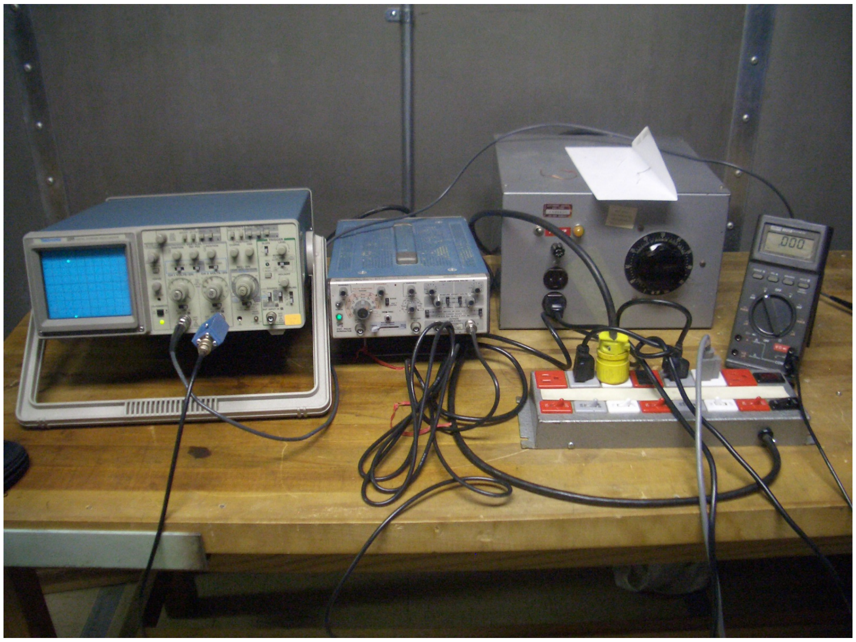


Figure 2-Controlling electronics

Wires are inserted by being dropped through a hole in the top electrode and then into a corresponding hole in the bottom electrode. Screws in the sides of each electrode allow the wire to be clamped into place. The holes are 0.125 in. in diameter and thus can accommodate several different thicknesses of wire.

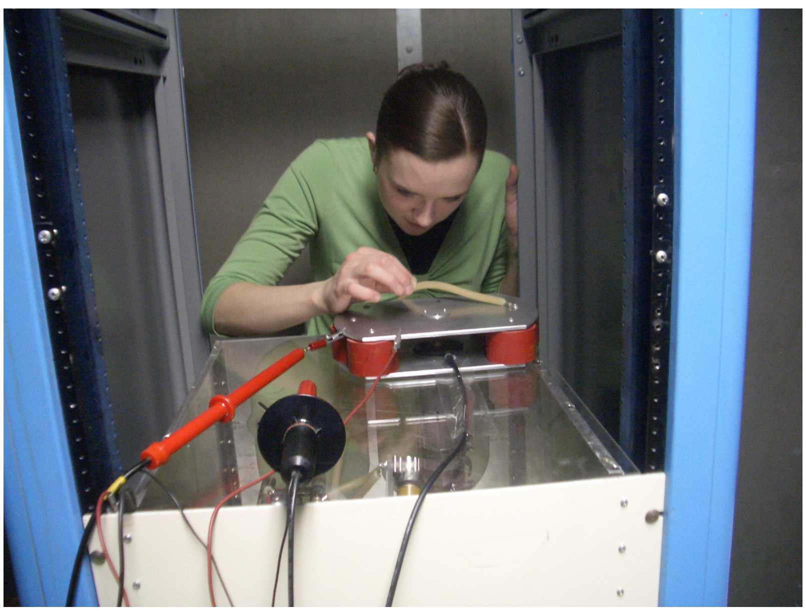


Figure 3-Insertion of wire into z-pinch

Measurements of the capacitors showed that each had a capacitance between 2110 and 2140 pF. This provides approximately 4 kJ of energy when the capacitors are charged to 25 kV.

2.2.2 The Triggering System

The next critical element in creating the z-pinch was finding a triggering mechanism that will discharge the capacitor bank through the wire in less than a microsecond. For this purpose, we used a National Electronic ignitron as the trigger for our z-pinch. It is capable of releasing 50 kV and 25 kA peak current in 2-5 microseconds, depending on the external circuitry. The copper electrode at the base of wire is screwed onto to top of the ignitron. An aluminum tube welded perpendicular to the bottom plate of the z-pinch is clamped around the ignitron; this provides the electric contact between the z-pinch and ignitron necessary for the ignitron to discharge the capacitors.

The ignitron has a repetition rate of no more than two cycles per minute. This repetition rate is acceptable for our experiment because discharging the capacitor bank and inserting a new wire between each firing requires more than 30 seconds. Thus, ordinary operation allows the ignitron the necessary time to recharge. Any time lost in reloading the device with wires is insignificant, as even five minutes per reloading allows several wires to be tested per hour. This is a much better rate of accumulating data than is achieved by beam and foil experiments, which require hours or days per test run.

The ignitron is triggered by a microsecond pulse produced by a pulse generator. The ignitron and capacitor bank are charged by a 50 kV power supply through a large resistor.

2.2.3 Safety Devices

The primary safety device on the z-pinch is a dump relay. Whenever the z-pinch is not in use, the dump relay connects all the capacitors to ground. This allows for complete discharge of the system between runs and prevents any residual voltage from building up on the capacitors which could prove hazardous to operators.

The z-pinch device is located in a Faraday cage as a precaution against the radiation and electromagnetic pulses produced by the explosion of the wire. This protects sensitive detectors and nearby experiments from any effects of our experiments. It also allows us to place sensitive equipment outside of the cage and away from the explosions.

III. Characterization of the Z-Pinch

3.1 Characterization of Voltage

To characterize the voltage of the z-pinch, we used a Simpson 50 kV test probe. The probe was originally meant to extend the range of a 20 kΩ per volt multimeter. However, we chose to use it with on oscilloscope to allow us to record the time dependence of the voltage. This required that the oscilloscope be connected to additional circuit elements so the oscilloscope can respond to the probe as the multimeter would. Additional calibration of the probe was also required. The benefit of this set-up was that we could determine the time-dependence of the voltage fluctuations. As the voltage during the explosion changes in microseconds, an ordinary multimeter would not have provided useful data.

Preliminary tests were done with an additional voltage probe connected to the capacitor bank. This probe was connected to a multimeter, and therefore cannot respond quickly enough to follow voltage fluctuations during the explosion of a wire. The purpose of this probe was to allow us to monitor the voltage on the capacitors while we calibrated the primary voltage probe and to allow us to test the effectiveness of the dump relay in discharging the capacitors.

3.2 Characterization of Current

Characterizing the current of the z-pinch proved more difficult. The high currents produced by the capacitor bank did not allow any direct measurement of the current that would not stress the electronics. We chose to use a Rogowski coil, which can detect changes in current without being placed directly in the circuit. A Rogowski coil is a toroidal coil of wire on a non-magnetic core. The coil is placed around the circuit element whose current we wish to measure. The voltage induced in the coil is passed through an integrator circuit, and the resulting voltage is proportional to the current through the coil. Thus, the Rogowski coil connected to an oscilloscope allows us to track the variations in time of the current through the exploding wire.

We choose to use a Rogowski coil to measure the current of the z-pinch because the coil is non-intrusive. Rogowski coils have been successfully used in similar applications in plasma physics for several years [17-19]. The coil does not need to be directly connected to the z-pinch in any way, so it and its attendant electronics do not need to be protected from the high voltages and currents produced by the z-pinch. The Rogowski coil is also known for being able to be deformed from ideal conditions such as perfectly even windings and circular shape significantly before it loses effectiveness. The Rogowski coil is sensitive to changes in current and therefore is optimized for alternating current devices. It has also been successfully used in pulsed-current and pulsed-voltage applications for many years. As we are primarily interested in the rise time and pulse characteristics of our apparatus, characteristics related to how the current changes, the Rogowski coil works well despite the fact that our device is direct-current.

We constructed our Rogowski coil by winding enameled copper wire around the dielectric core of RG-58 coaxial cable. The end of the copper wire was soldered to the cable's central core and the cable was then formed into a loop. This loop was covered in sheathing, in copper foil, and in another layer of sheathing. The sheathing is standard on Rogowski coils to protect the wire loops from outside influence, but the layer of copper foil was an innovation to shield the coil from the EMF generated by the z-pinch explosion and increase the accuracy of our current measurements.

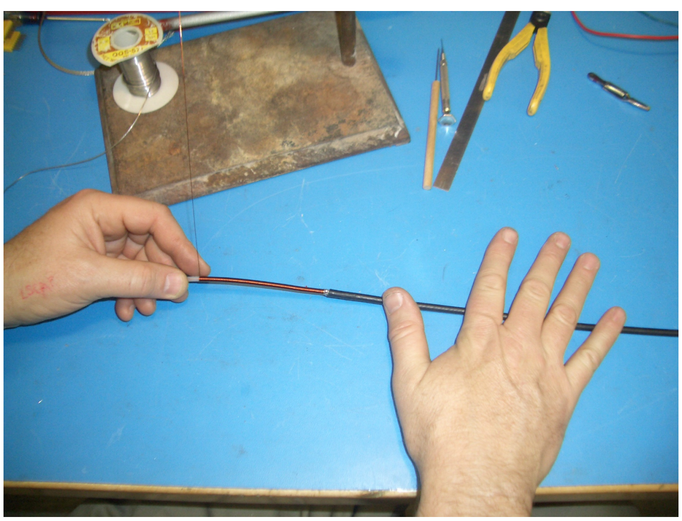


Figure 4-Wrapping copper wire onto the dielectric core

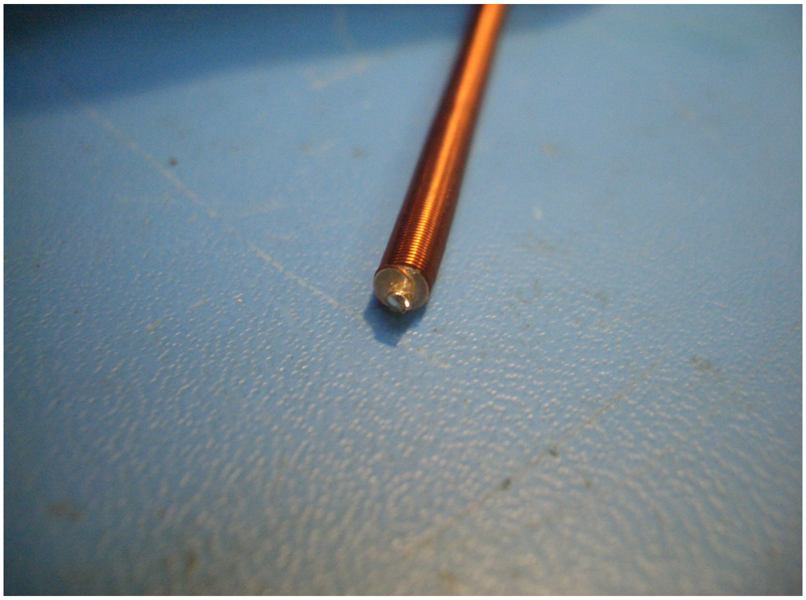
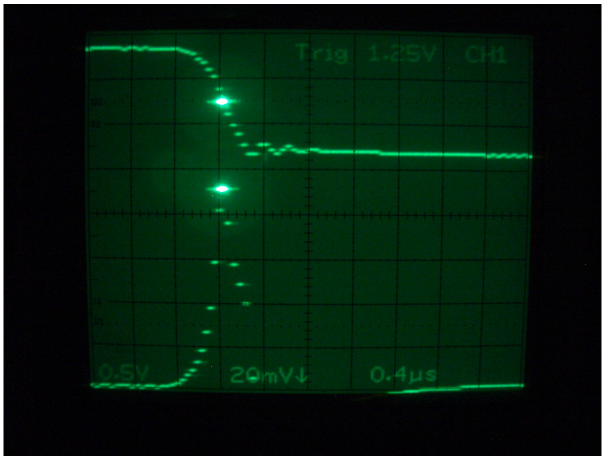


Figure 5-Soldered end of copper wire to core

IV. Conclusion

4.1 Evaluation of Z-Pinch

Our z-pinch device can successfully explode 25 micron copper wires. Initial charging of the capacitor bank could only achieve approximately 18 kV before a corona discharge occurred between the large resistor on the capacitor bank and the metal floor of the cabinet housing the z-pinch. A polymer box is currently being constructed to shield the resistor, which should allow us to charge the capacitor bank to 25 kV. The Rogowski coil shows distinct spikes in the current consistent with the discharge of the ignitron and ionization of the wire. However, additional calibration of the voltage probe and the Rogowski coil must be done before significant characterization of these quantities can be made.



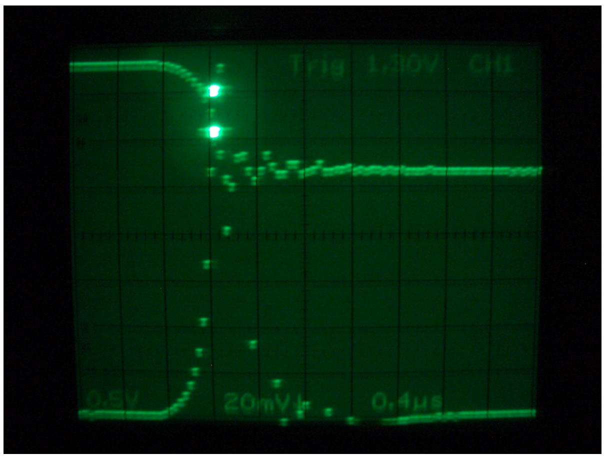


Figure 6-Preliminary testing: the upper line corresponds to the voltage, the lower one to current.

Tests with wires larger than 25 microns were not as successful, because the wires failed to fully ionize. We hypothesize this is caused by poor electrical contact between the wire and the electrodes. It has proven difficult to insert wires of these dimensions into the electrodes, due to bending of the wires. Alternate methods of inserting the wires are being considered.

4.2 Future Plans

Further calibration of the voltage and current sensors is planned with 25 micron copper wire. During this time, we plan to acquire a neutron detector and begin any necessary construction or calibration to set it up by the z-pinch. We chose not to make our preliminary tests in a vacuum- or gas-chamber, as these would have nominal effect on the characterization of the device or on the detection of neutrons. A vacuum system or gas chamber will be necessary when we begin to study the charged particles emitted by the explosion. We are considering various methods of implanting deuterium into wires, namely gas-loading or electrolysis embedding. When we have set up the neutron detector, we can begin testing the differences in neutron counts from pure metal wires, hydrogen-loaded wires, and deuterium-loaded wires to look for the possible enhancements due to metal-catalyzed fusion under these conditions.

REFERENCES

[1] S.E. Jones, et al., "Observation of Cold Nuclear Fusion in Condensed Matter," *Nature*, 338, 1989, pp. 737-740.

[2] S.E. Jones, et al., "Neutron Emissions from Metal Deuterides," presented at *Tenth International Conference on Cold Fusion,* Cambridge, MA, 2003, http://www.lenr-canr.org/acrobat/JonesSEneutronemi.pdf.

[3] S.E. Jones, et al., "Charged-particle Emissions from Metal Deuterides." presented at *Tenth International Conference on Cold Fusion*, Cambridge, MA, 2003, http://www.lenr-canr.org/acrobat/JonesSEchargedpar.pdf.

[4] H. Yuki, T. Satoh, and T. Ohtsuki, "D + D reaction in metal at bombarding energies below 5 keV," *J. Phys. G: Nucl. Part. Phys*., 23, 1997, pp. 1459-1464.

[5] H.Yuki, et al., "Measurement of the D(d,p) reaction in Ti for 2.5 < Ed < 6.5 keV and electron screening in metal," *J. Phys. Soc. Japan*, 66, 1997, pp. 73.

[6] H. Yuki, et al., "Anomalous Enhancement of DD Reaction in Pd and Au/Pd/PdO Heterostructure Targets Under Low-energy Deuteron Bombardment," *JETP Letters*, 68, 11, American Institute of Physics, 10 Dec 1998, pp. 823-829.

[7] K. Czerski, et al., "Enhancement of the Electron Screening Effect for d+d Fusion Reactions in Metallic Environments," *Europhys. Lett,* 54, 4, 2001, pp. 449-455.

[8] F. Raiola, et al., "Enhanced Electron Screening in d(d,p)t for Deuterated Ta," *Eur. Phys. J. A* 13, 2002, pp. 377-382.

[9] F. Raiola, et al., "Enhanced Electron Screening in d(d,p)t for Deuterated Metals," *Eur. Phys. J. A,* 19, 2004, pp. 283-287.

[10] Sweeney, Mary Ann. History of Z-pinch Research in the U.S. *5th International Conference on Dense Z-Pinches*. Albuquerque, New Mexico. 2002.

[11] Bishop, Amasa S. Project Sherwood: The U.S. Program in Controlled Fusion. Addison-Wesley Publishing, Inc. Reading, MA. 1958.

[12] Greene, John M.; Johnson, John L.; "Interchange Instabilities in Ideal Hydrodynamic Theory." *Plasma Physics*, 10, 1968. pp. 729-745.

[13] Liberman, Michael A.; De Groot, John; Toor, Arthur; Spielman, Rick B.; Physics of High-Density Z-Pinch Plasmas. Springer-Verlag, New York, 1999.

[14] Duselis, Peter U. and Kusse, Bruce R. "Experimental observation of plasma formation and current rransfer in fine wire expansion experiments." *Physics of Plasmas*, 10, 3, March 2003. pp. 565-568.

[15] Johnston, M. D.; Lau, Y. Y.; Gilgenbach, R. M.; Strickler, T. S.; Jones, M. C.; Cuneo, M. E.; and Mehlhorn, T. A. "Caterpillar structures in single-wire z-pinch experiments." *Applied Physics Letters*. 83, 24. 2003. pp. 4925-4917.

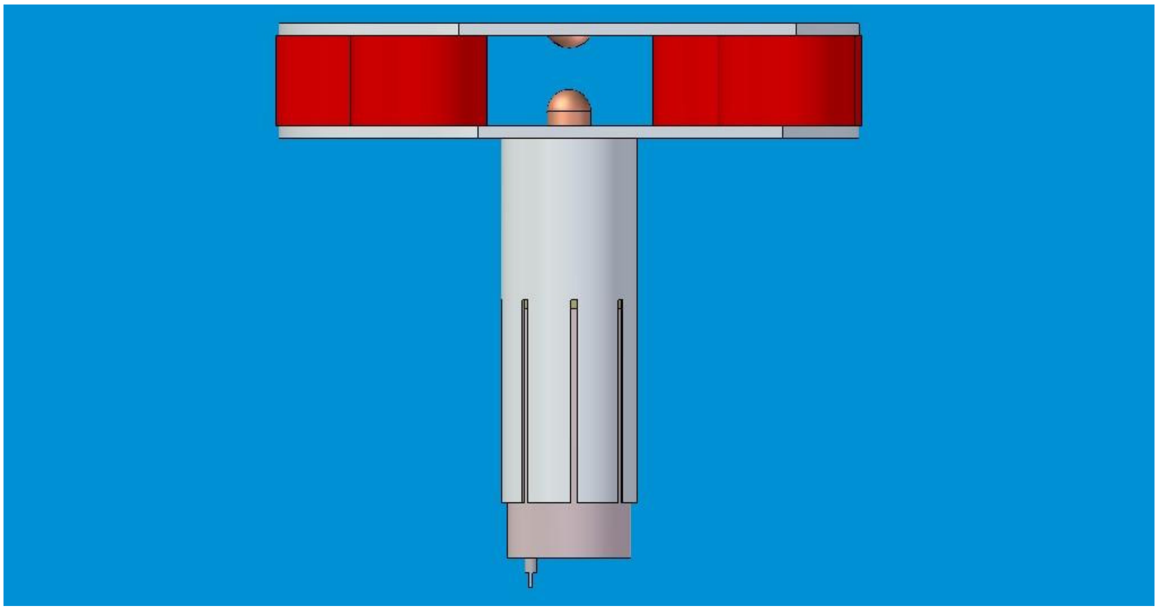
[16] Chandler, K. M.; Hammer, D. A.; Sinars, D. B.; Pikuz, S. A.; Shelkovenko, T. A. "The Relationship Between Exploding Wire Expansion Rates and Wire Material Properties Near the Boiling Temperature." *IEEE Transactions on Plasma Science*. 30, 2. 2002. pp. 577-587.

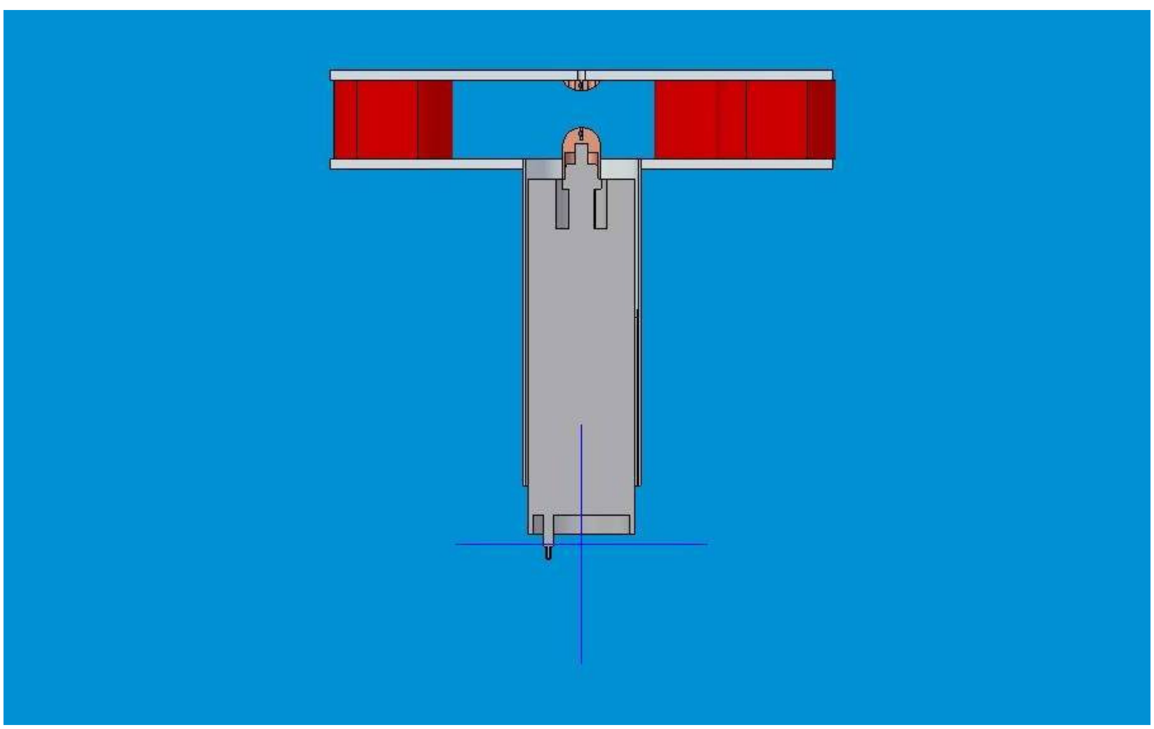
[17] Murgatroyd, P. N.; Chu, A. K. Y.; Richardson, G. K.; West, D.; Yearley, G. A.; and Spencer, A. J. "Making Rogowski Coils." *Meas. Sci. Technol.* 2. 1991. pp. 1218-1219.

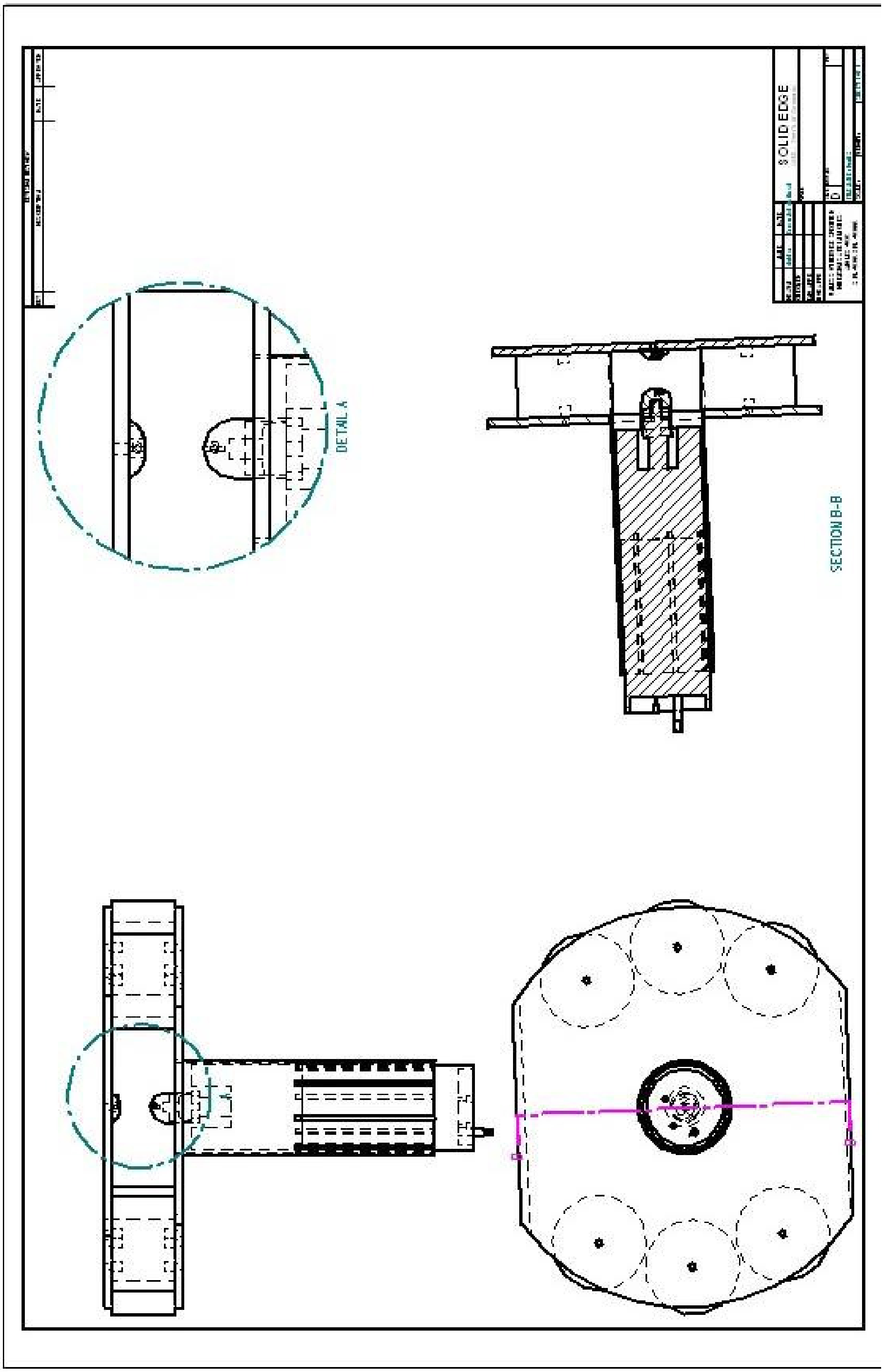
[18] Abdi- Jalebi, Ehsan and McMahon, Richard. "Simple and Practical Construction of High-Performance, Low-Cost Rogowski Transducers and Accompanying Circuitry for Research Applications." *Instrumental and Measurement Technology Conference.* May 2005. pp. 354-358.

[19] Honea, D. and Medley, S. S. "Improved construction of Rogowski coils for measurement of plasma currents." *Journal of Physics E: Scientific Instrumentation.*7, 1974. pp. 537-538.

APPENDIX I—Technical Drawings of Z-Pinch Device






DETAIL A
SECTION B-B
SOLID EDGE