# The Worlds’ Best Plasma Traps

## Introduction:

There is an exciting idea on the edge of fusion research. The idea is to use a plasmas’ magnetic properties to hold it in. This is not new; but it is getting renewed interest. In these plasmas, the soup of ions and electrons make their own fields - which are used to hold them in [40]. There are three recent examples of this:

**1. Lockheed Martin.** Lockheed is trying to make a machine where the plasma rejects the outside field [41]. The plasma goes diamagnetic. It pushes out the field, creating a region with no magnetic field; a region with high pressure plasma. This is known as cusp confinement [10, 14, 15].

**2. Field Reverse Configuration**. These devices create a spinning soup of ions and electrons. The moving charge makes its own magnetic fields – which self contains the plasma [42].

**3. EMC2 Cusp Confinement Work.** In a paper published over the summer, EMC2 gave data of a cusp confined plasma [43]. The company saw two zones inside the machine. In the center, there were high energy ions and electrons ricocheting around, with nearly no field. Surrounding this, were magnetic fields, with nearly no plasma.

I cannot understand why we are not seeing this topic addressed in the journals. One reason is that the data is new that folks are still skeptical. Another is that most physicists work with plasmas which mingle with the fields; like tokamaks and stellarators. It is not the convention. They are missing out. Field free plasmas represent a new frontier in fusion research. If they work, they could lead to the world’s greatest plasma traps.

## Executive Summary:

This post lays out the history of cusp confinement and walks through EMC2 experiment. A set of approaches - field reverse configurations, polywells and the compact fusion reactor - attempt to use the plasmas magnetic properties to self-contain it. Cusp confinement is one such method which reduces plasma losses to the axes and edges of cusp. Ideally, it leads to a free-boundary plasma by plugging the cusps with a high pressure plasma, forming a field-free region. EMC2 recently provided data of such an effect. Their new polywell is safer, more efficient and reaches a magnetic density 1.5 times higher than WB6. High pressure carbon and hydrogen plasma was fired into this using JXB emitters. These emitters are modelled, along with the electron guns and trace air in the chamber. The post ends with a list of questions that need to be answered and appeal for funding. Readers can download this and all other polywell posts on pdf from github.

***“Complexity is the enemy of execution” – Tony Robbins***

# Part 1: A History of Cusped Systems

## Introduction:

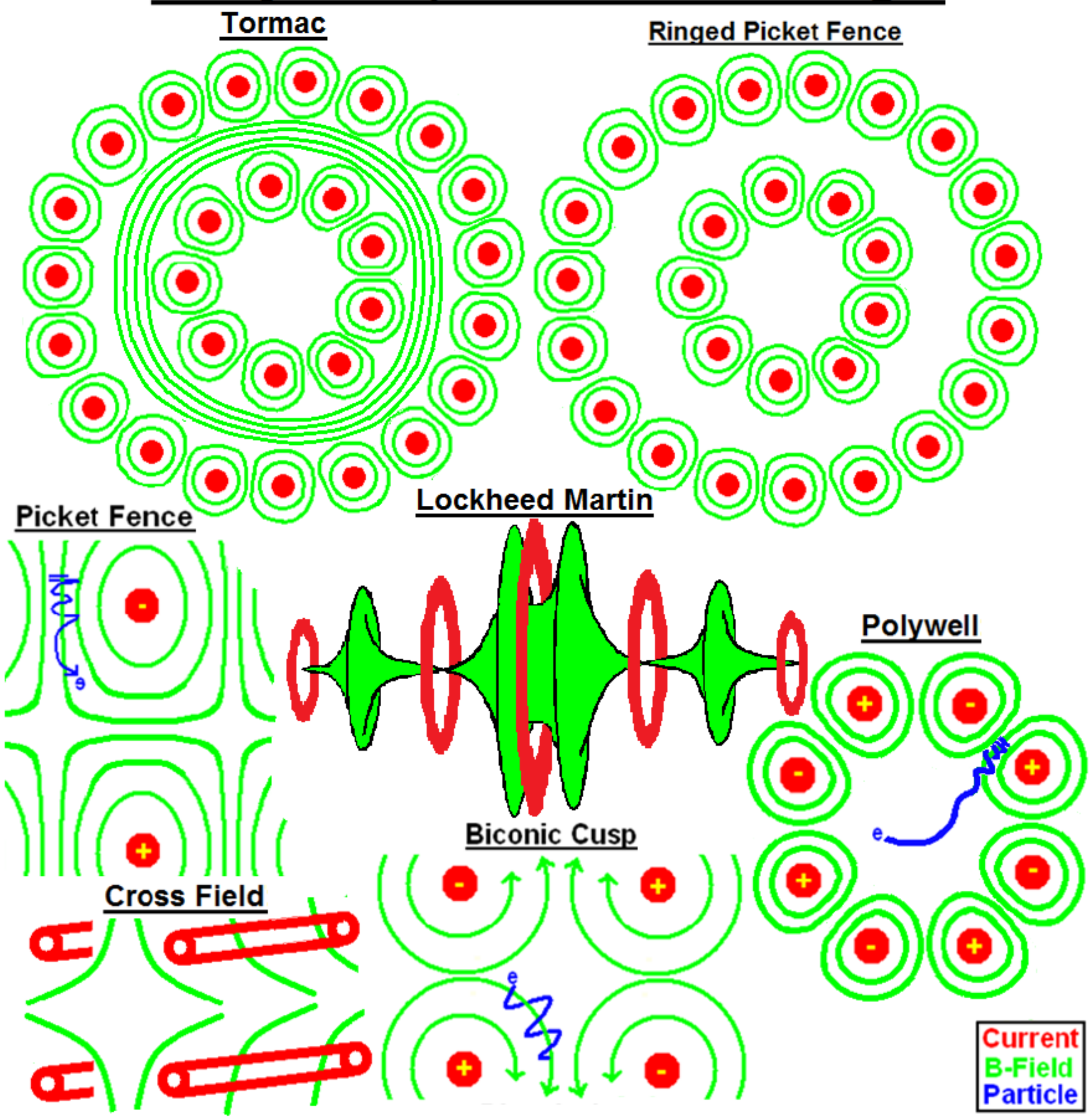
Harold Grad was a huge math nerd.  He was a professor at NYU in the fifties and sixties [1, 2].  He specialized in applying advanced math to plasmas.  Plasma is a fluid; which also happens to conduct.  The math controlling it is a merger of the fluids equations (navier-stokes) and the electricity equations (Maxwell's equations).  The two combine to make a whole new field: Magnetohydrodynamics.  Harold probed the math; looking for any kind of plasma structure.

Harold Grad and Cathleen Morawetz

## Cusps:

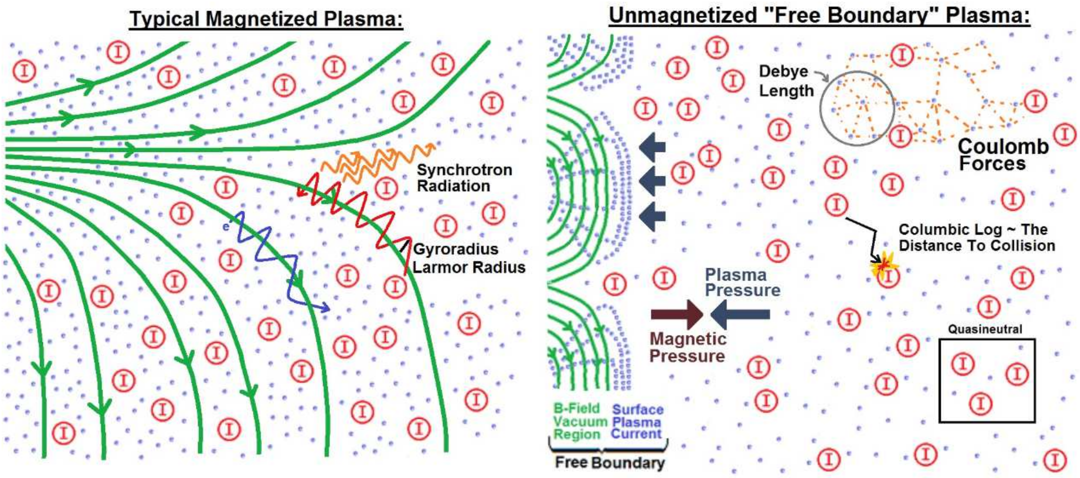
Dr. Grads' favorite geometry was the cusped system.  A cusp is a place where two magnetic fields sharply bend and repel one other [9]. One example is two north poles repelling.  Cusps are awesome because the plasma (mostly) leaks through the edges and apexes of cusps [41].  This shrinks the total area over which the plasma can be lost.  The plasma is contained in a trap with a few small holes.  Cusps have two major advantages. First, their fields are bent inward.  This is great.  Plasma tends to drift into bigger curved paths - so inward bending fields help to push material into the center [11].  That is helpful.  Second, cusps have a null point in the center.  The null point is a spot with no magnetic field.  It is a place where plasma can collect.  After Grad had shown the value of cusp geometry, other people latched onto this idea and a whole family of concepts were proposed [10].

## Family of Cusped Confinement Designs




**"Free Boundary" Plasmas**

Cusp systems can shrink losses, but Harold Grad found a way to go further. In some cases, the plasma can actually plug up the cusps [13]. Plasma is a moving soup of charged material. Its' motion can make its' own magnetic field. This can clash and reject the outside field. This can lead to a plugged cusp. Physically this is a diamagnetic plasma, rejecting the external field. Inside, material can move about, free of the externally applied fields. This system - theoretically - has a sharp boundary with a sheet of electrons moving on its' surface [13, 12, 15]. This is shown below.



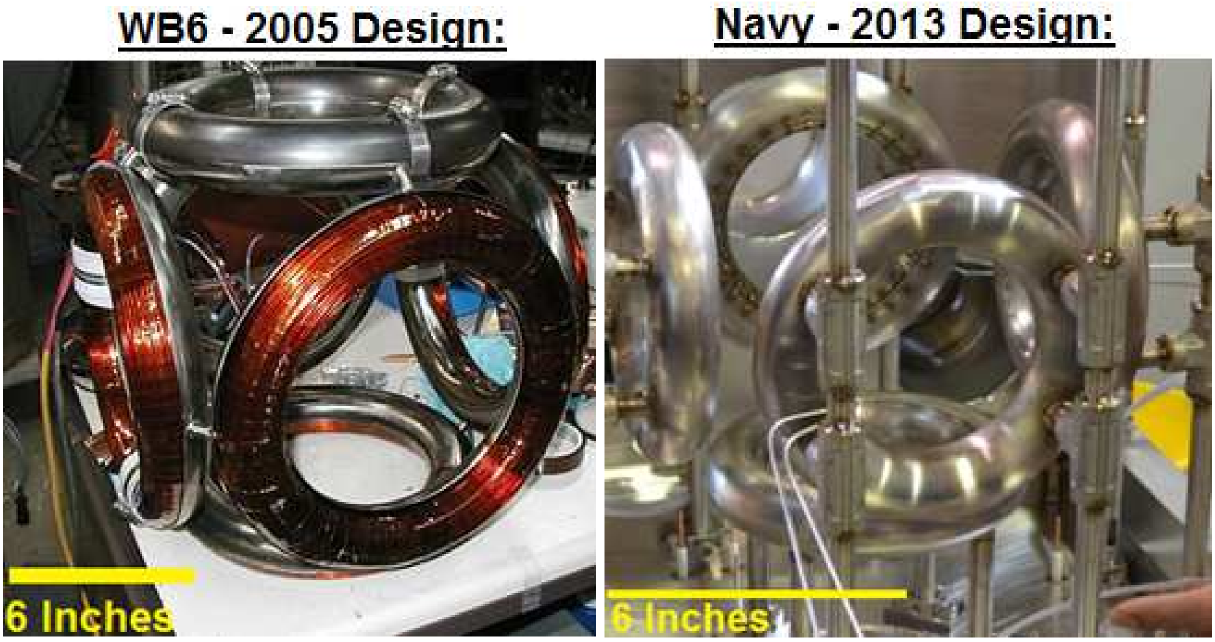

Theoretically, *this would be the world's best plasma trap*. Not only is material better contained, but the plasma also loses less energy as light [9].

**<u>The Lost Concept:</u>**

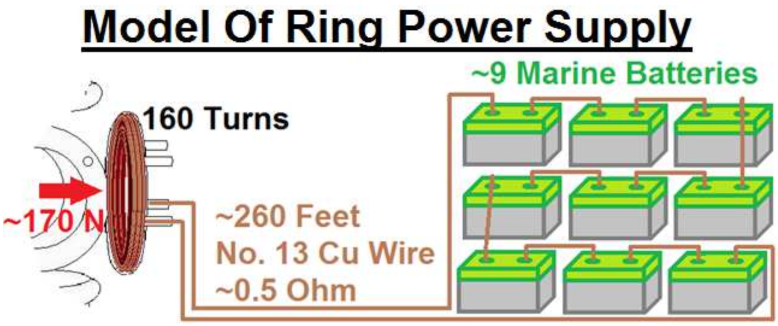
Free boundary plasma would be awesome; but despite many attempts, the system was never demonstrated [13-15]. There are two good reasons for this. First, high pressure plasmas are very hard to make. Secondly, the effect is hard to measure. By 1980, it had disappeared from most fusion programs. Most teams moved on from the cusp geometries; looping the field lines to make a tokamak. That was situation - until 2014 – when EMC2 reported making a free boundary plasma. It is still early days - but if the full potential of this discovery is realized – someone may win the Nobel Prize.

# Part 2: The New Machine

Sometimes better science comes from using better tools. The new machine is far better than Bussards' old WB6. The electromagnets or rings were designed better. The first change is its size; WB6 was much bigger. Its' rings filled six times more space [6,16]. The new machine is much slimmer, but more powerful. This will lead to higher energy densities. The devices are pictured below [3,4,16, 20].



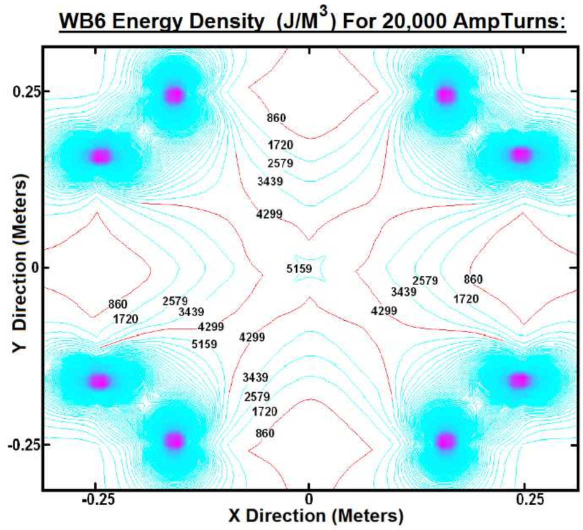

The new model does not link the rings together. They are mounted externally. This leaves more space for plasma recirculation - something both Rider and Bussard stressed as critical [16-18]. Recirculation, means plasma can move without touching metal. Recirculation is also used in the Lockheed Martin concept [41]. Mounting the rings externally also changes everything about how the rings are powered. The old machine formed its' electromagnets from one long wire. This long wire, snaked its way through all six magnets and ran to one big set of 240 batteries [16]. This wire was over three thousand feet long, overheated and had three ohm of resistance. The new machine broke the power supply up. Six distinct power supplies were used; nine batteries per ring. This is much safer. The wire also has a lower resistance. A diagram of the power supply for one electromagnet is shown below.

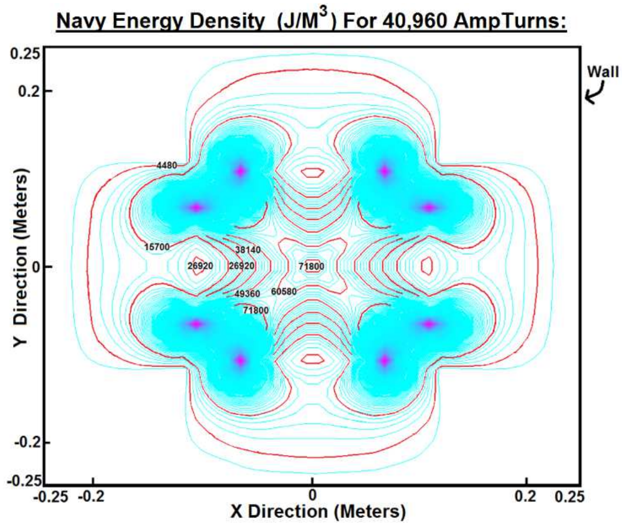



This new system is more powerful. The new design can reach energy densities at least three times higher in the center [appendix]. This is because the new rings are physically closer. You can demonstrate this by comparing the magnetomotive force on the rings at full power. This is the magnetic force that pushes the rings apart; they are like poles repelling one another. In WB6, this force was roughly 37 newtons; in this new machine, the force is roughly 170 newtons [appendix].

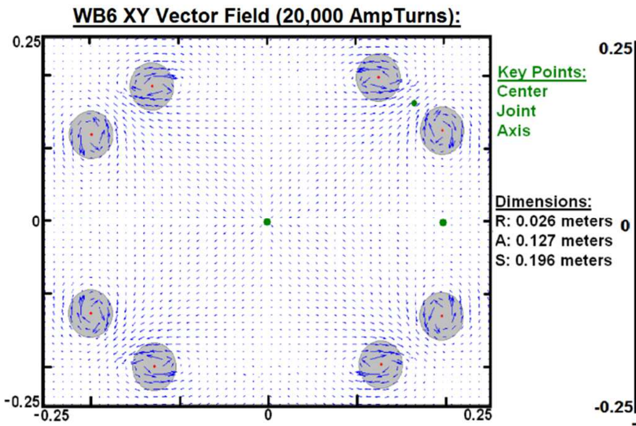
**Magnetic Geometry**

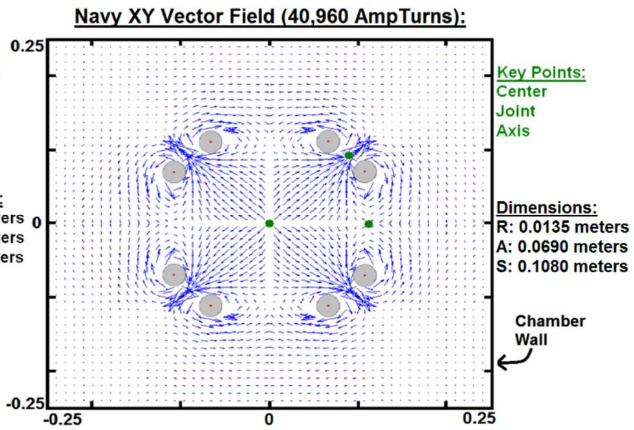
The rings are used to create a magnetic geometry. The geometry is custom designed; specific for this application. A comparison of the energy density made by WB6 and this machine are shown below.




These plots show the density of energy for an empty system. Things would change, if plasma was in here. The plots were made using a matlab code [19, 21]. Practically all of the energy comes from the magnetic field. Electric fields do not make nearly as much energy density. The reason for this comes from the fundamental electric and magnetic constants. The new machine is clearly better. The compact design lets this tool to cruise to an energy density one and a half times higher than Bussards' old machine [appendix]. This new machine also makes the stronger field for less power. This is also evident from the vector plots.



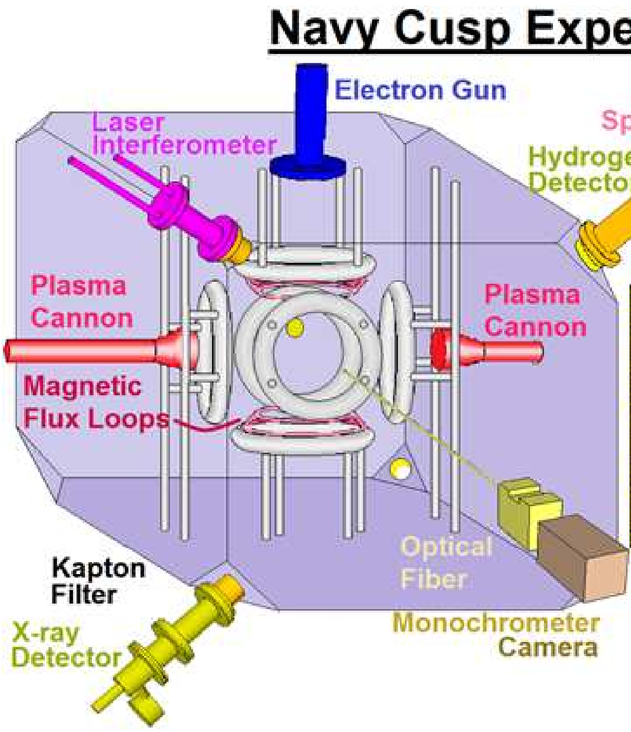

These two plots compare the XY field of Bussards old WB6 and the new Navy machine. The plot is made with the same parameters; so it is an apples to apples comparison. Putting all this analysis together: it is clear that the new machine is plainly better. It can produce a stronger containment more efficiently.

# Part 3: Machine Inputs

**Trapping Is All That Matters:**

The goal here, was *not* to build a polywell. All they wanted was plasma trapping. Hence, they do not care about: potential or composition. The plasma could have been made of anything; that was not important, as long as it was trapped. In this experiment, the plasma was made from vaporized plastics; with lots of carbon and hydrogen. Simultaneously, charge on this plasma cloud did not matter. They did not care if more electrons, than ions were in there. This also did not matter. Electrons were used to take a “snapshot” of the trapped plasma. The goal of this experiment was to demonstrate cusp confinement.

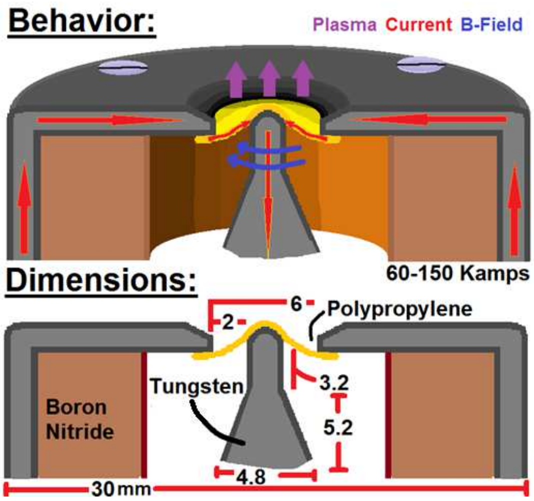
This is a big hairy experiment. Aside from the rings and the vacuum chamber, there are a twelve other tools in play. Three of these are used as inputs to the system; the rest measure something. A list of these tools and where they are located, is shown below.




| Tool/Diagnostic | #: | Used For: |
|---|---|---|
| Plasma Cannon | 2 | Plasma Injection |
| Electron Gun | 1 | Electron Injection |
| Magnetic Flux Loops | 2 | Magnetic Field Measurements |
| X-ray Detectors | 2 | Plasma Trapping Measurements |
| Laser Inferometer | 1 | Plasma Density Measurements |
| Grated Camera | 1 | Raw Video/Plasma Composition/Stark effect |
| Carbon Detector | 1 | The Amount of CII, CIII in Plasma |
| Hydrogen Detector | 1 | The Amount of H alpha in Plasma |
| Spectrometer | 1 | Emitted Light Spectrum |

**Two Plasma Emitters:**

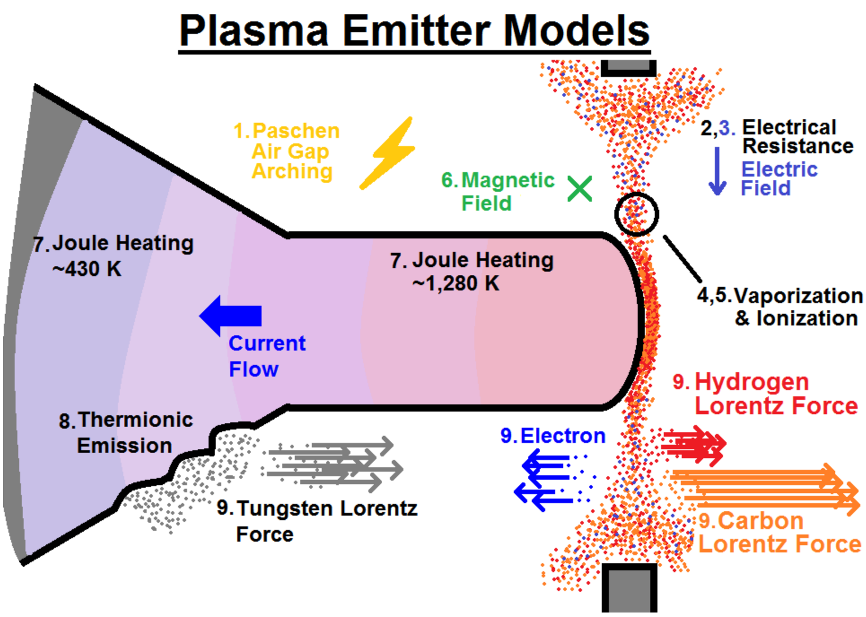
It is tough to make a pressurized plasma. Indeed, this is why cusp experiments have failed in the past [14, 2]. The team may have tried several things, before settling on the final plasma emitter. The final tool may have seemed like overkill. The plasma cannon flings vaporized carbon and hydrogen into the polywell. They pulled this off by vaporizing a polypropylene sheet (imagine vaporizing a sheet of plastic wrap). A picture of this tool is shown below.



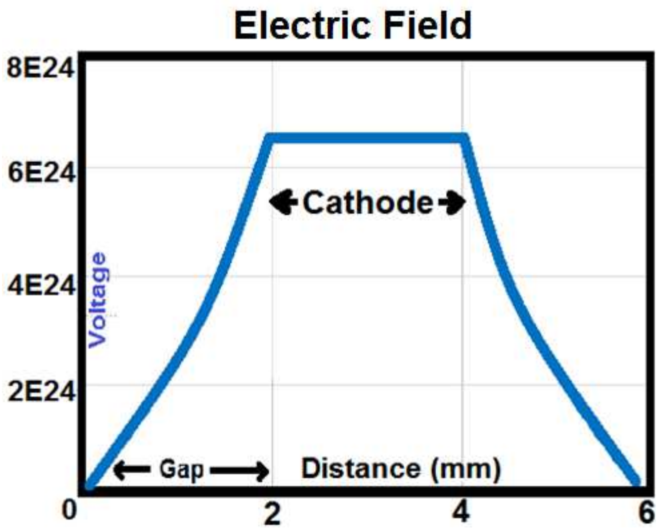

This design is brilliant.  At full power, it has one hundred and fifty thousand amps flowing along its' outside [12].  These electrons move into the center and jump across the plastic sheet.  The high current vaporize the plastic; making a plasma of carbon and hydrogen.  Once across the gap, the current leaves.  It moves down the inner metal and out of the device.  As it leaves, it makes a magnetic field. The brilliance of this device, is that all these effects happen simultaneously: the plastic wrap is fully vaporized, an electric field forms across the gap and a magnetic field spins around the center.  When these effects combine, they fling a plasma outwards.  This happens because the plasma feels both the electric and magnetic field simultaneously; creating a drive force pointed towards the polywell.

**Modeling Plasma Emitters**

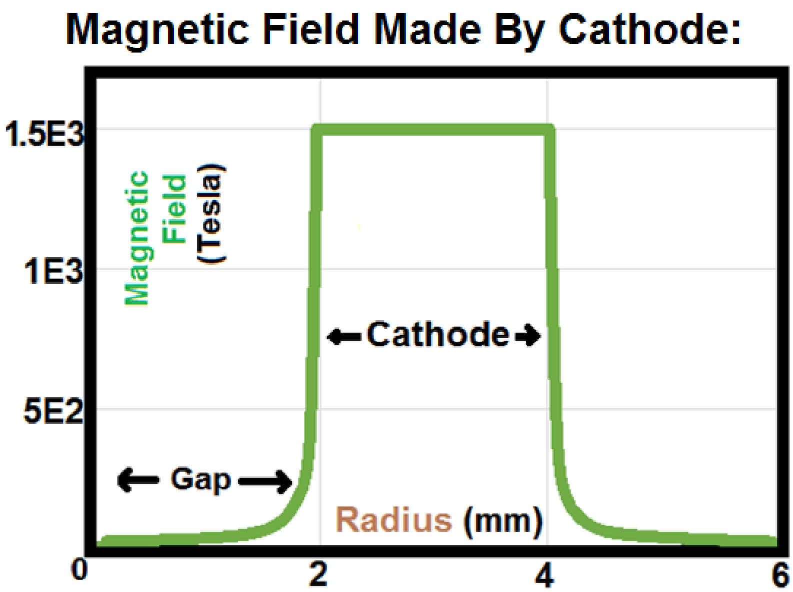
Modeling this emitter was not easy.  There are nine physical mechanisms that happen simultaneously.  I will spare you the math.  If you would like to dig into the numbers - you can see them all in this excel file.  All the effects that were modelled are shown below; effects are numbered in the order so you can follow along.



First, the current will not spark across the air gap [22, 23]. Electric arching can be modelled using Paschen law. Paschen's law tells us quickly that sparking will not happen. That means that all the current must move through the plastic sheet. This sheet has some electrical resistance. We can model the resistance this using the equations for a circular sheet of polypropylene [25, 26]. This number allows us to find the electric field inside this sheet. The field is plotted below. As the current moves through, this sheet will vaporize and ionize. This is because the energy needed to break the chemical bonds and fully ionize the plastic is only hundreds of joules [27-29]. Far more energy passes by. So much energy that the sheet probably ionizes instantly. It turns into a cloud of hydrogen and carbon ions.




As the current leaves the plastic and moves down the cathode, it starts a new series of physical effects. The current in the cathode creates a magnetic field. This field can be modelled by treating the cathode like a big wire. You can use the biot-savart law to model the field in a big wire [30]. The resulting magnetic field is plotted below. The cathode has a huge amount of electrons passing through it – which will heat it up. In fact, the metal likely reaches several hundred degrees kelvin [29, 31]. This causes the tungsten to chip away [2]. Overtime, the tungsten cathode degrades. This process is known as thermionic emission. It means that tungsten ions are also mixed into the plasma [32].




This model tells us that there are electrons, carbon, hydrogen and tungsten ions in the plasma. We need to know how much energy they have as they leave. The emitter makes both an magnetic and electric field which hit the plasma. With both fields in play, it creates a Lorentz force for all charged particles. This is also known as the J X B force [24]. Anything that is positive is pushed outward. This flings ions towards the rings. Anything that is negative is forced backwards. This pushes electrons back into the emitter. Bear in mind, these emitters are really close to the rings. They sit half a centimeter away. The navy *had to* do it this way. Unlike Bussard's 2005 experiment - there is no electric field to steer the plasma. The emitters are close, to catch all the particles before they spread out. Before they are lost. This experiment only used two injectors. They could have had many more. That is an important question for the next test. What happens when we have *many* plasma injectors? An overview of the equations used to model this system is shown below. You can look at all the numbers in this [excel]() file.

## Summary of Equations Used To Model Emitter:

### 1. Paschen Arching

$$\text{Arching Voltage} = \frac{A*\text{Pressure}*\text{Distance}}{\text{Ln}(\text{Pressure}*\text{Distance})+B}$$

### 2. Electrical Resistance

$$\text{Polypropylene Resistance} = \frac{\text{Polypropylene Resistivity}}{2*\pi*\text{Thickness(4 uM)}} * \text{Ln}\left[\frac{\text{Outer}}{\text{Inner}}\right]$$

### 3. Electric Field

$$\text{Max Voltage} = \text{Resistance} * \text{Current}$$

$$\text{Voltage} = \text{Max Voltage} * \frac{\text{Ln}\left[\frac{\text{Radius}}{\text{Outer}}\right]}{\text{Ln}\left[\frac{\text{Inner}}{\text{Outer}}\right]}$$

### 4, 5. Vaporization & Ionization

$$\text{Energy To Ionize} = \text{Polypropylene Moles} * \left[3*\text{C-C Bond Energy} + 6*\text{C-H Bond Energy}\right]$$

$$\text{Energy To Vaporize} = \text{Polypropylene Moles} * \left[3*\text{Energy Fully To Ionize C} + 6*\text{Energy Fully To Ionize H}\right]$$

### 6. Magnetic Field

$$\text{Magnetic Field} = \frac{\text{Magnetic Constant} * \text{Current}}{6.23 * \text{Radius}}$$

### 7. Joule Heating

$$\text{Tungsten Cone Resistance} = \frac{\text{Cone Length} * \text{Tungsten Resistivity}}{\pi * \text{Small Radius} * \text{Big Radius}}$$

$$\text{Tungsten Tip Resistance} = \frac{\text{Tip Length} * \text{Tungsten Resistivity}}{\text{Tip Cross Section}}$$

$$\text{Power Dispensed} = \text{Cathode Resistance} * \text{Current}^2 * \text{Emitter Shot Time}$$

$$\text{Cathode Temp} = \text{Room Temp} + \text{Tungsten Heat Capacity} * \frac{\text{Energy Dispensed}}{\text{Cathode Mass}}$$

### 8. Thermionic Emission

$$\text{Tip Cathode Thermionic Emission} = \text{Tip Surface Area} * 80\frac{\text{Amps}}{\text{cm}^2*\text{K}^2} * \text{Tip Temp}^2 * \text{Exp}\left(\frac{-4.5}{\text{Tip Temp}}\right)$$

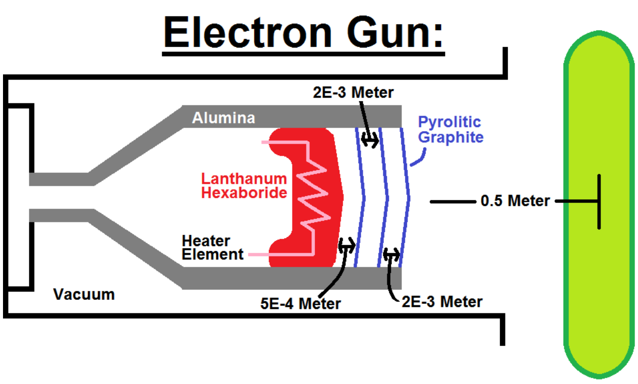
$$\text{Cone Cathode Thermionic Emission} = \text{Cone Surface Area} * 80\frac{\text{Amps}}{\text{cm}^2*\text{K}^2} * \text{Cone Temp}^2 * \text{Exp}\left(\frac{-4.5}{\text{Cone Temp}}\right)$$

### 9. Lorentz Force

$$\text{Carbon Lorentz Force} = 6*\text{Elemental Charge}\left[\frac{\text{Electric Field}}{\text{Gap}} + \text{Starting Velocity} * \text{Magnetic Field} * \text{Sin}(90)\right]$$

**Electron Gun:**

Material does not only come from the two plasma emitters. There is also an electron gun and trace air in the chamber. The chamber had a couple of millitorr of gas left in it [22]. Some quick math (see excel file) shows us this only has a small effect. Most of the plasma comes from the emitters. An electron gun was also used. Electrons were used to take a "snapshot" of the trapped plasma. This was done using X-rays. Electrons were released to make an "X-ray image" which could be read to show trapping. This is *very* different from normal polywell experiments, where electrons are used to heat ions to fusion conditions. A picture of the electron gun is shown below.




This electron gun was custom built by Heat Wave Laboratories in California [34]. It heats up a block of metal, to emit electrons. These electrons are accelerated using a voltage and shot into the rings. The metal is Lanthanum Hexaboride, a common electron emitter. You can model emission using the Richardson-Dushman equation. 3.4E15 electrons emerge in the 180 microseconds of shot time. These fly in at seven thousand electron volts of energy.

**Putting It All Together:**

All of these effects combine to make a plasma which is mostly hydrogen and carbon. The remaining 6 percent is trace elements. This includes tungsten, oxygen, nitrogen and the electrons. Below is a summary of the plasma composition. These amounts assume everything was injected instantly.

| Material | Source | Molecules* | Inject Force | Percentage |
|---|---|---|---|---|
| Hydrogen (+1) | 2 Plasma Emitters | ~ 3.6E18 | ~ 6.2E8 | 63.88% |
| Carbon (+6) | 2 Plasma Emitters | ~ 1.8E18 | ~ 3.7E9 | 30.26% |
| Tungsten (+2) | 2 Plasma Emitters | ~ 3.4E07 | ~ 1.2E9 | 0.00% |
| Electrons (-1) | 1 Electron Emitter | ~ 3.4E15 | N/A | 0.06% |
| Nitrogen | Trace Air | ~ 2.8E17 | N/A | 4.71% |
| Oxygen | Trace Air | ~ 6.4E16 | N/A | 1.08% |
| Trace | Trace Air | ~ 1.4E15 | N/A | 0.02% |

***Assuming instant emission**

## Conclusion: Lots to do with no funding

This post lays out the groundwork for a study of the EMC2 paper. So far, the science community has failed to scrutinize and explain this work. There is so much to do. For example, there are roughly 200 papers on cusp confinement experiments and theory [1]. This body of work needs to be integrated and contrasted to the EMC2 paper. Here is a list of the topics to address.

**1. Dose the EMC2 work agree with predictions?** Grad laid out what is needed to make this configuration stable [44]. Haines has spelled out how a plasma sheath may form in these geometries [15]. Dolan updated this work, summarizing the experiments that failed to see the effect [14]. We need to check the EMC2 tests against all of this. Do their test conditions meet the old predictions?

**2. What changed?** Why was this not seen before? The test must have changed between EMC2 and past work. It may turn out that previous teams fail to design the right experiments. They may have missed the right measurement tools or designed for other outcomes.

**3. What was the size of the sheath and the hole?** What is exciting about finding cusp confinement is it allows us to apply a backlog of theory. Two parts of the geometry is the plasma sheath and sheath holes. Several authors provide us with theory to predict the size of these sheaths and holes [35, 14]. These equations are shown below. They need to be applied to the EMC2 work.

## Relevant Cusp Models:

$$\text{Rosenbluth Sheath Thickness} = \sqrt{\text{Ion Gyroradius} * \text{Electron Gyroradius}}$$

$$\text{Chapman Sheath Thickness} = 2 * \text{Electron Gyroradius}$$

$$\text{Spindle Hole Size} \approx \sqrt{2 * \text{Sheath Thickness} * \text{Radius Of Spindle Cusp}}$$

$$\text{Sheath Hole Size} < \sqrt{\text{Electron Gyroradius} * \text{Ion Gyroradius}}$$

This containment method has so much potential. If cusp confinement works, it could be a better plasma trap then: pinches, tokamaks, stellorators and magnetic mirrors. In fact, it could trap better than any scheme with magnetized plasma. That drastically changes what a fusion plant looks like. It changes how soon we might expect one. There should be millions set aside for this research and groups should be desperate to find qualified researchers for the work. We could be looking at the best plasma trap in the world.

## Appendix:

**2 Magneto-motive force:**

You can estimate the magnetomotive force between the rings by treating them like two circular magnets facing each other. The equation for this is shown below. Below this are the numbers used for WB6 and WB8. The equations predicts 37.6 and 170 newtons for WB6 and WB8 respectively.

$$\text{Force} = \frac{\text{Field Strength}^2 * \text{Area}^2(\text{width}^2 + \text{Radius}^2)}{\pi * \text{width}^2 * \mu_o} * \left[\frac{1}{\text{Dis}^2} + \frac{1}{(\text{Dis}+2*\text{width})^2} - \frac{2}{(\text{Dis}+\text{width})^2}\right]$$

$$\text{WB6} = 2\,\frac{0.99T^2 * 5E\text{-}2M^2 * (0.05M^2 + 0.127M^2)}{\pi * 0.05M^2 * \mu_o}\left[\frac{1}{0.4M^2} + \frac{1}{(0.4M+2*0.05M)^2} - \frac{2}{(0.4M+0.05M)^2}\right]$$

$$\text{WB6} = \frac{0.37T^2 * 0.01M^2 * (0.01M^2 + 0.07M^2)}{\pi * 0.01M^2 * \mu_o} * \left[\frac{1}{0.2M^2} + \frac{1}{(0.2M+2*0.01M)^2} - \frac{2}{(0.2M+0.01M)^2}\right]$$

**1 & 3 Comparing Energy Density:**

Developing a full magnetic model of the polywell took over six months of work. The whole process is spelled out in: Taking A Stab At Simulation. You can download the matlab and excel files used to develop the model from GitHub. The model was benchmarked multiple times and in multiple ways. The theory and mathematics is spelled out in reference nineteen. The magnetic field inside the polywell can be modelled using the biot-savart law – specifically, it is a superposition of six electromagnets.

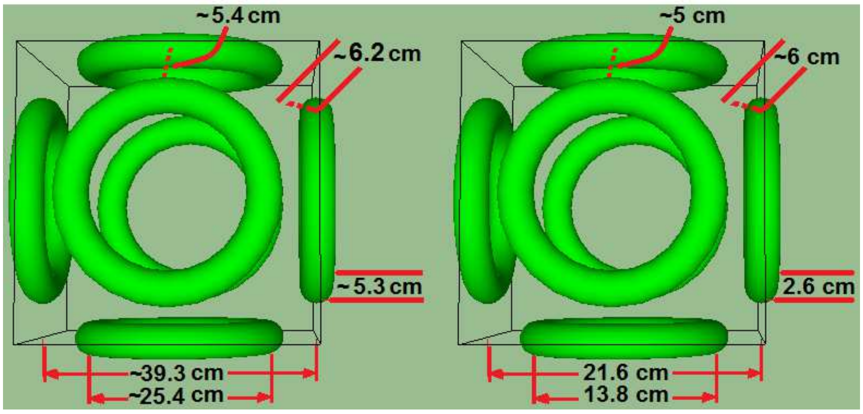
This tool was handy when comparing WB6 and WB8. The starting point is equations that can be used to estimate the field at key points. These points are the center, joint, axis and corner of the rings. The equations are shown in older posts. To do the math, you need the machines dimensions and the number ampturns in each ring [16,7]. Bussard's old machine had between 20 and 800 thousand amp turns. By contrast, WB8 had between 5 and 44.96 thousand per ring. The results of these calculations are shown below. The important point is that this new machine is one and a half times more powerful for the same number of ampturns, making it more efficient. The real experiment measured a lower magnetic field then predicted by about quarter; this was verified by the experimental team [12,7].

**Magnetic Field Comparison At Key Points (Gauss)**

| AmpTurns | Bussards Old WB6 Low 20K | Bussards Old WB6 High 800K | New WB8 Machine Low 5K | New WB8 Machine 20K | New WB8 Machine High 40.9K |
|---|---|---|---|---|---|
| Axis | 984 | 39,370 | 453 | 1,812 | $\boxed{3,710}$ |
| Corner | 964 | 38,560 | 298 | 1,194 | 2,445 |
| Joint | 1,474 | 58,974 | 332 | 1,326 | 2,716 |
| Center | 947 | 37,861 | 424 | 1,696 | 3,474 |

~2,700 Measured

**Bussards' Old WB6** **New WB8 Machine**




## Work Cited:


1. **Park, Jaeyoung. "Polywell Fusion: Electrostatic Fusion in a Magnetic Cusp." Microsoft Research. Microsoft Inc, 22 Jan. 2015. Web. 20 July 2015.**
2. **Park, Jaeyoung (12 June 2014). SPECIAL PLASMA SEMINAR: Measurement of Enhanced Cusp Confinement at High Beta (Speech). Plasma Physics Seminar. Department of Physics & Astronomy, University of California, Irvine: Energy Matter Conversion Corp (EMC2) url=http://www.physics.uci.edu/seminar/special-plasma-seminar-measurement-enhanced-cusp-confinement-high-beta**
3. **"Polywell Fusion – Electric Fusion in a Magnetic Cusp" Jaeyoung Park, Friday, December 5, 2014 - 1:00pm to 2:00pm, Physics and Astronomy Building (PAB) Room 4-330, UCLA**
4. **Talk at University of Wisconsin Madison, Monday, June 16, 2:30 PM room 106 ERB, Jaeyoung Park**
5. **University of Maryland, Colloquium & Seminars, "Measurement of Enhanced Confinement at High Pressure Magnetic Cusp System", Jaeyoung Park, September 9th 2014**
6. **"Polywell Fusion Electrostatic Fusion in a Magnetic Cusp", Jaeyoung Park, http://fire.pppl.gov/FPA14_IECM_EMC2_Park.pdf, Tuesday December 16, 2014 Hyatt Regency Capitol Hill 400 New Jersey Avenue NW, Washington, DC 20001**
7. **Private conversation, Jaeyoung Park, April 2015**
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