"Curve jumping is when innovations are not 10% better – they are ten times better." – Guy Kawasaki

Simulating WB6

The economist can suck it. Their article [36] "Dwindling Innovation" (Jan 22nd 2013) whined about the lack of true inventions. Most inventions are corporate backed, whiz bang gadgets. They complained: world has lost its tinkers, its new ideas. There is a dearth of really astounding inventions like electricity or the combustion engine. It was enraging to read.

In reality, there is a vast sea of ideas out there. These ideas come and go. Some gain traction, some wither and die. All new technology destroys old technology. Often, there is no space for a new idea, if an old idea refuses to get out of the way. That is what is needed in fusion. Old ideas need to move out of the way.

Some ideas are 40 years old. For fusion, there is a multitude of fresher, simpler and cheaper schemes out there. They are not ten percent better. They are ten times better. They represent a curve jump - and it is only a matter of time, before they gain prominence.

Executive Summary

This post reviews what is needed for a comprehensive simulation of the polywell. It has four sections: using WB6 as a benchmark, analytical expressions, the magnetic field in WB6 and the particle-in-cell method. Any code is first validated by duplicating the WB6 results. The machine is outline, including: the geometry, power supply, feedstock and diagnostics. Operation is summarized in five steps: tank pump down, applying the cage field, electron trapping, gas puffing and the neutrons produced. The electron emitter and beam are modeled. Beam speed is strongly controlled by emitter placement and this impacts trapping. Regardless of emitter placement, the magnetic will overpower the electric field. Energy loss from the beam is shown to be insignificant. Estimates of the field at the joint, corner and axis show that ring design emphasizes uniform containment. The axis and corner fields are close in value. The number of electron trapped is estimated. The magnetic field model for one ring of WB6 is encoded into Excel and MATLAB. The excel model required using a trapezoid approximation. Excel and MATLAB are compared against simple estimates and WB6 data, for benchmarking. Vector and energy density plots for a single ring, are generated.

The ring field is similar to the field made by two a-like poles placed close together. Therefore, the field points outward everywhere except through the rings themselves and the energy density is higher in machine center. It is suggested: that proper containment may balance the outward pointing fields and the magnetic mirror effect. This is not proven. The mathematical expression for all six rings is encoded into Excel and MATLAB. The field is modeled along three particle paths into machine center. These results are compared with

expectations, estimates, single ring models and WB6 data for benchmarking. Vector and energy density plots for six rings are generated. Typical geometry, time steps and particles needed for a particle in cell simulation are given. The ion to electron ratio for WB6 is estimated at 0.98. The post concludes with nine suggestions for future work.

"…. I can't help but wonder if IEC just might be the key to practical fusion power….These thoughts were painful to formulate. As a past leader of the U.S. federal fusion program, I played a significant role in establishing tokamak research to the U.S., and I had high hopes for its success…" - Dr. Robert Hirsche, 10/16/2012

News Updates:

After posting "Executive Summaries For Every Post" just before Thanksgiving, efforts shifted to the YouTube film: "The Polywell, Explained in 15 minutes." The film is based heavily on the posts: "How it works" and "The Physical Basis for the Polywell." Some of the concepts discussed there are featured in this work. In December, efforts shifted to creating: "Homage to the fusioneer". Hundreds of clips and still photos of fusion research over the past 60 years was collected. Collection was limited by what was available; so some ideas are not featured enough and others are featured too heavily. It is not perfect.

The film covers the history of fusion research in 5 minutes. It opens with a visual argument for fusion. This is based on four points: reliance on declining oil coal and gas supplies, wealth transfer to petro dictatorships, the loss of biodiversity and disruptive climate change. The film presents work related to: early atomic research, the perhapstron, cyclotrons, magnetic mirrors, Z-pinch machines, tokomaks, cold fusion, fusors, inertial confinement fusion, focus fusion, polywells and lithium compression. There is also a cursory reference to the failed bubble fusion effort. Not featured was efforts at Tri Alpha Energy Inc, as content was unavailable. The film is dedicated to fusioneers: both professional and amateur, mainstream and fringe; anyone that seeks to change the world with fusion power.

Events in the Polywell world have continued: in late October, Mark Suppes presented at the wired conference in London and the Talk-Polywell forum passed half a million registrants. In November, news surfaced on the internet that Iran had allocated 8 million to the Polywell. I am high skeptical of this. It may not be true. In January, this blog got its first hits from China. In February, Mr. Mitchel James posted on his latest efforts to get experimental work started at the National labs. He writes that he has submitted a proposal and met with folks at Sandia. This is through their "work for others" program. There may be an attempt to crowd fund his efforts. This community continues to grow. We need to communicate and work together positively. It is the best way forward. Enjoy.

Part 1: The WB6 Experiment

This post examines simulating the Polywell. All good simulations begin with a benchmark. The code must first duplicate a real world test. The test to simulate - is Bussards' WB6 results from November 10th 2005.

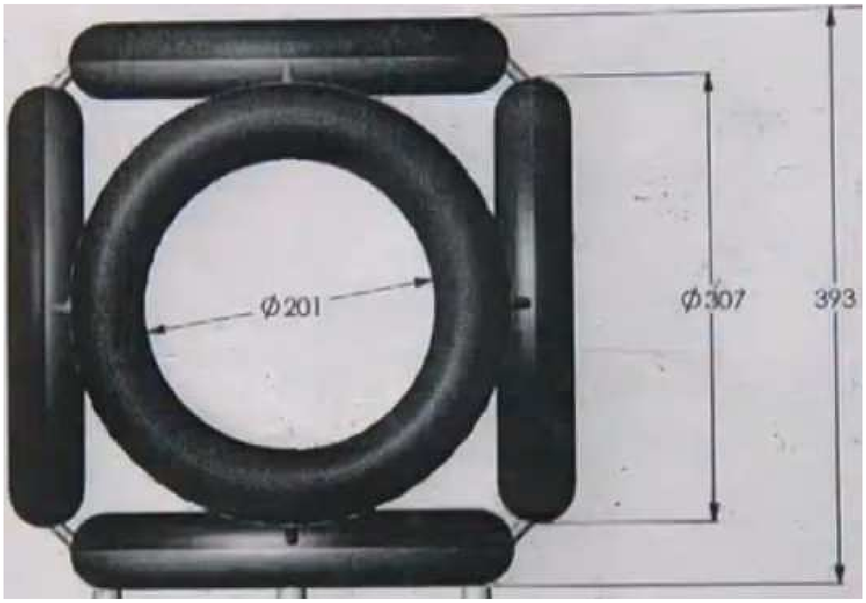


Figure 1: A blueprint of the ring structure in WB6. It is assumed these are meter distances.

Machine Geometry:

The ring geometry comes from a blueprint in Bussards' Google presentation [14]. The tank volume comes from Bussards Google presentation [14] and Mark Duncan's summary [16, page 15]. The tank had a two meter diameter and was 3.5 meters length. Inside the tank was a wire cage which is modeled as 3' 8" side. The size of wire cage is an estimate; based on the machine photos. Such a cage would fit inside the tank comfortably.

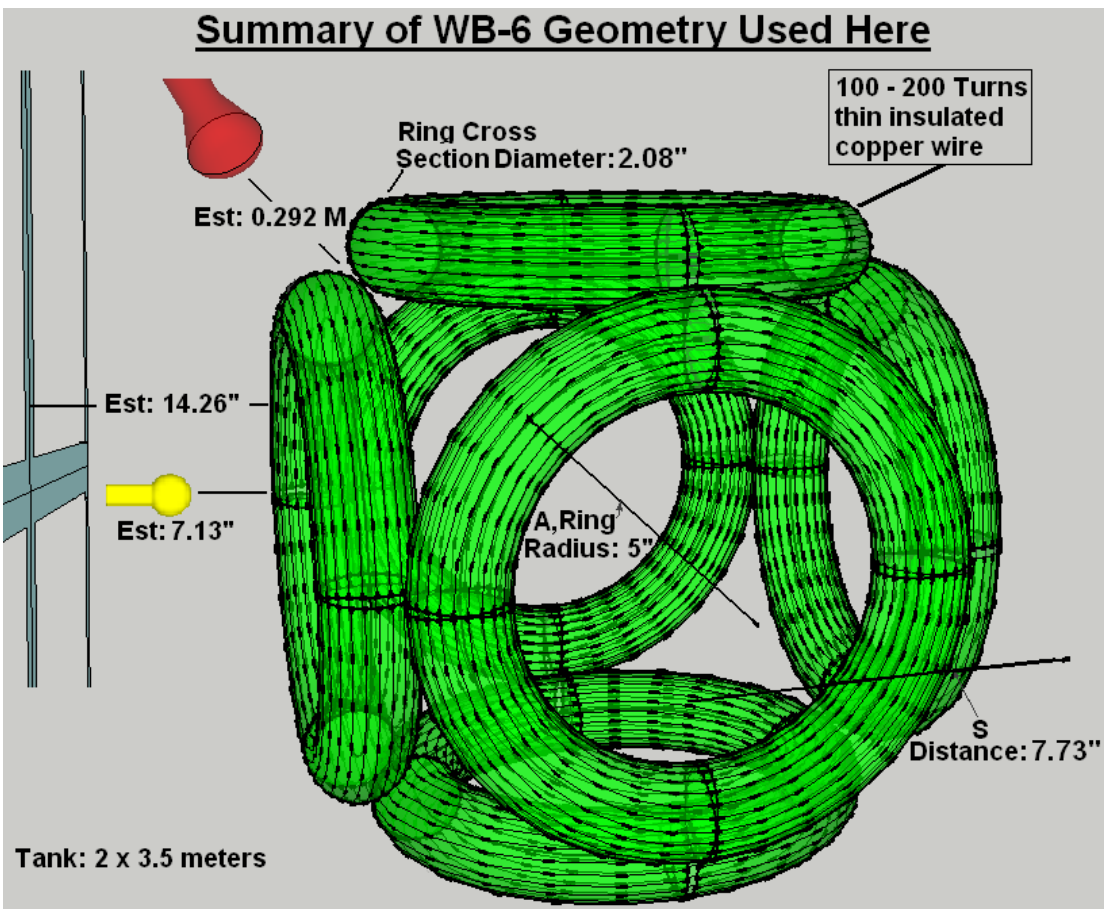


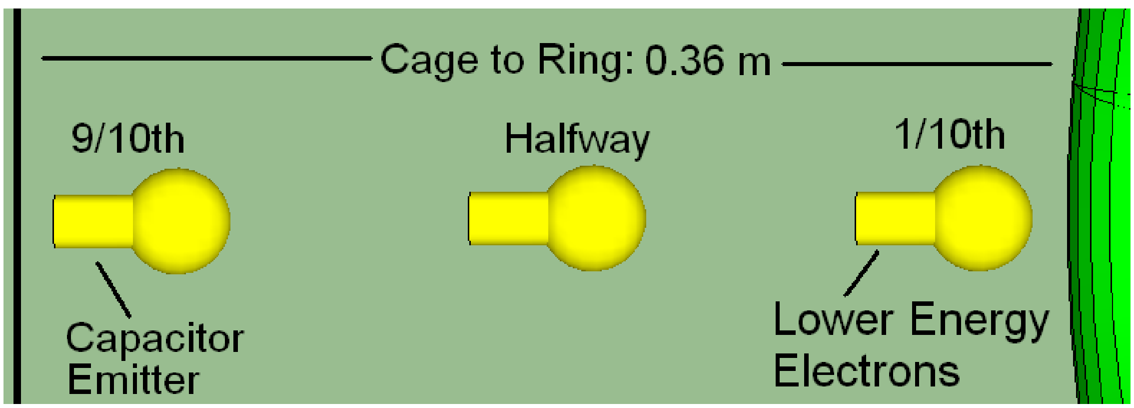
Figure 2: This shows the geometry of the machine used in this document. The red device represents the gas puffer tube. This is located at the corners of the rings. The yellow device represents the capacitor emitter this is located on the ring axis.

Ring Power Supply:

One long wire is wrapped through all six rings and was connected to 240 batteries [16]. These RV batteries will be modeled as having twelve volts and one hundred amps of current in each. This kind of battery is common [32]. These batteries were most likely wired in series. This makes a high voltage, low current source. This arrangement will use up electricity faster. But, this is ideal for a pulsed machine. This power source is superior for thin wire, many looped electromagnet [17]. Two hundred loops of No. 10 copper wire would fit easily inside the ring cross section [33]. The rings may have had between one and two hundred turns [31]. The rings were supplied with a current that ramped from zero to 4,000 amps. The number of amp turns was between 20,000 and 800,000. This is a critical number. The rings are mainly modeled here as having 20K amp turns.

The Emitter:

A capacitor electron emitter was used in the WB6 tests. In this work, the capacitor is placed halfway between the rings and the cage. The capacitors discharged between 0 and 40 amps of electrons.



The Gas Puffer:

Four gas puffers were used in the test [photos]. These consisted of long tube spaced out from the corners of the rings. It is estimated here that they were 0.292 meters from the ring center [photos]. About 4.5E-6 moles of gas was puffed into the cage [Estimated below]. This is a tiny amount. The gas entered the machine at 0.04 Pa [2, page 11]. This gas was likely depressurized from a high pressure (tens of atmospheres) feedstock [24]. Bussard estimated that the gas had a number density of one atom in 1e-19 cubic meters [2]. The amount of gas used was estimated using the ideal gas law and listed tank pressures [2, page 12].

$$P_{Start} V_{Start} = Moles_{Start} * R * T_{Start} \longrightarrow 1.33E-5Pa * 11 M\text{^}3 = Moles_{Start} * 8.3144 * 293\,K$$

$$Moles_{Start} = 6.0E-8 \text{ mole of air in tank at start}$$

$$P_{End} V_{End} = (Moles_{Start} + Moles_{added}) * R * T_{Start} \longrightarrow 0.011 = (6.0E-8 + Moles_{added}) * 8.3144 * 293K$$

$$Moles_{Added} = 4.5E-6 \text{ Moles of } D_2 \text{ Gas Puffed In}$$

$$\text{Gas Molecules} = Moles_{Added} * 6.0221E23 \qquad \text{Gas Molecules} = 2.7E18 \text{ Molecules}$$

$$\text{Possible Ions} = 2 * \text{Gas Molecules} \qquad \text{Possible Ions} = 5.4E18 \text{ Ions Possible}$$

The Neutron Detectors:

Two neutron detectors were used. These detectors could only record a portion of all the neutrons produced. This is related to the area they occupy on the chamber walls. Hence, the amount of neutrons produced in the test was extrapolated; from data for a single detector (Google presentation, 54:10).

The Experiment:

The experiment occurred in five distinct steps. First, the tank was pumped down to a starting pressure of 1.33E-5 Pa. About 6E-8 moles of air was in the tank at the beginning. Next, a potential of 12,500 volts between the cage and the rings was applied. Note: this voltage was described in the Google presentation as 12 kV. The capacitor emitters were switched on after this - at 40 amps for ~0.0005 seconds. The emitted electrons flew towards the rings. The magnetic Lorentz force overtook the electric Lorentz force and the electrons started following the magnetic fields [Estimated here]. The magnetic field generally pointed outward. The electrons recirculated along this field into the cusps. There, they hit magnetic mirror. This reflects them back into the machine. This trapped a cloud of electrons. This cloud generated a potential of 10,000 volts from the gas puffer to the center.

Roughly 1.2 to 1.5 E12 net electrons were trapped to create this drop [estimated here]. The electron lifetime was on average 1E7 seconds [Google presentation 44:50, 16, 2, page 12]. Bussard estimated that the electrons had a number density of 1E19 electrons/meters^3 [2]. This is the same as the gas. The electrons had a bell curve of energy. This was between 0 and 12,500 eV with an average of ~2,500 eV [2]. The electrons had an average velocity of between 1 and 4E7 meters per second [2, Google presentation (45:00)]. Bussard estimated that the electrons feel a 1,000 gauss containment field. These estimates were used in Bussards beta ratio calculation. Mark Duncan's work lists the WB6 strength as 1,300 Gauss, Dan Tibbets uses 1,000 gauss and the IAF paper said this is under 3,000 gauss [16, 31, 2 page 10]. However, it is unclear where in this field strength is calculated.

$$Beta_{electron} = 1 \rightarrow \frac{\text{Magnetic Field}^2}{2 * \text{Magnetic Constant}} = Density_{electrons} * K_{Boltzmann} * \text{Temperature}$$

$$Density_{electrons} = \frac{(1{,}000 \text{ Gauss})^2}{2 * 1.3806E-23 \, {}^{m^2Kg}\!/\!_{s^2K} * 2.9E7\,K * 1.2566E-6 \, {}^{M*Kg}\!/\!_{s^2A^2}}$$

$$Density_{electrons} = 9.94E18 \, {}^{Electrons}\!/\!_{Meter^3}$$

In the last step of operation: uncharged deuterium gas is puffed in at room temperature (0.02 eV). Because it is neutral it is not affected by the cage voltage. It can therefore reach the rings without trouble. About 2.7E+18 molecules of deuterium gas were puffed into the chamber. Because the ring structure only represented ~0.002 percent of the tank volume, there is good reason to think most of this gas did not enter the rings. When the gas reaches the edges of the electron cloud it exchanges energy with the electrons. If this exchange causes the molecule to heat up past ~16 eV, they break apart into two electrons and two deuterium ions. The ions see the 10,000 volt drop and fly towards the center building up speed. The ion is 35,461 times the diameter of the electrons and 3,626 times the mass of the electron [8, 9, 28, 29]. If two ions hit in the center, at 10 KeV, they may fuse. The product contains energy on the order of ~10 MeV. It has too much energy to be contained by the fields. It rapidly leaves the ring structure.

Bussard reported a total of ~2E5 neutrons were generated over the 0.0004 seconds of the test [2, page 11]. Note: Bussard states the test was 0.00025 seconds in his presentation (53:50) and 0.0004 seconds in his IAF paper. 0.0004 is more consistent with other information. For every neutron detected, four deuterium ions fused and two fusion reactions occurred. This means that a rate of ~1E9 fusions per second was produced (Google presentation 54:03, IAF paper, page 11). This also means 800,000 deuterium ions were fused. This is a tiny fraction of the deuterium atoms injected.

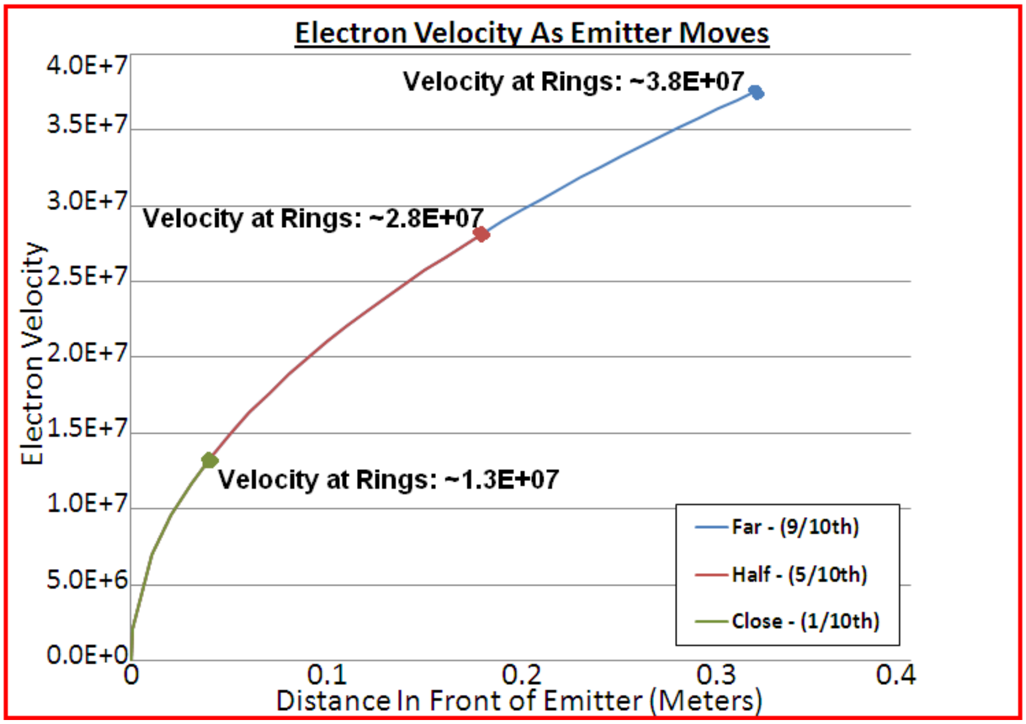
Part 2: Useful Analytical Models

Modeling Emitter Placement:

The electron speed depends heavily on where the emitter sits. Moving the emitter closer to the rings makes for lower energy electrons. The speed is one percent of the speed of light. This means that classical laws can be used to model the electron motion. These equations and a plot of electron velocity relative to emitter spacing is shown below.

$$\text{Acceleration} = \frac{12{,}500\ \text{volts} * 1.602E-19\ \text{columbs}}{9.109E-31\text{Kg}} = 2.2E15\ \frac{M}{S^2}$$

$$\text{Velocity}_{\text{Final}} = \sqrt{\text{Velocity}_0^2 + 2 * \text{acceleration} * \text{distance}}$$



This model assumes the electrons start with zero velocity. For the plot, the emitter was placed: far away (9/10th the distance), halfway and close (1/10th the distance) to the rings. The distance from the cage to the rings is 0.36 meters.

<u>Electron Beam Energy Loss:</u>

Every time a particle speeds up or slows down it loses energy as light. This can be predicted using the Larmor formula. This formula can be applied to the electron beam. The loss is insignificant.

$$\text{Power}_{\text{Loss}} = \frac{\text{Charge}^2 * \text{Acceleration}^2}{6 * \pi * \text{Electric Const} * \text{Speed of light}^3}$$

$$= 2.8E-23\ \frac{\text{Joules}}{\text{Second}} \quad \text{or} \quad \sim 3.8E\text{-}6\%\ \text{The Kinetic Energy}$$

<u>Modeling Electron Capture:</u>

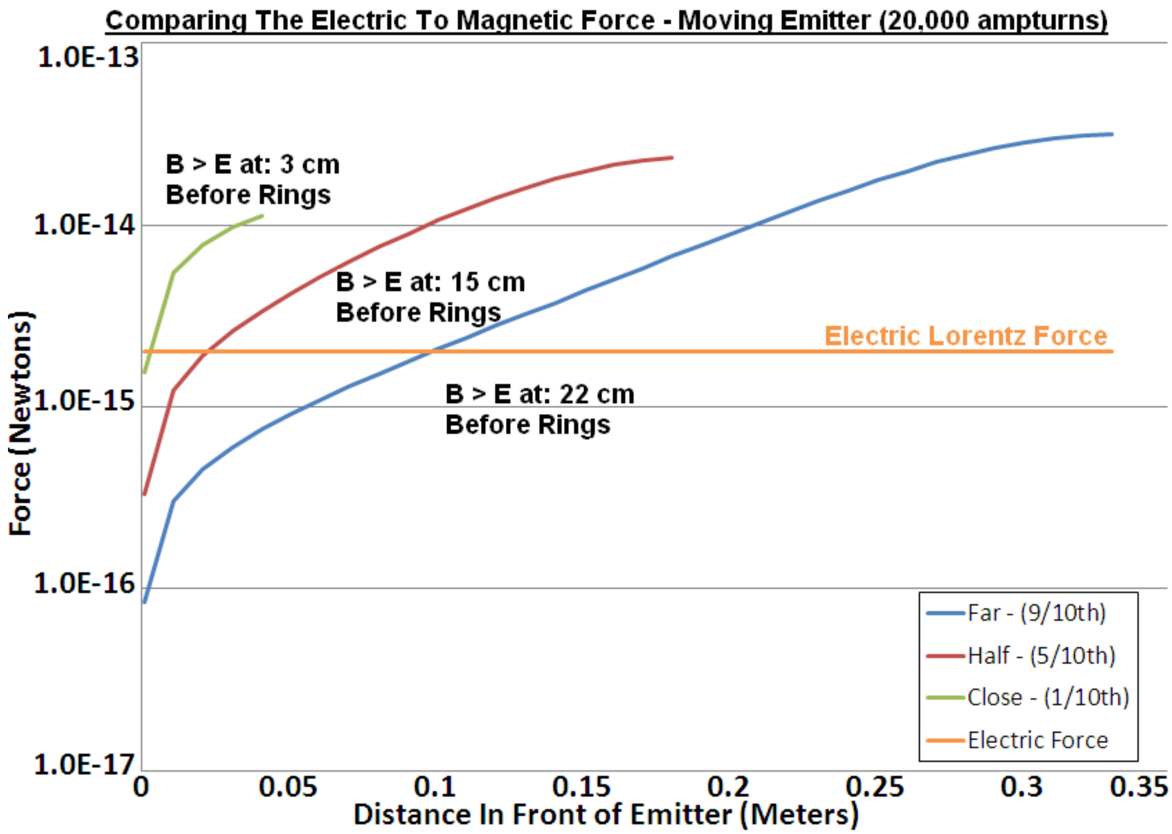
No matter where the emitter is placed – the rings should capture the emitted electrons. This is modeled by comparing the magnetic and electric Lorentz force. In all cases modeled here the magnetic overtakes the electric force. This model is only valid at the beginning of operations. Because the magnetic force is a cross product, it is the slower moving electrons are lost. This may imply that by moving the emitter further away, electron trapping improves.

This model is done iteratively, as the electrons move closer to the rings. The magnetic field is modeled directly on axis [21]. The equations used are shown below. As the emitter moves closer it experiences a higher magnetic field. It is assumed there is a three degree difference between the velocity and magnetic field vectors. This angle is important. The magnetic force is a vector cross product. If the magnetic and velocity vectors were pointed in the same direction – there would be no magnetic force. A plot comparing the magnetic and electric forces is given below. In all cases - the magnetic overtakes the electric force. This result is the same if the angle was one degree or if the magnetic fields increase.

$$\text{B Field}_{\text{Axis}} = \frac{\mu_0}{4\pi}\frac{2 * \pi * \text{Ring Radius}^2 \text{Turns(200)} * \text{Current (100 Amps)}}{(\text{Distance To Ring}^2 + \text{Ring Radius}^2)^{3/2}}$$

$$\text{Force}_{\text{Electric}} = \text{Charge} * \text{12,500 Volts}$$

$$\text{Force}_{\text{Magnetic}} = \text{Charge} * \text{Velocity} * \text{B Field}_{\text{Axis}} * \text{Sin}(3^0)$$



Modeling Moving Rings:

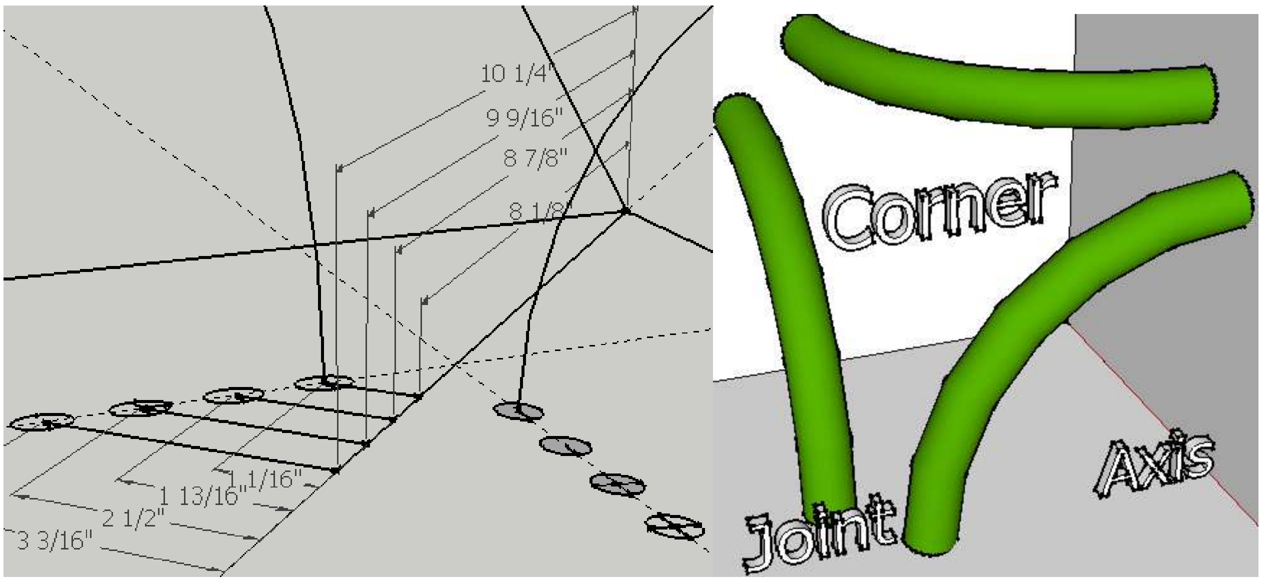
The rings are spaced so the containment field is more uniform. The field strength at the corner and on the axis, is close in value. This can be shown using simple equations for the magnetic field. The field can be modeled at four points of interest: the joint, corner, axis and center. The Biot-Savart law can be applied [11] to each location for simple estimates. These equations are shown below. This is a quick and valuable way to check any magnetic modeling of the Polywell.

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

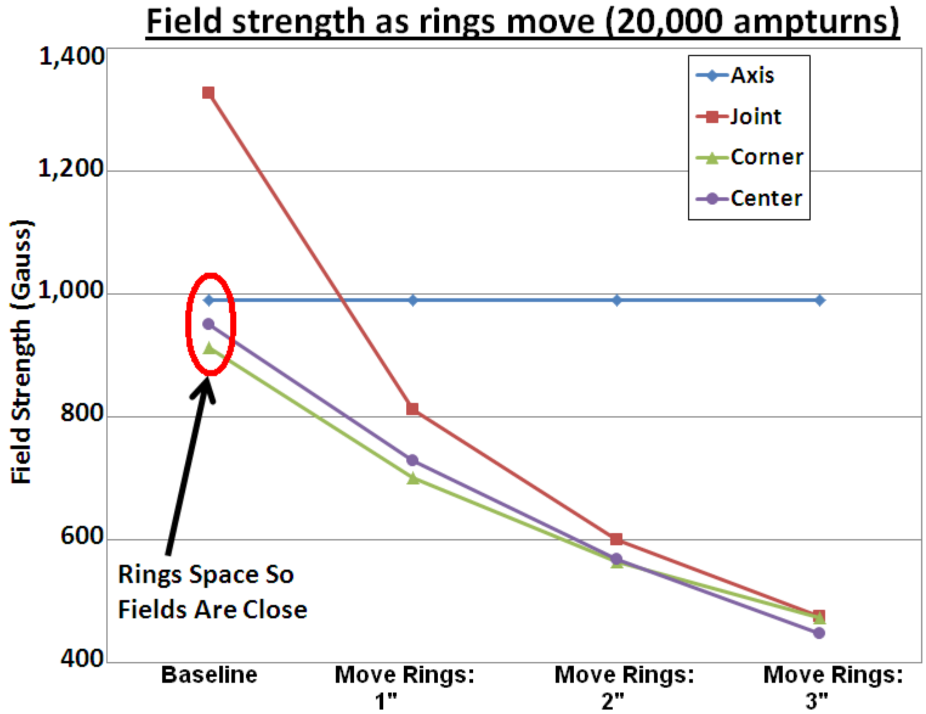
$$\text{Magnetic Field}_{\text{Joint,}} = \frac{2 * \mu_0 * \text{Current} * \text{Turns} * \sin(90) * 1 * \text{Distance to Ring}}{4 * \pi * \text{Distance to Ring}^2}$$

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

$$\text{Magnetic Field}_{\text{Center}} = \frac{6 * \mu_0 * 2 * \pi * \text{Current} * \text{Turns} * \text{Ring Radius}^2}{4 * \pi * \left(\text{Distance to Ring}^2 + \text{Ring Radius}^2\right)^{3/2}}$$



Using these simple equations, a model for the magnetic field strength is made. This is used as the rings move. These values are plotted below for 20,000 amp turns. The plot is identical if 800K amp turns were used. In that case, the joint strength is ~55K gauss and the corner, center and axis are all ~40K gauss. It is clear: the rings were spaced and designed to make a uniform containment field.



Number Of Electrons Trapped:

Either gausses law or coulombs law can be used to find how many electrons are in the center. The key inputs are the voltage drop (10 kV) and the distance at which it is measured. There is no indication that a Langmuir probe was used to measure the voltage drop. The drop must have been estimated. The distance therefore, is taken from where the deuterium ions form. This spot to ring center is 0.201 ± 0.017 meters. From this, coulomb's' law predicts between 1.5 and 1.2E12 net electrons.

$$\textbf{Coulombs Law} \Rightarrow \textbf{Voltage} = \frac{\textbf{8.98E9 * Net Charge in Center}}{\textbf{Radius}}$$

$$\textbf{10,000 volts} = \frac{\textbf{8.98E9 * Net Number of Electrons * 1.602E} - \textbf{19 Columbs}}{\textbf{0.201} \pm \textbf{0.017 m}}$$

Single Ring Magnetic Field:

The Sydney paper [35] models the magnetic field as a superposition of six, single ring fields. The field from a single of current can be predicted mathematically. This expression is found in reference [15] a classical physics textbook. It is an equation in polar coordinates (Z, Rho). This is written out below.

$$Z = |\text{Distance from ring}|$$

$$\rho = |\text{Distance from Centerline}|$$

$$M = \frac{4*0.127*\rho}{Z^2 + (0.127+\rho)^2} \qquad K(M) = \int_0^{\pi/2} \frac{d\theta}{(1-M*\sin^2\theta)^{1/2}} \quad 0 < M < 1$$

$$E(M) = \int_0^{\pi/2} (1-M*\sin^2\theta)^{1/2}\, d\theta \quad 0 < M < 1$$

$$B_{Radially} = \frac{\mu_0 * Current * Turns * Z}{2*Pi} \sqrt{\frac{M}{4*0.127*\rho^3}} \left[\frac{2-M}{2-2M} E(M) - K(M)\right]$$

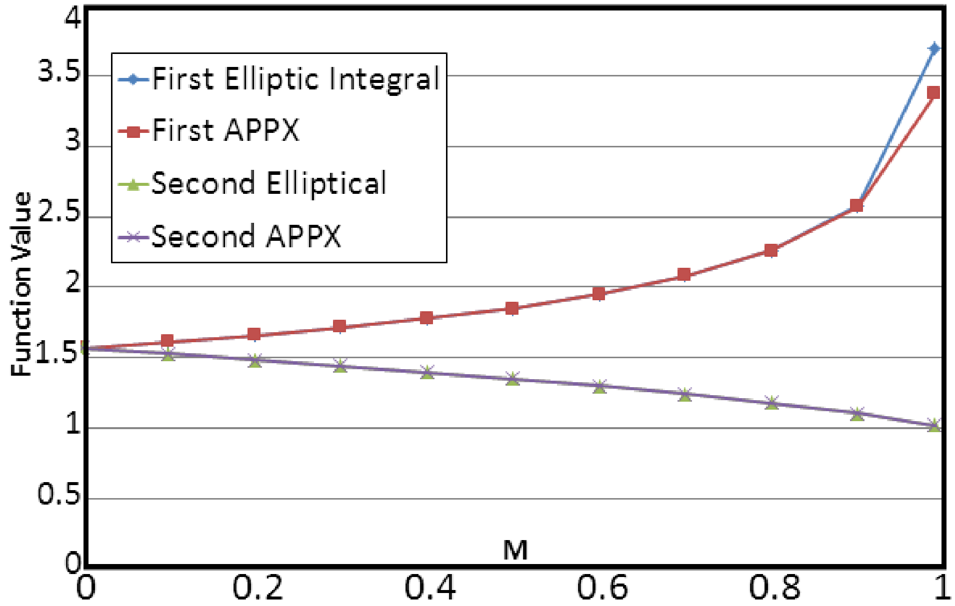
$$B_{Z-Direction} = \frac{\mu_0 * Current * Turns}{2*Pi} \sqrt{\frac{M}{4*0.127*\rho^3}} \left[\rho * K(M) + \frac{0.127*M - \rho(2-M)}{2-2M} E(M)\right]$$

In these equations, K and E are the complete elliptical integral of the first and second kind. They are difficult to deal with. They arise from ellipses. They are the arch length of an ellipse. They had to be looked up [25]. This math required that Z and rho had to be greater than zero and below one. This meant that absolute values were used. Additionally, this function cannot handle zero. When this occurred, these results were set to zero.

<u>Trapezoid Approximation In Excel:</u>

An excel model was created. The equations were easy to enter into a spreadsheet but the elliptical integrals had no function. To compute them, a simple approximation was needed. This was found [25]. The approximation estimated the elliptical integrals using the trapezoidal rule. This is done out to four terms. It is valid to three decimal places. The estimate is compared to the real values below. The difference is a problem at high field strengths. This happens at the joints. There will be a difference between Excel and MATLAB estimates at the joints.

The Trapezoid Approximation For The Elliptical Integrals



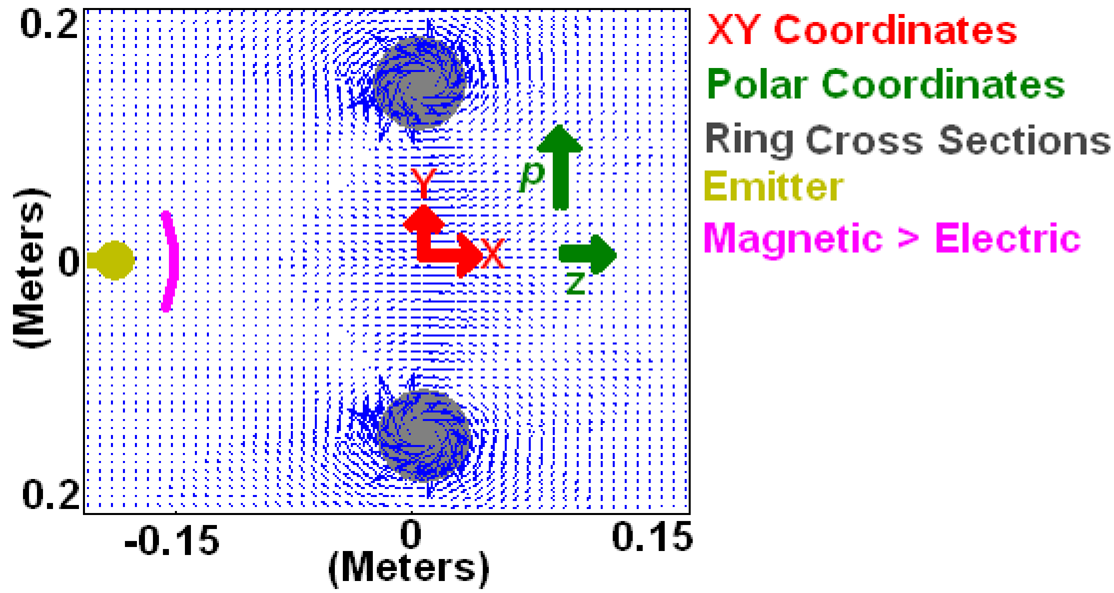
$$K(M) = \int_0^{\pi/2} \frac{d\theta}{(1 - M^* \sin^2\theta)^{1/2}} \approx 0.125\pi\left[\frac{1}{\sqrt{1-m\sin^2(0.435\pi)}} + \frac{1}{\sqrt{1-m\sin^2(0.3125\pi)}} + \frac{1}{\sqrt{1-m\sin^2(0.1875\pi)}} + \frac{1}{\sqrt{1-m\sin^2(0.0625\pi)}}\right]$$

$$E(M) = \int_0^{\pi/2} (1 - M^* \sin^2\theta)^{1/2}\, d\theta \approx 0.125\pi\left[\sqrt{1 - m\sin^2(0.435\pi)} + \sqrt{1 - m\sin^2(0.3125\pi)} + \sqrt{1 - m\sin^2(0.1875\pi)} + \sqrt{1 - m\sin^2(0.0625\pi)}\right]$$

MATLAB Model Of Single Ring:

A MATLAB model was also created. The program can solve the elliptic integrals with the command [K, E] = ellipke(M). This code gave the field for a single ring at any X Y and Z coordinates. From this code a vector field was generated. This is included below for the XY plane around a single isolated ring. As expected: the field swirls around the ring of current. The field generally points from left to right. The strength crests when the particle passes through ring center. On the right side the Y fields point away from the axis. I hope to upload this code online for others to use.

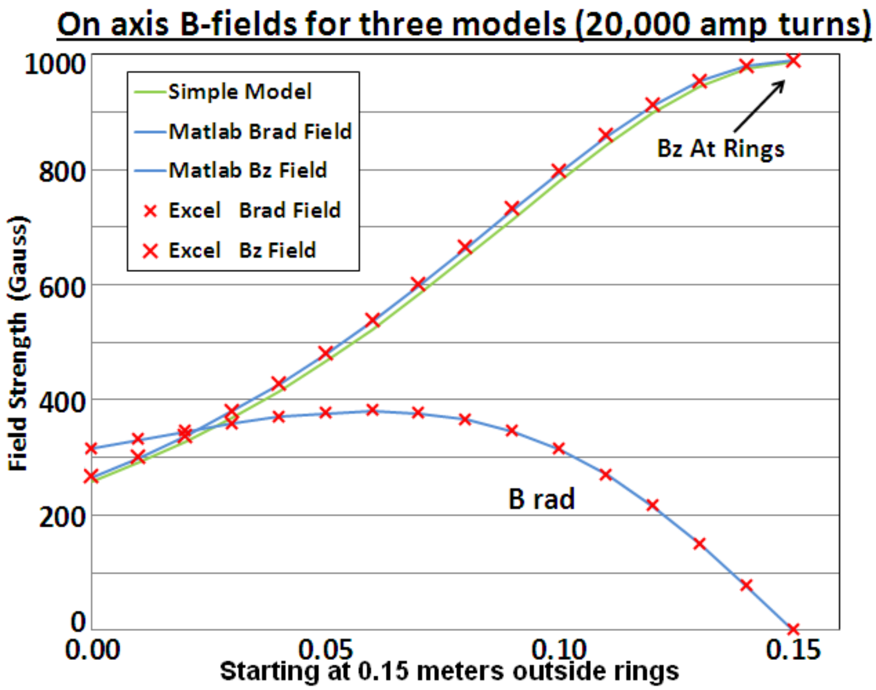
Vectors in a XY plane, for a single ring



Verifying Excel and MATLAB:

Both codes needed to be verified. Simple math is the best way to do this. The fields are modeled for a particle flying on axis towards one ring. There are five methods for calculating this field. The first is a simple calculator provided by hyper physics [21] and this is plotted below. The second is Bussards' estimation of ~1,000 gauss [2] inside the machine. The third is simple estimates from the "moving the rings" section. The last two methods are the Excel and MATLAB codes. For verification: each method should yield similar results.

Each of the five methods are plotted below. The models agree. The simple model plotted is the magnetic field calculated on axis [21]. One new result was the MATLAB and Excel codes show a radial field. This a reasonable result. The field generates the swirling vectors around the rings. This is symmetric around the axis so it could be in the Y or Z plane. This field causes the electrons to corkscrew as they approach the rings [34]. Beyond this, any prediction of electron motion is limited by electron-electron interactions.



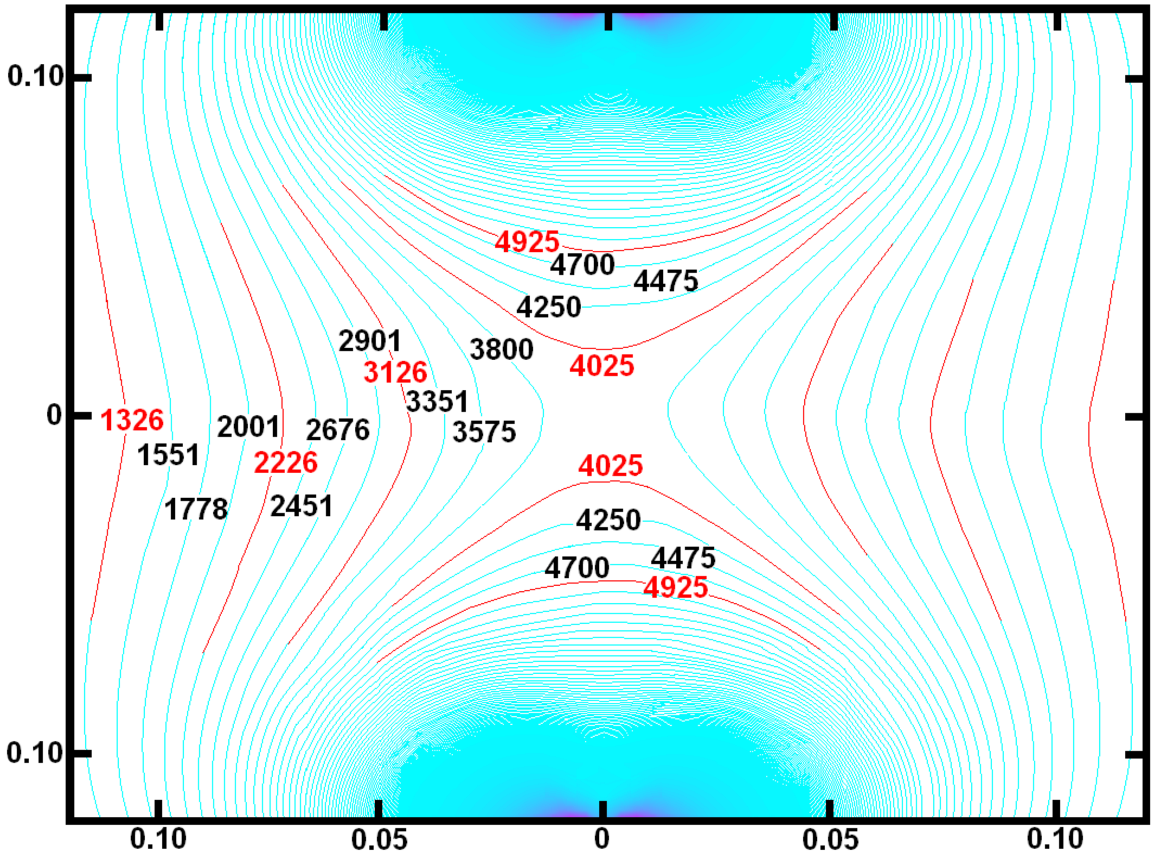
Energy Density Analysis

If you combine the electric and magnetic fields, you can make a total "energy density map" for the system. The equation used for this is shown below and typical numbers are shown for a single ring. Note that the equation requires magnetic field values in Teslas. The B field used is the average of the radial and z directed fields.

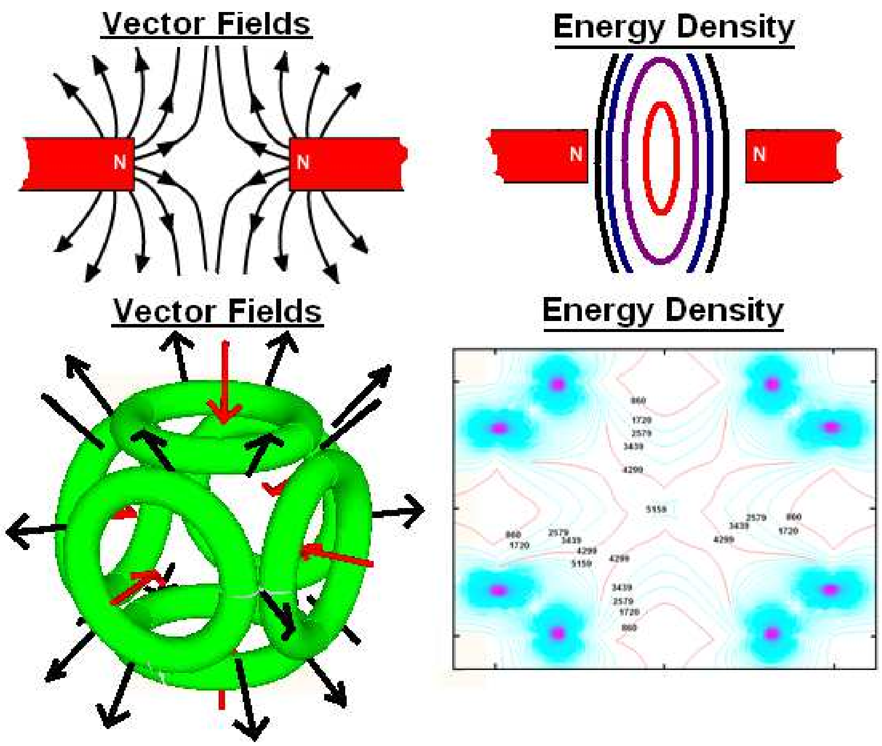
$$\text{Energy Density} = \frac{\text{Electric Constant}}{2} * \text{Electric Field}^2 + \frac{1}{2 * \text{Magnetic Constant}} * \text{Magnetic Field}^2$$

$$\text{Energy Density} = \frac{8.85\text{E-}12}{2} * \left(\frac{12{,}500 \text{ volts}}{0.36 \text{ Meters}}\right)^2 + \frac{1}{2 * 1.25\text{E-}6} * 0.0989^2 = 3912 \frac{\text{Joules}}{\text{Meter}^3}$$

Energy density contours (J/M³) for a single ring (20,000 Amp*Turns)



The energy density is almost entirely driven by the magnetic field. The electric field makes essentially no contribution. Above is a contour plot of the energy density generated by a single ring of current. The contours and values are shown for 20K amp turns. This indicates that the energy density values vary up to ~5,000 joules per cubic meter. The contour plot looks the same for 800K amp turns, except there the energy varies up to ~7.8 million joules per cubic meter.



Part 3: The Complete Magnetic Field

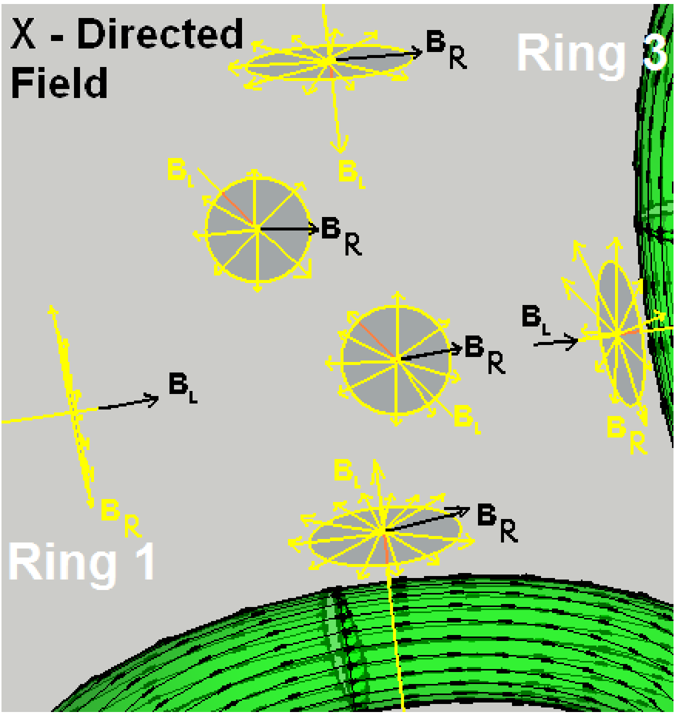
Put the same magnetic poles together, and they will push apart. Two north poles are not happy when shoved together. The vector field they make is shown in the above image. They also have a high energy density between them. The energy density goes up when a third north pole is add. The polywell is similar. It is six magnets in a cube. The same pole is pushed together six times. Intuitively then, we expect the vector field to fly outwards in all directions. In general, this is the case. The only place this is not true is through the rings themselves. The fields are pointed inward through the rings. In a way, the rings act like six “doors” to a home. The fields come in through the doors, and fly outwards everywhere else.

How could such a system contain electrons? The reason is the magnetic mirror effect. The electrons that fly away from the center and are moving into denser fields. The fields get so dense – especially at the corners – that the electron hits a magnetic mirror and are reflected. Containment inside the polywell may be a balance between these two physical mechanisms: the fields spraying material outward in all directions and the magnetic mirror reflecting material back into device center.

The Complete Magnetic Field:

To model all six rings, you need to combine each single ring field together. This is done using superposition. In practice, this means adding the vectors that are on axis, together. The vectors to are added when they point in the same directions. They are subtracted when they point in opposing directions. This is taken from the 2011 Sydney paper [35]. That paper used the model for one ring, six times. Each ring generates two polar fields; one in the z direction and one in the rho direction. This makes 12 vectors. So for any point inside the rings, there are twelve vectors which describe the B field. Now we need to combine them.

Combining means adding them together. Hence, the equations for the B field in the x, y and z directions are groups of these 12 vectors. In practice, the rings had to be numbered. The distances from the rings to the location of interest were either +S or -S depending which ring. Also, a term was also needed to account for the switch from polar to Cartesian coordinates. For example, six polar fields make up the x directed field. These are: four radial fields and two axis fields. It is easier to keep track of which polar field goes with the x direction when you see it. This is drawn out below.



$$\vec{B}_x = (B_{Line}(\rho_{yz}, x - S) \pm B_{Line}(\rho_{yz}, x + S) \pm B_{Rad}(\rho_{xz}, y - S)\frac{x}{\rho_{xz}} \pm B_{Rad}(\rho_{xz}, y + S)\frac{x}{\rho_{xz}} \pm B_{Rad}(\rho_{xy}, z - S)\frac{x}{\rho_{xy}} \pm B_{Rad}(\rho_{xy}, z + S)\frac{x}{\rho_{xy}})$$

$$**S = 0.1963\,\text{Meters}$$

$$*\rho_{xy} = \sqrt{x^2 + y^2}$$

There are several tricks with working with these equations. The first is keeping track of which coordinates go with which rings. For the modeling done here the point (0, 0, 0) is at the dead center of the rings. Following the conventions shown above, the other two vector fields can be described. These are shown below.

$$\vec{B}y = (B_{Line}(\rho_{xz}, y - S) \pm B_{Line}(\rho_{xz}, y + S) \pm B_{Rad}(\rho_{yz}, x - S) + \frac{y}{\rho_{yz}} \pm B_{Rad}(\rho_{yz}, x + S)\frac{y}{\rho_{yz}} \pm B_{Rad}(\rho_{xy}, z - S)\frac{y}{\rho_{xy}} \pm B_{Rad}(\rho_{xy}, z + S)\frac{y}{\rho_{xy}})$$

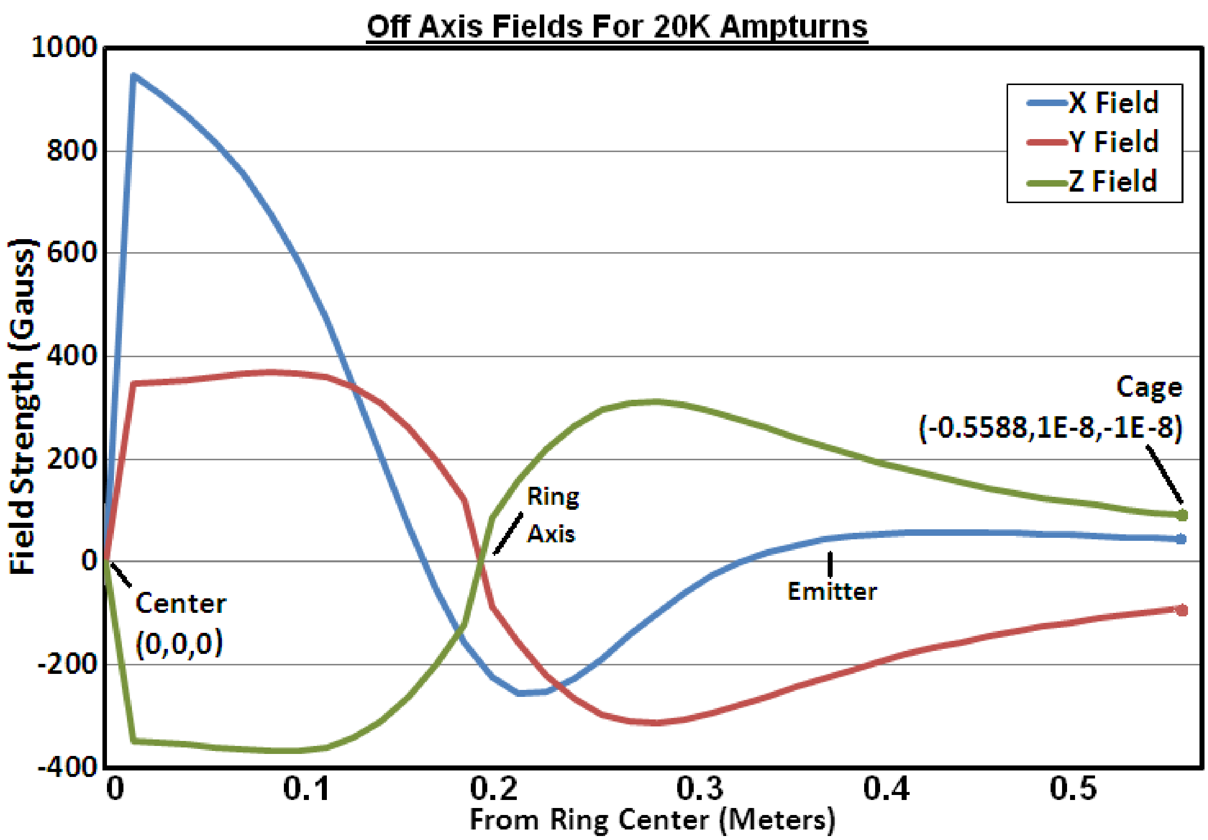
$$\vec{B}z = (B_{Line}(\rho_{xy}, z - S) \pm B_{Line}(\rho_{xy}, z + S) \pm B_{Rad}(\rho_{yz}, x - S) \pm \frac{z}{\rho_{yz}} + B_{Rad}(\rho_{yz}, x + S)\frac{z}{\rho_{yz}} \pm B_{Rad}(\rho_{xz}, y - S)\frac{z}{\rho_{xz}} \pm B_{Rad}(\rho_{xz}, y + S)\frac{z}{\rho_{xz}})$$

Working with these equations is difficult. The equations are easy to enter into excel and MATLAB; but getting the vectors to point in the correct directions is challenging. This MATLAB code may be uploaded to the web for others to push it too perfection. Any small flaws in the code are a moot point, since any model is not reality. The point of the model is a gain a deep physical understanding of this machine.

<u>Excel: Paths to Center</u>

The above equations tell us the magnetic field at different locations. These were put into excel. From the joint, corner and axis there are three paths into the center of the rings. The fields can be modeled as the particle “walks” these paths. This can be used as a check as models become more complex. We expect the repulsive force to increase as the particle moves into device center. This is analogous to the fields from two a-like poles placed close together. At the dead center, the fields should suddenly drop to zero. This is the null point and it scatters the electrons.

The first path of interest is just off axis. Imagine the particle starting at the cage and moving in to the center. As it moves inward it is buffeted by strong magnetic and electric fields. Off axis, there is a strong magnetic field pointing inwards. The particle is swimming along with this “current.” The strongest field (~250 G) is inside a single ring. This is pointing into the center. This field quickly reverses direction as the particle enters the ring structure. This is similar to the fields of six north poles facing inwards.



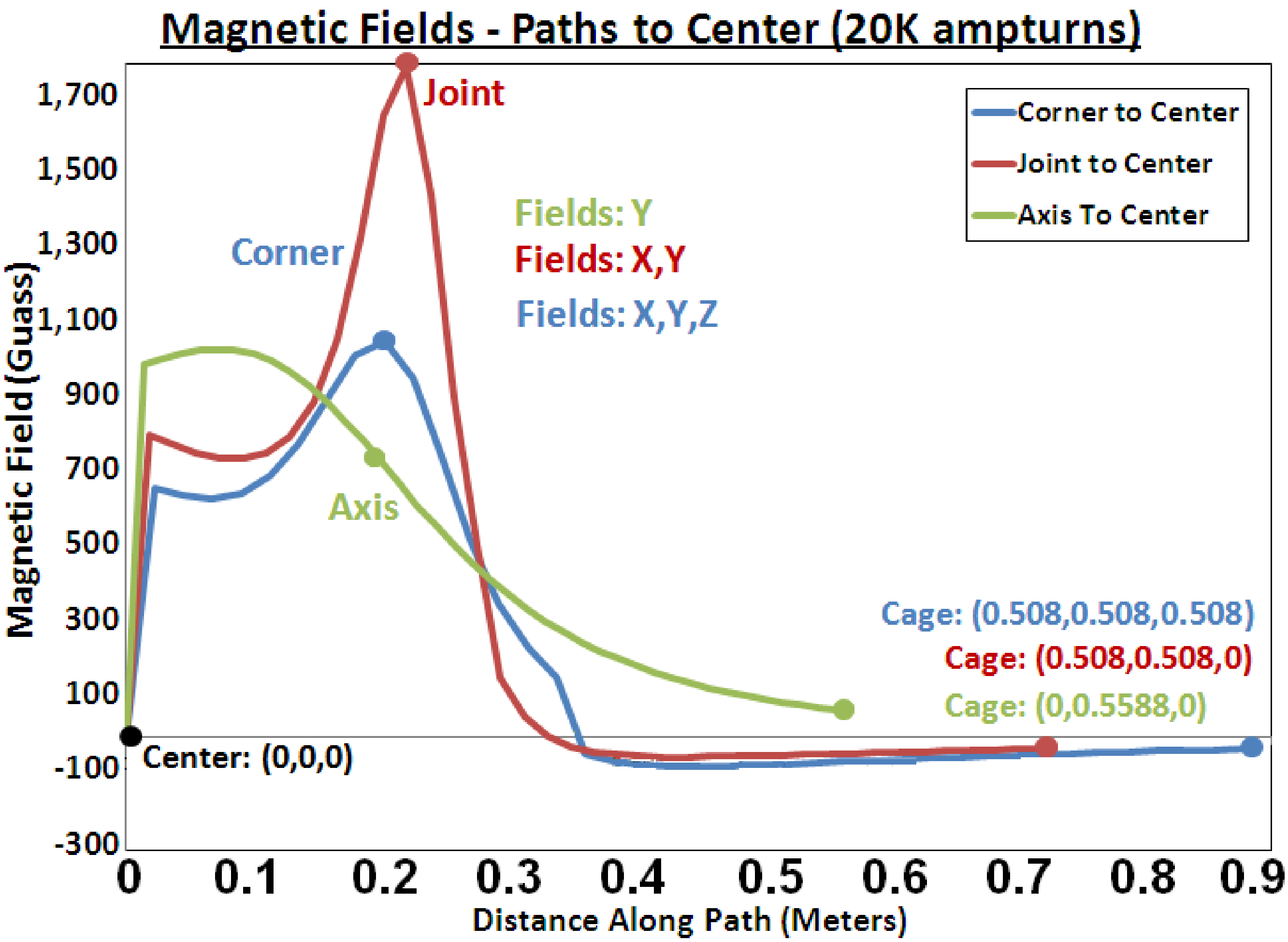
Difference: On-Axis/Off-Axis

The magnetic field is slightly different on-axis (0) and just off-axis (±1E-8). On axis, the vectors solely points outward, with all other vector set to zero. This is plotted below. The "current" is forever out from the center. These numbers are consistent with earlier estimates. Just off-axis the plots change dramatically. This is plotted above. Note the Y and Z fields in red and green. These change from zero to the S shaped curves. They are consistent with the radial fields for a single ring. They generate swirling field lines around the rings. These curves are symmetric. Any downward tug is equally offset by an upward pull. Outside the rings these point towards the axis and, on the inside they point away from the axis.

More Paths In To Center:

This path can be compared to two others. These are: a path from the corner into center and the joint into center. The joint is where the rings are connected. The magnetic field is the densest here. Assume a particle passes from the cage, through the joint into the center. This path is about three quarters of a meter long. All the fields along it are planar. The particle gets pushed left or right - but not up or down. The field points away from the center. The particle is “swimming upstream” as it moves into the rings. The field peaks at ~1,800 gauss directly between the rings. Note that this is lower than the field (1,300 gauss) calculated in “moving the rings” section above. The planer fields are symmetric - identical in strength, but opposing in direction

Another important path is from the corner of the cage into the center. This is the path the deuterium gas travels. The path is nearly a meter long. It starts from the cage corner and travels between three rings, into the center. These fields point outward from the center. The particle moves “upstream” as it head towards device center. The field peaks at about ~1,100 gauss when the rings are closest together. These three paths are compared below.

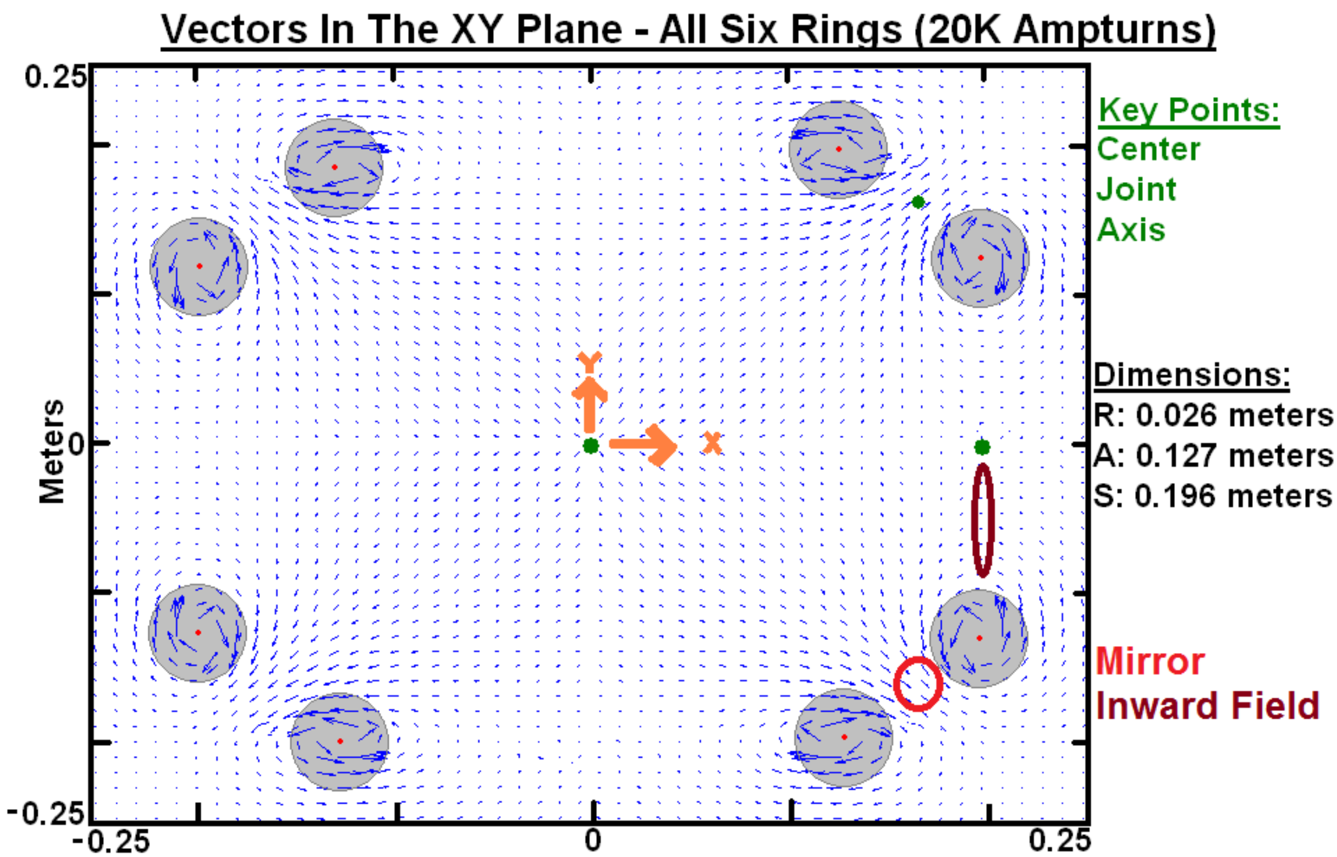


These plots can be checked against published literature. Figure three from [35] qualitatively agrees with these plots. The curves of the field represent a “magnetic cup.” It appears the easiest entrance to this field is along the axis. This is through the rings where the field lines can point inward. As the particle moves inward the fields point outward and this becomes stronger as the particle reaches machine center. At the center, the fields do drop to zero. This is the null point - and it is an important feature of the machines’ geometry.

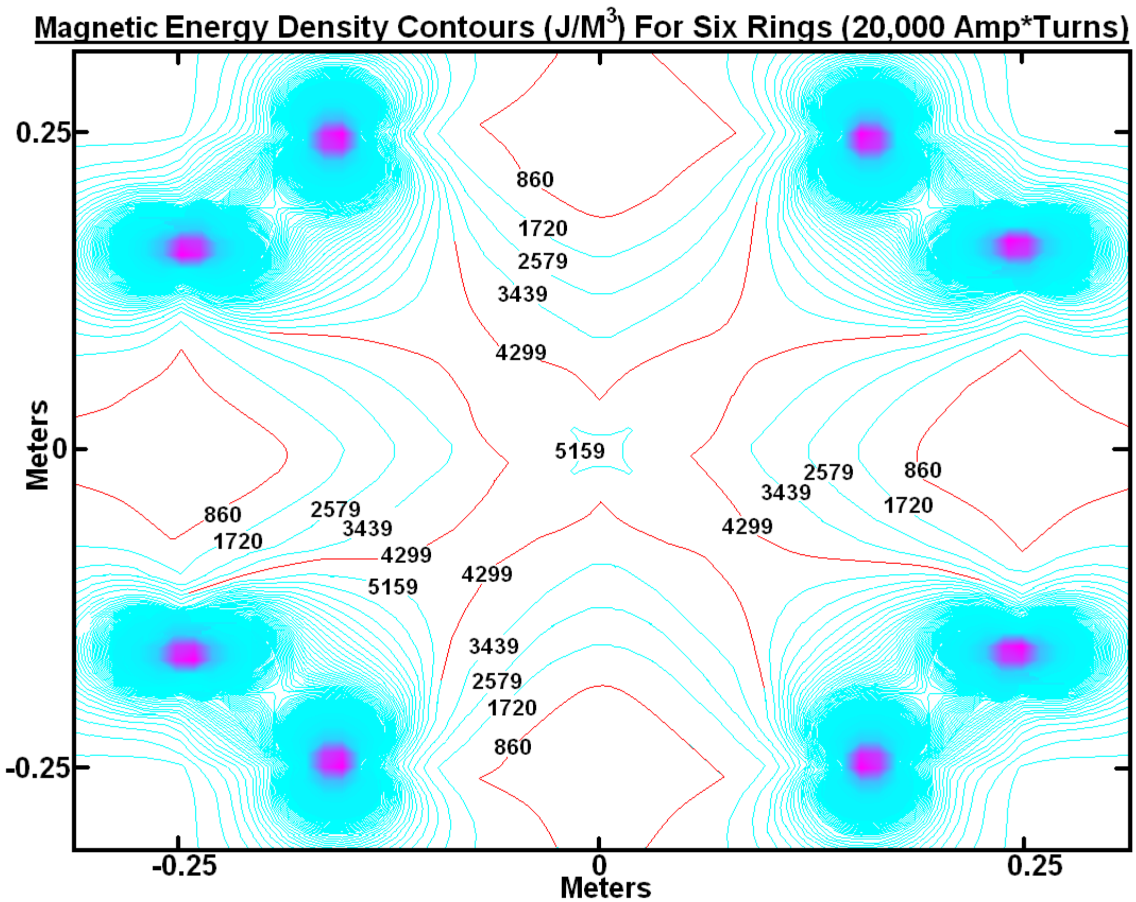
MATLAB Model:

From Excel, these equations were entered into MATLAB. The equations are easy to encode - but getting the correct vector field was very difficult. The better part of a month was spent attempting to get this vector field to align. A magnetic vector field is shown below for

WB6. These fields are consistent with a-like poles being placed close together. A “zone of no magnetic field” can be seen running along the X and Y axis. Particles can enter the ring structure along these field lines.



Using this vector field plot, a contour map of the magnetic energy density was generated. This is shown below. The plot is of the XY plane in the middle of the ring structure. What is surprising is that the energy density is so different from the energy density in a single ring. It was expected that the magnetic energy density would be lower in the center, not higher. This is consistent with multiple north pole magnets close together. If critics or experts have an opinion on this, please comment here. As of this writing, a flaw cannot be found in the code.



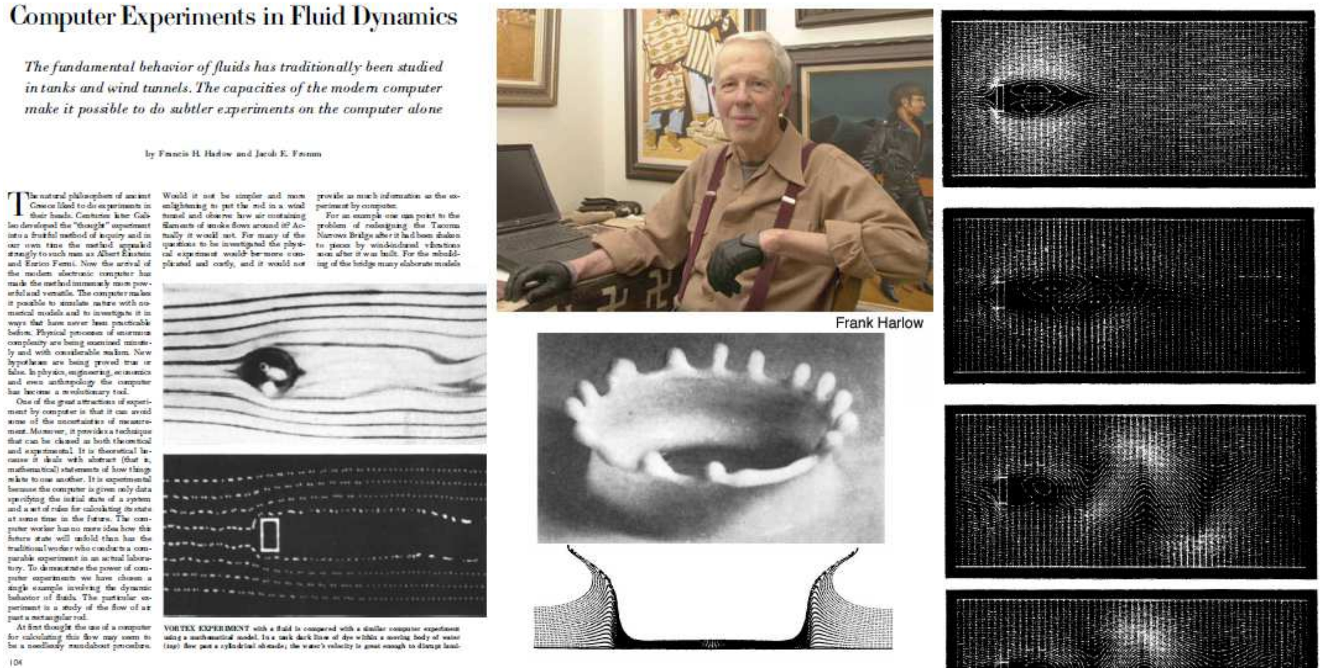
Part 4: Rudiments Of Simulation

When actually making a simulation, do not fall victim to cool options and flashy graphics of a software package. Stay focused on the questions you want to solve. The best simulations are the simplest and offer the deepest insights into experimentation.

Bussard would have loved an accurate computer model. Many do not believe that computers could handle a full Polywell [30]. I did not. I then heard, that the 2012 copy of the MCNPX software could handle 10^12th particles [37]. That code is a kinetics based software. It is often used for tracking neutrons. This was the evidence that pushed that modeling was indeed a possibility. Several models have already been made. A 1.5 dimensional model was done in the early nineties (dubbed the EXL code). Since then, models have been made by: HappyJack, AEO Iran [4], Indrek, The Navy Team, Dr. Joel Rogers, hobbyists and Randy. If the Polywell works, there will certainly be many more models. The goal here is not to duplicate the previous work. This post is going to broadly discuss modeling without focusing on any specific method.

The PIC Method:

One approach is to use is a particle in cell method. This code originated in the 1960s at the Los Alamos National Labs [6]. If you use it, you owe a debt of gratitude to Frank Harlow and his team. Below is a visual homage to franks' team [7].



What is important about the T3 group was their work was ignored and even criticized through most of the 1960's [6]. They published when nobody else seemed to care - and they were ultimately vindicated. The particle in cell method fractures volume into cells and material into particles. It tracks how sample particles move through these cells.

<u>Particles Needed:</u>

What particles will we need for modeling the Polywell? First, assume that the fusion products vanish. This makes sense. Helium at ~10 MeV, has so much energy it cannot be held by any of the reactor fields. Second, the neutrons can be ignored. Ideally, the code would just record when a fusion event occurred. This leaves: deuterium gas, electrons and ions, to be modeled. Each object is summarized below [8, 9, 28, 29]. A simulation will probably use "representative" particle to reduce the amount of material needed to be tracked. The computer may track 1 particle for every 1,000 real particles in an experiment.

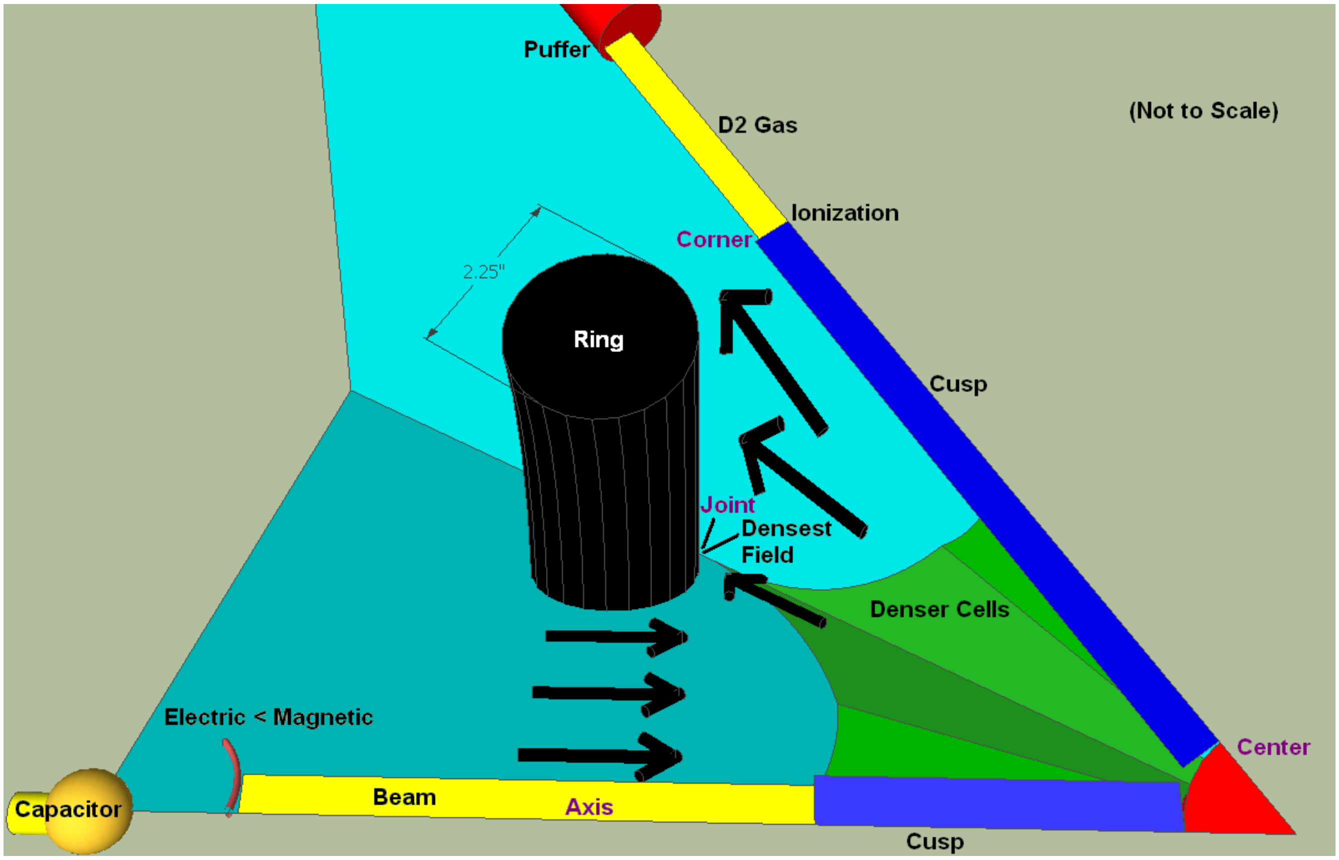
	(Real) Charge	Mass (Kg)	Diameter (M)	(Relative) Mass	Diameter
Deuterium Gas	0	6.7E-27	2.7E-10	7,363	95,745
Electron	-1	9.1E-31	2.8E-15	1	1
Ion	1	3.3E-27	1.0E-10	3,626	35,461

<u>Particles Energy:</u>

For this simulation the ions and electrons would be modeled as having bell curves of energy. Both bell curves have average energies of 2,500 eV. Rider argues that the rate of energy transfer from the electrons and ion cloud is so fast; that their energy is the same [10]. Rider even wrote a new energy transfer equation to show this [11]. In the 18 years since, only two papers have cited this work and both were written by Rider himself.

The 3D Mesh:

Meshing is the act of breaking the volume into small cells. The key is to simplify as much as you can. If you want to include the axis, joint, corner and center the smallest the polywell can be broken into, is 48 parts. What is left - looks like wedge. The wedge uses planes of symmetry to duplicate behavior and model the whole machine. It is much simpler to work with. The wedge can be broken down further into chucks of volume with specific particles energies and physical mechanisms. This is shown below.



Within this space there are several chunks of interest. The first is the electron beam. About 40 amps of electrons were released in the capacitor discharge [2]. It was assumed these capacitors were halfway between the rings and cage. The magnetic overtakes the electric field at 15 centimeters before the rings. The electrons reach the axis of the ring at ~2.8E7 meters per second. As they pass into the green region they being to experience a repelling field point outward from ring center. This pushes them towards the joints and corners. A simulation would need to model 2.5E10 net electrons.

The next region is where the deuterium gas is puffed in. About 2.7E+18 of deuterium gas molecules were puffed in. These start at 0.292 meters from ring center. This is a colossal number of molecules. This simulation would model one forty eight of 0.002 percent of this. That is 1E12 of uncharged gas molecules and two ions for each ionization event. The gas enters at room temperature (0.02 eV). When it reaches the corner of the rings it exchanges energy with the electrons and ionizes. These ions fly into ring center. If they hit, they may fuse. Only 800,000 deuterium ions actually fuse over the 0.0004 seconds of the experiment.

Electron to Ion Ratio:

Researchers use dimensionless ratios to reduce number of simulations needed. Using typical electron and ions numbers one can estimate the ion to electron ratio. This number needs to be below one to maintain they voltage drop. There is strong indication that this ratio should be very low (0.001 or lower).

$$\textbf{Ion To Electron Ratio} = \frac{\textbf{Ions In Simulation}}{\textbf{Electrons In Simulation}} = \frac{\textbf{2E12}}{\textbf{2E12} + \textbf{2.5E10}} = \textbf{0.98}$$

Meshing With Courant Numbers

The courant number [38] is used to properly mesh any simulation. The number relates the speed of the particle, the mesh size and the time step. This is shown below. The number should be on the order of one for all regions of the simulation. The number of cells and the time step is worked out for typical particle speeds. These numbers will likely change, but the mesh can be planned using this approach. Typical numbers are shown below.

Example: Meshing Scheme

	Volume (M^3)	Cells #	Distance (M)	Speed (M/S)	Courant #
Beam	1.E-06	10,000	5.8E-04	2.8E+07	4.83
D2 Gas	1.E-06	30,000	4.3E-04	1.4E+03	0.00
Center	1.E-06	15,000	5.7E-04	3.0E+07	5.29
Axis Cusp	3.E-06	60,000	4.4E-04	3.0E+06	0.68
Corner Cusp	3.E-06	60,000	4.6E-04	3.0E+06	0.65
Flux Surface	1.E-04	70,000	1.4E-03	3.0E+06	0.21
Remaining	6.E-03	50,000	6.0E-03	1.0E+03	0.00
Ring	3.E-04	-	-	-	-

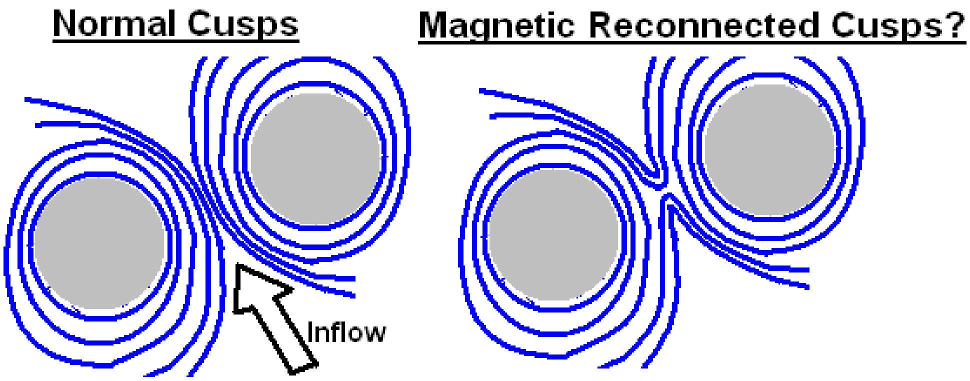
Time Step:	1.00E-10
Steps Needed:	4.E+06
Cells:	295,000

$$\textbf{Courant Number:}\quad 1 < \frac{\textbf{Velocity} * \textbf{Time Step}}{\textbf{Distance}}$$

Ideas For Future Work:

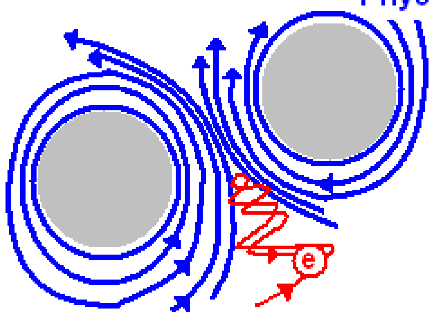
There is plenty of work to be done. It is the hope of this blog that the US government wakes up and funds this research accordant with its potential. If they fail to do this, other nations may rapidly catch up. Here are some ideas for future questions.

1. **Magnetic reconnection at the cusps**. In certain plasma settings magnetic field lines reconnect [39]. Are there any configurations in Polywells, where this exists?



2. **Ratio: magnetic mirrors verses rejection**. The field lines point outward everywhere except through the rings. Particles follow these fields into the cusps and corners. They enter a dense vector field. The field gets so dense the particles hits a magnetic mirror and are reflected. Is there a dimensionless ratio for this?

$$\text{Dimensionless Ratio (?)} = \frac{\text{Physical Mechanism: Magnetic Mirror}}{\text{Physical Mechanism: Following Outward Field}}$$

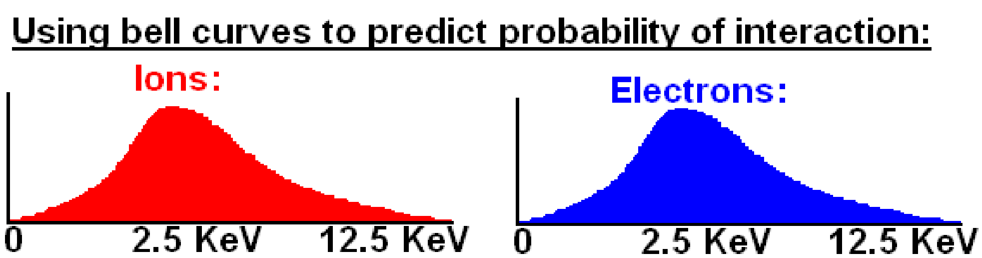


Conditions For Mirror

$$\text{Radius}_{\text{Gyration}} \left| \frac{\nabla B}{B} \right| < 1$$

$$B_{\text{Peak}} > \frac{\text{Electron Kinetic Energy}}{\text{Electron Magnetic Moment}}$$

3. **X-ray radiation with probabilities**. We can model the ion and electrons clouds as having densities of 1E19 and have a bell curve of energy centered at 2,500 eV. With this information, the coulomb logarithm and the Debye length [40] one may estimate the average distance between electrons or ions. From this, are we able to predict the amount, rate and type of X-rays coming off the cloud?



$$F(\text{Particles}, \text{Energy}_1, \text{Energy}_2, \text{Distance}) = \text{X-ray}$$

4. **Reactor design: avoid arching**. If you had been at the WB6 test, the main thing you would have seen was a burst of lightening from inside the machine. This was arching. It is a problem. Bussard raised this issue in his Google presentation. Any experimental system needs to avoid this. Can reactors be designed to avoid this problem?

5. **Estimating the mirror ratio.** Thomas Dolan reviewed the magnetic mirror ratio in the nineties. What ratio did Rider use when he assessed the Polywell? What was the actual mirror ratio in WB6? Do these agree?

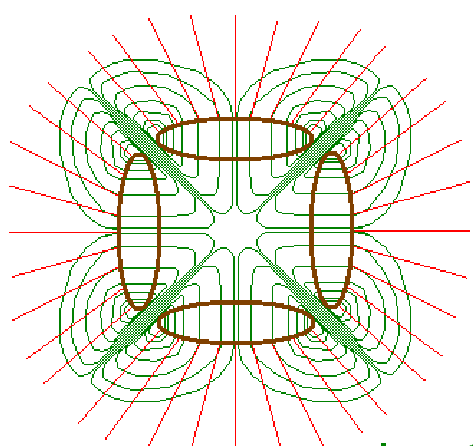
$$\textbf{Mirror Ratio} = \frac{\textbf{Maximum Magnetic Field}}{\textbf{Minimum Magnetic Field}}$$

6. **Fusor modes of operation**. George Miley has shown that fusors have modes of operation. He has published work on the subject. Do Polywells show similar modes of operations under similar conditions?

7. **Energy transfer.** Lyman Spitzer wrote "physics of fully ionized gases" the bible on low density plasmas. In it, there is an equation to model energy transfer for ions entering an electron cloud. Riders' 1995 papers similar equations to argue against the Polywell. Can these equations be applied to WB6?

8. **Plasma instabilities**. Marshall Rosenbluth – the pope of plasma physics – worked out a slew of plasma instabilities for almost any plasma structure. Which ones apply to the polywell? Is there a way to qualitatively compare these competing instabilities with other physical mechanisms?

9. **Ratio: magnetic verses electric fields**. Can sets of experiments be simplified by combining the electric and magnetic field strength into one dimensionless number? There may be a way to express this mathematically. Simulations are ideal for exploring the impact of this number – as the magnetic and electric fields can be changed quickly.



$$\textbf{Dimensionless Ratio (?)} = \frac{\textbf{Impact of Magnetic Field}}{\textbf{Impact of Electric Field}}$$

<u>Conclusion:</u>

Yet again, The Polywell Blog has pushed the boundaries of knowledge. If you think this work is stellar, that's because it is. This was done by an A player. Several times, this blog has gotten ahead of published literature – only to have concepts printed later. The Polywell represents frontier technology, new science and promising potential. It is a pleasure to work on. It has also been fun explaining these complex issues in simple language. Work cannot continue without funding. Interested parties can contact ThePolywellGuy@gmail.com for more information.

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