Effects of Cathode Shielding Methods in an Inertial Electrostatic Confinement Fusion Reactor

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Abstract

For fusion to become a useful source of energy, many improvements to reactors must be made to match its output energy with its input energy. An inertial electrostatic confinement fusion reactor, or an IEC fusor, is a device that fuses deuterium nuclei. It works by creating deuterium plasma which is accelerating towards a negatively charged grid where they fuse. The wire grid is impacted by these fast moving nuclei which transfer to heat, resulting in inefficiency. To solve this, I proposed that if magnetic fields or positively charged plates were introduced in the correct configuration, ion impacts would decrease. Since a fusing fusor was not necessary when testing the grid shielding methods, a demo fusor was built. This type of fusor does not produce fusion because it uses air. The pressure and voltage were kept the same and the time it took for solder on the grid wires to melt was recorded. To reach 577°C, the control, magnet method, and plate method took 101, 62, and 87 seconds respectively. When the magnets were moved closer to the grid, the time it took for the grid to reach 652°C increased from 32 (regular distance) to 36 seconds. The plate shielding method proved to be unsuccessful because of the stronger electric field between the cathode and anode, heating the grid due to field emission. For the magnetic field method however, decreasing the voltage and moving the magnets closer seemed to distort the plasma around the grid wires quite well.

Introduction

In inertial electrostatic confinement fusors, shielding the grid from fast moving ions has largely been untried. People on fusor.net have been discussing ways to possibly avoid grid collisions but no methods have been tested. There has been an attempt to get rid of the cathode grid entirely by use of something called a Polywell device (talk-polywell.org). This type of fusion reactor confines electrons in a magnetic field creating a virtual cathode. It eliminates the need for a wire grid and thus avoids all grid collisions. This method of fusion, which Robert Bussard experimented with, unfortunately didn't prove successful as it didn't create more energy than that was put into it (talk-polywell.org).

What I planned to do was to try to shield the grid using two methods. One was to use the electrostatic force and the other was to use magnetism. Experimenting with these two methods will determine if further research should be conducted on either of the two.

How I came up for the idea for my project took months of research and a lot of thinking. I first had to know how an inertial electrostatic confinement fusor worked in order to fully understand the problems and to invent ways to improve its efficiency. After searching the internet and library, I came across a few places where people were discussing ways to shield the inner grid to improve efficiency. From the book I read and pictures on the internet showing the effects of magnetism on plasma, I determined that using magnets may be an effective way of directing the ions away from the grid wires. After building my demo fusor, I placed a magnet next to the cathode grid to observe its effects. The plasma seemed to be focused around the poles and redirected away from the space in between the poles. This is what I decided to work my design off of. For the other grid shielding method, I wanted to use the positively charged anode as a way to deter ions from going near the inner grid. My first thought was to add similar, positively charged grid wires located very close to the inner grid wires. This, I thought, would repel positively charged ions when they came very close to the inner grid. After doing more research, I found that Steven Sesselmann proposed a better idea on fusor.net of using plates extending from the inner grid and outwards. This would repel ions all along its entire path instead of just near the inner grid.

Purpose

For fusion to be a useful source of energy, reactors need many improvements before matching its output energy with its input energy (Rider). One of the major losses in a typical inertial electrostatic confinement fusor is deuterium ion collisions with the inner grid (Rider). When the ions are accelerated towards the cathode, some of them collide with the grid, transferring their energy into heat. As a result, the grid's temperature increases. If the grid gets too hot, it deteriorates, rendering the fusor useless at very high voltages. Since the inner grid is essential in the fusing process, a way of deflecting the ions from the grid must be developed to improve the fusor's efficiency.

The two methods of cathode shielding I have decided to test will determine if they reduce heat loss to the grid. If one or any of the methods reduce the amount of heat being transferred to the grid by the plasma, the efficiency of the fusion reactor will have been increased. Reduced heat being transferred to the grid will result in increased ion lifetime because when an ion impacts the cathode grid, its usefulness ends, wasting the deuterium fuel. Ultimately, this experiment will gather data that is useful for improving fusion efficiency.

Hypothesis

If magnetic fields or positively charged plates are introduced in the correct configuration within an inertial electrostatic confinement fusion reactor, the ions will avoid impacting with the cathode grid, reducing heat transfer to the grid and ultimately improving its efficiency.

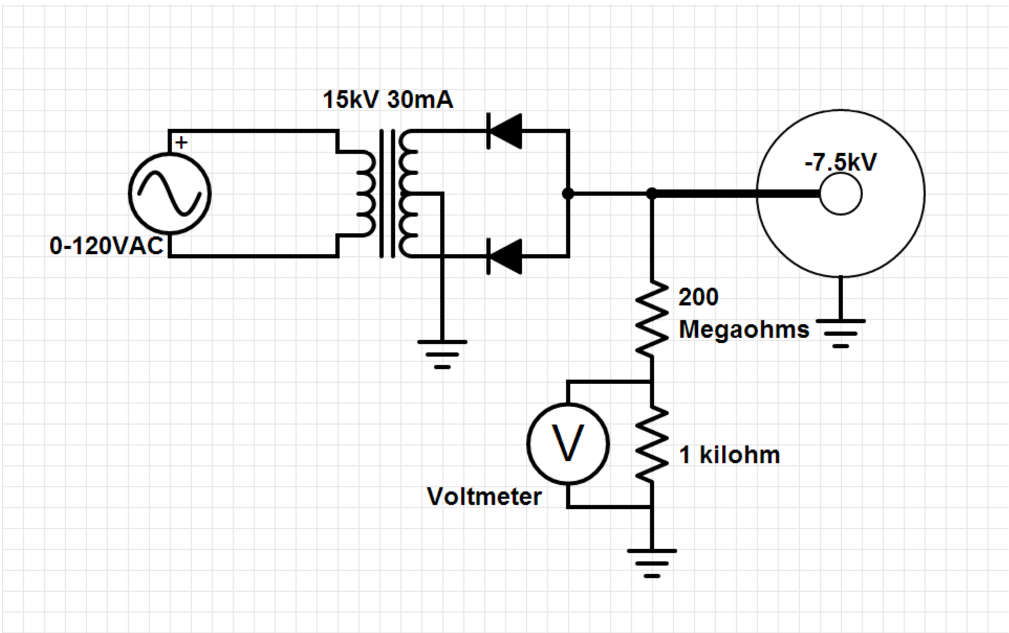
Materials and Methods

The device that was built was designed to take temperature data and therefore did not need to fuse deuterium to produce results that pertain to IEC fusion reactors. Essentially, I didn't need to build an actual fusor to conduct my research. Also, constructing a fusing fusor would limit my flexibility to test the grid shielding methods.

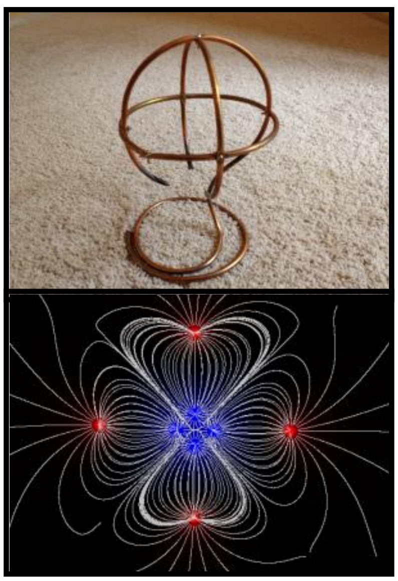
An inertial electrostatic confinement fusion reactor, or known as an IEC fusor, is a type of reactor that uses the electrostatic force to collide deuterium ions (LaPoint). The device I built, known as a demo fusor, uses atmosphere instead of deuterium and uses lower voltage. In order for the demo fusor to produce plasma, a vacuum chamber was needed (Hull). I used an 8.5in x 12in glass bell jar paired with a rubber gasket and vacuum grease to prevent leakage out the bottom of the bell jar. The gasket was put on an aluminum plate which was sealed using vacuum grease as well. This would prove to be airtight and capable of pulling down to high vacuum pressures. The Welch 1400 vacuum pump I purchased was cleaned with a flushing of vacuum oil and then refilled as required when buying a used pump. The Welch 1400 pump is standard for fusor projects and is a scientific grade vacuum pump (Hull). It was connected with plastic tubing and the threads were sealed with vacuum grease and Teflon tape. Along the tubing I installed a vacuum gauge which measured in inches of Hg. This was not particularly useful because it doesn't measure very accurately in high vacuum situations. The gauge I used was more of a reference to see if the vacuum pump was actually working or if there was a leak. The pump was fitted with a valve to release the air back into the bell jar when finished collecting data. I have included a picture below of the setup:

Setup

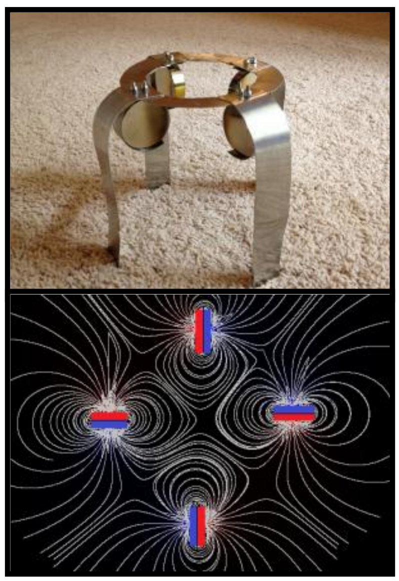
For the electrical component of the demo fusor, a neon sign transformer was used as the source of high voltage. Neon sign transformers are used to light up neon signs and are the standard when dealing with high voltage experiments (LaPointe). The one I purchased was rated at 15,000V 30mA but in reality it outputs half of the voltage out of one side of the transformer and half out the other. The transformer is powered by the outlet which is regulated by a 5 amp variable transformer that controls the voltage from the outlet. This was added so I could control the voltage being put into the demo fusor. The high voltage can't enter the demo fusor at 60Hz from the outlet because the inner grid needs to be at a constant negative voltage. To convert AC to DC, I needed a pair of high voltage diodes that would rectify the voltage. One diode was connected to each end of the transformer so that only negative voltage would pass through. With each end of the transformer connected to form one line of negative voltage, it could be connected to the inner grid through the aluminum plate, leading into the bell jar. A spark plug was used as the high voltage feedthrough to the stainless steel inner grid and was sealed with epoxy (fusor.net). This insulated the high voltage output from the grounded aluminum plate. A voltage meter was put in place to determine the voltage output of the transformer but it couldn't be measured directly because voltage meters don't reach into the thousand volt range. A way of measuring the voltage was found and implemented (Hull). A schematic of the demo fusor has been added below:



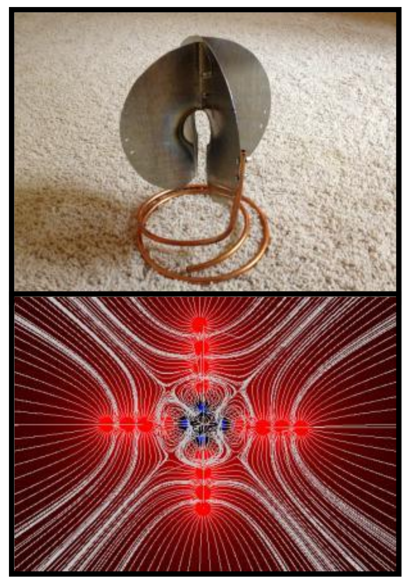
The independent variable in the experiment would be the different types of cathode shielding apparatuses. For the arrangement of the four neodymium magnets (1.25 Tesla in strength and very powerful), each one was assigned to each half loop of the grid. After determining experimentally that plasma focuses around the poles and not in between, I pointed the space in between the poles towards each loop. This, I thought, would create a zone of minimal plasma in the places where grid wires are present. I used parts of an iron plate to secure the magnets in place and cut out pieces from an aluminum sheet to screw them into place and to make legs. The method where I used the anode as a way to deflect ions traveling towards the cathode grid was constructed using the same type of aluminum sheets. They were set up parallel to the inner grid and directed outwards (Sesselmann). The space where the grid goes was cut out using sheers and the whole apparatus was put together with screws. It was kept in place and stood up by copper tubing. The control was a grid connected to ground as used in many demo fusors and was made out of copper tubing. There were three loops aligned on the x y and z axis. This was connected mechanically as using solder proved to be unsuccessful because it melted, causing the grid to fall apart. Pictures of each grid and their corresponding field lines are shown below (note that the four zones in the center where plasma is not present are clearly seen in the magnetic field lines picture):



Control



Magnetic Shielding



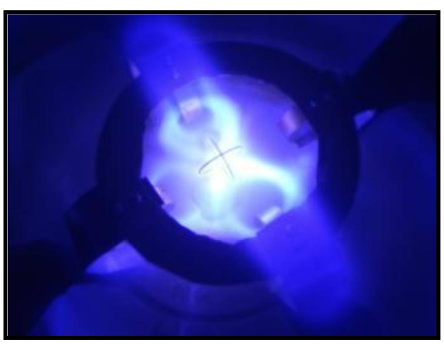
Electrostatic Shielding

To measure the temperature of the inner grid, I had to be creative. I had planned and tried using a thermocouple that would be in contact with the cathode grid to get temperature readings. An aluminum nitride chip was placed in between the thermocouple junction and the grid to prevent the high voltage from conducting to the junction. Since there was no way to make the thermocouple stay in contact with the chip, and because there wasn't an adhesive that could withstand temperatures that high, the thermocouple idea had to be abandoned. I thought about using a spectrometer to measure the wavelength of the photons being emitted by the grid and to convert those wavelengths into temperature data by Wien's law. I also had the idea of using an inferred temperature sensor to measure temperature directly and more easily, but both of these ideas cost upwards of a thousand dollars. I then invented my own way of measuring temperature, which was to take soldering wire, something that had an exact melting point, and attach it to the grid. I would put it on the bottom of the circular grid as to not interfere with how the grid operated. This would make it possible to record the amount of time for the grid to reach a certain temperature. The more heat being transferred to the grid, the faster the solder will melt. I used three different types of solder: silver bearing wire with a melting point of 221°C, aluminum and silicon brazing wire with a melting point of 577°C, and a 56% silver brazing alloy with a melting point of 652°C. The time it took for the wires to melt for each shielding method was recorded.

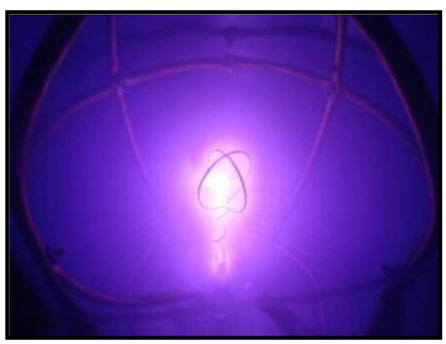
When recording the data, several variables needed to remain constant to receive consistent and valuable data. Since I did not have an accurate vacuum gauge, a way of consistently getting the same pressure was thought of. This was done by giving the pump a time of eleven minutes to pump the bell jar down to a low pressure, creating the same pressure in the bell jar each time. To keep the voltage the same for each trial, the variac was set to 110V, this made the voltage and current output of the transformer the same as well. Using the voltage meter, it was determined to be at 7,000 volts. Consistent voltage is crucial because as the voltage increases, the electron volts of plasma increase as well. Converting the electron volts into joules, the kinetic energy formula ($KE=1/2mv^2$) can be used to determine the particle's velocity. Increasing volts increases the velocity and therefore the temperature of the plasma rises too.

Results

Temperature data was recorded and visual observations were made to determine the effectiveness of the shielding methods. The plasma gives off a blue and purple glow due to photons being emitted when electrons recombine with the ions (Hull). This makes it easy to see where the plasma is and isn't. It was useful in the magnetic shielding experiment because a clear pattern was made by each magnet. Pictures were included to show the pattern of the magnetic fields and of the plasmas created in presence of the control and electrostatic shielding method:



Magnetic Fields

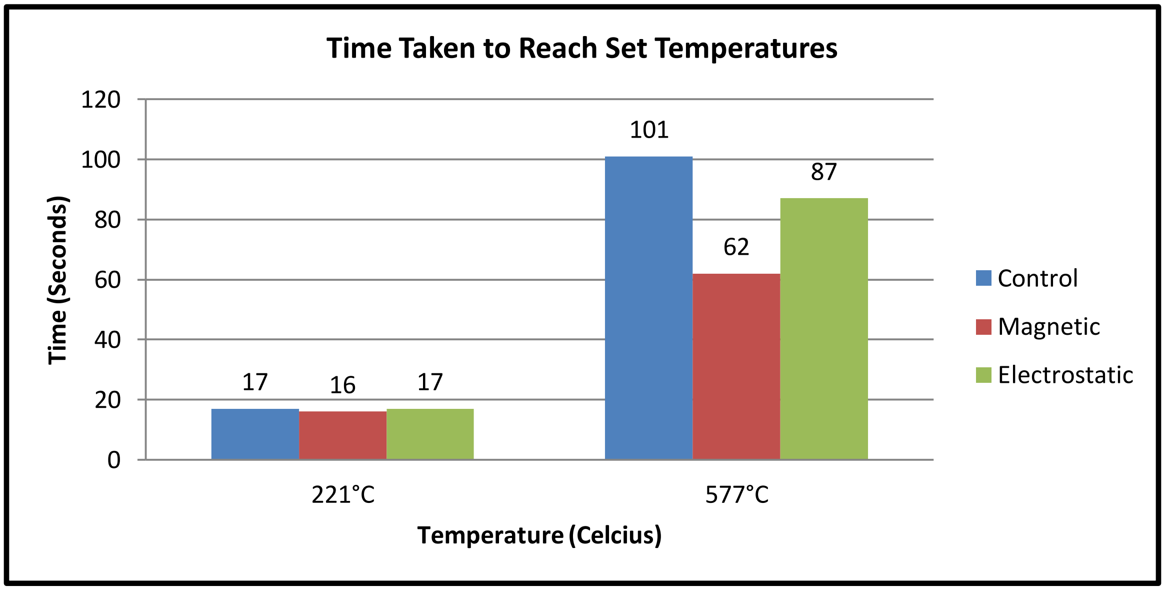


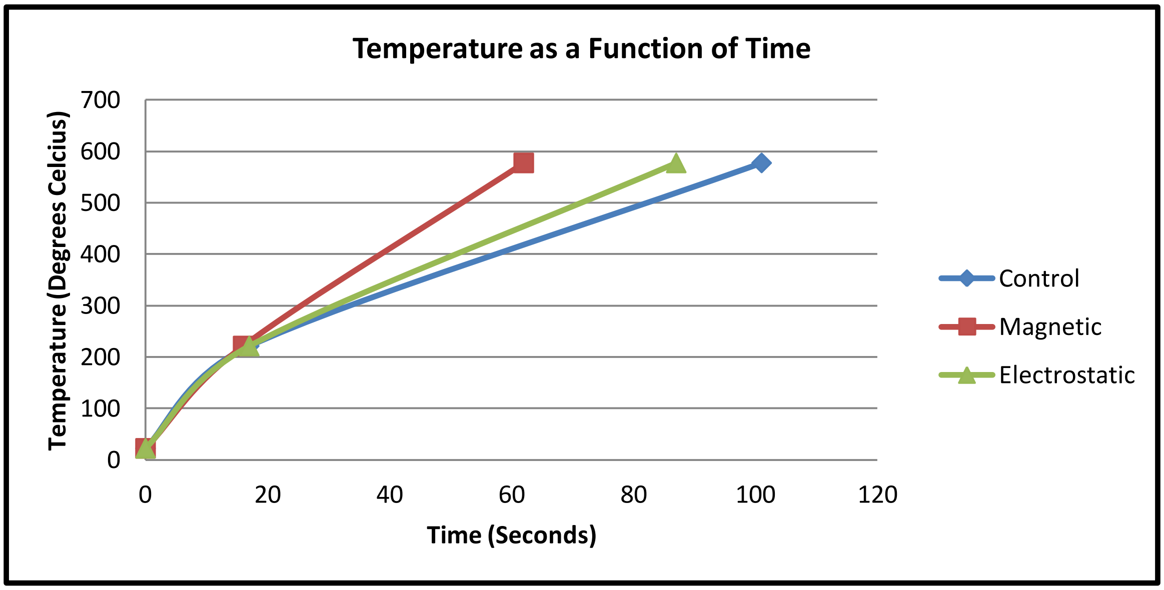
Control

Electrostatically Charged Plates

From the magnetic fields picture, the areas around the magnets are void of the glowing plasma. Those areas stop at the grid wires indicating that there are still ions impacting the grid. The spaces in between the grids have the most plasma present because it seems as if the magnetic fields are pushing the plasma away and in the process, creating a dense are of ions ready to accelerate in between the grid wires. Logically, the magnets need to be moved closer to the grid to envelope the wires in the void zone of plasma. After testing the magnets, they appeared discolored and so did the plates. This is an indication of heat being transferred to the shielding apparatuses. There is no visual difference between the control and the electrostatically charged plates as far as intensity or distortion of plasma.

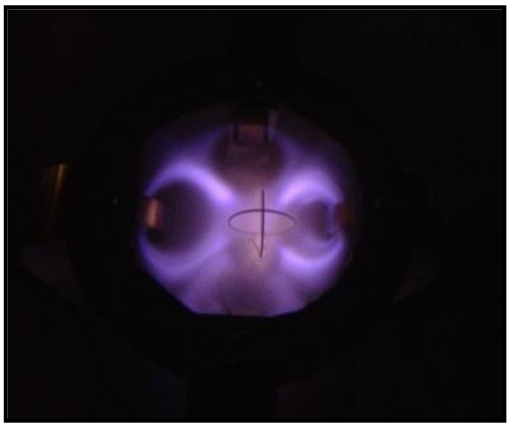
The time it took for the bottom of the circular grid loops to reach the temperature of the two types of wire for each method was recorded. The first bar graph shows the times that were recorded with the voltage at 7kV and with 11 minutes of vacuum pumping. The wire that melted at 652°C was not used as it was not as thick as the other wires and therefore melted faster. The second graph shows the temperature as a function of time as if the recording of temperature was taken throughout the trial.



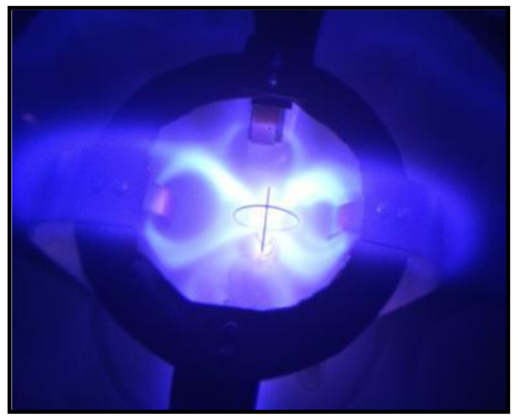


From the graphs it is apparent that the control has taken the longest to reach the set temperatures and the magnetic fields heated the grid the fastest. The variability of the data decreases as the temperature decreases because heat transfer is rapid in the beginning and that pattern shows itself well in the functions. If a prediction is made for higher temperatures, the variability will increase even more (physicsclassroom.com).

Since it is reasonable to assume that moving the magnets closer to the grid will decrease grid temperature, I have decided to test it. For this test, the wire that melts at 652°C was used and since it was thin, it wasn't wrapped around the bottom of the grid, but at the middle part. Data was recorded for the copper tubing control grid, the regular configuration of the magnets, and for one where one of the magnets was placed close to the grid. I have taken pictures of the pattern of plasma that took place when one of the magnets (the one on the right) was put close to the grid. The picture on the left shows the plasma at a lower voltage where the pattern is shown very neatly and the picture on the right shows it at a higher voltage.

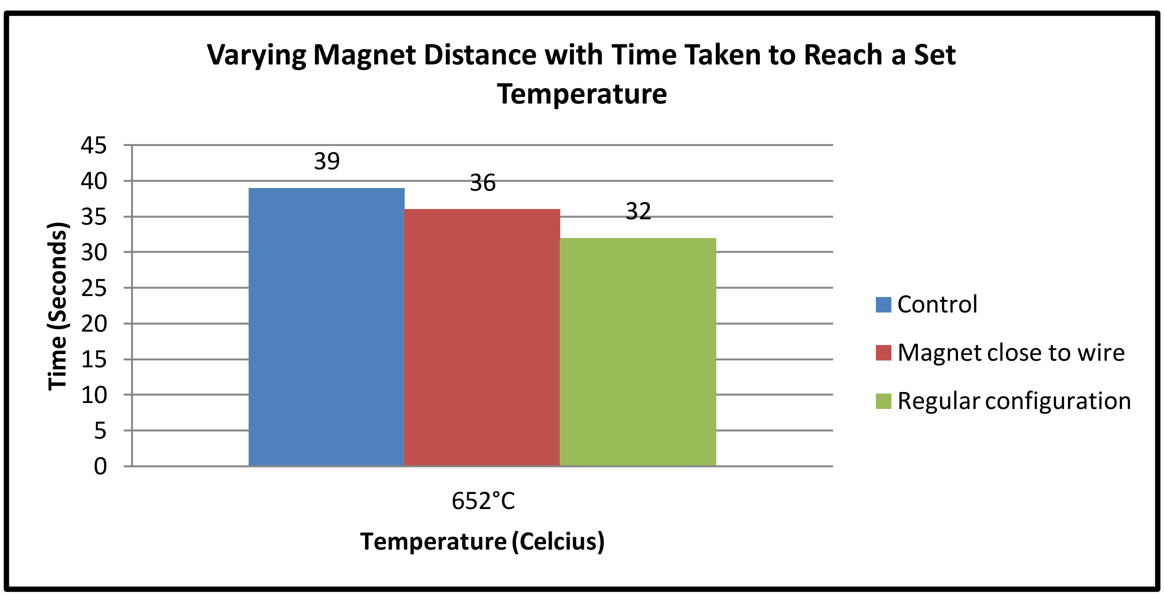


Lower Voltage



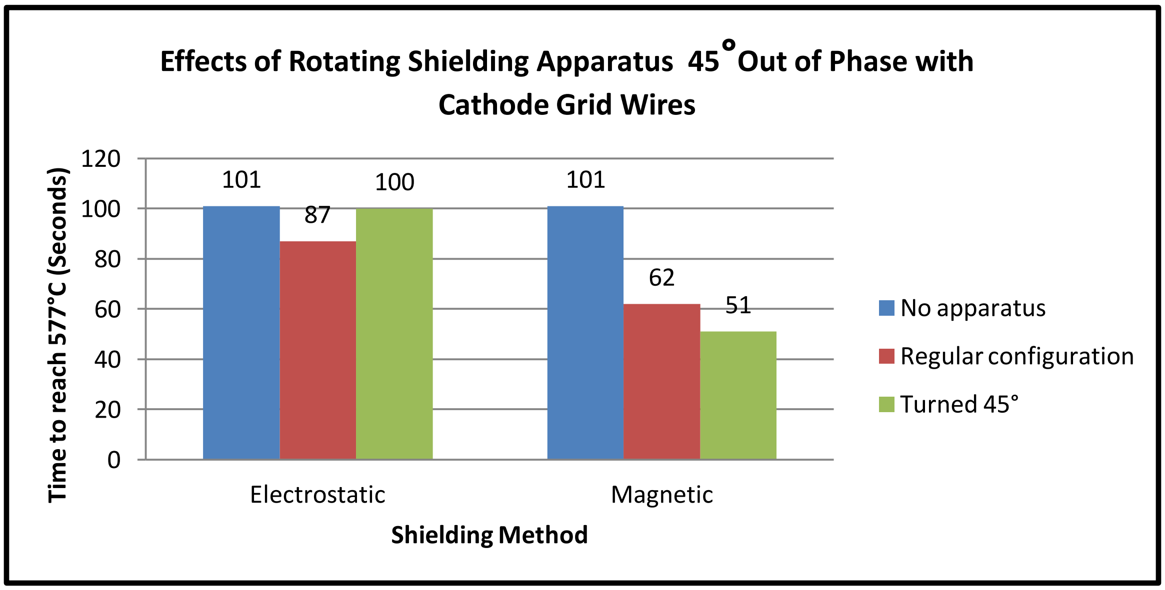
Higher Voltage

From the lower voltage picture, the grid loop on the right seems to be immersed in the zone where there appears to be no plasma. A second ring of plasma has formed inside of the other zone and from the higher voltage picture the gap in between them has closed. With higher voltage the ring shrinks down to a size small enough so that the zone of no plasma cannot reach it. The temperature data from this test is shown in a bar graph below:



The control test still shows less heat being lost but something interesting happens when the distances of the magnets are compared. The grid loop that was closer to the magnet rose in temperature at a slower rate than did the magnet that was farther away in the regular configuration. Combining this data with the visual observations I noted, the part of the grid loop that was close to the magnet did not turn red hot. The other grid loops were turning red which heated the brazing wire on the loop being measured. This matches with the data because the regular configuration loop that was being measured turned red at the time the brazing wire melted. All four magnets would have to be moved closer to confirm and implement this in a fusing fusion reactor.

A test was performed to determine if the arrangement of the shielding methods had anything to do with its success or failure. To do this, the apparatuses were turned 45° to misalign the grid wires with the shielding methods. A graph was made to show the results.



Surprisingly, when the electrostatically charged plates were turned so that they didn't line up with the wires, it performed almost the same as the copper tubing control grid. As for the magnetic shielding, the wires were put in direct path of the dense plasma, heating it faster than the regular configuration. Visually, the magnets that were rotated 45° turned the wire red hot and more so than any other configuration.

Discussion of Results

Because of the lack of a variety of data points, most of the graphs that were used were histograms. It worked well to convey the results and from the few data points, a line could be fit to it determine what the temperature would be in between the points through interpolation.

Since a few multiple trials were used because of the lengthy process of data collection, the results could be off. From the multiple trials that I did, I determined that they were sufficient to represent the actual temperature because of how close they were. The human element that was added to the data collecting process could skew the results one way or another. This is because the solder and brazing wire didn't have an exact time that they melted, which would through a time off a few seconds. The exception to this would be with the 652°C wire because at a certain temperature the plasma turned white almost instantly; marking the point where the time was taken. The time it took for one of the wires to melt depended on how thick it was and how much of it was touching the grid wires. The application of the wire was consistent but there was room for error. When determining the temperature for one side of the loop when the magnet was close, a source of error arose when the misaligned magnets started heating the other loops of the grid. This heat would interfere with the temperature of the loop being measured.

Despite the sources of error, the experiments are still precise, but not accurate. This is because it takes time for the heat of the grid to transfer to the solder and melt it. Because of this, the temperatures recorded lag behind the actual ones. The data is still valid however, because it is relative to the control and or the other methods.

Conclusion

When a configuration of magnets was placed inside the inertial electrostatic confinement demo fusor, it ultimately increased the rate of heating. I did, however, succeed in distorting the plasma by use of magnetic fields so that areas void of plasma existed near the grid wires, and so that the densest areas were focused towards the spaces between the inner grid wires. In the first trials, magnets were placed in a configuration too wide so that the grid wires weren't in the area that was void of plasma. Compared to the control rate of heating, the magnets increased it by 63%. When one of the magnets was moved closer to one of the grid loops, that loop performed better than the magnets that were in their normal configuration. In fact, the grid that was closer to the magnet heated 13% slower than the one that was farther away. By moving the magnet closer, the amount of watts lost to the grid was decreased. Since the other magnets were interfering with the wire that was close to the magnet, further testing must be done to prove if it is effective or not in decreasing ion collisions to the grid. When the magnets were rotated 45° so that the grid wires were receiving the bulk of the plasma, the grid temperature rose faster than the regular configuration. This, with the other experiments, proves that plasma densities are higher near the poles and lower in between the poles. The problem is getting the grid wire inside this area of lower plasma density. Looking at the visual evidence, moving the magnets closer or farther away increases or decreases the space of this lower density area so that it is just outside the grid wires. This makes it difficult to shield the grid using magnets. A possible reason for the area of lower density decreasing as it gets closer to the cathode grid is that it has to do with where the plasma is focused. The plasma is most dense and most energetic near the cathode grid (fusor.net). This means that if the magnet is put closer to the center, the plasma will gradually increase in density and speed, making it more difficult to contain. If this is correct, then an electromagnet stronger than 1.25 Teslas must be created in the same configuration to correct this problem. This method of cathode grid shielding shows potential, but a magnet configuration that is tighter must be made to determine if it is worth implementing in an IEC fusion reactor.

When the positively charged plates were introduced in the demo fusor, the rate of heat transfer to the cathode grid increased by 16% in comparison with the control. In the ideal situation, ions will be created somewhere along the positively charged plates, giving them a chance to be deflected while being accelerated by the cathode. But since plasma is created everywhere inside a fusor (fusor.net), a lot of ions are created near the cathode so that they don't have a chance to be deflected by the plates. Also, the stronger electric field due to the shortened distance between the cathode and the anode seemed to be the cause of the heating. This is because of field emission, which in this case is the emission of electrons from the cathode flowing to the anode, heating the grid. Overall, this method proves to be an ineffective way to decrease ion collisions and to lower the temperature of the cathode grid.

Future Work

In continuation of this research, it would be reasonable to part with the electrostatic shielding method and do more research with magnetic shielding. It is difficult to put the strong neodymium magnets in place so a stronger and possibly adjustable apparatus must be built in order to vary the distance incrementally and sturdily. My prediction is that if each magnet is moved closer to the grid, the amount of ion collisions to the grid will decrease. After determining if this is a useful method to shield the cathode grid, it should be implemented in an IEC fusion reactor to test if it affects neutron emission, a byproduct of fusion. To increase the accuracy of the temperature data, an infrared temperature sensor should be used. This would give real time data of the exact temperature of the grid. A source of higher voltage would be needed to test plasma at even higher temperatures and with that I would need a metal vacuum chamber. Since the cathode grid deteriorates with high temperature and therefore high voltage, the time for grid deterioration could be recorded to determine if the grid shielding method works (fusor.net). For coming up with new methods or for improving upon the magnetic shielding one, I would need a better knowledge of plasma physics among many other things.

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