An Analysis of Lockheed-Martins' Fusion Effort

This article was written over a few weeks in November and December of 2016. As always, the best way to read this is on PDF – so I encourage you to download this off GitHub. The article is not perfect, but nothing ever is. I wanted to give fusion supporters the benefit of my ten years of experience in this field. That is why I am giving away this work for free. Hopefully, it helps scientists, advocates, students and policy makers understand the newest and greatest insights into fusion research. Enjoy.

Introduction:

Much has been made about Lockheed Martins' announcement that the company was developing a Compact Fusion Reactor. Unfortunately, they have been extremely lax on details. Many people - myself included - have called for a peer reviewed publication [12]. This is how science is done. It is non-negotiable. Lockheed still has not published. What we know about this effort, to date, comes from 3 patents [4, 5, 7], a presentation at Princeton [8], some off-hand comments by managers [9] and a dreamy YouTube video [6]. The dreamy YouTube video is particularly disappointing. It lacks any details or technical rigor. Hence, it was surprising this past October, when the company presented a poster at the 2016 American Physics Society conference. Details finally came out. With this poster, I have written the following analysis. This is a real treat for the community of fusion supporters out there. It is a rare chance to look at some really bleeding edge research.

"Don't worry about people stealing an idea. If it's original, you will have to ram it down their throats." - Howard Aiken

Secrecy Is Dangerous:

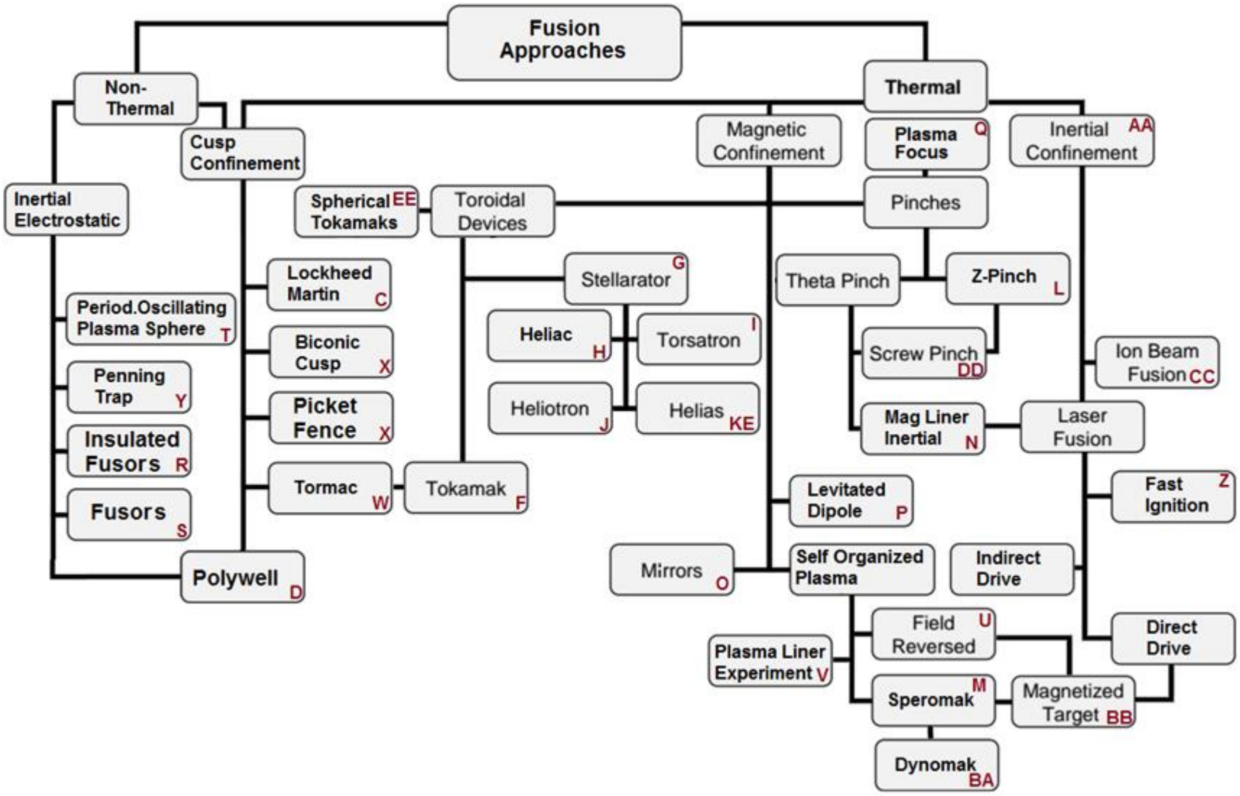
Secrecy in fusion is dangerous for many reasons. First, the public sees fusion power as impossible. The fusion community faces this problem every day. At some level, people will just not believe in fusion, until they can touch a power plant. So, it is in the fusion community's best interest to be as open as they possibly can be. Second, with no details, no one can follow in Lockheeds' footsteps. Science is a collaborative effort. You need multiple teams looking at any given research, from multiple directions. You need critics. You need debate. Lockheed foolishly thinks that it is protecting vital work. In fact – most of the fusion community is not interested; most of the fusion community is solely focused on the tokamak. The third danger arises from fusions' long history with wild claims. This means that Lockheeds' announcement can be dismissed as just around wild fusion claim. We know that story. We have heard it before: MIGMA in the 1970's, Cold Fusion in the 1990's and Bubble Fusion in the 2000's [10, 11]. People make a lot of noise - but give no data – and over time the science falters. All fusion teams should be aware of this. To avoid the dust bin of history – you must publish in a peer-reviewed journal. Lockheed needs to publish.

ITER Is Killing Us:

The Lockheed effort is happening at a time of great problems inside the fusion community. For many years, US fusion funding has been heavily focused on just one machine: ITER. This single project is eating the larger budget of the Office of Fusion Energy Sciences. Because of ITERs' thirst for cash, many other concepts have been strangled or shut down. Often, researchers need to "show relevance" to ITER, otherwise they will run the risk of getting closed down. After years of this kind of single minded support, many good ideas are languishing. For example, the University of Washington has invented a new fusion concept called the dynomak. The team is seeking 30 million over five years [13]. Their idea has a lot of promise. But the Office of Fusion Energy Sciences cannot and will not help them. The agency only cares about ITER. So the team, is turning to ARPA-E and private investment for support [14]. In another example, the company EMC2, has published promising results on the polywell [15]. To take the concept further they need 30 million in investment, but again – the Office of Fusion Energy Sciences is not helping [16]. So many projects are hurting. In October, MIT had to shut down the Alacator tokamak due to a lack of funding [17]. Also, the Levitating Dipole Experiment needs a few million over several years and the Plasma Liner Experiment at Los Alamos is surviving on limited ARPA-E funding [18, 19]. All this funding is being redistributed to ITER - and there is a strong argument that ITER will never lead to a commercial fusion power plant [20]. As an American, this hurts my pride. The US has led the way in fusion research and we need to stay in front it. This technology has vast implications for our military, economic and cultural dominance. If the US want to change, it should try to use government money to lure dollars from private sector. A public-private partnerships is a good path forward.

Progress Despite ITER:

Fusion researchers are finding ways to work around the Office of Fusion Energy Sciences' narrow minded support. We are following a diverse set of approaches and relying on private capital to get there. There will be more of this in the future. The prize of zero-carbon, abundant and cheap energy is too big for people to ignore. There are several teams, innovators and new ideas jumping into the game. The two big companies in this space are Tri Alpha Energy and General Fusion. Both companies have followed a Silicon Valley model, raising investment from venture capitalists and wealthy benefactors. Paul Allen of Microsoft, has invested in Tri Alpha Energy and Jeff Bezsos of Amazon has invested in General Fusion [22]. Right now, it looks like Tri Alpha is the stronger of the pair; both technically and finically. Currently, they have an estimated half a billion dollars in total investments [1]. The company was hiring extensively at the 2016 APS conference. Aside from their headquarters in Los Angles, Tri Alpha is opening up new field offices at Princeton and Los Alamos. Last May, they set a record for the longest stable Field Reversed Configuration, at five microseconds [21]. This might not sound momentous, but critically, their machine was fusing for the ***duration*** of the run. This implies that if TAEs' machine can run for two hours, then they can get two hours of continuous fusion. Beyond these two companies, there are a slew of smaller groups trying to raise investment with other ideas. Just how many fusion concepts are there, out there? In February, I pulled together a list of several fusion concepts: from mainstream to highly experimental. Each concept was pulled from a literature reference [A-CC] and are grouped by family and type below. For every concept listed below, there is a group, a researcher or a company trying to make something happen.

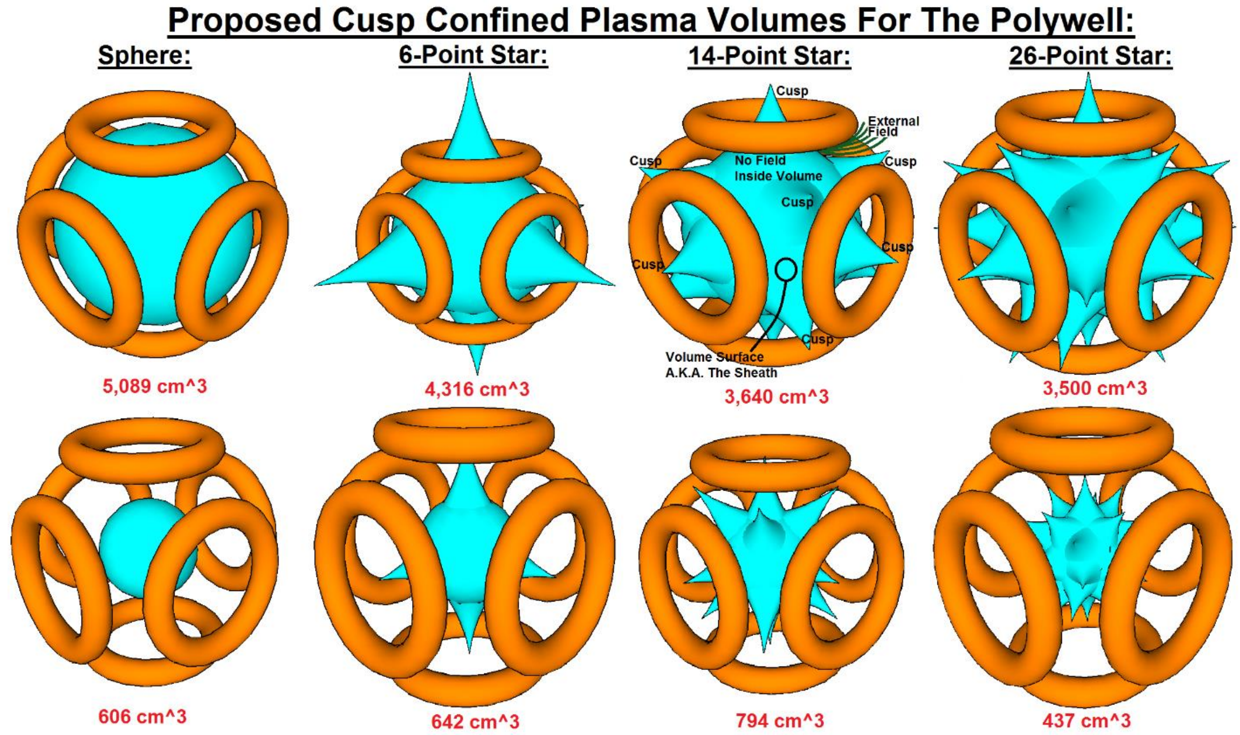


Lockheeds' Effort:

Where does Lockheeds' effort fit in this ecosystem? I would argue that Lockheeds' effort is one the most innovative fusion efforts, but that means it has the highest inherent risk. The secret to Lockheed's' work is the way they trap the plasma. This is their secret sauce. Their idea is radical: use a plasma's own internal diamagnetism to reject the outside field. Plasma is a soup of (+) and (-) charges. It moves. As the charges move, they makes a magnetic field [24]. So – plasma has its own internal magnetic properties. This is technically known as its' diamagnetism [23]. Lockheeds' idea to use this internal magnetic property to push against the sharply bent containing field. Dr. Bussard called the concept "the whiffle ball trap" [49]. If Lockheed can do this, they could create ***the worlds' best plasma trap***.

Making the worlds' best plasma trap, gets you pretty far down the road to a fusion reactor. Efficient trapping is a huge problem in fusion research. This type of trap would have three key traits. First, the idea aims to hold a high pressure plasma inside it [25]. This is known as a "beta = 1" plasma – where the plasma pressure matches with the outside magnetic field pressure [26]. That helps the overall fusion rate by raising the density. Second, the outside field is ***blocked*** from entering the inner plasma. This is awesome. That reduces the energy leaking from the plasma as light. Technically, it lowers the cyclotron and synchrotron losses

[25, 27, 28]. Third, the surface of this plasma trap would basically have a thin skin with holes in it. The holes would be at the cusp. These are spots where the field is sharply bent; and can be considered places where plasma leaks out. We want to design the trap with cusps as small, and as few, as possible. Along this surface or skin the trap, material would be much better trapped. The surface may also have electrons streaming on it; models by Lockheed and others have talked about a surface current [29, 30, 31]. In a perfect world, mass would be trapped inside this surface with losses only happening through the cusps [25]. That would be awesome. It would lower conduction losses – a major problem across all of fusion research – and make the machine yet more efficient. What would such a volume look like? For the polywell, many people have proposed different shapes; including: spheres and multi-pointed stars shapes [32 - 34]. These are shown below for the 2014 Navy machine. At this point, it would be guesswork as to what the shape would be.

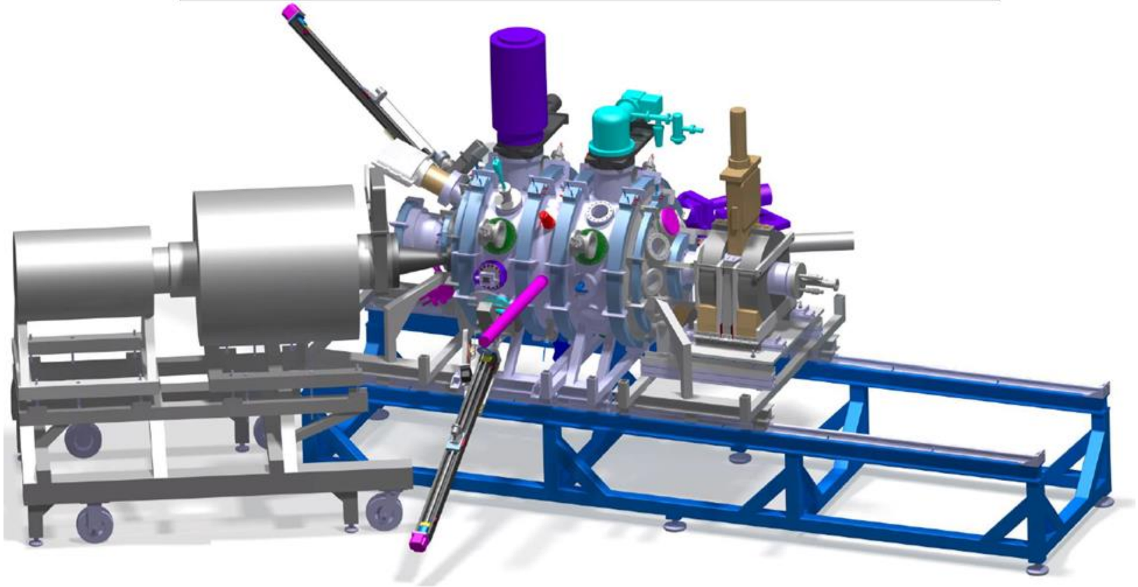


"Wherever I see people doing something the way it's always been done ... well, that's just a big red flag to me to go look somewhere else." - Mark Cuban

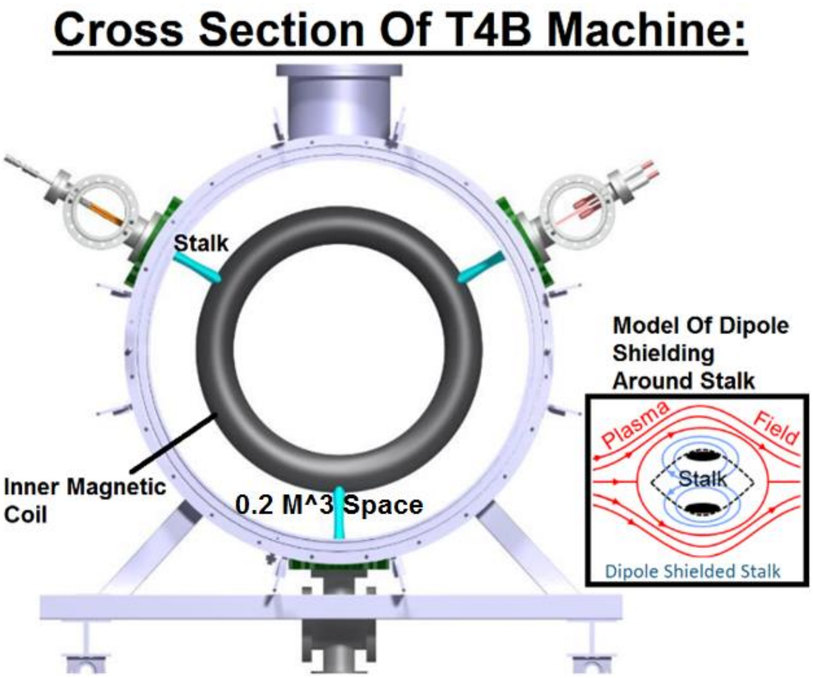
Lockheed Is Positioned To Surpass EMC2:

Lockheed is positioned to show cusp confinement better than EMC2 was able to. So far, EMC2 is the only group that has published data on cusp confinement. This has been presented at a slew of professional talks [39 - 44] and in a published paper from 2014 [35]. The company used x-rays to prove electrons were trapped for tens of microseconds longer than they should have been. They also used flux loops to measure a plasma-generated magnetic field. The team estimated a trapped plasma volume of ~5,000 cubic centimeters. This is not much data. This lack of interest frustrates me. We need multiple universities and companies looking at this – its implications are huge. This is also why Lockheeds' effort is so exciting. Lockheed is positioned with the team, the tools and the funding to press forward - where EMC2 could not.

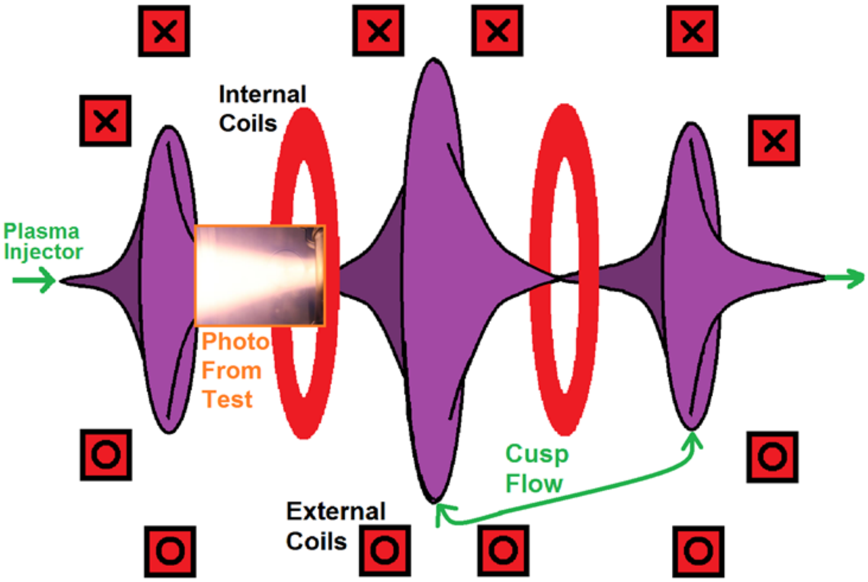
Model Of Lockheed's' TB4 Experiment - 2016



To test this type of trap, Lockheed has built a small machine. It is known as the T4B experiment, shown above. I often wonder why researchers give their experiments such drab names. It is unclear when Lockheed started developing this thing. The first time it was pictured was at this Solve For X talk back in 2013. The effort maybe stretch back to when Dr. Tom McGuire was first recruited in 2007 [62]. The machine is a simple canister filled with plasma. It has magnetic coils embedded inside it. This actually breaks a paradigm of fusion research. Lockheed has made a Galatea. This is a Russian term, popularized by A Morozov [38]. This is a type of machine, where the coil and plasma mingle together. This is why the polywell and the T4B can be considered in the same vein of approaches.



The T4B and the development behind it were presented the APS conference. For me, there were four surprises from this presentation. First, the poster refers to the plasma as “inflating” to fill the trap [31]. The use of this term and its implied mechanism was wholly new to me. Secondly, the models assume the electrons and ions have different temperatures in this trap. This is actually a debatable question within the physics community. Rider showed that any temperature difference, in such a system, would be short lived. Energy transfer between the ions and electrons would happen so quickly that differences would quickly lost [45, 46]. Meanwhile, people have made the argument that the opposite case is true [47, 48]. Lockheed actually measured a temperature difference – but that measurement was not done at steady state. I think it is still an open question. The last surprise was how Lockheed is trying to shield the machines’ stalks, using a dipole field [31]. The stalk is a hunk of material you shove into the plasma to hold up the magnetic coil, shown above. This is a problem for many fusion researchers. Dr. Bussard had problems with mass being lost through the stalks holding the polywell [49]. If it works, shielding with a dipole field would be a very clever innovation; I had personally never heard of such an idea being tried. Unfortunately, Lockheed is not giving details on if it is working or not. To give you a sense of the inside of this machine, I have laid out a possible shape for this plasma trap below. This is based off images presented at a talk at Princeton, in 2015 [8].

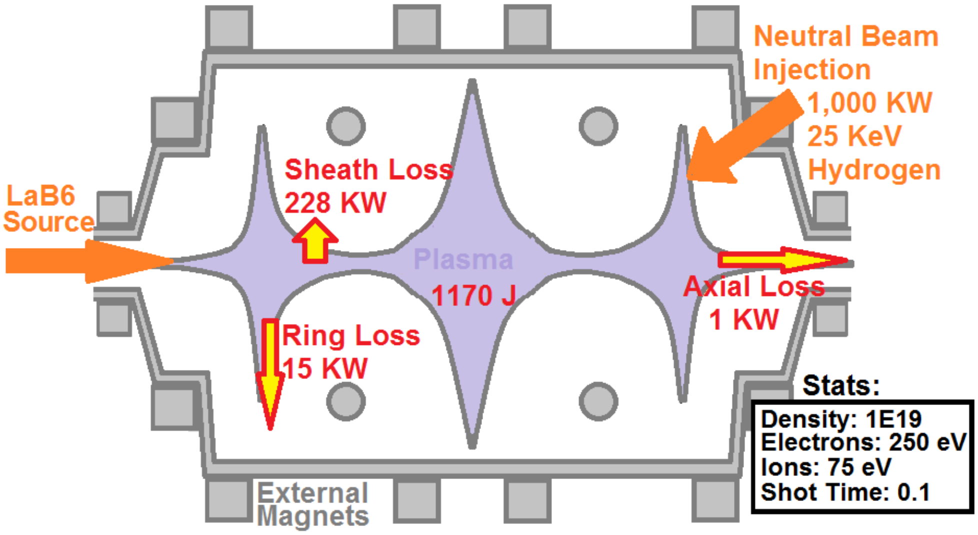


Possible Plasma Shape Inside T4B Machine:

The T4B Experiment:

The best way to understand this experiment, is to walk through how it works. Inside the canister is a set of rings [31]. These are electromagnets. There are also electromagnets on the outside of the chamber. When mixed together, Lockheed has a field with a full strength of 0.6 Tesla and an equilibrium field of 0.1 Tesla. The rings are likely powered using supercapacitors, like those featured in the Lockheed video [6]. This allows the team to fire its' machine for a tenth of second, ***once every minute*** [31]. That is fast. The omega laser usually needs a full day, to do a couple of tests. This speed offers a big advantage. It means Lockheed can get lots of data, very quickly. At the start of a shot, the vacuum is pumped down and the magnets are fired. This establishes the fields for the oncoming plasma. The plasma is released, like runners out of starting block. It comes from two sources. The first is, a source of electrons at the far end of the tank. Lockheed is using Lanthanum Hexaboride cathode as their source; the same device EMC2 used [31, 35]. The strength of this emitter, is that it can make a ton of electrons, quickly. You heat this metal, electrons come off and you can coarsely direct them into the chamber [63]. This makes 1E19 particles per cubic meter. The other source of plasma is the neutral beam. This is a more refined, controlled source of hotter material. The neutral beam fires for 3 milliseconds. Each shot is 1 megawatt of hot (25,000 electronvolts) hydrogen ions. Notice that they are just shooting regular old hydrogen, not fusion fuel. Lockheed figures that half of these ions stay hot – known as fast ions. Fast ion are the thing most likely to fuse, anywhere in the machine. With both emitters fired, the T4B is chock full of plasma. The plasma stays trapped even after the sources are shut off. This is a promising sign that cusp confinement is happening. The team then measures this plasma. They use 18 different tools. What they want to know is the energy and mass flows inside the chamber. They measured some of these things and they report them in the poster; shown below. Knowing how energy moves inside is key if you want to make a fusion power plant out of this thing.

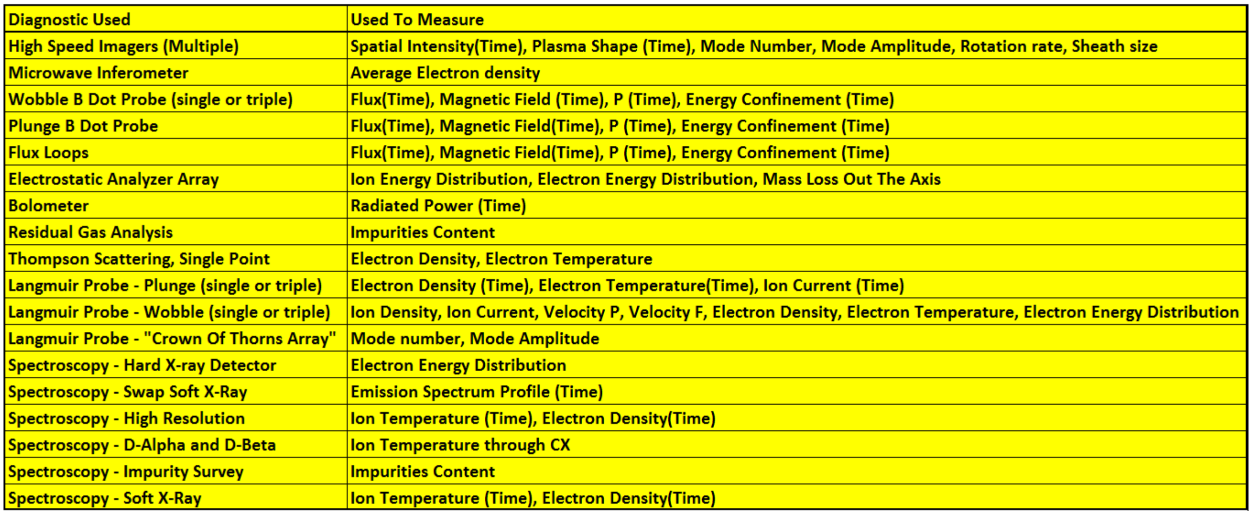
Energy Flows Inside the T4B Experiment



Results:

Results from the T4B have come out in two ways. There are results that they have explicitly told us; and then there are results that have been implied. We'll start with what we know. The stated goal of the T4B is to understand how the neutral beam source behave in this geometry [31]. But, given the number and kind of diagnostics the team has – they are trying to answer many more questions simultaneously. This is exciting. The Skunkworks has decked the team out with more and better measurement tools then ECM2 could afford [35, 31]. These are listed below.

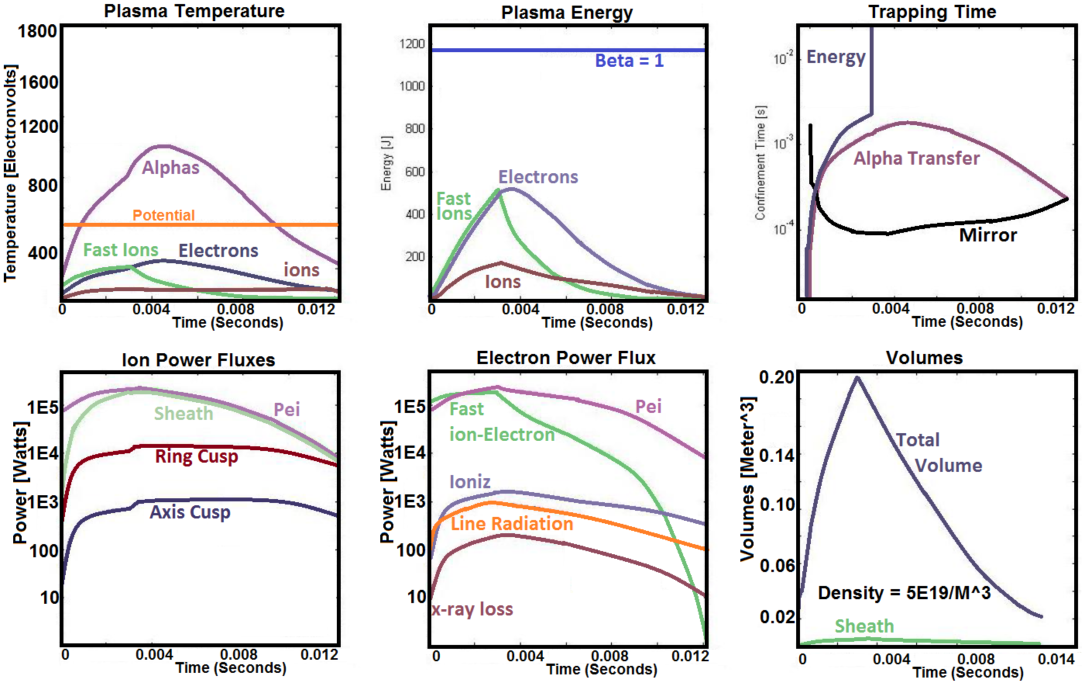
Measurement Tools Used On The TB4



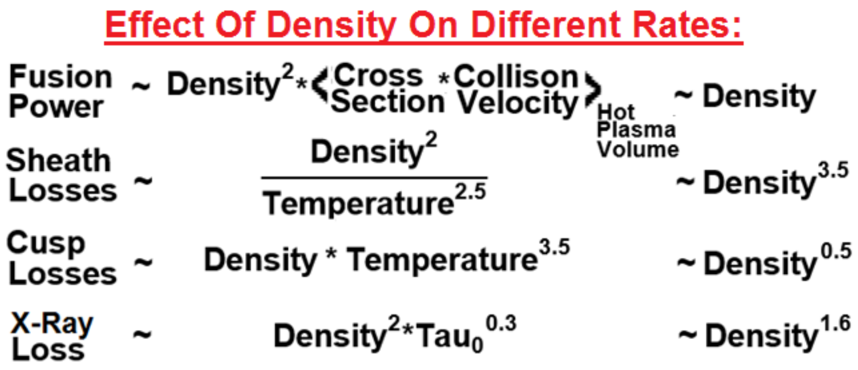
Diagnostic Used	Used To Measure
High Speed Imagers (Multiple)	Spatial Intensity(Time), Plasma Shape (Time), Mode Number, Mode Amplitude, Rotation rate, Sheath size
Microwave Inferometer	Average Electron density
Wobble B Dot Probe (single or triple)	Flux(Time), Magnetic Field (Time), P (Time), Energy Confinement (Time)
Plunge B Dot Probe	Flux(Time), Magnetic Field(Time), P (Time), Energy Confinement (Time)
Flux Loops	Flux(Time), Magnetic Field(Time), P (Time), Energy Confinement (Time)
Electrostatic Analyzer Array	Ion Energy Distribution, Electron Energy Distribution, Mass Loss Out The Axis
Bolometer	Radiated Power (Time)
Residual Gas Analysis	Impurities Content
Thompson Scattering, Single Point	Electron Density, Electron Temperature
Langmuir Probe - Plunge (single or triple)	Electron Density (Time), Electron Temperature(Time), Ion Current (Time)
Langmuir Probe - Wobble (single or triple)	Ion Density, Ion Current, Velocity P, Velocity F, Electron Density, Electron Temperature, Electron Energy Distribution
Langmuir Probe - "Crown Of Thorns Array"	Mode number, Mode Amplitude
Spectroscopy - Hard X-ray Detector	Electron Energy Distribution
Spectroscopy - Swap Soft X-Ray	Emission Spectrum Profile (Time)
Spectroscopy - High Resolution	Ion Temperature (Time), Electron Density(Time)
Spectroscopy - D-Alpha and D-Beta	Ion Temperature through CX
Spectroscopy - Impurity Survey	Impurities Content
Spectroscopy - Soft X-Ray	Ion Temperature (Time), Electron Density(Time)

With these tools, the team can test key ideas about this trap. First, Lockheed claims that their plasm has inflated to high beta. This means that the plasma is pressing against the magnetic field; behavior you would expect from a cusp confined trap. But unfortunately, they are not saying what their beta is. If they reached 1, then they have a world changing, pressurized plasma. Next, Lockheed has demonstrated that everything is ***very sensitive*** to plasma density. If the density changes by a factor of ten (1E19 to 1E20) then the behavior becomes very different. It is like they are seeking a sweet spot for this machine. At the lower density, they get hot electrons and the hot ions, stay hot. Lower density means the fast ions are less likely to collide. Meanwhile, the electrons are small and light. If the ions were small marbles, the electrons would be the size of atmospheric dust [57 - 59]. These electrons can pick up the fast ions' energy. By contrast, at high densities, the ions actually get heated inside the machine, while the electrons get cold [31]. Notice in both cases that there are temperature differences between the ions and electrons. This difference may not persist in a full scale machine - running for say - 25 minutes. We need to test that idea. Finally, Lockheed provided data from the T4B. This is shown below. Most of the rest of this poster, is modeling work.

Real Data From The T4B Machine



Aside from what they stated, Lockheed management has also hinted at results. Things seem to be going well. The team has upgraded to a larger lab. They have hired more people. This means they have seen an increase in funding [36]. We also know that Rob Wiess, director of the Skunkworks, has said they have had success at trapping, at the lower temperatures. He said they are raising the temperatures for more tests [37]. Things look promising.



Effect Of Density On Different Rates:

Fusion Power $\sim \text{Density}^2 * \left\langle \text{Cross Section} * \text{Collison Velocity} \right\rangle_{\text{Hot Plasma Volume}} \sim \text{Density}$

Sheath Losses $\sim \dfrac{\text{Density}^2}{\text{Temperature}^{2.5}} \sim \text{Density}^{3.5}$

Cusp Losses $\sim \text{Density} * \text{Temperature}^{3.5} \sim \text{Density}^{0.5}$

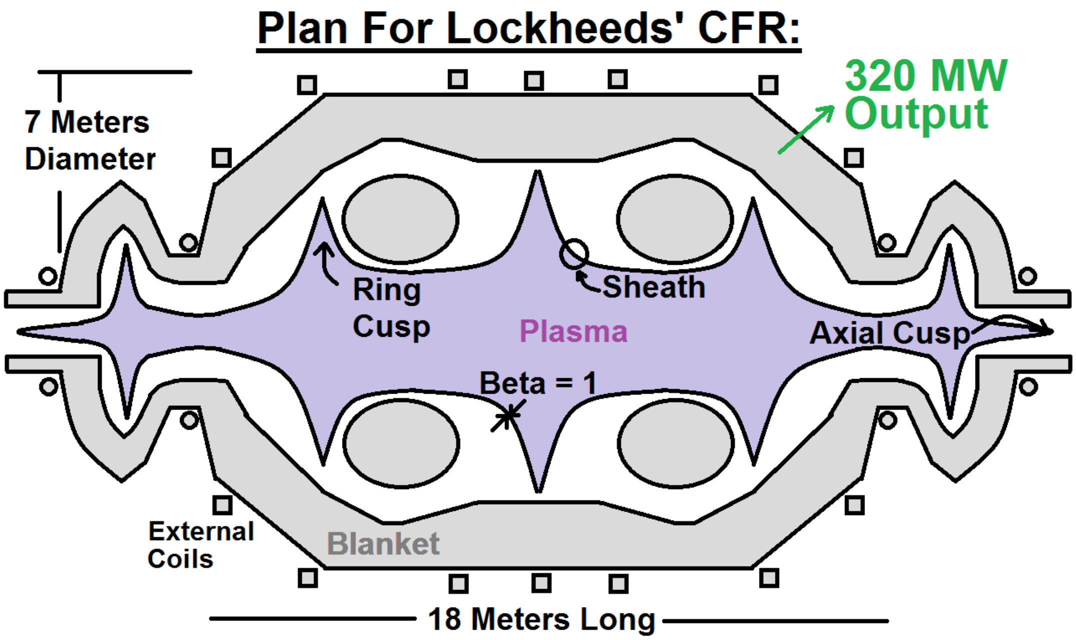
X-Ray Loss $\sim \text{Density}^2 * \text{Tau}_0{}^{0.3} \sim \text{Density}^{1.6}$

The Rest of This Post:

The rest of this poster is all modelling. Lockheed created three models. The first uses some math and software to understand this plasma trap. The second model is a particle-based simulation of plasma inside the machine. The last model is a gritty, hands-on, math model of different physical processes. They use these tools to explore chunks of the machine, the T4B and their ultimate goal: the CFR power plant concept. So, to be clear, there is no data in the rest of this post. It is still worth reading, if you want a deep sense of what is going on in this research.

Reprinted – The Poster Abstract:

The Lockheed Martin Compact Fusion Reactor concept relies on a diamagnetic plasma behavior to produce sharp magnetic field boundaries and confine fusion plasma in a magnetically encapsulated, linear ring cusp geometry. Simulations show stable inflation to the high beta, sharp boundary state with constant thickness sheaths. Zero dimensional confinement models predict effectiveness of neutral beam heating to produce high electron temperatures in the T4B experiment. Those same models are used to determine the feasibility of an operation reactor and determine the required magnetic shielding performance for design closure. The T4B experiment will characterize and test plasma sources in the Compact Fusion Reactor geometry and conduct initial neutral beam heating experiments. The T4B design and diagnostics suite are presented.



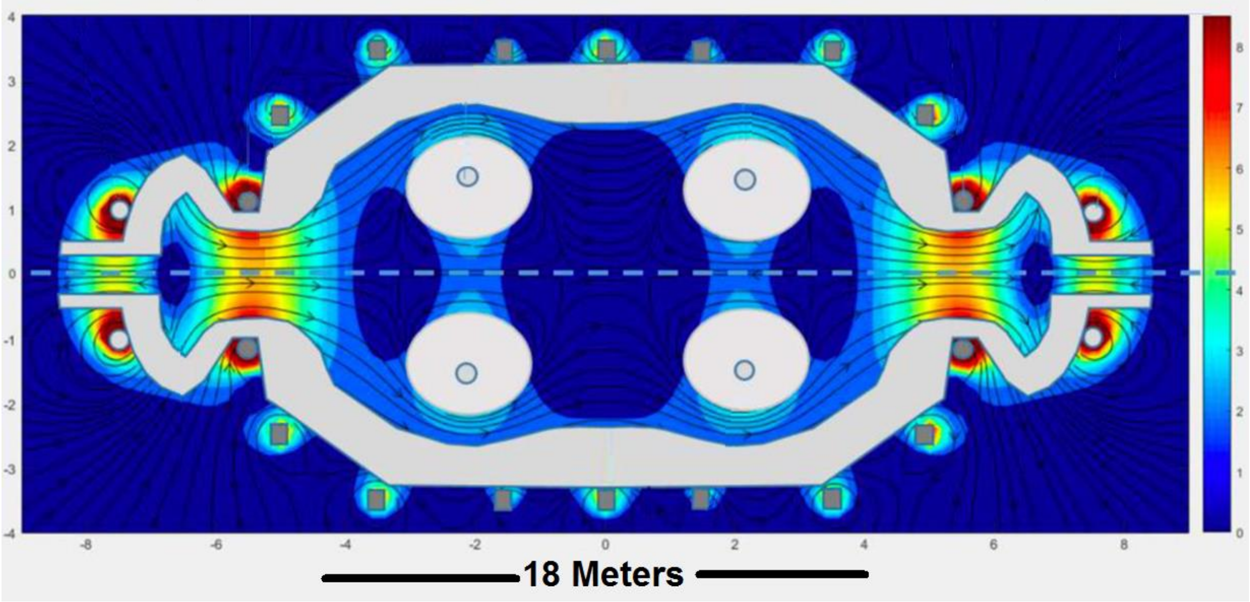
The Compact Fusion Reactor

The Compact Fusion Reactor is the name for the fusion power plant idea put forth by Lockheed Martin. This plant is projected to make ~320 megawatts of electricity. That would make it a fusion reactor, on par with a combined cycle natural gas plant. It would make it smaller than todays' nuclear reactors and more powerful than current solar plants. Its fuel source could be cheap, and its' radioactive waste could be very low. But - based on the newest numbers - the CFR is not as compact as we had thought [31]. The core looks to be over 50 feet long and 20 feet in diameter. A hot plasma will sit inside this ~16.3 cubic meter space. That is enough space to fit two yellow school buses, with some extra room. Lockheed estimates the plasma in center will be around ~5E+20 particles per cubic meter. That is ten times higher than the density they currently get in the T4B. That density is a hundred times less than the Joint European Torus – the current standard for fusion research [55]. This plasma will ideally, be held in a diamagnetic cusp trap. That means it can reach relative high temperatures and pressures. Around the edge of this plasma is a thick blanket which will absorb the products and energy from the fusion reaction within. That blanket is key. It is how the energy gets made into electricity. But, Lockheed has not offer any details about this blanket. They model the blanket as having ~4.2 megawatts/meter^2 of hot neutrons to hitting it, during operation. Below are some other key aspects of this machine [31]. Below that, is a computer model of its' magnetic fields.

- Plasma trapping happens inside a magnetic well, with self-producing sharp field boundary.
- The trap is encloses 200 MW of thermal plasma. This assumes the plasma trap has a sheath or skin which is the size of the hybrid gyroradius.

- The CFR uses neutral beams, to heat the plasma to an ignited state.
- The losses that dominate, are the ion losses through the ring cusps, into stalks and axially through the sheath.
- If the CFR gets good global curvature in the magnetic fields, then the plasma will be have interchange stability, over the entire volume.
- Bad curvature does exist. But it is confined to the bridge region. In this region, the plasma has a significantly reduced density. It also streaming and non-maxwellian.
- A big advantage of the CFR is its small size. That lets you make quick changes.
- The major physics concern with this concept is the sheath size, the stability, the plasma inflation, the stalks shielding and finally the blanket material.

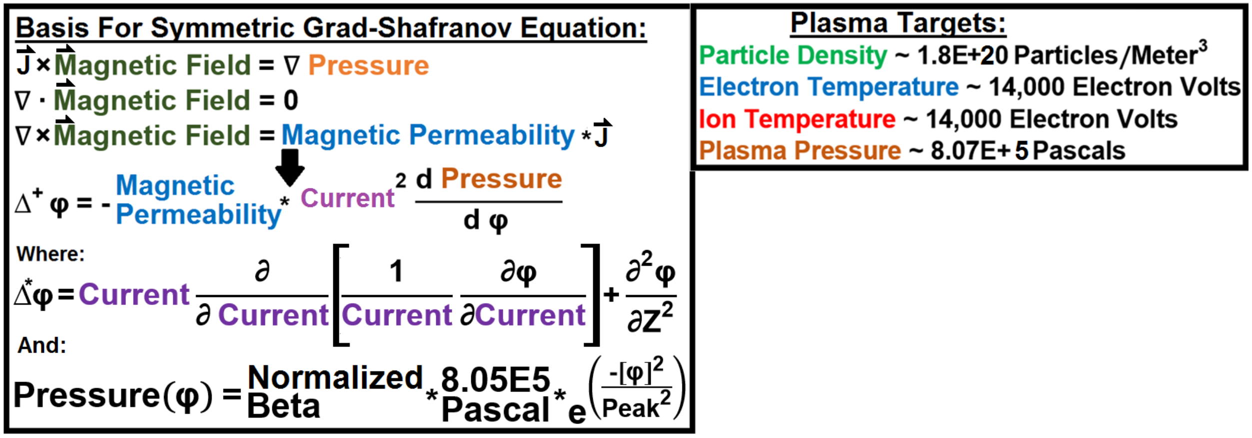
Lockheeds' Compact Fusion Power Plant Concept:



Model 1 – Using Grad-Shafranov

How would we model the CFR? Engineering Associates Incorporated was hired to do an estimate of the plasma pressure inside the machine. Everything in their model was based on a cusp confined plasma. That means they are assuming the plasma pressure is balanced against the magnetic field. They are assuming that it is at equilibrium. So the model would fail - if cusp confinement does not work as promised. This was only two dimensional model. That is fine, everything is symmetric around an axis. Fortunately, there is a ready-made solution for this problem: the Grad-Shafranov equation. It is a perfect fit. It works for 2 dimensional plasmas, at equilibrium. Many other math assumptions went into this; these are shown below. Engineering Associates used COMSOL - a physics program - to do the needed math. Their software shows that a stable plasma will “inflates” to the high pressure condition. The term “inflates” is new to me; it is an interesting choice of words. Engineering Associates produced a pressure profile of the plasma inside the CFR. They are saying that this thing can reach plasma pressures that are ***8 times higher*** than the Joint European Torus (JET) [50].

Math Behind Model 1:



Basis For Symmetric Grad-Shafranov Equation:

$$\vec{J}\times\overrightarrow{\text{Magnetic Field}} = \nabla\,\text{Pressure}$$

$$\nabla\cdot\overrightarrow{\text{Magnetic Field}} = 0$$

$$\nabla\times\overrightarrow{\text{Magnetic Field}} = \text{Magnetic Permeability} * \vec{J}$$

$$\Big\downarrow$$

$$\Delta^{+}\varphi = -\,\text{Magnetic Permeability} * \text{Current}^{2}\,\frac{d\,\text{Pressure}}{d\,\varphi}$$

Where:

$$\Delta^{*}\varphi = \text{Current}\,\frac{\partial}{\partial\,\text{Current}}\left[\frac{1}{\text{Current}}\,\frac{\partial\varphi}{\partial\text{Current}}\right] + \frac{\partial^{2}\varphi}{\partial Z^{2}}$$

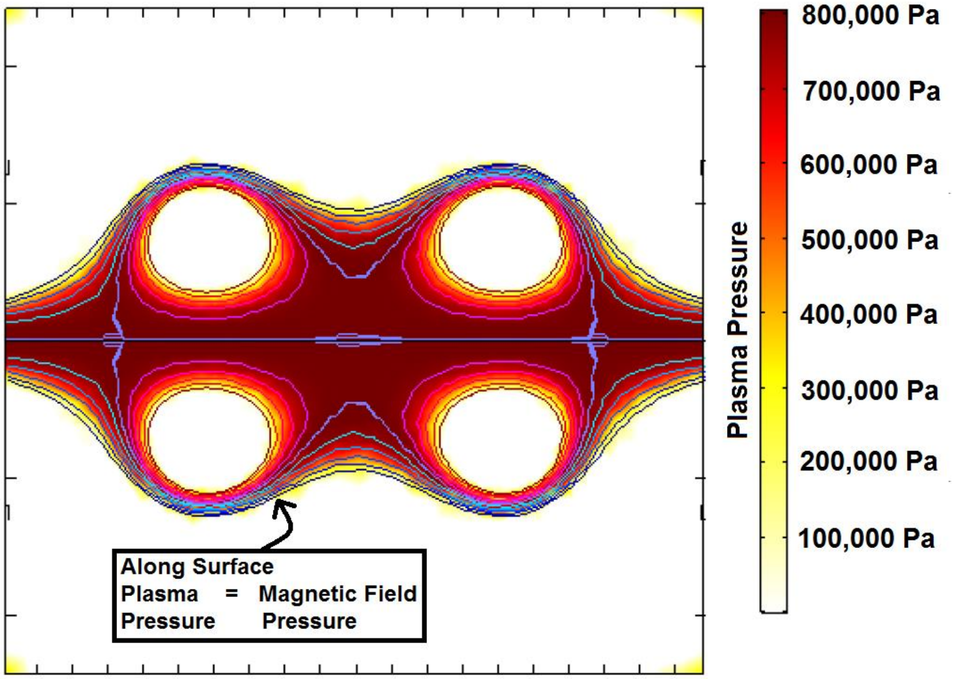
And:

$$\text{Pressure}(\varphi) = \text{Normalized Beta} * 8.05\text{E}5\ \text{Pascal} * e^{\left(\frac{-[\varphi]^{2}}{\text{Peak}^{2}}\right)}$$

Plasma Targets:

Particle Density ~ 1.8E+20 Particles/Meter^3
Electron Temperature ~ 14,000 Electron Volts
Ion Temperature ~ 14,000 Electron Volts
Plasma Pressure ~ 8.07E+5 Pascals

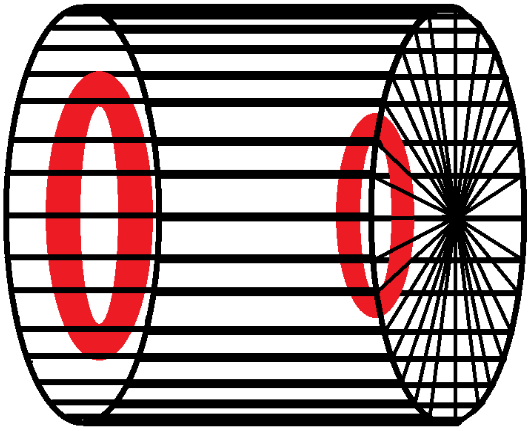
Simulation Results: Plasma Pressure



Along Surface
Plasma Pressure = Magnetic Field Pressure

Model 2 – Particles in Cells

The next model uses a particle in cell code to understand the machine. Lockheed did this internally. They decided to look at the smallest chunk of the machine possible. A small chunk, which would still capture all the key physics. They choose a volume with two differently sized magnetic rings. They then implemented a particle in cell software. You break the space up into little cells. You then use representative particles to model how plasma moves through this space. PIC simulations have been around since the 1960’s, when they were developed at Los Alamos [51, 52]. They are more accurate than the math work by Engineering Associates. But they still have flaws. For example: this model was only two dimensional. They simulated one plane and then “spun” it around to make a cylinder of space. The details of this work, and the shape examined is shown below.



Particle-In-Cell Simulation of Lockheed Geometry

- **LSP Code**
- **Two dimensional simulation**
- **Area simulated: 10 cm by 18 cm**
- **0.5 mm mesh size**
- **2 million representative particles**
- **400 nanoseconds of real time simulated**
- **20 processors used**
- **72 hours of computational time**

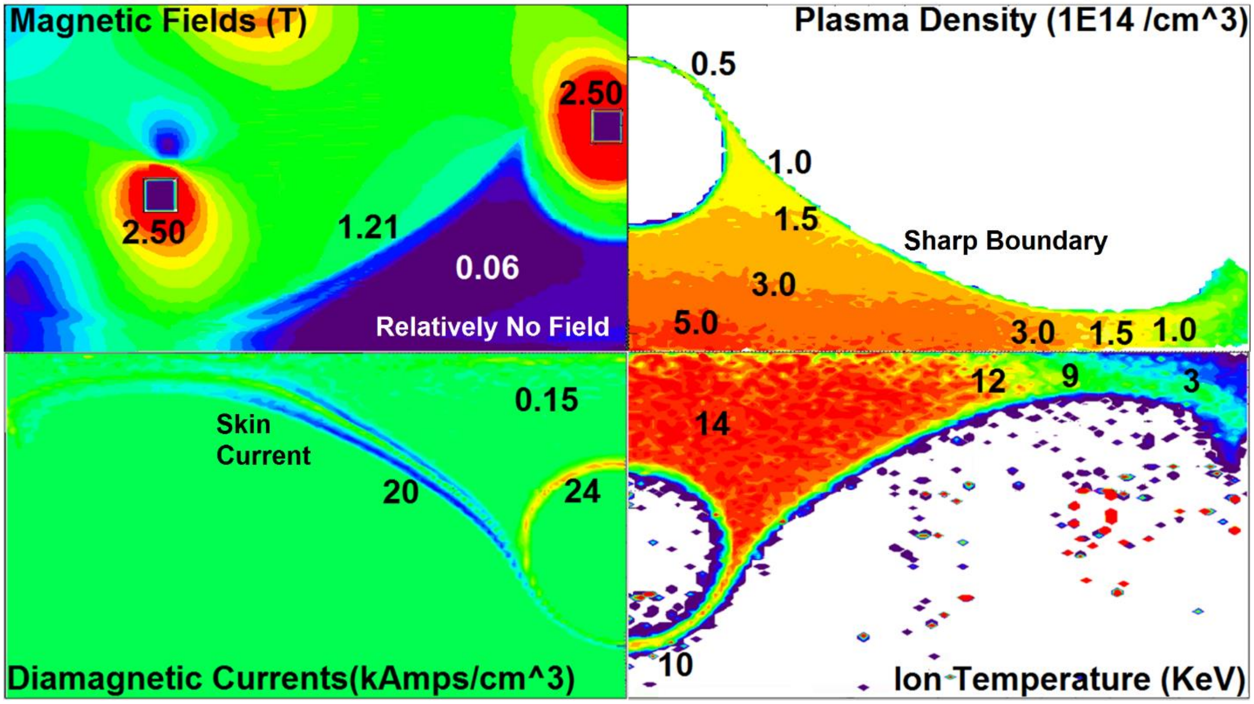
Below is a summary of what they found:

- After an initial load of plasma, the simulation quickly settles into a high pressure, equilibrium state.
- Diamagnetic currents form. This is a surface current along the plasmas’ skin. This makes a near field-free region inside the surface.
- Fast ions, which are shot in using neutral beam injection, are effectively trapped.
- The plasma density is highest in the center. Density falls as you travel along the axis. It falls as you move through the small ring, by a factor of five. The density also falls outside the big ring, by a factor of ten.
- The sheath width is pretty much constant. It is dominated by an electric field; which is made by the plasma’s inner diamagnetic currents.
- The size of the cusps along the axis and by the rings, are decoupled. These are the holes in the trap. This seems to mean that the size of one, does not affect the other.
- They hypothesize that the size of the cusp will change, when they get to a stronger magnetic field.

Flaws in Model 2:

This model definitely needs work. For one thing, it just looks at the starting of the machine. Lockheed needs to understand what happens when it reaches steady state. At steady state, the plasma will be colliding with itself. They also need to understand the skin of the trap, its’ sheath. This model shows that the trap makes a self-generated current on its skin. This confirmation of an idea put forth by Dr. Joel Rogers a few years ago [29 – 31]. They need to know: what is a good energy distribution for material along this skin of the trap? Finally, they need to include the machines' full geometry and it would be nice to match this model with a real world experiment like the T4B. To do that, they must include the effects of the conductive metal walls. They would also need to scale up to running this software on supercomputers.

Simulation Results Of Particle In Cell - Model 2:



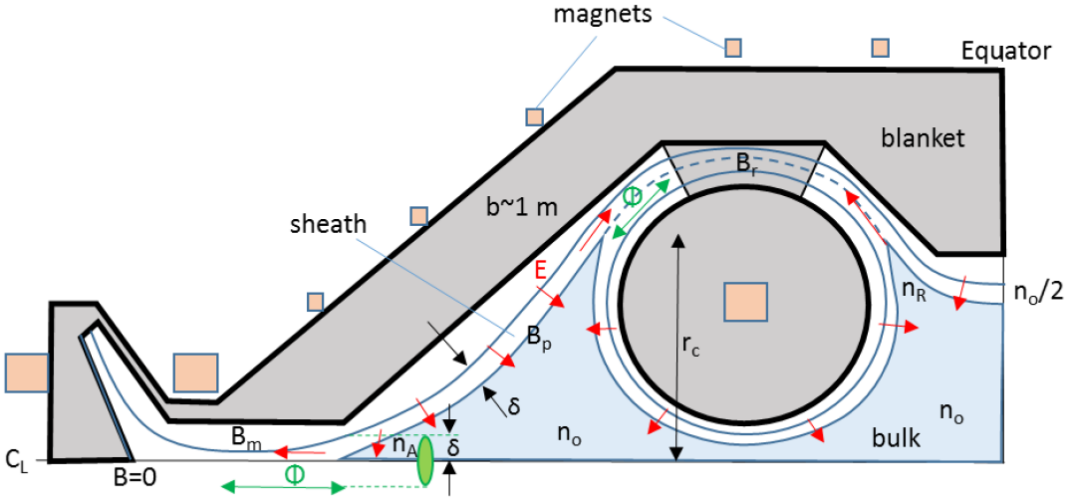
Results of Model 2

Even though this model is very limited – the results definitely look like a cusp confined plasma. You can examine these above. First, notice that in the density plot, the boundary is ***sharp***. If this is proved out by data, this would be unusual trait for any kind of fusion experiment. If you look at the magnetic field plot, there is almost no magnetic field inside this boundary. That is a field-free region – just like the one predicted by a cusp confined plasma [25]. Next, the plasma has a skin current running over its' surface. This offers support to statements made by folks in the polywell community years ago [29 - 30]. Finally, look at the overall shape of the trap. It is sharply bent shape with holes in the current along the axis and the rings. This strikes of what we expected to see. Again – it is only a model though, not confirmation.

Model 3 – Straight Up Math:

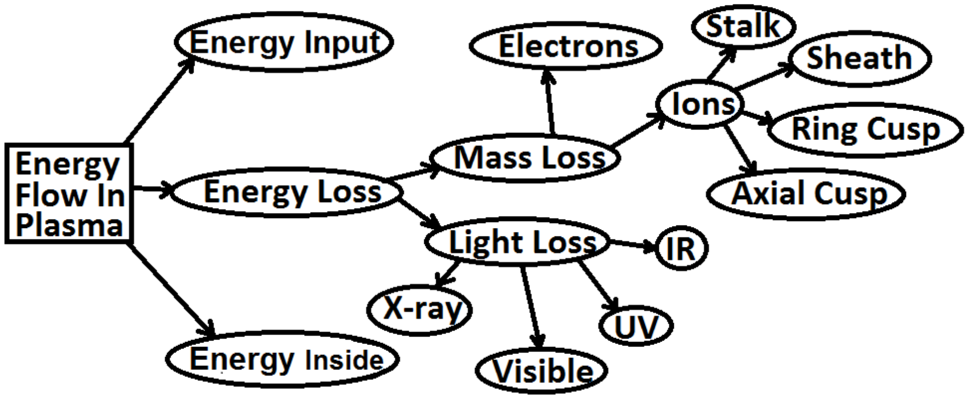
So far, none of this has looked at the Compact Fusion Reactor in deep detail. That is tough to do with software. The Grad- Shafranov model is too simple to cover this. The particle-in-cell model is too limited. Management at the Skunkworks needed more assurance that this would be interesting, before they funded it. So the team tried to pick apart the physics inside the machine and write an equation for everything they thought would happen. Making the simple model helps a researcher get a feel for what is going on. When it was finished, the math used in this model was very extensive. Below, I have tried my best to pull it apart and explain the reasoning behind it. Unfortunately, I do not have the variables and some details are not included in the poster. The raw equations are given at the end of this post. The next four paragraphs walk you through Lockheeds' assumptions and reasoning. After examination, it is clear to me that ***many*** assumptions went into this, and that leaves me very skeptical.

Quick Geometric Sketch Used For CFR Model:



Model 3 - Introduction:

This model is all about energy. Like an account at a bank: how much is coming in, how much is made and how much is going out? At full force, the CFR would in ignition mode. Ignition is a fusion ***chain*** reaction. Hot helium made by fusion, would kick off new fusion reactions before exiting the machine. So it is making energy – but that is offset by how much energy is leaving and being added. There are two ways that energy leaves the machine: through light or through mass loss [64]. Light losses are easy to find. Lockheed uses several typical expressions to account for this [31, 45, 60]. They figure that 20.8 megawatts of energy is lost as light. The mass loss are harder to find. As the mass leaves, it pull energy away with it. This is known as conduction losses. There are two kinds of particles in this machine: electrons and ions. Right away Lockheed ignores the electron losses. They make this assumption based on the idea that the plasma is mostly ions. I am skeptical of this claim, but it seems to be a big part of running the CFR power plant. They want to make the plasma as positive as they can. They do this by manipulating the ion temperature, the electron temperatures and the mirror ratio. The mirror ratio is the ratio of the self-generated and external magnetic fields along the skin of the trap [25, 31, 61]. If they can tune things just right - they assume the plasma will become mostly ions, because of ambipolar effects [53]. Crudely speaking: amibipolar means that the electrons and the ions are moving differently. I do not fully understand this mechanism. Apparently, reference 53 explains this effect well. For visual learners, I have made a flow chart of these concepts.

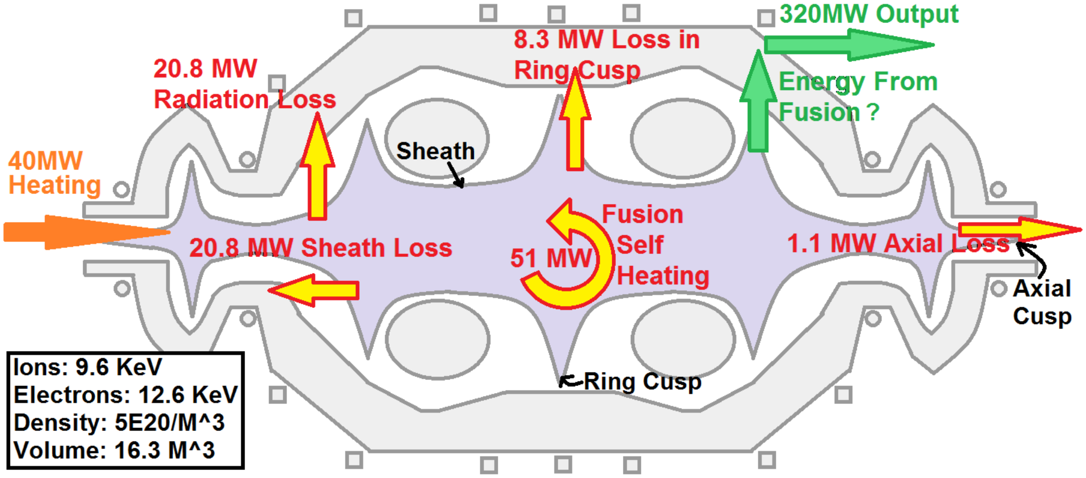


Model 1 - Energy Flow Chart

Model 3 – Ions Escaping

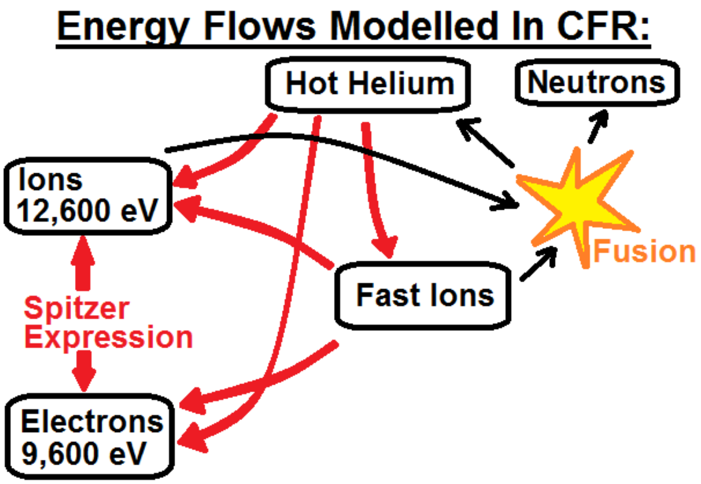
After we have dealt with light and electron losses, the only thing left to explore are ions leaving. Ions have four paths out this machine. First, they can be conducted out, through the stalks. Lockheed figures it can both shield and lower the density around these stalk by a factor of a 100. That curbs stalk conduction. The other three ion losses are through: the sheath, the axial cusp and the ring cusps. You can't estimate any of these losses, without something called: the ion distribution function. The distribution function is an equation that tells you how many ions, have how much energy. Lockheed uses some math to estimate this. If they build the CFR, they can measure it directly. The first losses are through the skin of the trap. These are the sheath losses. Here, they make two more assumptions: the density of the ions and the ratio of the magnetic fields, along the sheath. Next, there are the losses through the cusps along the axis. You can think of cusps as a hole in the trap. The axial cusps sit along the axis of the plasma (see picture below). You need a few assumptions here: a sheath thickness around the cusp, a mirror ratio and the plasma potential. Finally, there are the loss through the ring cusp. To find ring losses, you need to make all the same assumptions as above, plus two more: a geometric transparency and magnetic shielding near the ring. Here - Lockheed chooses to be optimistic. They assume a 5% reduction in ring cusp losses, because of shielding [31]. Wow. There are a ton of assumptions in this model. Notice there are assumptions, based on other assumptions. That is scientifically risky.

Model 3 - Predicted Energy Flows Inside CFR



Model 3 - Particles Inside

Aside from the losses, researchers also needed a way to understand the energy inside the machine. Lockheed assumes that the plasma has five parts to it. The most common part is the regular ions. Lockheed predicts that the average ion will be at 9,600 electronvolts [31]. That is 111 million degrees kelvin. It is not impossible for fusion to occur at these temperatures – but most ion do not fuse. It is all governed by probabilities, known as the cross section. The rates will rise as things get hotter [54]. So, Lockheed is probably not relying on this ion population to give the machine its' fusion kick. The second most common component is the electrons. Surprisingly, the electrons are modelled as ***hotter*** than the ions. At 12,600 electronvolts, the electrons are 35 million degrees hotter than the ions [31]. Wow. Remember these electrons are far smaller and lighter, when compared to the ions. The analogy is, if the ions were small marbles, the electrons would be the size of atmospheric dust [57 - 59]. Energy moves to and from these two populations. Lockheed uses a classical Spritzer expression to nail down these energy flows [31, 45, 60]. Mixed in with all of this, is a small population of fast ions. The fast ions are the particles most likely to fuse. They are recently injected, and very hot. The model says that the ions will heat just about everything else inside this trap. Lockheed uses a common equation to estimate this rate [54]. The math says the ions will be trapped longer than their energy transfer time; so these ions will heat things. This claim is supported with data from an old mirror experiment in the eighties - but they do not give us a citation. Finally, the smallest population is the hot helium atoms and the neutrons. These come out of fusion reactions themselves. The neutrons leave immediately; they are ignored. Getting the hot Helium to hang around, is critical. Ideally, the Helium would dump its' energy into the plasma before leaving. This would start more fusion reactions; it would start a fusion ***chain*** reaction. That is the concept of Ignition. An igniting plasma is something all fusion researchers would love to have. Lockheed is assuming the CFR will reach an ignited state and that is a big part of making the concept work.

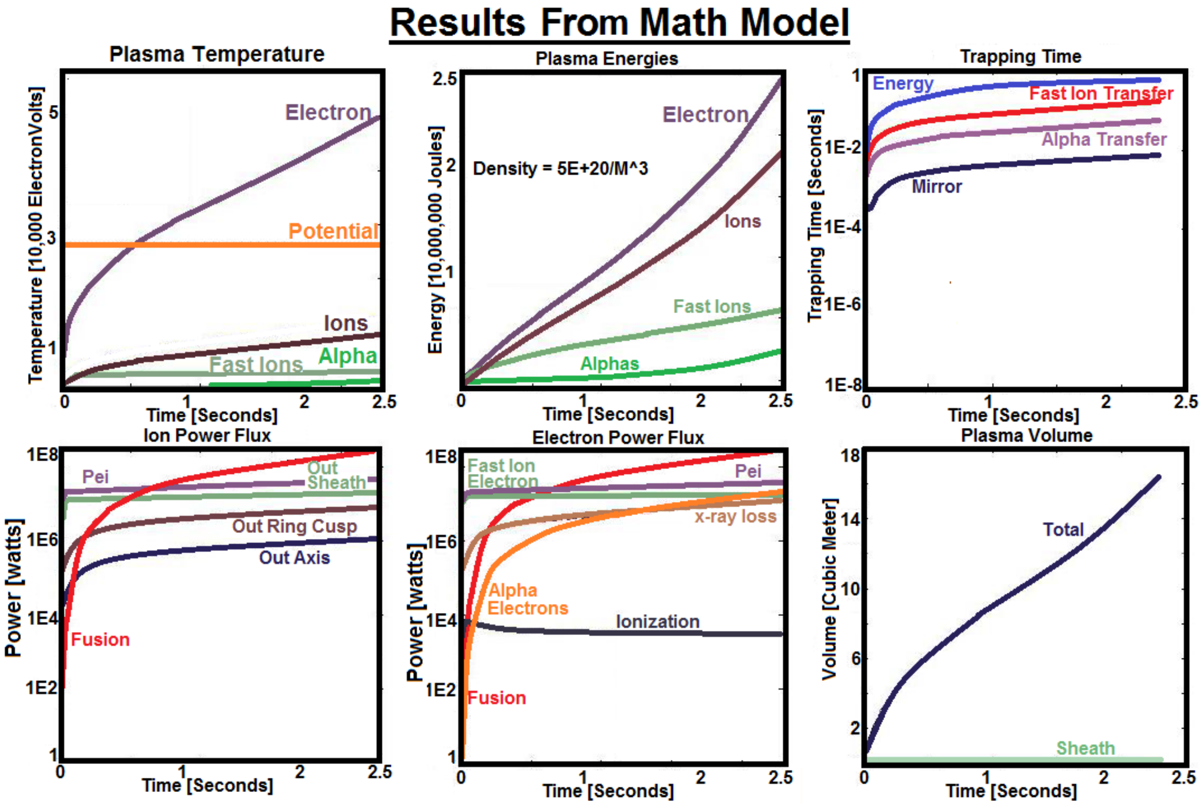


Model 3 – Dealing With Time

All of this math, moves forward in time. Everything is calculated, then a step in time is taken and then everything is recalculated. The model starts with the reactor empty. A beam of fast ions is injected. This is done with neutral beam injection, a common method in fusion. The fast ions get trapped and they start to fill up the space. At each step, the math tries to balance the plasma and the magnetic field pressures. It tries to solve for the volume at that time step. ***So, in time, the plasma blows up like a balloon.*** It inflates, stabilizes, finding the "beta=1" shape and then inflates some more. That is how the model works. The magnetic field is assumed to grow linearly with radius. This means, as plasma balloons outward the magnetic pressure rises linearly. Over time, the trap fills up. Once the trap is full, the model stops. This happens when the plasma pressure matches a 2.3 tesla magnetic field pressure. The model assume the field is constant around this plasma. With competing physical effects, that probably won't be true. Lastly, this model is not addressing the steady state condition. It is clear, this model definitely has some flaws.

Model 3 - Results:

The goal of this work was to understand out how to design, operate and run the CFR. For the CFR to work, you must nail the plasma trapping physics. This critical to making it work. The model tells us that the physics are driven by the cusp sizes and the plasma density. It also says you have to make the cusps as small as you can. The size you want to hit is the "hybrid gyroradius" – but Lockheed gives no numbers on what this size is. It must be close to the radius of a spinning ion and spinning electron, near the cusps in question. The plasma density is key to controlling electron to ion energy transfer; which makes it central to keeping the ions and electrons at two different temperatures. Moreover, Lockheed plans to ***hold*** this temperature difference, throughout operations [31]. Frankly, Rider has a theory arguing that this is impossible [45, 46]. Rider argues that temperature differences overtime evaporate, because of constant energy transfer. I would say the argument is not settled. Lockheed links this temperature difference to making the plasma positive through ambipolar effects. Those effects, in turn, help the ion trapping. Here, Lockheed provides some data for support [53]. Put everything together, and this model lays out a chain of effects ***that must all work together,*** for this to work. It seems like a tall order. The density must drives a persistent temperature difference, which in turn, drives ambipolar effects, which in turn, makes the plasma positive, which in turn, helps ion trapping. Wow. Critics will surely argue you can’t do this and the whole thing would fall apart. Supporters would disagree. We have heard similar arguments, in the past, over the polywell [65, 45, 46, 48, 49, 34]. We need data. Only data will settle these kinds of debates.


Results From Math Model

If everything works as planned, this model predicts that you can turn off the neutral beam injection after a certain amount of time. That would be great - if it works. It means, you can fill it, get it fusing and then let it run. Awesome. This depends on the machine igniting. If everything works as planned, the CFR should generate about 320 megawatts of net power.

“It does not matter how elegant your theory is, if it disagrees with experiment … it's’ wrong.” – Richard Feynman

Conclusion:

So we are left again with a lack of data. We need to change that. Fusion power would change the world. Its implications are huge. It is the kind of research that cannot be left to chance. Especially for the United States. Our country depends on a nuclear edge for military, economic and technical prowess. Right now, it is considered impossible by the general public. But, many things have been considered impossible in the past. History rewards the nations that stay technically savvy and the US cannot fall behind.

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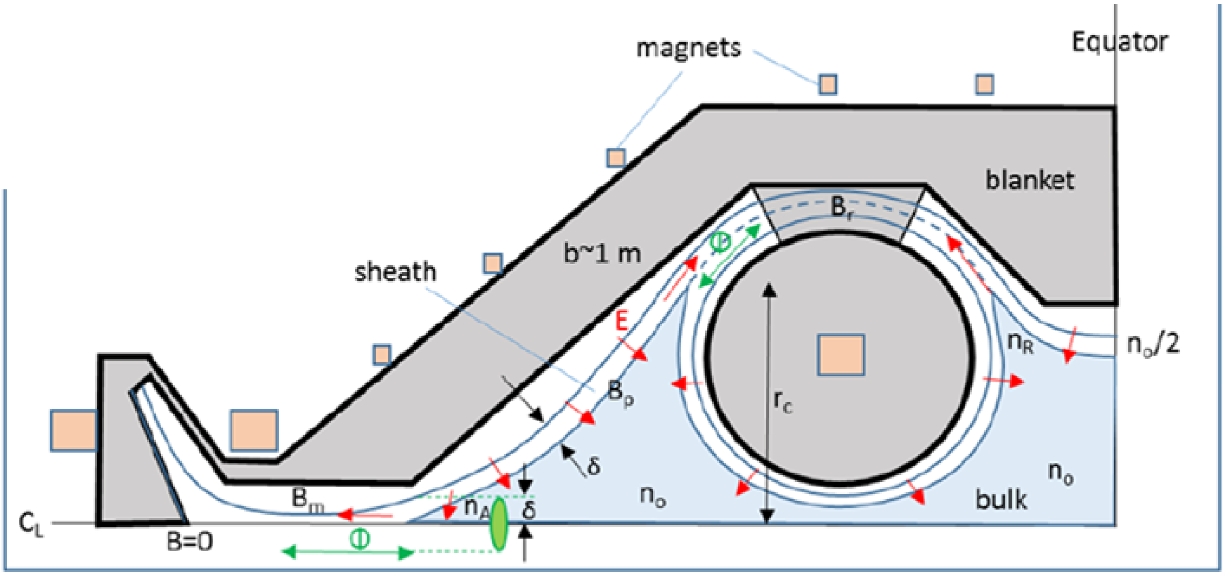
Appendix: The Math Model Used For An Ignited Compact Fusion Reactor:



$$E = Ei + Ee + Efi + E_\alpha$$

$$V = VF\pi r^3 \qquad SA = SAF\pi r^2$$

$$V = \left[V_F\pi\left(\frac{r_c}{B_{pD}}\right)^3\left(\frac{4}{3}\mu_o E\right)^{1.5}\right]^{0.4}$$

$$T_i = \frac{2Ei}{3enV} \quad T_e = \frac{2Ee}{3enV}$$

$$T_{fi} = \frac{2Efi}{3enV} \quad T_\alpha = \frac{2E_\alpha}{3enV}$$

$$\emptyset = Te \times phifactor$$

$$p = n(Ti + Te + Tfi + T_\alpha)$$

$$B_p = \sqrt{2\mu_o p}$$

$$A_r = 2\pi r \cdot 2\delta \cdot 4 \cdot 0.5 \cdot S \cdot \left(\frac{N_s a}{2\pi rc}\right)$$

$$\Gamma_{ir} = \frac{4Arn\left(\frac{n_r}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty \int_0^{\sqrt{v_\parallel^2\frac{1}{MR_r-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\,dv_\perp\,dv_\parallel$$

$$P_{ir} = \frac{4Arn\left(\frac{n_r}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty \int_0^{\sqrt{v_\parallel^2\frac{1}{MR_r-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp \left[\frac{m_i}{2}\left(v_\perp^2+v_\parallel^2\right)+e\emptyset\right] e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\,dv_\perp\,dv_\parallel$$

$$A_a = \pi\delta^2$$

$$\Gamma_{ia} = \frac{4Aan\left(\frac{n_a}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty \int_0^{\sqrt{v_\parallel^2\frac{1}{MR_a-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\,dv_\perp\,dv_\parallel$$

$$P_{ia} = \frac{4Aan\left(\frac{n_r}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty \int_0^{\sqrt{v_\parallel^2\frac{1}{MR_a-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp \left[\frac{m_i}{2}\left(v_\perp^2+v_\parallel^2\right)+e\emptyset\right] e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\,dv_\perp\,dv_\parallel$$

$$r = \frac{B_p}{B_{pD}}r_c$$

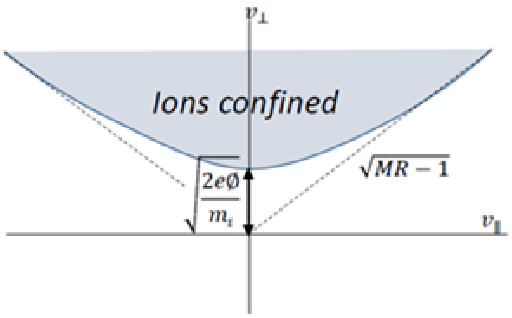
$$v_{Ti} = \sqrt{\frac{2eTi}{m_i}} \quad v_{Te} = \sqrt{\frac{2eTe}{m_e}}$$

$$\rho_e = \frac{1}{B_p}\sqrt{\frac{2meTe}{e}} \quad \rho_i = \frac{1}{B_p}\sqrt{\frac{2miTi}{e}}$$

$$\rho_{ie} = \sqrt{\rho_i\rho_e}$$

$$MR = \frac{B_m}{B_p}$$

$$t_{GDT} = \frac{LM \times MR}{\sqrt{\frac{8eTi}{\pi mi}}}$$



$$P_f = \frac{n^2}{4}\langle\sigma v\rangle YV \qquad P_\alpha = \frac{Y_\alpha}{Y_f}P_f \qquad Y = Yf + TBR \cdot Y_{breed}$$

$$\Lambda_{ii} = 23 - ln\left(Z_{eff}^{3}\left(\frac{2n}{1e6}\right)^{0.5} T_i^{-1.5}\right)$$

$$t_{ii} = \frac{2.08e13\ \mu^{0.5} T_i^{-1.5}}{n\left(\frac{n_s}{n}\right)\Lambda_{ii}}$$

$$G = \frac{2}{\sqrt{\pi} v_{th}^{3}} \int_{-\infty}^{\infty} \int_{0}^{v_{\perp lim}=\sqrt{v_{\parallel}^{2}\frac{1}{MR-1}+\frac{2e\emptyset}{m_i}}} v_{\perp} e^{-\frac{(v_{\perp}^{2}+v_{\parallel}^{2})}{v_{th}^{2}}} dv_{\perp}\, dv_{\parallel}$$

$$t_s = \max(tGDT, \frac{t_{ii}}{G})$$

$$\Lambda_{ie} = 24 - ln\left(\frac{\sqrt{n}}{T_e}\right)$$

$$V_s = SA \cdot \delta$$

$$\Gamma_s = \frac{n\left(\frac{n_s}{n}\right)V_s}{t_s}$$

$$P_s = e(1.5Ti + \phi)\Gamma_s$$

$$P_{rad} = \%I \cdot 2 \cdot 10^{-34} n^2 V$$

$$P_{Bremms} = 1.7 \cdot 10^{-38} Z_{eff} n^2 T_e^{0.5} V$$

$$P_{ei} = 7.61 \cdot 10^{-34} \frac{n^2 Z_i^2 \lambda_{ie}}{\mu_i T_e^{\frac{3}{2}}} (T_e - T_i) V$$

$$P_{fie} = -\frac{E_{fi}}{t_{fie}} \qquad t_{fie} = \frac{6.2e14\ \mu T_e^{1.5}}{n Z_i^2 \left(2 - \frac{3Te}{E_{NB}}\right)\Lambda_{ie}}$$

$$P_{ae} = -\frac{E_{ae}}{t_{ae}} \qquad t_{ae} = \frac{6.2e14\ \mu T_e^{1.5}}{4n\left(2 - \frac{3Te}{E_{\alpha}}\right)\Lambda_{ie}}$$

$$P_{iT} = \mathrm{P_{ei}} - \mathrm{P_{ia}} - \mathrm{P_{ir}} - \mathrm{P_{iS}}$$

$$P_{eT} = -\mathrm{P_{ei}} - \mathrm{P_{Bremms}} - \mathrm{P_{rad}} + \mathrm{P_{fi}} + \mathrm{P_{ae}}$$

$$E_{e,i+1} = E_{e,i} + dt(P_{eT})$$

$$E_{i,i+1} = E_{i,i} + dt(P_{iT})$$

$$E_{\alpha,i+1} = E_{\alpha,i} + dt(P_{ae} + P_{\alpha})$$

$$\tau_E = \frac{E}{P_{hfi} + P_{he} + P_{ae}}$$