We Have to Try

Mankind is facing a storm. From shrinking water, energy and resources - we have problems. Climate change does not help this. Neither does the population boom. To solve this, we must try some new ideas.

Fusion power would be a tool; like a hammer or a gun. Like them, this tool can have a big impact. Like them, it can be used to help or to hurt us. Our goal is to get this to mankind. But our other hope is that we use it wisely.

We need to try it. We need to act. The Polywell needs to be developed. Ultimately, it may not be the tool we seek. But, it will move us forward; beyond the unknowns. It may even usher us into a new age. The age of fusion.

Summary:

This post covers work from Convergent Scientific Incorporated. It has four parts: experimental work, modeling, talk highlights and a conclusion. Experiment details were imperfect. CSI trapped electrons for 20 seconds, using: model one. It is assume this is a wire shaped into a diamond - 14 cm a side with 1,500 amps and held at +500 volts. This was within a ~0.6 pascal vacuum with four emitters at each corner. Model one was cooled with a chilling system. The emitter voltage was varied from -500 to -9,500 volts and a probe measured the resulting trapping. Results were questioned because the emitters remained on the whole test. The magnetic and electric fields are mapped using single wire and point charge models. The [excel file] is open to the public. The forces are plotted along the face path of the diamond. The resulting motion is described. The effect of sliding or rotating the emitters is explored. Talk highlights are given. These include: the impact of pressurizing, moving, shaping and forming structure within the plasma. The relevant plasma instabilities are mentioned as well as a discussion of structure. Finally a call for experiments is made, with a list of good reference material.

"Innovation is what separates leaders from followers." – Steve Jobs

Part 1: Experimental Work:

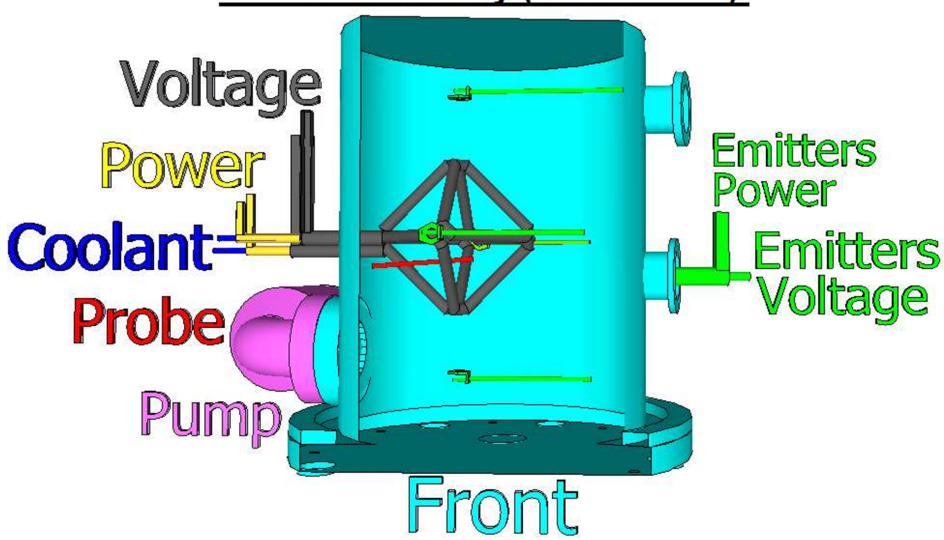
Overview:

Between October 22nd and December 17th CSI did a number of web talks. Discerning the real tests from the plans was hard. Moreover, CSI did not want to give the details outright. Specific dimensions were the hardest to get. Sizes were extracted from photos and emails. But, the same parameters likely changed between individual tests. Hence, this analysis is not going to be perfect. To circumvent this, ranges are often used. This research is still in the early phases. Early on, it is important to get something that ***works***. This allows you to troubleshoot everything else. The team has not done fusion. They have trapped electrons long-term inside model one. Long-term is subjective. The world record for a tokamak is six and a half minutes [6]. WB6 ran for less than a second [8]. Model one was a low power, low cost and simple device. Despite these limitations, it held in plasma for twenty seconds [1]. The run was limited by the cooling system. If the team had the cash, they could run much longer. Long term trapping is the direction to go in.

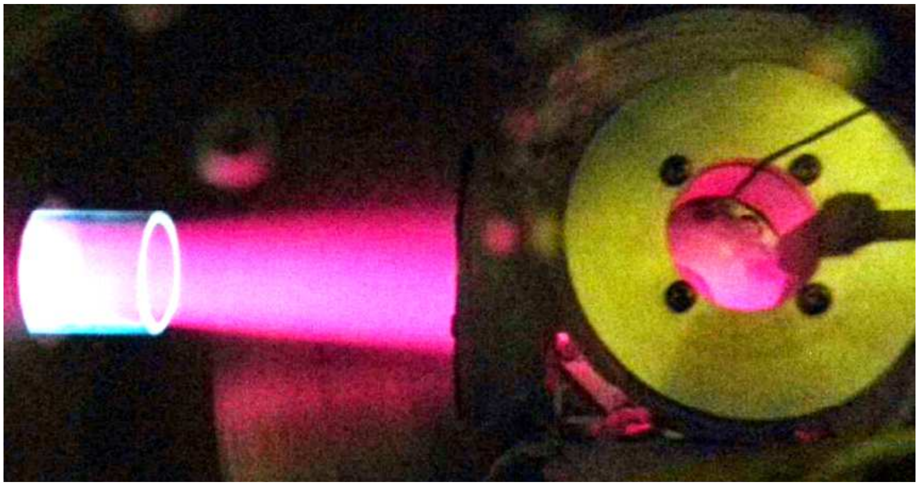
Experimental Setup:

The team is testing model 1. This is a single tungsten or rhodium wire bent into a diamond shape [10]. Attached to it, is a cooling system, power supply and voltage source. This is placed inside a cylindrical vacuum chamber, about the size of a trash bin [6]. Four electron emitters sit around model one [1]. They may align with the device's corners. There is also a Langmuir probe. The probe may be a simple wire, or a fancy tool with software. The probe is critical. It proves the concept. If everything works correctly, it should measure a negative voltage. The chamber is also connected to a pump and a gas supply. One possible chamber configuration is shown below.

Chamber Cutaway (Not to Scale):



We have seen this experiment before. The 2010 Khachan paper is very similar [9]. A picture of Khachans work is shown below [14]. You spray electrons from an emitter. They enter a device. You see if they can be trapped. The main difference is the trap: a diamond verse a ring structure. If CSI can detect trapping; then it validates Khachans published work.

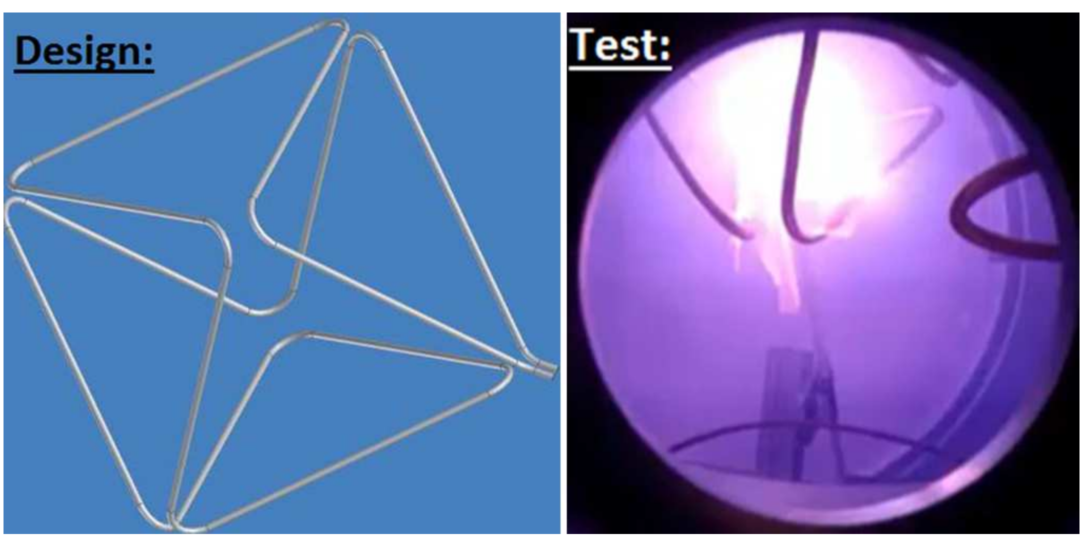


Vacuum Chamber:

The vacuum chamber is filled with nitrogen or helium gas [6, 22]. This is common in vacuums. Nitrogen blocks water vapor from entering the chamber [42]. Helium is used to check for leaks [42]. From here, they pump down the chamber. This is done using a turbomolecular pump [10]. It reaches pressures between 1.3 and 0.04 Pascals [22]. This is still thousands of times higher than the WB6 system [6]. There is still gas inside. This background gas, will impact performance. It can create fast moving neutral atoms. It can also be a source of unwanted of positive ions. Both can hurt performance.

Model one:

Inside the chamber is model one. It is the most unique device in the chamber. It is shaped like a diamond, shown below.



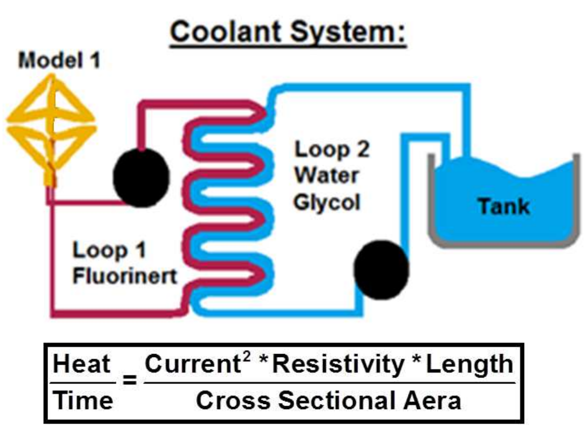
This is a single wire. With only one pass, a lot of current will be needed. At full power, 1,500 amps flow through this wire; creating a 1,000 gauss field at the corners [22]. This current, heats up the wire [7]. The team tried to re-snake this many times – but the heat still built up [1]. As you will see, heat is a common problem with model one. Hot wires create problems, like arching. Moreover, this problem grows as the device runs “long-term”. Tests could have been longer - if they could just keep the thing cold!

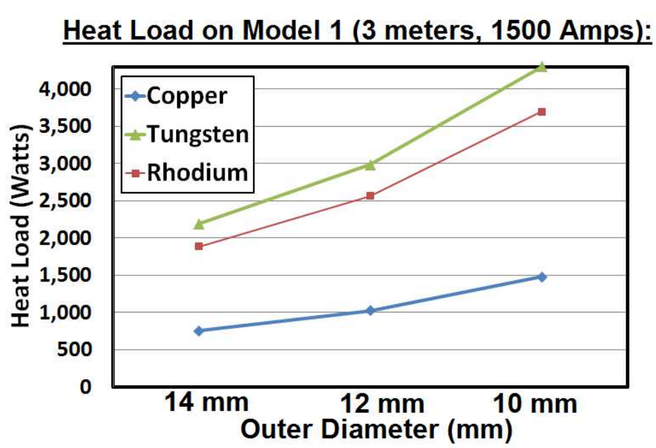
Cooling Issues:

The first version of model one was a bent copper pipe. Coolant moved inside the pipe, while, current moved in its walls. This failed. The copper overheated. It exploded. The team wants you to know: do not use melting copper. They switched to a tungsten or rhodium wire. Both are very hard materials, with high melting points [12, 13]. Tungsten will be used for modeling [10]. Unfortunately, a wire does not have a cavity for coolant. The team tried an outside ring of coolant - but this behaved poorly [1]. Finally, Model one was merely arranged to touch a chilling system [10]. Heat was conducted away. This is a mediocre solution. Better chillers would allow longer runs.

Chilling System:

The chilling system is rather elaborate. The first cooling loop uses a Fluorinert. This is a liquid, often used to cool electronics. The fluid does not conduct; lowering its negative impacts on electric conduction [1]. The fluid moves in a closed loop: from the pump, near the device, and into a heat exchanger. The exchanger moves heat into a second water and glycol loop. This flows into a giant open tank. A sketch and model of the cooling system is shown below [7]. This coolant system can pull about six kilowatts of heat from model one [5]. Estimates (using joule heating) show that this is probably more than they need.

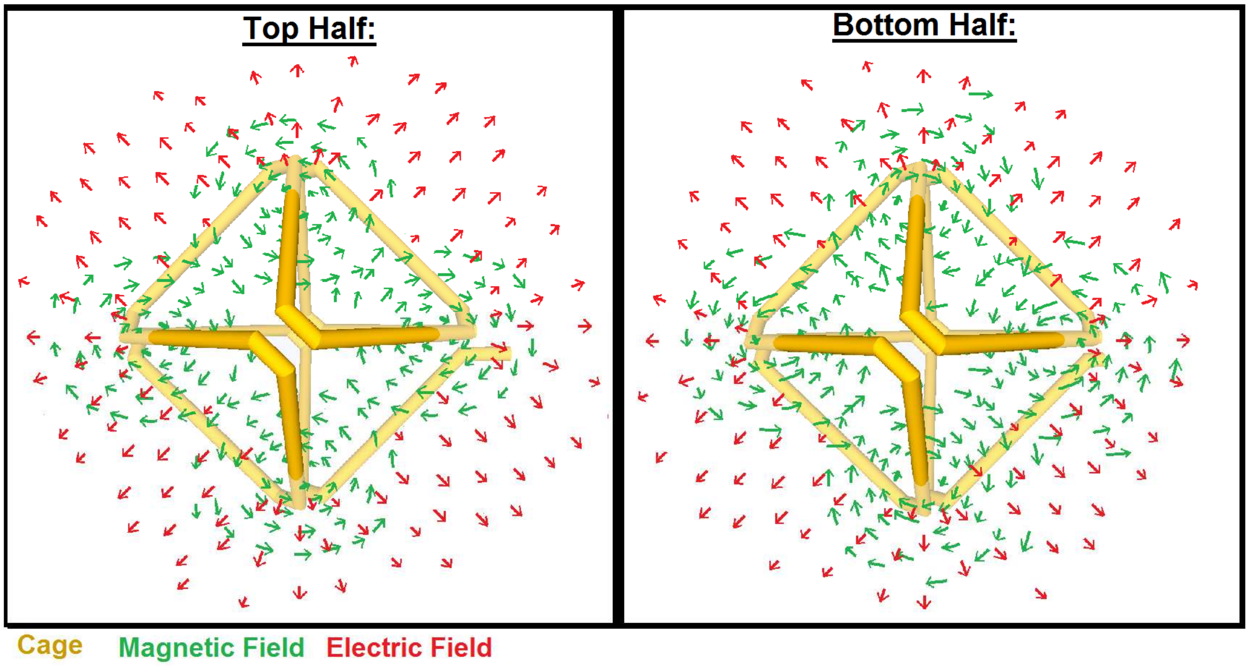




The Fields:

Model one is kept cold so that it can generate an electric and magnetic field. The device needs to attract, affect and trap electrons. Negative electrons are attracted to a positive object. Model one must be biased positive. The team used a transformer to put it at a positive 500 volts [1]. When everything is turned on, model one makes a web of electric and magnetic fields. These are shown below.

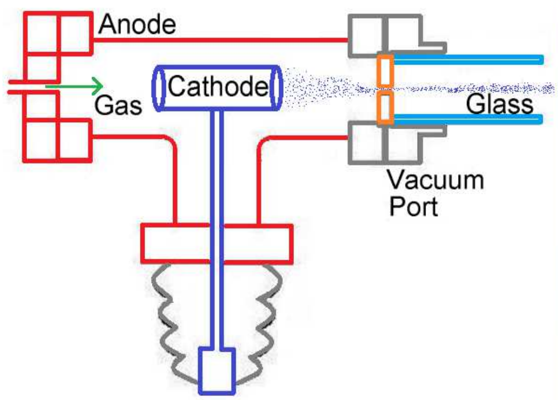
The Fields of Model One:



Electron Emitters:

CSI examined three ways to make electrons [1]. The first is field emission. Electrons can spontaneously leave metals in a vacuum. This can happen at room temperature and may have happen inside CSI's chamber [2]. However this can easily avoided by engineering. The effect amplifies as the temperature rises. This is known thermionic emission. If you heat the wire, more electrons will leave. CSI purposely used four heated nichrome wires to do this. Nichrome is a common emitter [3]. In addition, these wires can be part of a proper electron gun. This was CSI third method [1]. The company altered an e-gun design from the Sydney team [10]. A schematic and picture of their electron gun is shown below [14].

Sydney Electron Gun:



CSI's design may have been as simple as: a heated wire next to a positive disc, with a hole in it. The disc focuses the electrons in a beam [4]. All the tests used at least four emitters [1]. They had a voltage placed on them. Using a transformer and a Labview program, the team could vary the emitters up to a negative 9,500 volts [23]. The combined positive model one and negative emitters - made a hill for the electrons to roll down. They fell into model one. Their flow was constant; emitters ran throughout the runs [5].

Operating Procedure:

CSI ran experiments from January to late summer 2012 [5]. Many tests were done. These included: several geometries, various emitters and even a fusor/polywell hybrid. Tests meant several steps. First, the vacuum chamber was prepared. The chamber was filled with helium, to check for leaks. Once sealed, nitrogen was pumped in. Next, they pumped down the chamber. It reached pressures between 1.3 and 0.04 Pascals [22]. The next step is turning on the coolant system. This makes the chamber, low pressure and cool. Next, the voltages are applied. From here the test can start. The device and emitters are turned on. Runs typically lasted for 35 seconds [1]. CSI states that for 20 of those seconds, it measured a steady, constant voltage drop.

Experimental Results:

The company ran three tests. But, CSI would not give the results for the 1,500 volt test. In each test, the drive voltage was changed. This is the drop between the emitters and device. The device was always at a positive 500 volts; but the four emitters were set at lower voltages. Each time, the probe measured a negative voltage in the center. This meant that electrons were present. Gausses' law gives a rough estimate of how many electrons (multiply by 5.5E7).

Experimental Results: Emitter to Device:	Probe Measured:	Electrons Caught:
1,000 volts	- 600 volts	3.3E+10
10,000 volts	- 900 volts	5.0E+10

These results prompt some questions. First, why were the emitters left on throughout the test? How does the company know it measured trapping – and not electrons merely streaming past? There are many good practices that need to be followed here, such as control tests and checking equipment. We must assume that CSI abided by these rules. Despite these flaws, one must respect the amount of work it took to get these numbers.

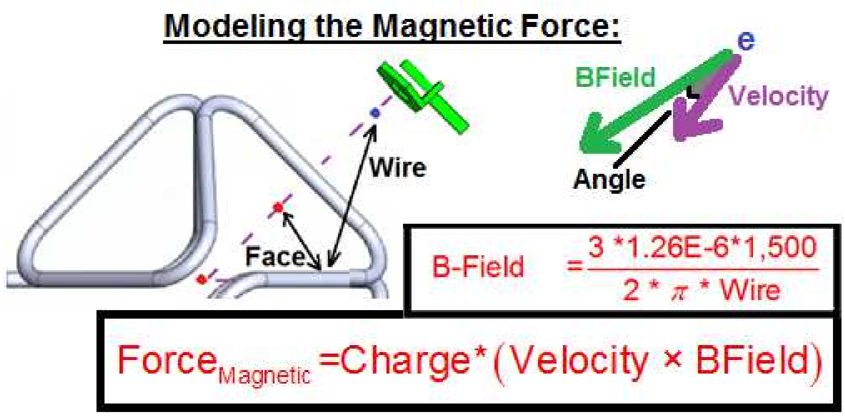
Part 2: Modeling

Device Geometry:

The magnetic and electric fields need to be modeled. They create a Lorentz force which guides the electrons in. CSI gives some of specifications of model one. It lists the plasma volume as 1.4E-3 cubic meters [5]. If this is the total volume, than model one is fourteen centimeters per side. We take the current to be 1,500 amps with a 1,000 gauss field at the corners. The electrons modelled as flying into the face of the diamond. The emitters are 30 centimeters from device center. This is the geometry to simulate.

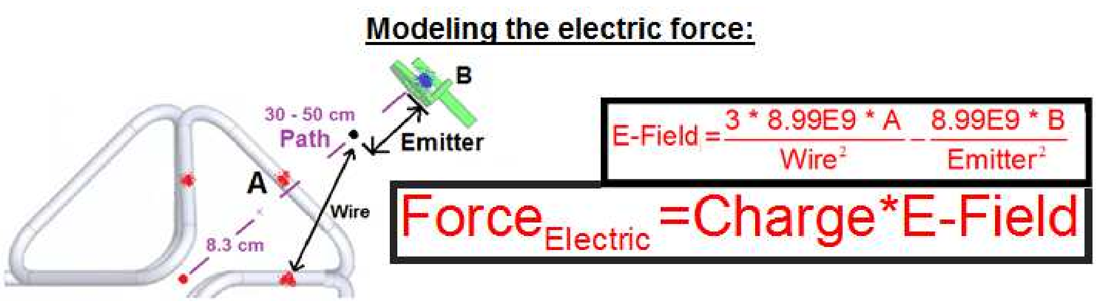
Simple Models:

The best kind of models, are always the simplest. The fields can be estimated using material from high school physics. For instance, the magnetic field made by a straight wire - can be used to map out the B-field [15]. The device is twelve straight wires in a diamond. This was used in a previous post to look at how the magnetic fields change with geometry [11]. That analysis yielded three rules. First, as the diamond gets bigger, its' field strength drops exponentially. Second, the field rises linearly with higher current. Finally, the highest fields were at the device corners. This model is shown below. The key length to find is the distance to the wire, as the electrons fly in. The magnetic force is a cross product between the velocity and the magnetic vector. This creates problems. The magnetic force is very sensitive to the angle between the vectors. The force can vary as much as ten thousand fold! For this work, an angle of less than 3 degrees is assumed.



Electric Field:

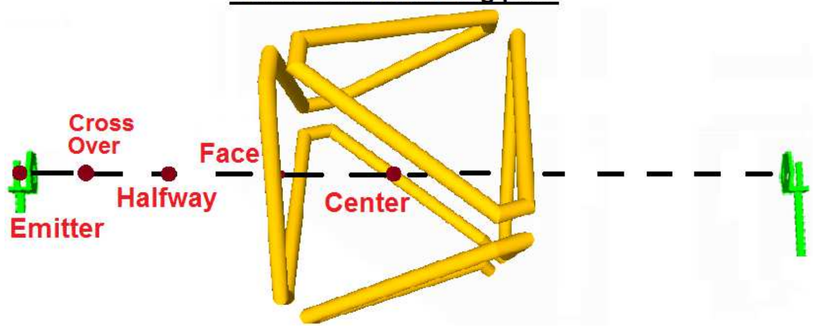
The electron starts at the emitter. This emitter is biased as negative 500 volts [10]. The electron is repelled from this; and moves towards the positive device. We do not know how far away the emitter was placed – so a range was picked. This was 30 to 50 centimeters; center to center. The electric field was modeled using simple point charges [16]. The three wires were represented by three points. These are like piles of positive charge. The emitter became a heap of negative charge, at one point. This is shown below. A key parameter was finding the amounts of charge at each point. To do this, it was assumed that halfway between the wires and emitter – there was no electric field. This provided a nice check. From here, it was easy to find the amount of charge.



Electron Worldview:

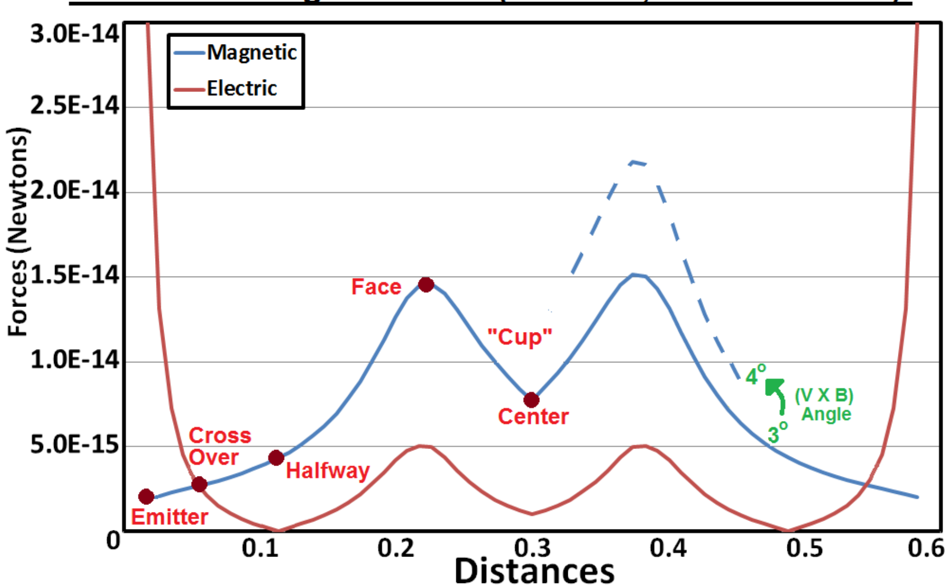
These models were put into excel. The sheet can be downloaded here. The velocity is modelled using newtons' equations of motion. There are several points of interest along this path.

Points of interest along path:



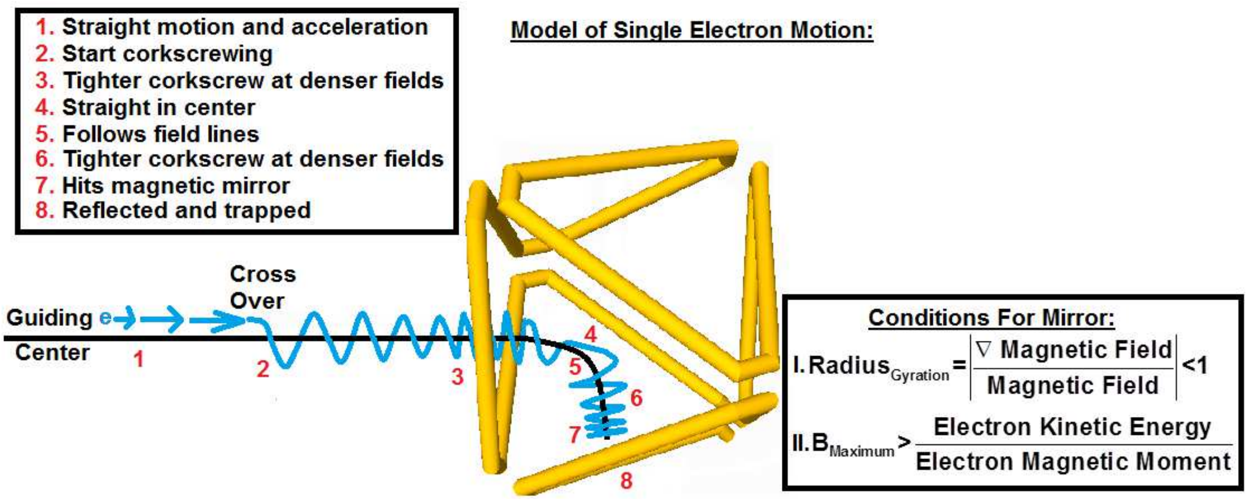
The first is next to the emitter. The electron starts here with no velocity. But immediately, it feels a strong repelling force. This is because it is next to a large negative charge. It speeds away, building up velocity. Very soon, the magnetic force overtakes the electric force. When this happens, the electron starts to corkscrew. It spirals along the magnetic field line [17]. It reaches a halfway point between the device and emitters. Here, the electric field is zero: the device and emitter fields cancel out. The electron is now being tugged towards the positive device. Despite this, the magnetic force still dominates the electric. It peaks as the electron pass through the face of the diamond. The electrons enter a magnetic "cup". Ideally, they oscillate around inside this field. These forces are plotted below. To truly measure trapping – the probe must detect them after the emitters are off. This raises questions about the CSI test. The four emitters were on the whole time. Did the probe merely see electrons as they streamed past - or did it see trapped electrons?

Electric vrs magnetic force (absolute, 30 cm emitters):



Electron Motion:

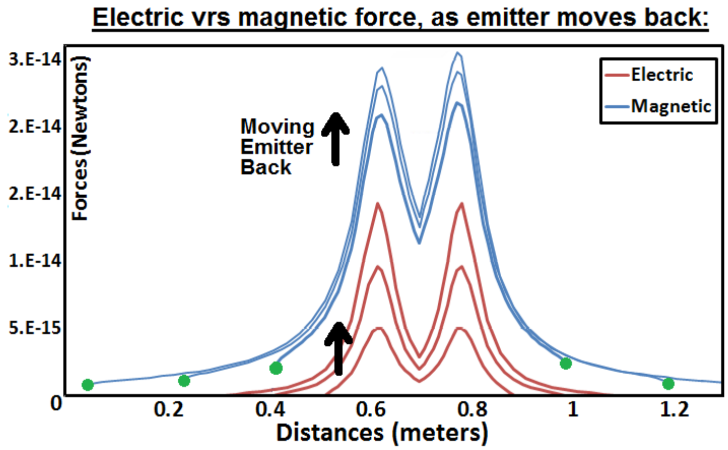
We know how electrons move under such forces [17]. When the electric force dominates; particles move in a straight line. When the magnetic force dominates; the electrons spiral. As the magnetic field rises, electrons spin in a tighter corkscrew. The stronger force should prevail. This is critical inside model one. The negative electron is surrounded by positive wires. The magnetic must overpower the electric field; otherwise the electron would hit the wires. This would drive up conduction losses. It would kill trapping. Hence, the particles should follow the B-fields inside model one. An example of what this motion might look like is shown below.

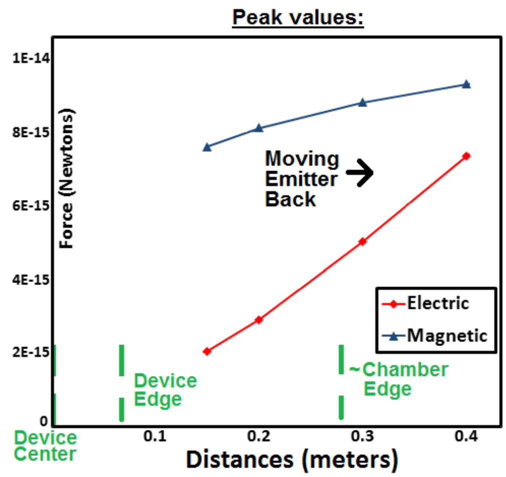


The motion of a beam is wildly different than one electron. Electrons in a beam interact. They ricochet off one another, vary the surround fields and shift the forces. Hence, beams are modeled differently than one electron [19, 20, 21]. Also, the fields change once electrons fill the device center.

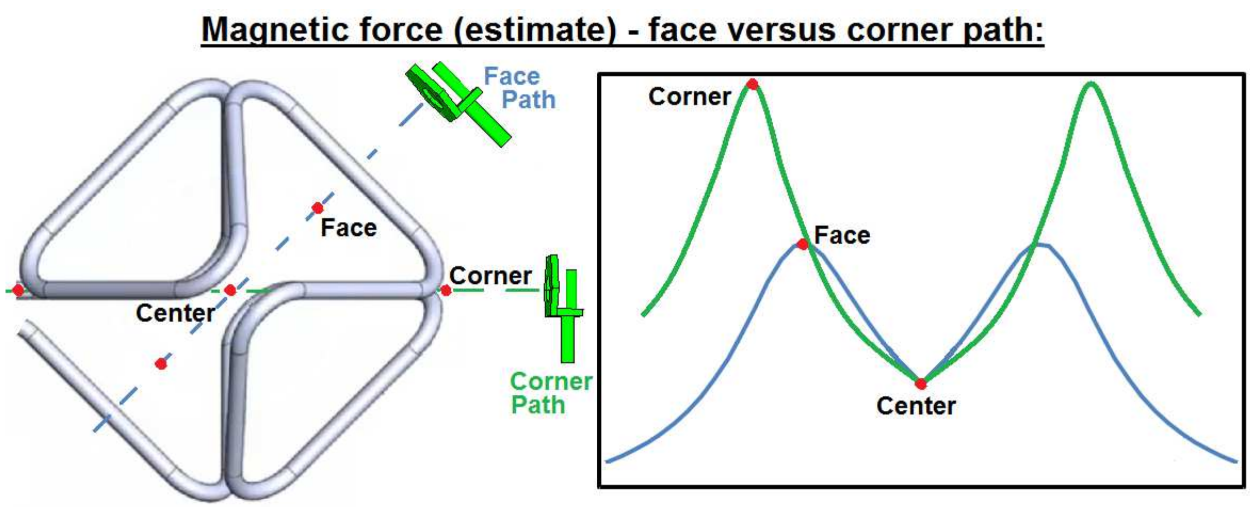
Changing The Geometry:

Excel shows what happens as the geometry changes. For instance, what happens when the emitters are moved backwards? If the electron has farther to travel, it has more time to accelerate. This raises its velocity. That creates a stronger magnetic force. Previous posts have shown the same idea [18]. The electric force also rises, but for different reasons. We assume that there is a zero voltage - halfway between the emitter and device. This underpins the model. If the two are farther apart, it takes more charge to get zero. Excel creates stronger point charges, as the emitter moves away. This creates stronger electric forces. This is shown below.





There was no time to look at the other path into model one. Here, the particles enter through the corners of the diamond. They reach the device sooner, and pass through the biggest magnetic field possible. This occurs at the tiny gap between the two wires. After this, they see a very sharp decline in the field. The sharper field should improve containment [5]. Based on this knowledge, a rough sketch of the force plots is shown below. Between these two paths, there is a sense of the fields inside model one.



Part 3: Talk Highlights

October Talk:

The company's first talk: [physics of IEC devices] will not clarify their experiments, like this post. The details listed above were from emails with CSI. The talks cover the issues they have found, after doing the tests. Lets' assume the tests worked - and CSI can trap electrons. The next question is how to confine them. Here, the tokamak world can help. Plasma has been confined magnetically for many decades. There is plenty of literature that CSI can use.

Talk Highlights:

The rule for magnetic confinement is this: as the machine gets bigger, the confinement gets worse. Nobody understands why this is (in all cases) [5]. But, we have some tips to avoid problems. Devlin mentions four:

1. **Pressurize It.** The plasma is held in by a magnetic field. The higher the field, the better the hold. This is the approach Lockheed martin is taking [41].

2. **Keep It Moving.** It helps to keep plasma moving. Especially on the outside edge. The easiest way to do this is to spin it. You can do this by applying a revolving current. Once, a team stabilized a tiny amount of plasma for weeks this way [24]. Both tokamaks and stellarators spin material for stability [38]. People have also tried collapsing or converging it [40]. You can also oscillate it in a wave, as LANL tried a few years ago [39].

3. **Make Structure.** Riders argues that if you merely had a hot blob of plasma (unstructured, thermalized, isentropic, uniform) that you cannot expect net power [29, 30, 31]. Hence, anything you do to move plasma away from a blob - helps. This means forcing any structure, through steep fields or steep density changes inside the cloud [5]. It also means using clouds which are mainly positive or negative.

4. **Shape it.** We like big plasma volumes - with small skin areas [5]. The best example is the sun. It is a big sphere. It has a tiny surface-area to volume ratio. Hence, the polywell improves as it gets bigger. It also improves if the cusps are pinched off; and the plasma balloons into a sphere [8].

A key question is: which of these effects trumps the others? Does having a high beta number trump a high velocity? If an expert wants to weigh in here, we would appreciate it.

Structure verses Instabilities:

There are two trends working within plasma: structure and instability. For every structure, there is normally instability there to wreck it. The growth or suppression of these is well understood. Marshall Rosenbluth was the instability king [22]. He sorted out many of the instabilities known today. CSI mentions two:

1. **Weibel instability.** When a beam enters plasma, there is a chance that it can break up into filaments [49]. This is the due to the fields that it generates during its motion. This has been studied extensively.

2. **Diocotron instability.** When two sheets of plasma move past one another, eddies form. This represents an energy loss mechanism.

CSI also hints at a structure within the cloud. Specifically: an edge and a core region. This is a bit controversial. Critics would argue the cloud lacks that level of detail. Supporters have opposed this. Now, we have some data. Khachans' 2013 paper measured electron densities inside the cloud [48]. The results hint at different density in center verses the edge. CSI want these densities to be vastly different, but, so far they have only found a 5 or 10 times difference [5].

Part 4: Conclusion

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." - Richard Feynman

Modeling is for wimps:

No model is a substitute for data. This could be an excel worksheet, a matlab program or a vast FORTRAN code. This became clear - in 2012 - when NIF failed to get ignition. Vast teams of experts used models to predict success. Their models were flawed. For example, excel shows that CSI has met a condition for the mirror. Does this mean the device traps? Hell no. Only data can prove trapping. The model only helps you get a sense of the physics.

Theory is also for wimps:

Also, theory is no substitute for data. When it comes to theory; one must admit human frailty. The body of physics literature is vast and constantly growing. No one can stay abreast of all of it. There is theory work arguing against the polywell [29, 30, 31, 32]. There are also papers arguing for it [8, 34, 35]. However, none of that matters if the data turns up something unexpected. That said; here are some sources which have been helpful. Feel free to comment below. For magnetic mirrors, there are several. Richard Post developed the mechanics of magnetic mirrors in the sixties [26]. Francis Chen and Richard Fitzpatrick have good notes on its' effect on bulk plasmas [27, 45]. Also, Peter Catto did nice work on reflections for any ratio [28]. These mirrors have holes in them (cusps). Thomas Dolan wrote a great review of confinement in cusp geometries [36] and Harold Grad modeled the behavior of the particles that dwell inside them [42, 43, 44]. Lyman Spitzer's book gives the rate equations for different plasma effects [37] (this text underpins Riders work). Also, Tim Thorson wrote the best explanation of fusors I have ever read [33]. Finally, William Barr was the guy nearest to direct conversion [46, 47, 25]. Each represents a part of this great scientific conversation. Our hope is, the debate continues. Our hope is, this leads to changing the world.

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