The Physical Basis For The Polywell

"We're borrowing money from China to buy oil from the Persian Gulf to burn it in ways that destroy the planet. Every part of that sentence has to change." – Al Gore.

"Don't accept doctrine. Which is someone else's thinking on a problem." – Steve Jobs

We've got a problem. We are going to run out of oil. We are going overheat this planet. We are in deep trouble and we know it. Many people are just trying to have fun before the clock runs out. They have given up trying to fix this. We have tried so many outside solutions and they have failed, so why keep trying? In todays' world money speaks the loudest and the longest, and thus far, the money has been in burning carbon to heat the planet. Not anymore. Not if the polywell works. We are talking about an invention that can run every oil, coal and gas company out of business. This machine can sell energy at a fraction of gas prices. It can produce more energy, in more places than any other invention in the history of the world. Whomever can build the first working Polywell reactor will be the most respected, wealthiest and most powerful organization on the planet, period.

Will it be America, will it be China, or Iran? Will it be a startup, a university or a military organization? Whomever gets there first will benefit from a giant windfall. A polywell company will create tens thousands of new jobs in an entirely new industry. The nation that pulls this off first will be the dominate nation for the foreseeable future. This machine is screaming at the world to be researched. Mankind needs to wake up and realize that so many of the paradigms the world has operated under are meaningless if this machine works. There should be a no-holds-barred, all out scramble to get there first.

The Polywell community is growing. Over the past year, the traffic on this site has steadily increased. With so much new interest, there is pressure is on this community to better explain this machine. To better communicate the arguments for and against it. The learning curve is steep. The basic conception - of a point charge accelerating ions to a speed where they can fuse – can be hard enough to understand. At the beginning, it can take several months to comprehend this. After that, you start learning the basic physics. Envisioning an ion, an electron and a field has to become natural. Manipulating them and predicting their behavior has to become old hat. From this comes a grasp of the counter argument. Mainly that X-rays may bleed away all the reactor energy and the plasma may be an unstructured mess. Finally, you start to see how many unknowns, yet-to-be-researched topics and questions still remain.

For new people, this learning curve is not helped by jargon, conflicting descriptions, inaccurate information and competing arguments. You are excited about the promise this machine, but trying to understand what is going on is daunting. You also have the sneaking suspicion this is too good to be true. This is hard to predict. There are theoretical arguments against, but there is a serious lack of experimental evidence. This may be a great idea, a failure or some third grey option. But check yourself - nobody can yet say with absolute certainty that this idea will fail. This post is an attempt to explain how this machine works, in clear basic language. There may be some mistakes or places where more clarity is needed. The physical mechanism will likely continue to evolve as more information is uncovered. However, this is a historic tipping point. Whenever the mechanism behind a new idea can finally be fully explained – interest and research will follow.

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"I never invest in things I cannot understand." – Warren Buffet

Executive Summary:

This work explains much of the underlining physics of the Polywell reactor idea, in conversational language. The work is based off Dr. Bussards' last machine, built in the fall of 2005. The important machine components are discussed first: the cage, electron emitters, gas puffers and the rings. A model of $1/8^{th}$ the rings is posited, with the joint, center, axis and corners listed as locations of interest. The rings are placed, such that, the joint and axis magnetic fields equal each other. The orientation of the ring current, magnetic and electric fields are then described; for this work all the north poles face inward. Next, the steps to turn on the machine are discussed – as adapted from Bussards description [8]. The device is turned on in five steps: by evacuating the chamber, turning on the cage voltage, turning on the electromagnetic rings, emitting electrons and finally puffing in deuterium gas. The physics of ionizing the gas are laid out next, followed by the equilibrating of electron temperature to ~2,500 eV [8].

From this description of the machine, the work then shifts to simple models for the plasma and fields inside the reactor. A possible physical mechanism for the electron cloud going diamagnetic and increasing containment inside the rings is briefly mentioned. The number of electrons is then approximated. The electric potential for the electron is then estimated, across the middle of the device. This is based one of five different electron cloud shapes in the middle: an infinitesimally small point, a small sphere, a large sphere, a 14 point star and a diamagnetic cloud. Next the magnetic field is modeled at the four points of interest: the center, joint, axis and corner. This model is used to predict the magnetic field strength as the rings are moved outward. Specifically, the magnetic field, energy density and electron potential energy are all estimated. Unfortunately, the small magnetic moment of the electron means the magnetic field has a diminished role in its potential energy. Lastly, three other issues are also briefly examined. The first is the possibility of reaching the critical electron density to reduce x-ray losses; this is regarded as unlikely. The second problem addressed is sparking inside the device; which was listed as occurring in Bussards' work [8]. The last issue explores the theoretical upper bounds of how many x-rays could be reflected.

Several issues remain to be addressed. These include how to reduce or reflect x-ray losses, which much of the counter argument has centered on [17, 26, 31, 33]. A solution to this problem would revolutionize the outlook for this reactor. Additionally, the process for "filling up" the device center with electrons has not been addressed, for lack of time. The electric potential is modeled after the device has been filled with electrons - and by this stage the model predicts electron injection will be a problem. Other topics not addressed were: the relevant plasma instabilities to avoid, the possibility of magnetic reconnection and its effect on the magnetic mirror ratio and an estimate of the electron gyroradius. Feedback is appreciated.

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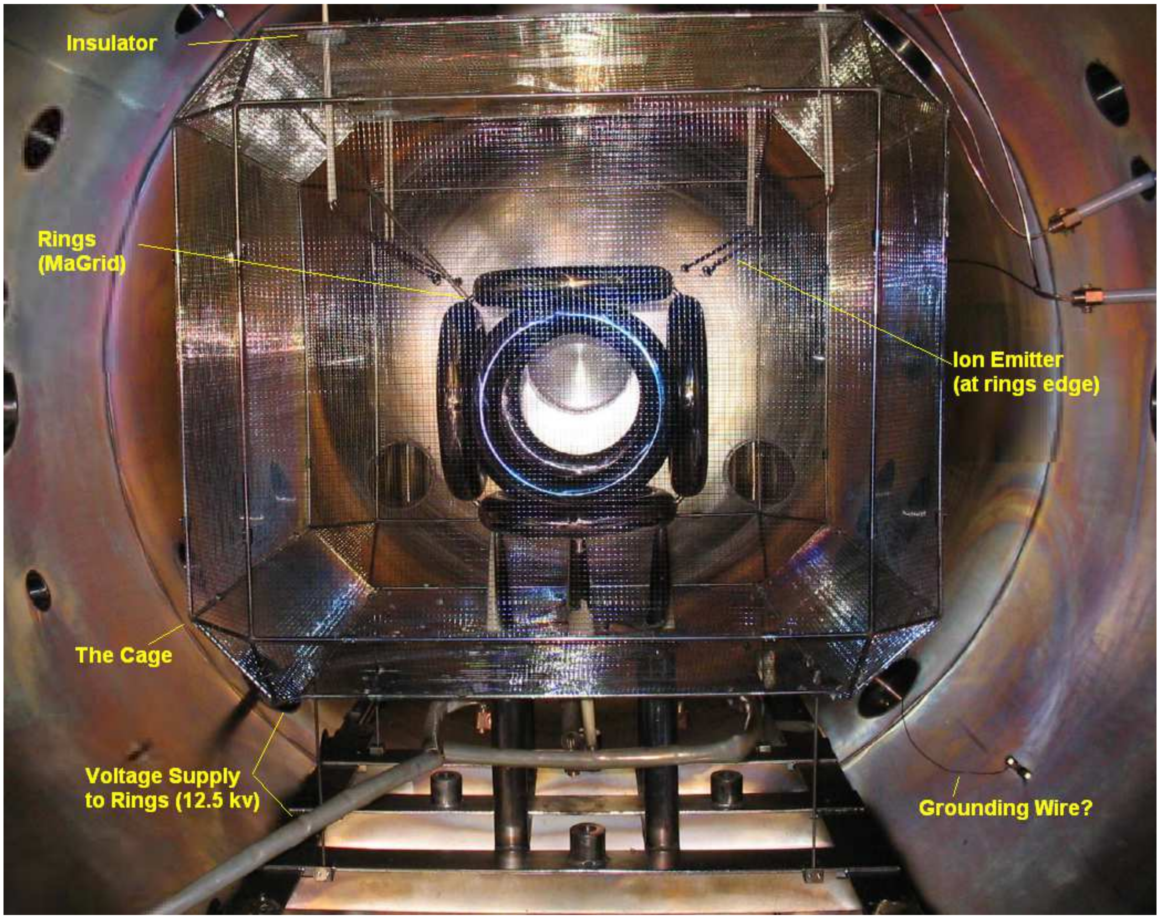
"If the solution is not beautiful, I know it is wrong." - R. Buckminster Fuller

1. WB-6 Geometry

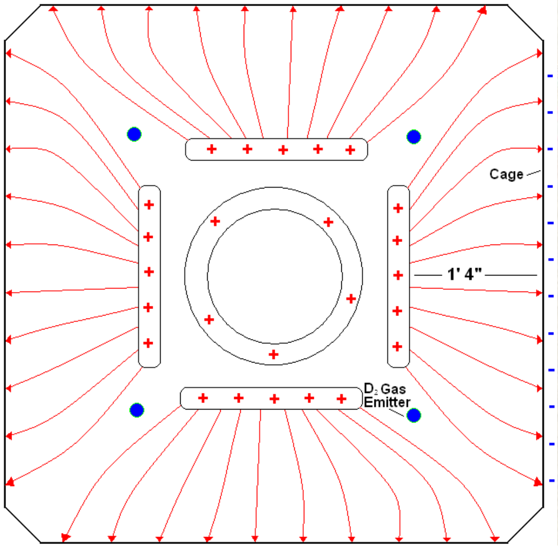
Form follows function. To start understanding WB-6 we need a keen understanding of its' geometry. The geometry described in here is based off of photos of the machine. The best photo we could find was from Bussards' 2006 paper [8].

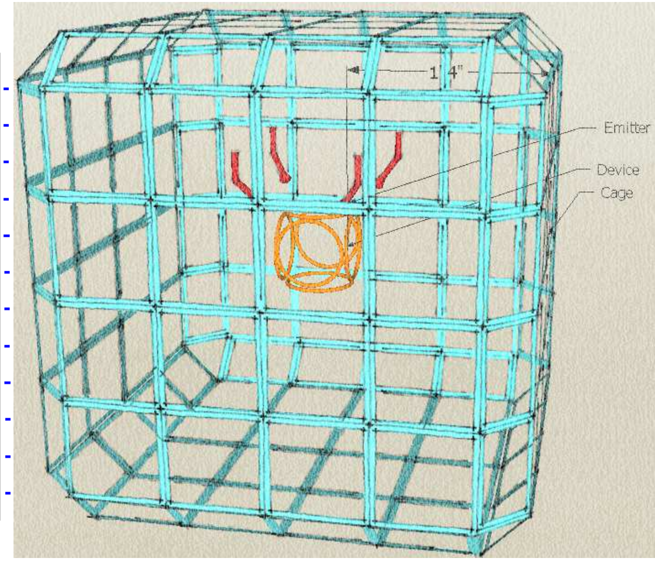


This photograph was taken sometime in the Fall of 2005. It is WB-6, ready for testing. This was Bussards last machine. There are six rings, each a foot to a side, loaded into a wire cage. That structure is inside a tube shaped vaccume chamber. Wires, both insulated and not insulated feed electricity into the device. Deterium gas lines which lie just outside the rings, feed gas into the center for fusing. Emitters are located inside the cage and they supply electrons to the device. Let us dig in; understanding this geometry is the first step in understanding how this machine works.

<u>The Cage:</u>

This cage is often referred to as the “walls” of the device. A good estimate is that it is 3’ 8” to a side. The purpose of the cage is to hold in electrons which get outside the rings. This is done with a voltage drop. The drop spans from the rings to the cage wall. The drop is like a “hill” outside the rings. Any electron will see this hill and reverse its' direction, heading back towards the rings. This helps contain electrons in the center. The voltage drop for WB6 was 12.5 kilovolts. A model for this setup, cage included, is shown below.





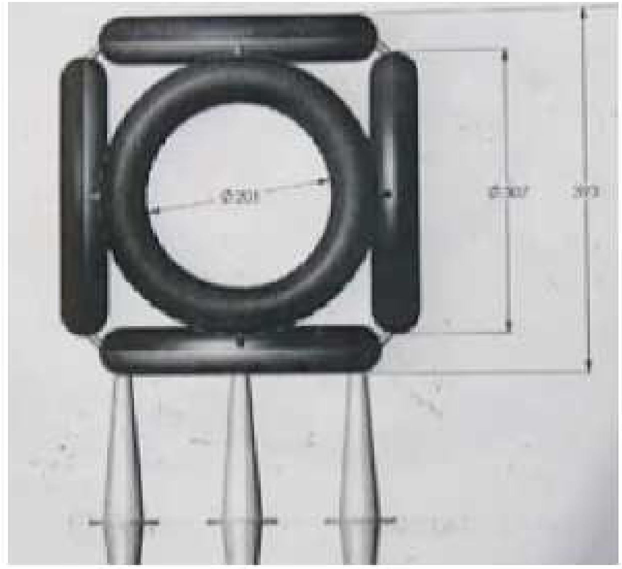
The Emitters:

Above the rings, there are four bulb looking tubes. These are Deterium gas emitters. Note: these do not inject ions. This is an important point. The tubes puff out deterium only. Later on, this gas will become ions through a physical mechanism described here. The deuterium is cheap. It comes in small lecture bottles and is puffed directly into the rings. This is done at a relatively high pressure (3E-4 torr) against the vacuum (1E-7 torr). In the future, there may be better ways to do this. This gas puff system could be swapped for an ion gun. This gun would form the ions, before they enter the device.

Where these tubes are placed is important. The location is important for the following reason. The gas is the fuel for the fusion reactor. Once injected, the gas becomes ionized, forming the ions. The ions are what is actually fused. They fuse because there are attracted to a big cloud of electrons in the center. This is like a marble rolling around in a bowl. You can let the marble go in three spots. In the center, where the marble will just sit. On the lip, where the marble will roll from one side to the other side. Or above the bowl. If you let a marble go above a bowl, the marble will crash downward, zip across the center and fly out the other side. The marble is lost! The ions are the marble and the bowl is the voltage drop. If an ion is formed in the wrong place, it will not be caught by the voltage drop. It will have too much energy. It will crash towards the center, zip through the middle and fly out the other side hitting the metal cages. The ion will be lost! Where you form the ions is important. Hence, where you place the emitters is important.

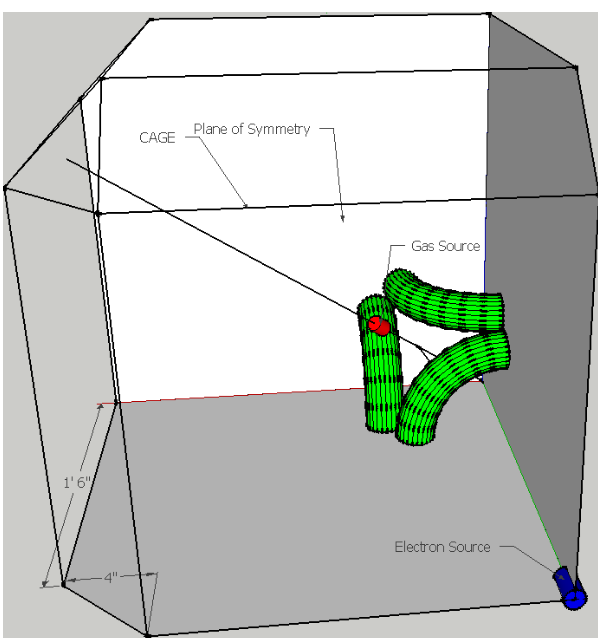
The Rings:

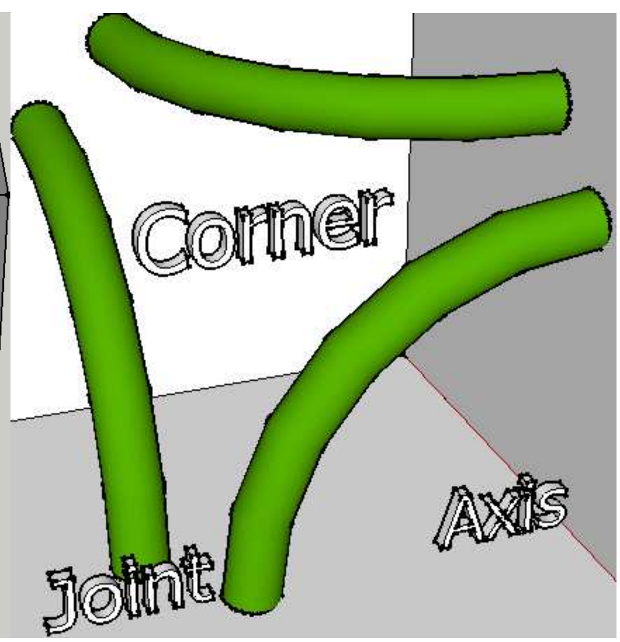
The rings are the most iconic structure for this device. Many people, new to this machine, have to spend a long time just understanding the rings. In WB-6, the rings were beautifully smooth hula hoop shaped objects, about the size of a hub cap. A close up is shown here.

The ring dimensions used in this post were from the blue print shown on the right. Upon detailed analysis [25] the ring surface was probably stainless steel. They have got to be smooth. Rough spots will build up charge or cut the magnetic field. Remember, these rings are swimming in magnetic field lines which trace right along their smooth surface. A bump will cut those lines. Inside these rings is a long spool of thin copper wire. The wire may snake several hundread times through one ring before it exits through small connectors. These connectors hold the six rings together in a square shape. The connectors are non-conductive. They also supply power. Electricity is supplied to the rings through white non conductive feet on the floor. Electricity can move from one ring to another inside the connector.

For the purposes of modeling, the rings can broken down into a repeating cell. The rings can be cleaved by three planes of symmetry, making a cell 1/8th the actual ring volume. This model is a boiled down version of reality, containing no connectors. A picture of the model is shown below.





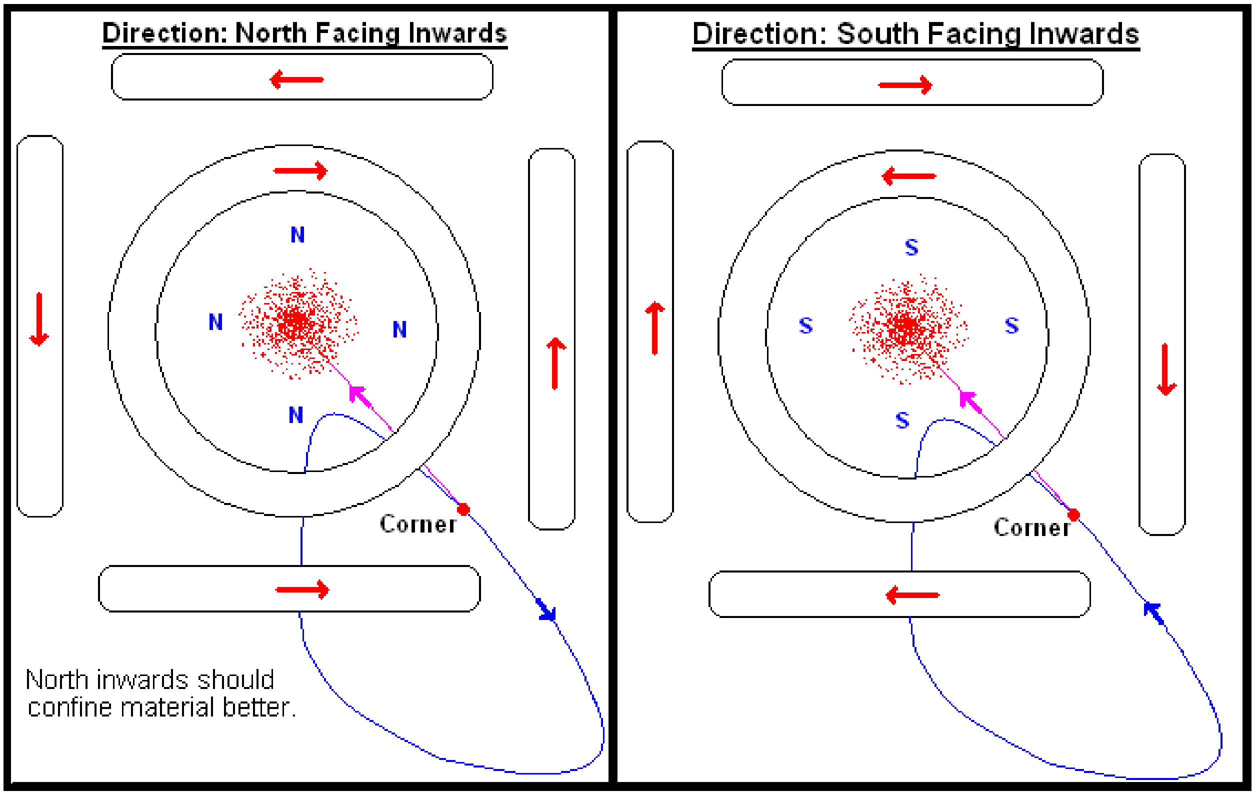
There are four points of interest in this geometry. The first is the center. This is where the action happens. It is where fast ions slam into one another and fuse. If someone were to model this reactor, the center is a good place for a high density of cells. There is no magnetic field here because the fields cancel. The second spot is the joint. Here, the rings at are their closest. The connectors would go here. The joint has strongest magnetic field of all four spots (~296 Gauss). The next location is the axis. It is sitting at the center of each ring and has a (~197 Gauss) field. The last spot of the four is the corner. The corner is equadistance from each of the three rings and has the weakest magnetic field (~193 Gauss). It should be mentioned that this corner field calculation does not agree with Bussard's estimates. Bussard estimated that the field was 70 to 100 Gauss [8]. Aside from field strength each location has a very different magnetic and electric environment and therefore the electron and ion behavior will change radically at each of the four locations. For a complete description of how these fields were calculated, see below.

2. Important Design Consideration

Did you notice the corner field and the axis fields were the same? (197 verse 193 gauss). This is on purpose. This was a major realization by Bussard. He quotes this in his paper: "…The spacing between coils should be such that the central plane B field is approximately the same as that of the B field on main face axes…" [8]. Making these fields the same will make the electron containment more uniform. It will very likely improve electron containment. It is the driving force behind where the rings are placed.

3. Which way are the fields pointing?

Each ring is an electromagnet. As current races around the rings it makes a magnetic field. All the fields point into the center. For this analysis, we arbitrarily picked the north poles to face in. The rings are like six bar magnets in a box, with all their north poles facing in. In the center there is a spot where there are no fields. This is a star with 14 points. Each point, points at a corner or a side of the rings. It is within this star that the electrons pile up. This pile of electrons is what accelerates the ions to a speed where they can slam together and fuse. You can find the orientation of everything by using the right hand rule. If you curl your fingers on your right hand, so that the fingers point in the direction of the current, your thumb is pointing at the north pole of the electromagnet. We picked all the north poles to face in, but both possibilities are shown below. Red arrows show the direction the current flowing in through the rings - which for the WB-6 test is 4,000 amps in each ring. Pink arrows show the direction of the electric field. It points towards the negative ball of electrons in the center. A blue line shows the path a recirculating particle would take in the magnetic field.



4. The Steps To Turn WB-6 On

Bussards' paper provides us with some idea of how to startup his last machine. This description represents our current conception of starting up; there may be some mistakes. It should be noted that fill up has not been modeled. The rings are placed in a cage, in a vacuum chamber. The chamber is first pumped down to <1E-7 torr. This is the vacuum environment. There is still air in the chamber. This trace air will remain there throughout the run. Next, the voltage between the cage and the rings is switched on. This creates a voltage valley. The cage is the high side of the valley and the rings are sitting at the bottom. At this point, sparking between the cage and the rings is a dangerous possibility. Sparking across this gap (16”) would kill the machine. This valley is 12,500 volts high.

The third step in starting up the machine is switching on the rings. The rings are copper wires wound in a loop, probably encased in smooth stainless steel. This steel has got to be smooth. All six rings are held to one voltage, relative to the cage. This dual use for the rings can get confusing: they are simultaneously generating the magnetic field, while maintaining a voltage drop with the cage. Inside one ring, there are about 4,000 amps of current. This moving current generates six magnetic fields. These fields all point inward. For this analysis all the north poles are facing in. At the center, there is a pocket of no magnetic field. It is a star structure with 14 points; one point pointing to each corner and each side. It may be possible that these magnetic fields reconnect. Reconnection is when magnetic fields, in the presence of plasma, recombine. This counterintuitive idea – where magnetic field lines cross and connect – was discovered first in the late 50’s. If this happened, it may be really good for machine performance. This is a totally open question. Someone please look into this: would we even expect this to occur, under these conditions?

With the first three steps done, the environment is all set for the release ions and electrons. It is analogous to setting up a racetrack, before starting the cars. The fields have been designed to pull and funnel material into the center. The goal is to get ions to fall down a big enough hill to crash into each other in the center. “Big enough” is 10,000 volts; this should be enough to get at least some of the ions fusing.

Now electrons are emitted. There are many options for doing this, but they all boil down to the same physical mechanism. An electron is sitting on the surface of a metal. It feels a tug. This tug is from the voltage valley between the cage and the rings. The electron wants to fall towards the rings. The electron can be kicked off by heating the metal surface, this is thermionic emission. The electron can be kicked off because there are too many electrons occupying the surface already – this is a capacitor discharge. This was the method Bussard used in his last machine; referred to as the “cap-discharge” system. Fancier tools for releasing electrons such as electron guns or e-guns can also be used. The Navy has bought several 10kV electron guns for their reactor. When these electrons leave the surface they experience a Lorentz force. This force draws them towards the positive voltage rings. When they get close, the magnetic part of the Lorentz force takes over. They start to recirculate on the magnetic field lines. Some pile up in the center. This creates a voltage drop for the ion to speed up on and to slam into one another and fuse.

The fifth and final step in starting up this machine is the deuterium emission. The deuterium gas comes in a small lecture bottles. The material is cheap. It is really important to emit this stuff at the edge of the ring field. Again, there are a variety of ways to emit the gas. Attempts can be to ionize the gas when it is emitted, or just bleed the stuff into the chamber, as is. This latter method was used by Bussard. The gas was puffed out into the chamber, under a relatively high pressure of 3E-4 torr. This was done from four tubes sitting a few inches outside the rings. When the gas left it was not ionized.

5. The Gas Becomes The Ions

Once all the fields are set, the electrons are flying into the center and the deuterium gas is being puffed in, the next step is ionization. Bussard described this mechanism in reference [8]. The fast moving electrons are entering the device center. These electrons could potentially have as much as 12,500 eV of energy. These electrons hit the gas atoms. This heats up the deuterium atom. If the deuterium is now “hotter” than 14.9 eV, its own electron fly off. This kicks off a slow moving electron. The atom becomes an ion. This process ionizes the gas inside WB-6. It increases the number of free electrons and free ions flying around. It separates the material. Ideally, both clouds of electrons and ions have too much energy to recombine. At most it takes 14.9 eV to strip off electrons from deuterium. This is much less than the typical electron energy. Now you can see one reason why the Navy wants to get several 10,000 volt electron guns for their reactor [10]. The higher voltage electrons will ionize the gas much faster. Bussard stated in his Google presentation that the electron voltage for the PZL-1 machine (built in 2003) was 15,000 volts [19] and the drive voltage was 12,500 volts for WB-6.

The number of electrons is growing inside the machine. As the electron cloud grows the cloud of ionized deuterium grows. Bussard estimated that this process happens on the order of several microseconds. He estimated that all the electrons were stripped off the deuterium in about this amount of time. At this point the beta ratio is 0.01. The beta ratio is the ratio of the plasma pressure to the magnetic field pressure. It sets the limits to this process. When the beta ratio is 1 the plasma pressure has equaled the magnetic field pressure outside. The device is full. The device can fill up with ions and/or electrons - hence there are two beta ratios. When the electron beta ratio is 1, no more electrons can fit into the rings. More cannot be contained. This instability comes from magnetohydrodynamics. When the electron beta ratio is 0.01, Bussard estimated that the electrons are at 100 eV [8].

6. Electrons Heat Up

Bussard now proposes a mechanism for electron heating. There are now two clouds of electrons inside the device. These are hot electrons, which have been created by falling down the outside voltage drop. There are also cold electrons, which came out of the deuterium gas. The hot group is flying into device center with as much as 12,500 eV. The cold group has an average temperature of 100 eV. The electrons hit one another in the center. They exchange energy. Bussard estimates this heating takes about a microsecond. Within a few microseconds, the gas is entirely ionized and in about 20 microseconds all the electrons are at about 2,500 eV [8]. This is a mild temperature. It is about one fourth the temperature the ion needs to fuse. Yet it is many times greater than the temperature needed to strip off an electron from deuterium (14.9 eV). Hence, the electrons and ions will never recombine. Incidentally, this ion energy is consistent with NIF and ITER. Their goal is to push the average cloud temperature to around 10 to 20 KeV. The polywell does this by accelerating ions towards a 10 kV negative point. However, there is a big difference between getting a handful of ions to this level and pushing an entire cloud to this average temperature.

Having distinct temperatures is a sore subject. Rider would fervently disagree. He predicts that the ions cannot have more than 5% variation in temperature [17]. More importantly, Rider argues that the ion and electron energies would all be the same. Wither or not the cloud is one temperature hinges on the rate of energy transfer. Rider argues that energy transfer essentially depends on the ratio of the number of electrons moving more slowly than the ions [18]. This is shown below.

$$\textbf{Electron} - \textbf{Ion Heating Rate} \propto \frac{\textbf{Electrons With Lower Energy Than Ion Mean}}{\textbf{Electrons With Higher Energy Than Ion Mean}}$$

Hence, Rider argues, the cloud must all be at roughly one temperature.

It may be that Rider and Bussard are both correct. Everything could be at an average temperature of 2,500 eV. What if the ions just had a broader bell curve of energies? If part of that bell curve falls above 10,000 eV, then fusion seems possible for some of the ions. Someone needs to address these issues. The process described here is the “two color” electron start up. Bussard believed that this would be ideal for large machines. The machine would essentially inject a high energy electron population with a low energy electron population which was self-generated. The energies of these two electron populations would merge.

7. Recirculation: A Big Deal.

Efficient recirculation is a big deal. Ions and electrons must recirculate without touching conductive metal. As obvious as this may seem – it is astounding how many smart people get it wrong. The latest simulation work from Iran is a prime example [28]. Their reactor has way too much metal inside it. Dr. Joel Roger’s purposed a similar flawed design in 2009 [29]. Dr. Khachans' reactor from last year would have probably been improved by reducing the amount of metal inside the device [30]. Hence, simpler, more elegant designs are better. Here is why.

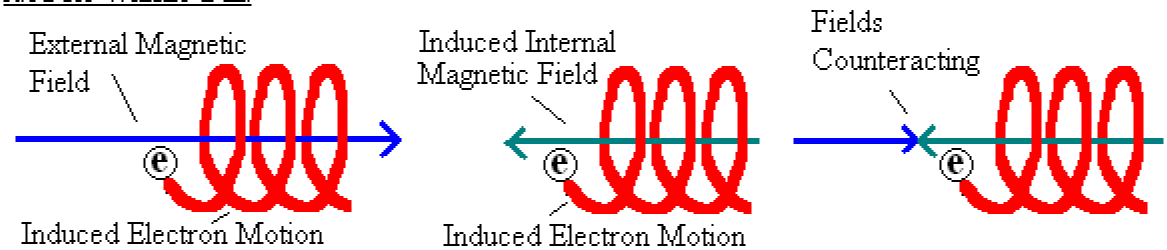
The center contains a swarm of electrons. For modeling, it is easy to treat this like a static point charge. But in reality, these electrons move. They swirl along the magnetic field lines. They ride these lines like cars on the highway: cycling out and back into the device center. They must be able to swirl around without hitting a conductive surface. Both Rider and Bussard agree on this point. Rider states this on page 2 of his doctoral thesis: “So barring the discovery of methods for recirculating the power at exceedingly high efficiencies, reactors employing plasmas not in thermodynamic equilibrium will not be able to produce net power" [26]. We argue that Rider never built this machine - his theoretical arguments are not substantiated by any real polywell data. The recirculation realization was a flash of genius for Bussard. It led to WB-6. "…we all missed the obvious, for 15 years none of our consultants, none of our reviewer panels, none of our opponents, none of our staff … saw these obvious facts."[27] Recirculation means elegant reactor designs. It means minimal metal in the center. Any surface you have to use - must be shielded. Shielding should be non-conductive, reducing conduction losses.

Conduction losses are a big part of John Lawson's famous 1957 fusion paper [31]. In summary, Lawson argues that a hot cloud will lose energy through conduction and radiation. Because of this, the cloud must reach a certain temperature. At that temperature, the energy produced will overtake the energy lost. But what if we reduced the loss mechanisms? Could we get net power at lower plasma energies? This would be an alternative to the fusion efforts for the past 55 years – which have focused on reaching a high enough temperature or density. One way to reduce losses is by reducing conduction. Hence, efficient recirculation – without conduction losses - is a big deal. This leaves radiation. A plasma cloud can bleed away all of its energy by X-rays. This is why so much of Riders and Nevins work focused on X-ray losses. Can these X-rays be recycled in some way?

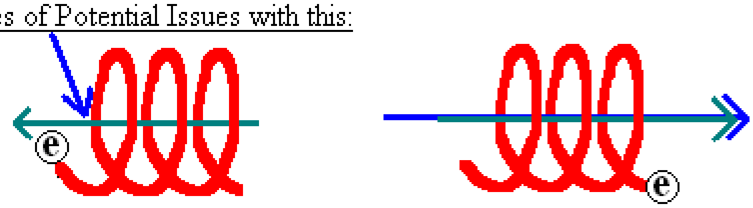
8. The Whiffle Ball

The Whiffle ball is purposed mechanism for how the machine would better trap material. Right now, it is just an idea. There is no published work confirming that this happens inside Polywells. The electrons are moving in the center. All moving charge generates a magnetic field. Each electron creates its own magnetic field. The argument is that these mini fields can oppose the ring fields. The fields push against one another. The cloud pushes back the ring fields, which pinches off the "leaks" in containment. This is analogous to a "magnetic resistance" inside the cloud. In doing this, the cloud has gone diamagnetic. This is supposed to increase electron containment, efficiency, fusion rate, well depth and reduce constraints on ion injection. The basic physical mechanism is shown below.

Idea for Whiffle Ball:



Examples of Potential Issues with this:



Just reasoning: there are two scenarios where this does not work. The first is when the mini field is aligned with the ring field. This may happen roughly half the time. The second is when the electrons are at an odd angle with the magnetic field. The Whiffleball effect was not on Riders' radar screen when he wrote his 1995 paper. It has been raised as one possible reason against Rider’s analysis. Diamagnetism itself only gained notoriety two years after, when researchers levitated a frog using a super conducting magnetic.

9. The Number of Electrons Inside WB-6

To do this calculation, you must have a distance. This distance is from where the voltage drop starts, to the device center. This is where the deuterium gas emitters are placed. If someone has schematics showing where the emitters were placed, we would appreciate it. This distance is not trivial - and we can only estimate it. Finding this distance is listed as a major accomplishment by Bussard. The gas is puffed out on the edge of a giant hole. The hole is a 10,000 volt drop. The hole is made by a swarm of electrons in the center. You can use either gausses law or coulombs law to find how many electrons are in the swarm. Based on photos, we estimated the tubes were 29.2 cm from the center.

$$\mathbf{Coulombs\,Law} \Rightarrow \mathbf{Voltage} = \frac{\mathbf{8.987551E9 * Charge\,Contained\,in\,Center}}{\mathbf{Radius}}$$

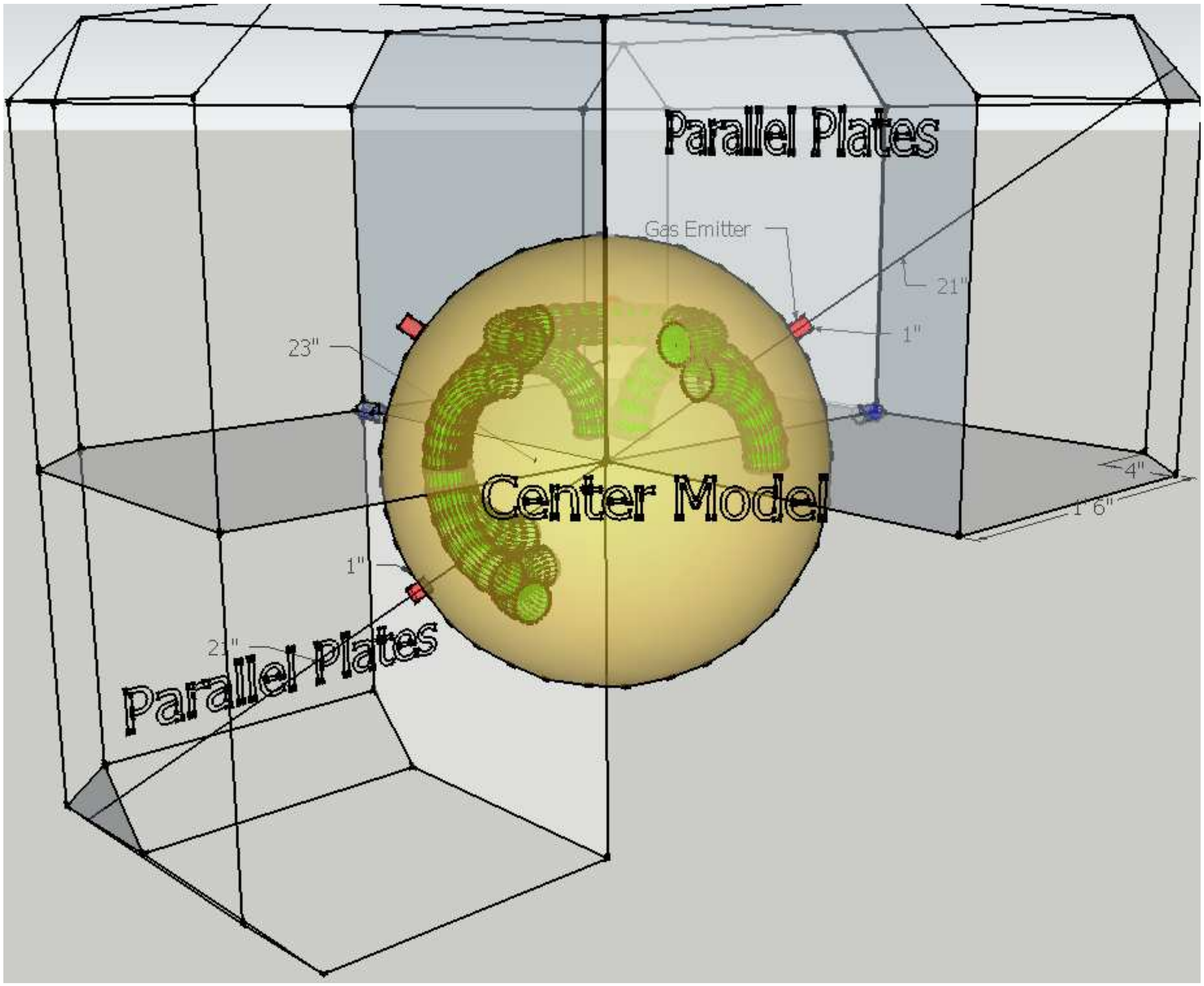
$$\mathbf{10{,}000\,volts} = \frac{\mathbf{8.987551E9 * Net\,Number\,of\,Electrons * 1.602E{-}19\,Columbs}}{\mathbf{0.292m}}$$

This estimates that there were 2.0E12 net electrons inside WB-6. Two trillion electrons is very hard to model.

Unfortunately, this number changes drastically, if the distance changes. The number of electrons is a very important for this model. It should not be so dependent on a distance that must be estimated from photographs. For example, if the voltage valley started at the corner (between the rings) there would be 1.4E12 electrons. Three inches inward and there would be 1.0E12 electrons. If someone has the real distance for where the gas tubes were placed, this would be appreciated.

10. Where are the electrons?

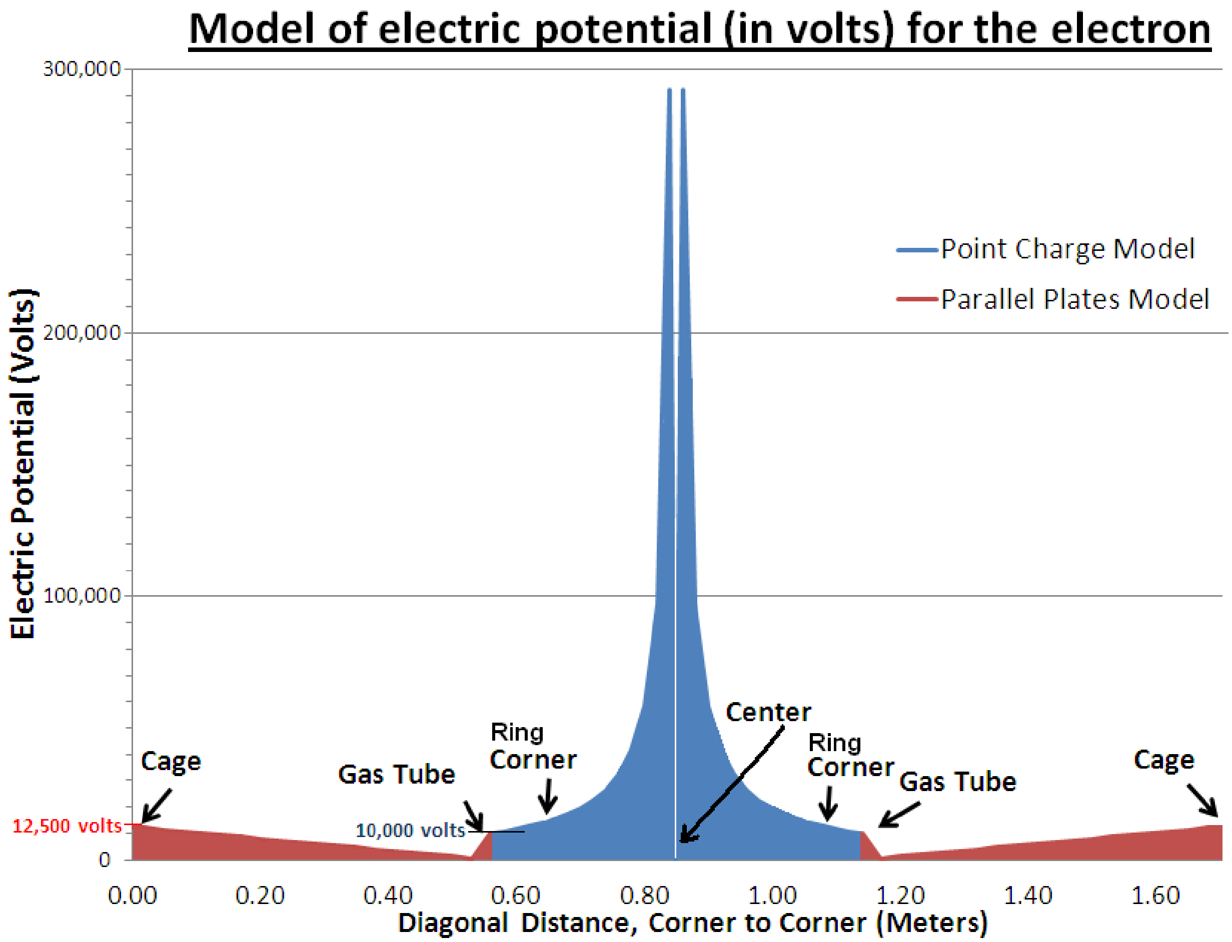
In real life, the electrons are recirculating in and out of the center, in a giant swarm. The easiest way is to model the swarm is like a point charge in the center. This would be an infinitesimally small point which contains all the electrons. Point charges are easy to understand and to model. The goal here would be to map the electric potential, field and energy density from one corner of the cage to the other corner of the cage. This path is shown below.



If an electron were to travel from one corner of the cage, what would it experience as it moves into device center? At the start in the corner, it will feel a voltage like being within two parallel plates. This is the voltage valley. The positive charge would be in front of the electron. The electron starts falling down a 12,500 voltage hill towards the center. It feels a Lorentz force, this is shown below.

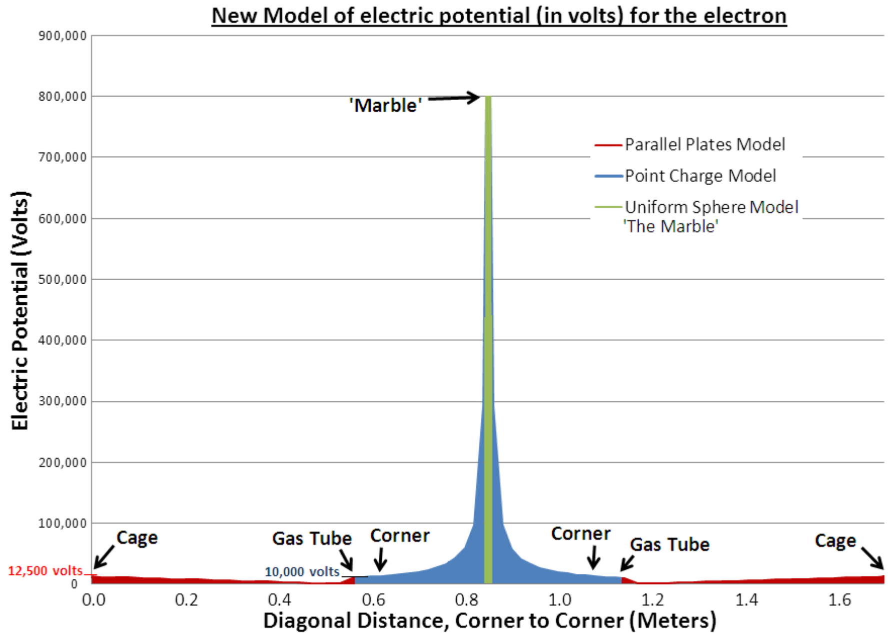
$$\textbf{Lorentz Force} = \textbf{Charge}\left[\textbf{Electric Field} + \left(\textbf{Velocity} \times \textbf{Magnetic Field}\right)\right]$$

Inside the voltage valley the electric field dominates this force – the electron falls towards the rings. As it reaches the gas emitters it starts to feel the magnetic field. Over time, the magnetic fields start to dominate the electrons' motion. The electron gets caught by the rings, and recirculates. Ignore the magnetic field for the moment. When the electron crosses the gas emitters, it enters center zone. There are many ways to model the electron cloud here. For now, we will model it like an infinitesimally small point. This point contains all the electrons. This structure can be modeled like a point charge. The electron sees strong columbic repulsion from the cloud. This spikes as the electron closes in on the center. For this analysis we argue that when the electron reaches dead center, there is no magnetic field. This would occur if the dead center had uniform charge in all directions. The electron feels the reverse as it comes out the other side of the cage. As it passes the far gas emitter, it once again sees the voltage valley, before reaching the cages edge at 1.70 meters. This electric potential is graphed out below.

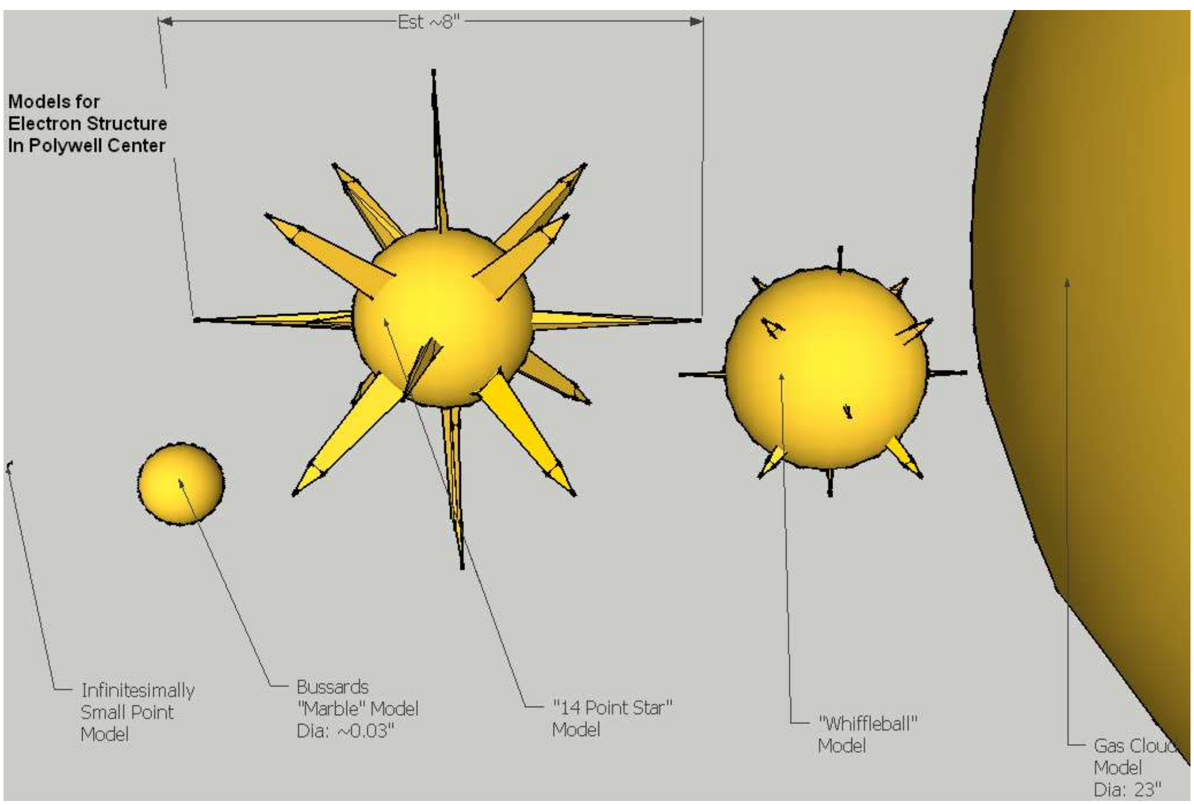


11. The Center: A Point? A Marble?

What is the best way to model the cloud of electrons in the center? in the graph above these electrons were modeled as an infinitesimally small point. This is most certainly incorrect. The electrons could fill a sphere of some radius. Consider though, all uniform spherical models for the electron cloud are essentially the same. Outside the sphere, the voltage field can be modeled like a point charge. Inside the sphere the voltage is uniform everywhere. Hence, under this conception, the magnetic fields would drive electron motion inside the center cloud. Using Bussards' density (1E19 Electrons/M^3) and the numbers estimated here, the center is a "marble" sized ball of electrons in the middle [8]. The "marble" is ~0.3 inches in diameter. You can model that "marble" like a sphere with uniform charge.



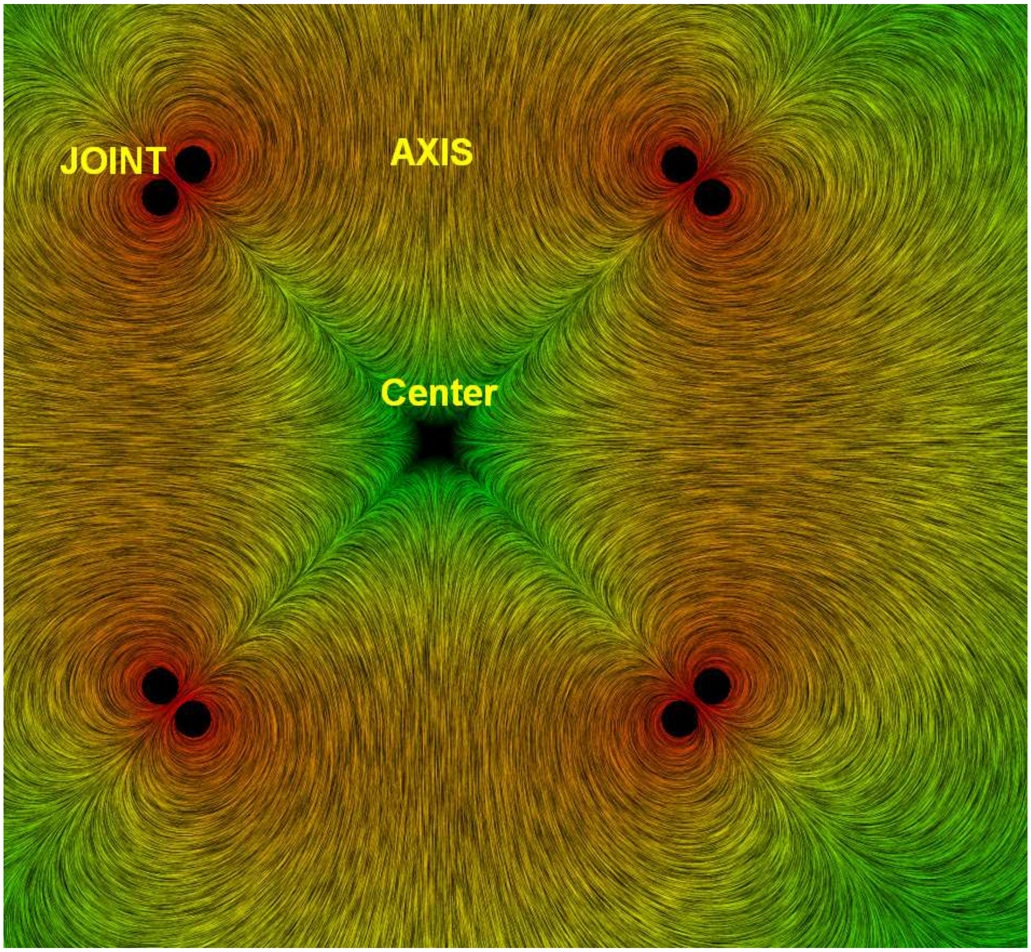
The spherical model is probably flawed anyways because these electrons are probably filling in a pocket inside the magnetic fields - and that pocket is not spherical, it is star shaped. If this is the case, the electron cloud would look like a 14 point star. This is shown below. Notice, the points of the star are all the same size. This is because the magnetic fields at the corner and axis are the same. This creates a more uniform containment of the electrons. It is important fact to consider in ring design. Lastly, If the Whiffleball mechanism is real, then that star shape would swell into a sphere with 14 nubs. This would be due to the electrons pushing back the ring fields and pinching off the loss points. These nubs represent remaining holes in containment. The holes are like holes in a real Whiffleball - hence the concepts' name.



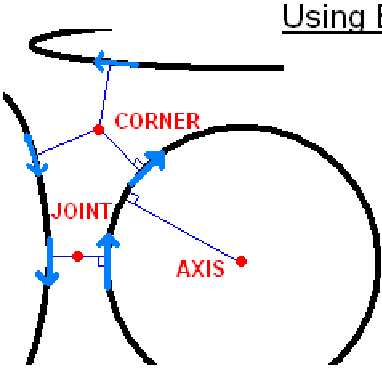
12. The Magnetic Field

The electrons would not be contained in the center without the magnetic fields holding them in. The center is a giant point charge. The repulsion from that point would force the electrons out. This is a “double edged sword”: we want a sharp point charge in the center – it speeds up the ions to fuse – but at the same time the sharp point cause columbic repulsion which forces the electrons out. Unfortunately, because the magnetic moment of an electron is so low, the magnetic field has a much smaller role in determining the potential energy of the electron.

Still, the magnetic field should be able to fight columbic repulsion and contain material. It can offer the electrons highways on which they can re-circulate. A picture of the magnetic field from Indreks simulation work is shown below [6]. In this image you are looking down on the rings in a plane. The 14 point star occupies the black pocket in the middle. Here you can see four of the stars’ points, one heading to each corner. The swirling magnetic field lines act like highways on which material can ride, from the center out to the edges and back into the middle. The electrons spiral up and down these field lines and some pile up in the black spot in the center. This can be seen in this simulation. http://www.youtube.com/watch?v=ao0Erhsnor4&feature=results_video&playnext=1&list=PL5B658B587D042A41 If the Whiffleball happens, then over time, this black spot starts to look more round and bulges into a ball shape. A ball with leaks, a whiffle ball.



Accurate models the magnetic field are damn difficult. In reality, the rings are two inch diameter tubes containing hundreds of coils of copper wire. Also, the moving electrons themselves generate mini fields which affect this estimate. Lastly, the model only accounts for the rings close by. But, we need some first approximation. Magnetic fields are calculated using the Biot-Savart law, but you need to make some assumptions to adapt the law. In the center, there is no magnetic field. However, for comparison with the other spots it was modeled like a point equidistant from the six rings. The axis sits in the middle of a ring of current. The joint was modeled as a point between two straight wires. The corner was a point equidistant from three straight wires. Fortunately, standard formulas exist for each of these configurations and these are shown below.



Using Biot-Savart To Find Magnetic Field

$$\text{Magnetic Field}_{Joint} = \frac{2 * \mu_0 * 4000\ \text{Amps} * \sin(90) * 1 * \text{Distance to Ring}}{4 * \pi * \text{Distance to Ring}^2}$$

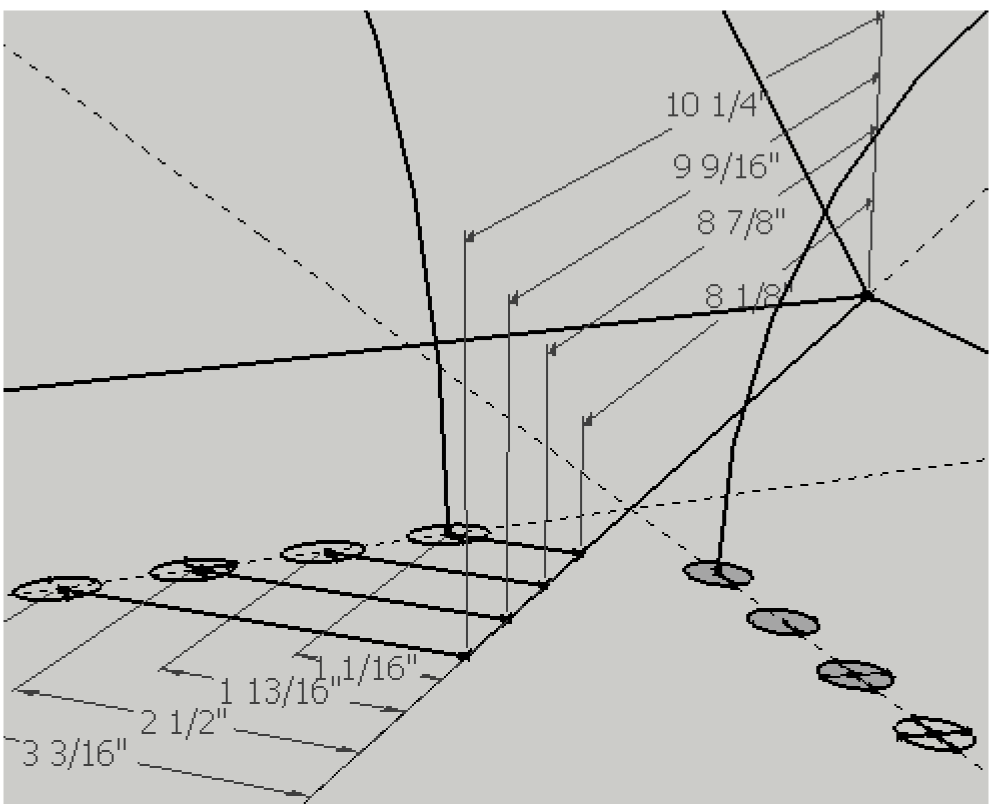
$$\text{Magnetic Field}_{Corner} = \frac{3 * \mu_0 * 4000\ \text{Amps} * \sin(90) * 1 * \text{Distance to Ring}}{4 * \pi * \text{Distance to Ring}^2}$$

$$\text{Magnetic Field}_{Axis} = \frac{\mu_0 * \text{Ring Current}}{2 * \text{Distance to Ring}}$$

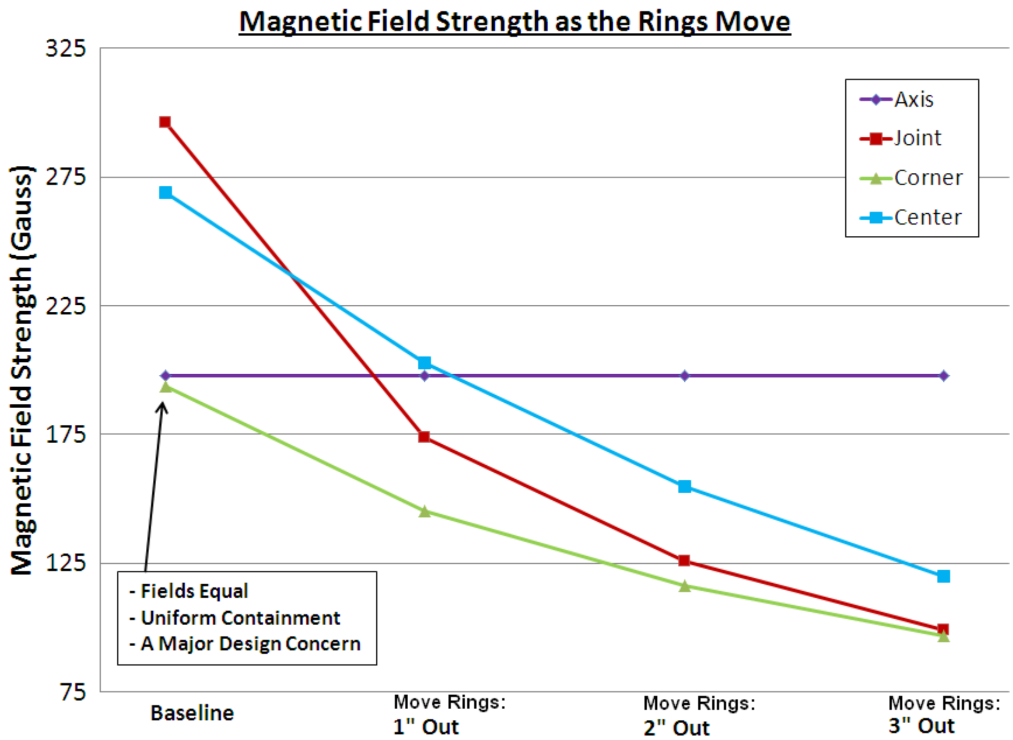
$$\text{Magnetic Field}_{Center} = \frac{6 * \mu_0 * 2 * \pi * \text{Ring Radius}^2 * 4000\ \text{Amps}}{4\pi * (\text{Distance To Ring}^2 + \text{Ring Radius}^2)^{3/2}}$$

13. Magnetic Field and Moving The Rings

Bussard lists balancing the corner and the axis fields as a major design realization. If the magnetic field strength at the corner and the axis are the same, then containment of the electrons is more uniform. It is a major driver for why the rings are spaced out the way they are. What would happen if we move the rings? Unfortunately, the rings cannot be moved closer, but they can be pulled apart. The magnetic field model depends on how far away the location of interest is from ring center. The electric field model depends on how far away the point is from the the center. As we change geometry, these are the important distances we will need for the equations. A picture showing the distances measured (for the joint only) is shown below.



Using these distances for each point, we can graph what magnetic field as the rings move apart. This graph is shown below. There is a ton of information contained within this graph. First, the center field should probably not be shown. It is in fact zero. It is shown here – as what it would be for 6 non-interacting ring fields - for comparison. It is the distance to the rings that drives this model. At the joint, the rings close in quicker; this drives the magnetic field up faster, than at the corner. This happens despite the corner accounting for one more ring. The axis field comes from being in the middle of the ring. Therefore the axis moves in tandem with the rings – so the axis field remains constant. The last and most important observation is that the rings are placed where they are, so that the axis and corner fields are the same. Overall, the model predicts what you might expect. As the rings get closer together, the magnetic effects increase in strength.



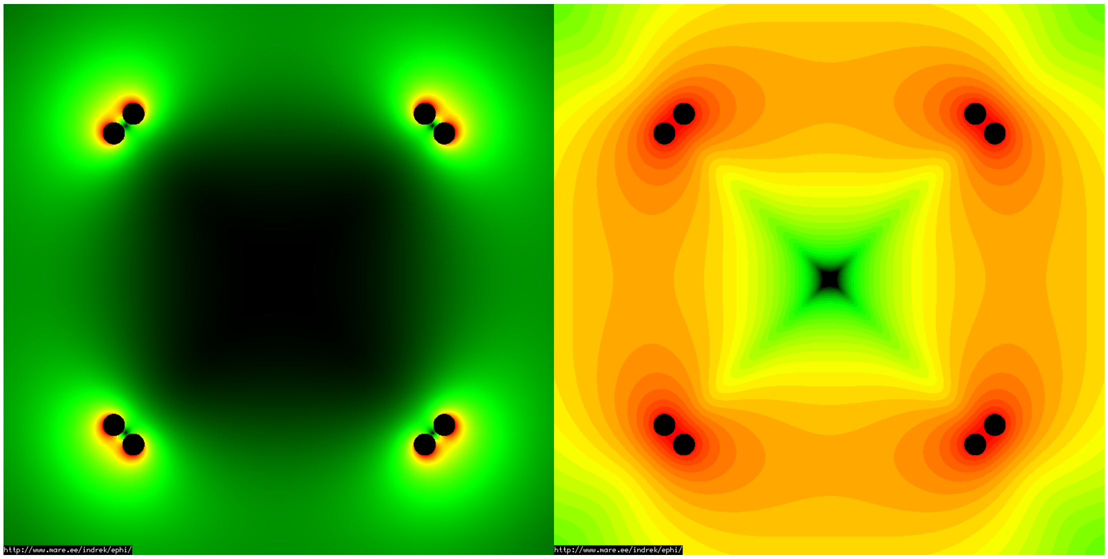
14. Energy Density Analysis

In physics, an energy analysis is a surefire way to understand any system. The polywell is no exception. The reactor is filled with electric and magnetic fields. If you combine the electric and magnetic fields, it will yield the energy density equation. This looks to be a nice first approach to analyzing any reactor design. This energy map represents the ability for the machine to hold in, or keep out, all of its particles. Though it is only a first approximation, it is a really great way to think about the reactor. Here is the energy density equation for a perfect vacuum.

$$\text{Energy Density} = \frac{\text{Electric Constant}}{2} * \text{Electric Field}^2 + \frac{1}{2 * \text{Magnetic Constant}} * \text{Magnetic Field}^2$$

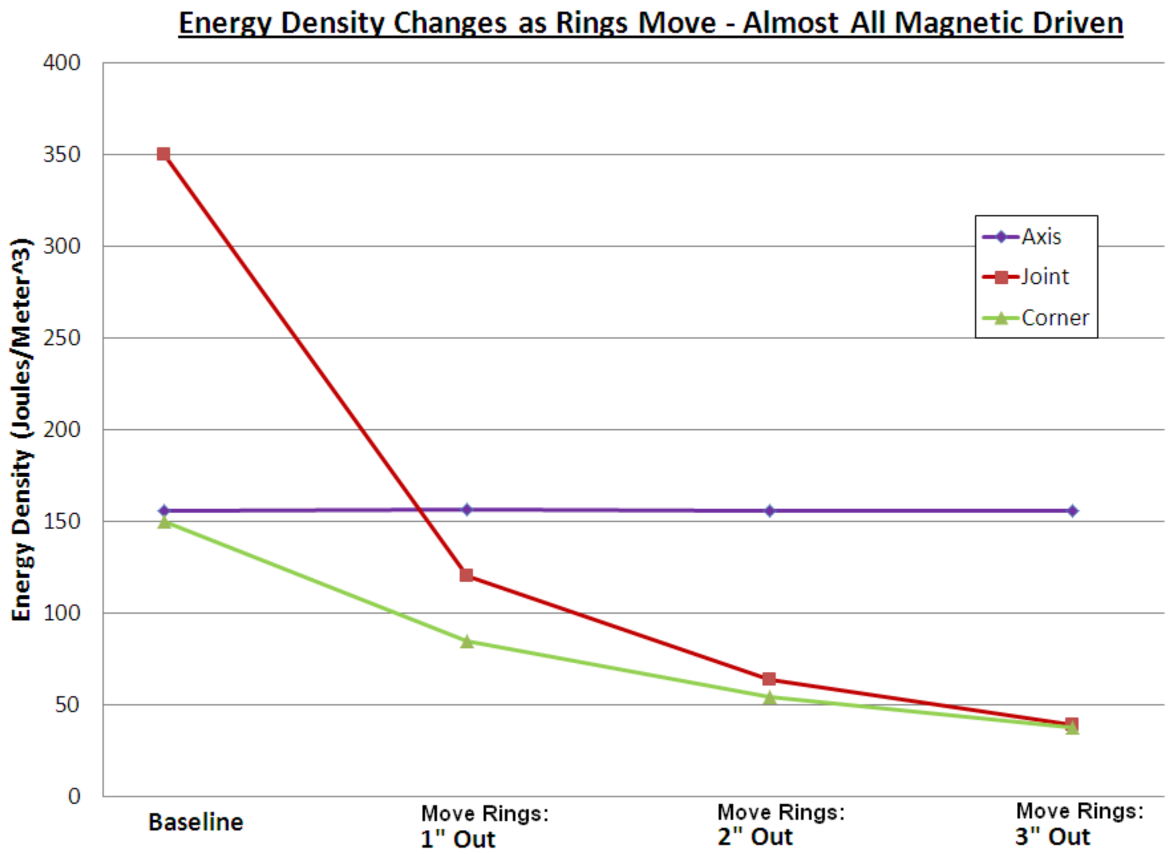
So if one combines the electric and magnetic fields, you have a total “energy density map” for the system. This is important. It tells you where high energy and low energy locations are. Think of this energy map like the hills and valleys of a mountainous terrain. The high energy spots are the high peaks, the low energy spots are the low valleys. For a particle to occupy a given location, it must have at least this amount of kinetic energy. When the electron turns around, the potential energy is the same as the electrons total energy. This energy map should give you a basic sense of where an ion or an electron can go, if it is injected at a given energy.

Indrek already did some preliminary modeling of the electric and magnetic fields, here are images taken from his work [6].



This is the electric and magnetic fields for a polywell, from Indrek's simulation. The image on the left is the electric field and does not appear to include electrons. It may be that the green outside the rings is the voltage valley generated by the cage. The image one on the right is the magnetic field. Ideally, Indrek would have combined both these images to create an energy density map. Unfortunately, because the magnetic moment of the electron is so small, the magnetic field should have a diminished role determining the electrons potential energy.

When you calculate the energy density at these points, you realize that it is almost exclusively driven by the magnetic field. The reason for this comes from the fundamental electric and magnetic constants. The electric field gets multiplied by (8.85E-12) while the magnetic field gets divided by (1.26E-6). This causes the magnetic field to almost entirely drive the energy density. With the electron cloud contributing so little, it should not matter which center model is used to do this calculation. The energy density is shown below, for moving the rings.



15. Potential Energy Analysis:

As stated above, the magnetic field contributes almost nothing to the potential energy of the electron. The reason for this is the magnetic moment of an electron is so small. The magnetic moment I used was 2.96E-23 Joules/Tesla. If you study atomic physics, you will know that there are lots of magnetic moments in the world. There are several moments for the electrons. The value changes if electron occupies different locations within the atom. It also changes if the electron spins in different ways. It is not an easy value to solve/estimate. Nominally, the moment is some multiple of the Bohr magneton (9.87E-24 J/T). The magnetic potential energy is the cross product of the moment and the field. If the moment was higher the magnetic contribution to potential energy would be higher. But, even if the moment was 3 times the Bohr value – the magnetic contribution to potential energy would still be tiny. The equations used to find the potential energy are shown below.

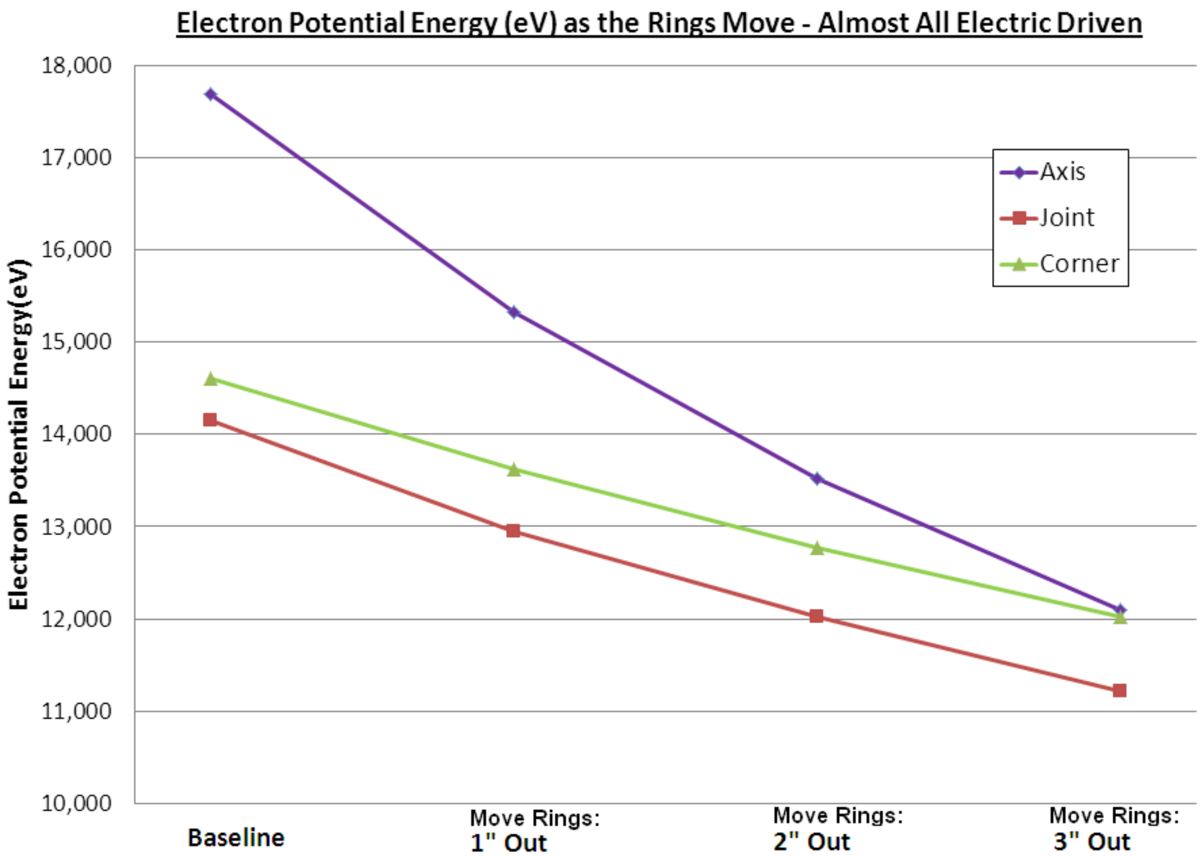
$$\textbf{Magnetic Potential Electron}_{\textbf{Joint, Axis, Corner}} = \textbf{Moment * Magnetic Field * cos(90)}$$

$$\textbf{Electric Potential Electron}_{\textbf{Joint, Axis, Corner}} = \frac{\textbf{K * One Electron Charge * Charge In Center}}{\textbf{Distance to Center}}$$

$$\textbf{Total Potential Electron}_{\textbf{Joint, Axis, Corner}} = \textbf{Electric Potential} + \textbf{Magnetic Potential}$$

Because the electron moment is so small the electric field dominates its potential energy. The electric field can be modeled as originating from a spherical cloud in the center. As was stated above, it does not matter what the diameter of this sphere is. Any electron outside a sphere of uniform charge, acts the same, regardless of the diameter of the sphere. The sphere always looks like a point field, which is located at the spheres' center. Improvements to this would incorporate more exotic shapes for the electron cloud – such as the

14 point star or the Whiffle ball. Improved models would have far more complex electric potentials. When the rings are moved away from the center the electric potential energy decreases. The potential energy, shown below, is converted to electron volts and displayed.



This model says the device is overflowing with electrons. The electrons are coming in with at most 12,500 eV of energy. However, at all three points of interest the potential energy is too high to allow the electrons in. This was also seen in mapping the voltage across the middle of the device (section 11). Future work should use this fact to determine what the potential at the corner is overtime as the device fills with electrons.

16. Electron Injection:

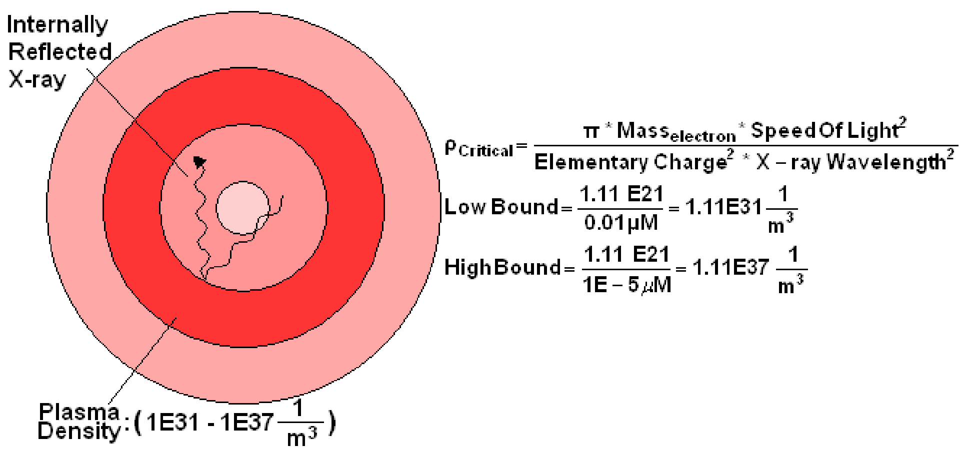
Based on the analysis above the best location to inject electrons is the joints. It has the lowest potential energy that the electron have to overcome. In practice however, the corner may have been used. This is because the electron path was not as hemmed in by the rings at the corner. We now have hints that containing the electrons also creates problems injecting them. This seems to be the reason the Navy team asked for improved (10kV) electron guns in their most recent contract extension on March 10th 2012 [10], here is text taken from that contract.

"…During the course of the contracted study several anomalies related to how electrons were fed into the device were discovered. These anomalies must be characterized and solutions created if the device is to be made functional. To solve these anomalies, the additional effort will require the incumbent contractor to further their studies by employing independently powered electron gun arrays operating at up to 10 kilovolt (kV) to inject high energy electrons onto the Plasma Wiffleball 8 core and control the WB format ion process. Additionally, a separate pulsed power system with minimum 100 amperes current rating will be utilized to power the electron gun arrays…"

We can glean much from this text. First, what is a "WB formation process"? If it is, in fact, a physical process for forming a Whiffleball - then that would be big. This would mean the electrons are rejecting the ring fields and pinching off the holes.

17. Critical Density: Probably Not A way to Reduce X-ray losses…

In fusion science there is an electron density known as the critical density. This acts as a brick wall for x-rays. When electrons reach this density the x-rays cannot get through [32]. If the electrons were this density in the polywell, the x-ray losses may be reduced. That is because x-rays, generated in the interior could not escape. The formula for the critical density is shown below. Based on the properties of x-rays, typical numbers are shown. Unfortunately, these densities are so much higher than those estimated for the polywell (1E19 electrons/m^3) this idea seems like a long shot. Moreover, ICF is going this route - and from that work we know compressing plasma to this density requires a great deal of energy. The polywell may need to go in a fundamentally different direction.



Idea: If the plasma density reaches beyond the critical density, X-ray losses may be reduced because of internal reflection.

18. The Cage and Arching

A spark between the cage and the rings will kill the polywell. It can't spark. In his Google talk, Bussard presented this as an important "engineering problem" for the polywell. He also stated that this occurred at the end of his experiment [8]. This is predicted by modeling here. Sparking in gases was well studied in the first half of the 20th century. Sparking depends on the medium, the gap, the temperature, the voltage, the surfaces and the pressure [22, 23]. There are multiple physical mechanisms for sparking. The simplest is the electron avalanche. When one free electron strikes an atom, it can kick off a second electron. This turns the atom into an ion and doubles the number of electrons. These two electrons can then double as more atoms are ionized, and this effect builds quickly into an electron filled spark. Theoretically, this will never happen in a perfect vacuum, because matter is needed to carry electric charge [21]. Paschen's law helps predict at what voltage this will occur.

Using this law, we can get a rough estimate if wither sparking was a problem for WB-6. A practical equation and useful data for this calculation was found in reference [24], from NASA. The equation is applied to gap between the rings and the cage. This equation disagrees with the one listed in wikipedia. This is shown below, along with useful constants for different materials and gases.

$$\textbf{Voltage[volts]} = \frac{\textbf{B * Pressure[Torr] * Distance[mm]}}{\textbf{Ln}\left(\dfrac{\textbf{A * Pressure[torr] * Distance[mm]}}{\textbf{Ln}\left(\dfrac{\textbf{1}}{\textbf{Gas} - \textbf{Metal Coefficent}}\right)}\right)}$$

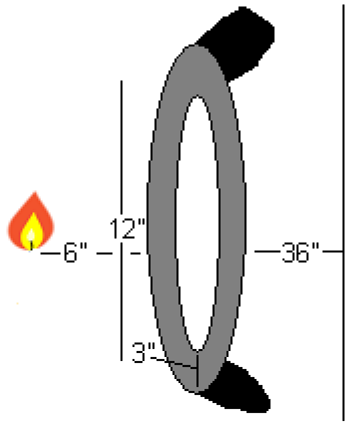
	A	B		Gas-Metal Coefficent			
Air	14.6	365		Hydrogen	Helium	Air	Nitrogen
Hydrogen	5	130	Aluminum	0.095	0.021	0.035	0.100
Nitrogen	12.39	342	Copper	0.050		0.025	0.066
Water	12.9	289	Iron	0.061	0.015	0.020	0.059
Helium	2.8	34	Nickel	0.053	0.019	0.036	0.077

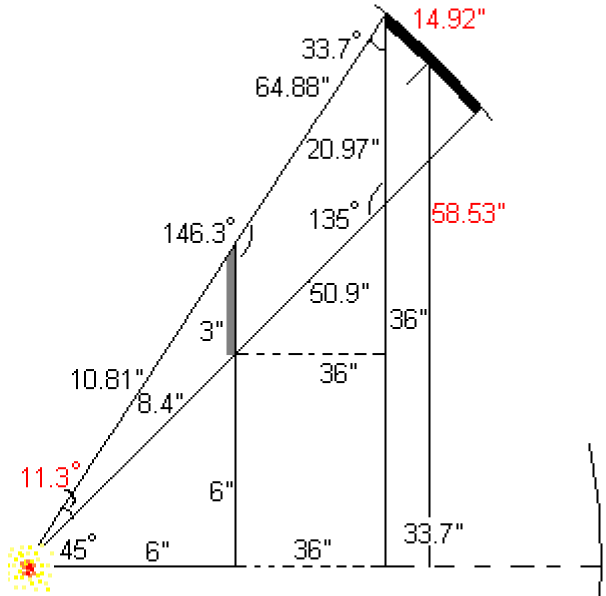
Previously, [25] it was found that the rings could be made from stainless steel. This is modeled as a combination of nickel (10%) and iron (90%). The deuterium gas is treated like hydrogen. This model predicts that sparking between the cage and the rings will occur, as Bussard stated it did.

Gap:	508	mm
	Breakdown Voltage:	
Pressures (torr):	**1.E-07**	**3.E-04**
Air - Copper	-2.E-03	-110.0
Air - Iron	-2.E-03	-98.6
Air - Nickel	-2.E-03	-138.6
Air - Aluminum	-2.E-03	-135.7
Air - S.S. est.	-2.E-03	-102.2
H2 - Copper	-7.E-04	-14.5
H2 - Iron	-7.E-04	-15.2
H2 - Nickel	-7.E-04	-14.7
H2 - Aluminum	-7.E-04	-17.6
H2 - S.S. est.	-7.E-04	-15.2

19. X-ray Illumination

In order to calculate the Polywells ability to reflect x-rays we need to know: what is the maximum fraction of X-rays we can hope to reflect? Some of the x-rays coming off the center will hit the rings. For now, assume we cannot reflect these. So, what remaining percent of light hits the walls? This problem was simplified to just a point source shining on a flat 12" ring, six inches away. The ring casts a shadow on a sphere, which is 75.7" in radius. Using trigonometry you can find that the surface area cast in shadow is 5,487 square inches for just one ring. You can also find that the total area of the circle of that radius is 72,011 square inches. Hence, when all six rings are considered together, the percentage of chamber walls illuminated by the x-rays was about 54.2 percent. This was surprising low. It seems that shadows cast by the rings cover quite a large proportion of the reactor chamber. A diagram with the distances used and a sketch of the problem is included here.

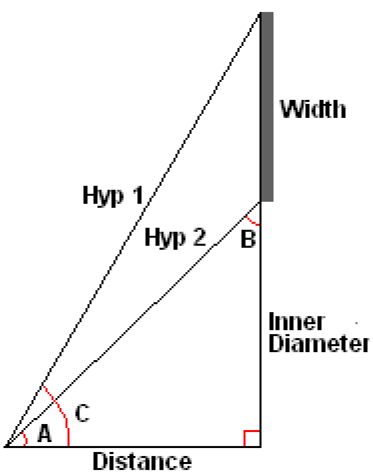




$$\frac{75.7''}{\text{Sin}(90)} = \frac{58.53}{\sin(50.65)}$$

Shadow Aera ≈ 14.92"*2*π*58.53 = 5487 inch^2 * 6 Rings = 32925inch^2
All Aera = (75.7")^2 * 4 * π = 72011 Inch^2

How does this change, when we change the geometry? Unfortunately, just increasing the chamber size always yields the same 54.2 percent. In this model, making a bigger or smaller chamber has no effect on the percentage of X-rays hitting the walls. Even though the shadow gets larger as you increase the chamber size, the percentage always stays the same. The key then is to move the rings relative to the fusing cloud in the center. To keep it simple, assume the light is always in the middle of the rings. A formula derived from this setup predicts how different geometries will change the percentage of x-rays hitting the walls. The model predicts what you may expect. The farther away the rings are from the center, the less x-rays hit the rings and the thinner the rings are the less x-rays hit the rings.



$$\text{Hyp 1} = \sqrt{(\text{Inner Diameter} + \text{Width})^2 + \text{Distance}^2}$$

$$C = \text{Sin}^{-1}\left[\frac{\text{Width} + \text{Inner Diameter}}{\left(\frac{\text{Hyp 1}}{\text{Sin}(90)}\right)}\right]$$

$$\text{Hyp 2} = \sqrt{\text{Inner Diameter}^2 + \text{Distance}^2}$$

$$A = \text{Sin}^{-1}\left[\frac{\text{Inner Diameter}}{\left(\frac{\text{Hyp 2}}{\text{Sin}(90)}\right)}\right]$$

$$\text{Angle} = C - A$$

Device	% Rays Hit Wall	Device	% Rays Hit Wall
1 foot, 3 in Rings	54.2%	6 feet, 6 in Rings	83.1%
2 feet, 3 in Rings	75.3%	6 feet, 8 in Rings	77.8%
2 feet, 4 in Rings	67.8%	10 feet, 4 in Rings	93.1%
3 feet, 1 in Rings	94.2%	10 feet, 6 in Rings	89.7%
3 feet, 4 in Rings	77.8%	10 feet, 10 in Rings	83.1%
3 feet, 6 in Rings	67.8%	12 feet, 8 in Rings	88.6%
6 feet, 4 in Rings	88.6%	12 feet, 10 in Rings	85.8%

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