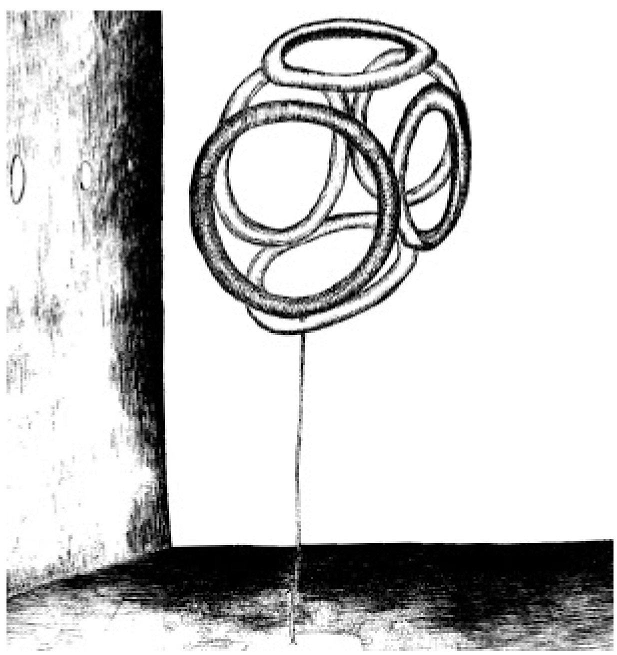
Explaining the Counter Argument (Part II)

Over 400 Polywellers read the last post. The link got reposted on Twitter and was viewed on smart phones and ipads. We had views from Russia, Sweden and Australia. That is the power of the internet; coupled with this ideas' potential.

From his IAF conference paper Dr. Bussard gives us some sense of what an ideal machine would look like. A Polywell fusing boron-11 would have rings roughly 6.5 feet in diameter. Ample space would be needed to surround the rings in all directions. Outside this, the rings could be encased inside a faraday cage and that inside a vacuum chamber. The parts near the electron cloud would need to be shielded from conduction out of the device. Bussard stated that the fraction of unshielded surfaces had to be less than 3E-5 [1]. The rings would probably be smooth circular superconductors2, spaced apart and held by a non conductive material. The rings would probably be a cube, plain, with excessive space in all directions. The chamber will probably need vacuum equipment, ion guns, a cooling system and electron guns attached [1]. Boron fusion would burn off a number of things, including some neutrons2, heat, light and hot helium. The helium would need to strike the conductive chamber walls and generate current. This direct current would need to be stored, converted and fed out to the grid. Dr. Bussard argued that if electron conduction and drive were the only significant energy losses; then output would scale as the 5th of the radius1. That means enlarging the reactor volume - amounts to raising your net energy by a factor of five.



This implies there is a path to cheap, environmentally clean power. That is quite a dream. But Dr. Riders' work argues that it is a meaningless one. The machine thermalizes, x-rays sap energy away, neutrons cook the magnets, arching occurs, direct conversion is wrought with issues and ion injection is too difficult. Rider says this is a dead end. We need to know what his arguments are. Below is an explanation of his work. This is a result of many months of translating Riders paper into something the general audience can follow. We do this as a public service. The only goal is to present the most accurate depiction of published Polywell science - in the most understandable way. We invite you to disagree.

We also invite criticism, because that strengthens our material. We are not pigheaded, if there are mistakes they will acknowledged and corrected. All we ask is that you argue on the high plain of ideas - not degenerate into name calling. A number of people have found mistakes in past posts. These people include: Chrismb, kcdodd and, D Tibbets. There were two errors in "Explaining The Counter Argument Part 1". It is reposted below.

Sources:

1. Bussard, Robert. "The Advent of Clean Nuclear Fusion: Superperformance Space Power and Propulsion." Proc. of 57th International Astronautical Congress, Spain, Valencia. Vol. 57. International Astronautical Federation, 2006. Print.

2. An Interview with Thomas Ligon about the Polywell. Perf. Thomas Ligon. An Interview with Thomas Ligon about the Polywell. YouTube, 16 May 2009. Web. 10 Jan. 2011. http://www.youtube.com/watch?v=1HatEDkNnn8.

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Synopsis of “A general critique of internal-electrostatic confinement fusion systems”

Author: Dr. Todd Rider, MIT
Published: Plasma Physics, June 1995

Rider opens his paper with a description of electrostatic confinement devices. These devices make deep electrostatic wells. Ions are shot into the center of these wells. The ions fall down the well. They build up speed and smash together in the center. They can hit hard enough to fuse. Here is a graphic of this from Mr. Kralls’ paper:

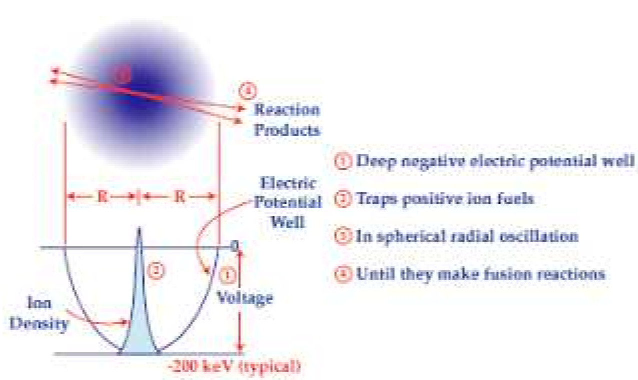
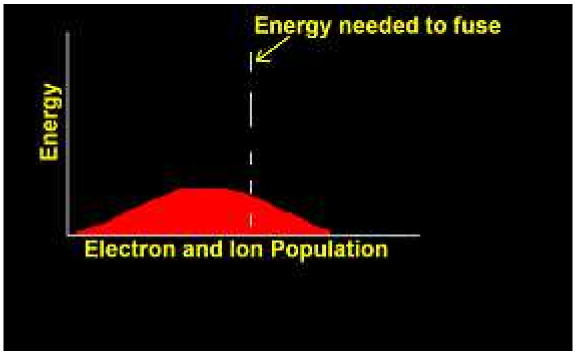


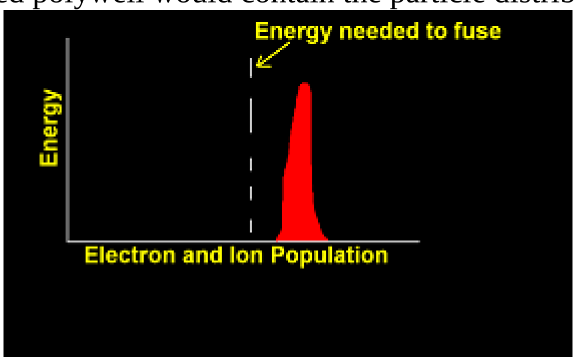
Figure 1: Mr. Kralls’ diagram describing the polywell.

Mr. Kralls’ paper also suggests that you could “squeeze” the plasma using sound waves. The idea is by blasting microwaves into the center the plasma would squeeze together. Riders’ paper will look at both normal Polywells and these, microwave enhanced Polywells. There are two important polywell properties that Krall and Bussard suggested:

1. That the material inside the polywell could maintain a sharp energy distribution1,2. The ions would not thermalize or go to a bell curve. This is shown below in figure two.



A thermalized polywell would contain the particle distribution above.



A non thermalized polywell would contain the particle distribution above.
Figure 2: A comparison of a non-thermalized and thermalized polywell.

2. That polywell could maintain two different ion temperatures2. For example, if we were fusing deuterium and deuterium -the second easiest fusion reaction- one group of ions could be cold, one group could be hot. These temperature differences could be maintained.

Rider is going to look at both these claims. First, can the material inside the polywell not go to a bell curve? This is very important. On this point, there is agreement from Rider, Ligon, Bussard and Krall. If the material goes to a bell curve, if the polywell thermalizes, it will fail. Rider starts by figuring out where to look for thermalization: in the center. Rider models the ions inside the Polywell into three parts: the core, the mantle and the edge. A picture of this model is below in figure three. Rider showed that collisional effects were about 100 times less in the edges, then in the dense central core.

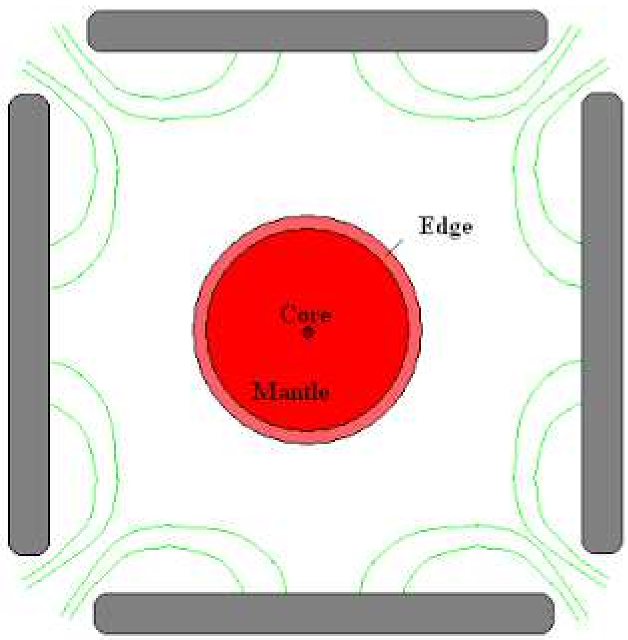


Figure 3: This is a rough sketch of ion distributions inside the Polywell, as modeled by Rider (not to scale). Some magnetic field lines are shown in green, the magnetics are shown in gray. Ion density gets higher as you get closer to the center. Rider broke up the ion concentrations in three zones, the core, the mantle and the edge. He even assigned rough radiuses to these sizes. The core radius was about 1unit, the mantle radius was between 50 and 80 units, while the edge was about 100 units out.

<u>Assumptions' Rider Makes:</u>

These collisional effects lead to the focused ion ball in the center to spread out. This is degradation of focusing and, is a problem Rider states he will ignore for this paper. There is good reason to believe that core convergence will rapidly degrade. By not assuming any degradation of focusing, Rider is assuming that the picture above remains constant throughout all of the Polywell's operation; a core, a mantle and an edge. Rider then looks at various effects inside the polywell and notes how some depend on where you are relative to the center, and some depend on the plasma volume and density.

1/Radius Dependent Effects (outside core)	Effects Independent of Plasma Volume, Density (everywhere)
1. Fusion	1. Fusion
2. X-ray cooling	2. X-ray cooling
3. Ion and Electron Energy Exchange	3. Scattering
4. Thermalization	

Table 1: This is effects and their dependence on radius, volume and density inside the polywell (for good converged systems).

This means that the size of the core will only slightly change fusion, x-ray cooling, thermalization and ion to electron energy exchange. This also means it is safe for Rider to compare fusion, x-ray cooling and scattering effects without having to worry about the specific volume or density of the polywell. I want to point out that these assumptions - are just that - assumptions, not absolute truths. In reality, fusion rate, x-ray cooling, energy exchange, thermalization and scattering are not absolutely radially dependent nor are they independent of volume and density.

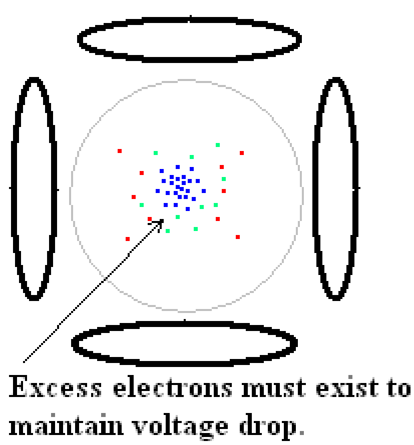
Rider is going to assume the core as uniform in all directions, with the same energy amounts and temperatures inside the core. If the core was not uniform, one would have to deal with Weibel and counter streaming instabilities. Rider assumes that the fusion fuel is uniformly mixed everywhere with any significant density. He also assumes the plasma is quasineutral. Quasineutral means that there is no net charge in volume, the density of negative electrons and the density of positive ions cancel out. This is shown mathematically below.

$$\text{Density}_{\text{electrons}} = \text{Density}_{\text{Fuel1}} * \text{Charge}_{\text{Fuel1}} + \text{Density}_{\text{Fuel2}} * \text{Charge}_{\text{Fuel2}} \quad (1)$$

The quasineutral assumption stated mathematically: the density of the electric charge equals the density of the ion charge.

This seems to be one of the most questionable assumptions. It is a clear fact that to maintain a potential well, there needs to be more electrons than ions inside the polywell. The polywell cannot work any other way. If there are more electrons, then only under specific conditions would their densities work out, such that the above expression would hold. Conditions where the electrons occupied a different volume, the charges worked out or the assumption was for a local volume, not the entire reactor. Furthermore, if the Whiffle ball and the virtual anode do exist, then there will be regions of the center with excess ions and excess electrons. There, quasineutrality may not hold. Below is an example explaining quasineutrality, using DT fuel.

$$\frac{\text{Electrons}}{\text{Volume}} = \frac{\text{Deuterium Ions}}{\text{Volume}} * \text{Charge On Dueterium} + \frac{\text{Tritium Ions}}{\text{Volume}} * \text{Charge On Tritium} \rightarrow$$
$$\frac{25}{10} \neq \frac{10}{10} * 1 + \frac{10}{10} * 1$$



Example 1: working out what the quasineutrality assumption would be for an example polywell reactor.

A. Calculating The Fusion Power Density:

It makes sense to start by calculating how fast you expect to get energy out of this device. That way, you can compare this rate to the rates of all these other effects.

$$\frac{\text{FusionPower}}{\text{Volume}} = \langle \text{CrossSection} * \text{velocity} \rangle * \text{EnergyReleased} * n_{fuel1} * n_{fuel3} \quad (2)$$

Equation two is the fusion power per volume. The cross section is the measure of the "fusibility" of two atoms when they smash into one another at some velocity. Rider applies the quasineutral assumption to this equation, changes the units to cgs -except for energy (eV)- and, rearranges the equation. Looking at the case of deuterium, deuterium fusion, where the fuel densities are the same for all the deuterium ions, Rider can make the following approximation:

$$\frac{\text{FusionPower}}{\text{Volume}} \approx 1.6E-19 * \langle \text{CrossSection} * \text{Velocity} \rangle * \text{EnergyReleased} * \frac{\text{ElectronDensity}^2}{2 * \text{ChargeOnIons}^2} \quad (3)$$

Rider now has the equation in the form he wanted all along; one independent of fuel density. The above expression estimates the rate of fusion power coming off the reactor in a given volume.

B. Calculating An Ion Lifetime In Device:

Based on this equation above, Rider figures that the time it would take an ion entering the system and getting fused would be.

$$\text{Time To Fusion} = \frac{1}{\text{Effective Density Of Ions} * < \text{CrossSection} * \text{Velocity} >} \quad (4)$$

This equation works for dissimilar ion fusion (aka A+B fusion) in the case of A + A fusion you divide the above equation by two.

C. Rate of Energy Transfer Between Two Groups of Ions:

We have an equation for how energy is transferred from two different clouds of ions. The guy who figured this out was Lyman J Spitzer, a physics professor at Princeton, back in the '50s and '60s. We assume that the clouds both have bell curve energy distributions. We also know this equation works even if the clouds have very different temperatures16. If you are just looking at ion cloud two being heated by ion cloud one, here is the equation:

$$\frac{\text{Energy Transferred To Ion 2}}{\text{Volume}} = \frac{3}{2} * \text{Density Ion 2} * \frac{d(\text{Temperatrue Of Ion 2})}{d\,\text{time}} \quad (5)$$

D. Can you keep ions at 2 different temperatures? Case 1:

Rider wants to use equation five above to answer a very important question: can you keep two ion clouds at two different temperatures? This is a really important question to answer. Lets' assume inside the polywell we have cold ions and hot ions. First looking at the cold ions; we are injecting cold ions and as they get fused they leave. Also the cold ions pick up energy from the hot ions also flying around in the center. Given this, Rider gives us the following energy balance:

$$\text{Energy Of Cold Ions} = \text{Energy Of Cold Ions Injected} - \text{Energy Of Fused Ions Leaving} + \text{Energy From Hot Ions} \quad (6)$$

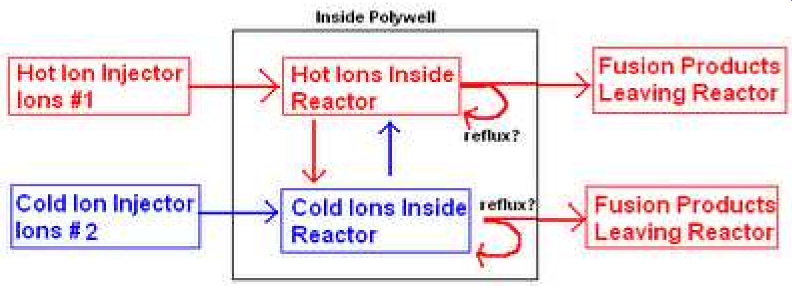


Figure 4: Schematic of some of the energy flows analyzed in section D, by no means a complete picture of the energy flows inside the polywell.

This energy balance, equation six, is also shown schematically in figure four, which shows the flow of energy inside just the ion cloud. I have a few questions here. I can think of a few other sources of heat, I do not know if Rider did not include them because they are insignificant, or if they cannot be a mechanism for heating. Some suggestions would be: heat transfer from the electron cloud, annealing from the potential well, radiation from the walls, and x-ray heating from within the cloud. Electron heating of the ion cloud is an easy thing to ignore; an electron is about 1,836 times less massive then an ion. Also the fusion products leaving have lots of energy, and they will re-heat material as they bump into ions on their flight out (for DD fusion this is about 3.64 MeV, loads of energy). Incidentally, they will probably not incite other fusion reactions, though the products of DD fusion can, in theory, undergo a cascade of other fusion reactions. Rider now works out two equations: the ion to ion heating rate, and the ion cooling rate. The ion cooling rate is solely due to the replacement of hot fused ions with cold ions coming in from outside.

$$\frac{\text{Ion}_1 \text{ To Ion}_2 \text{ Heating}}{\text{Volume}} = \frac{3}{2} * \text{Density}_{ion2} * \frac{d(\text{Temp}_{ion2})}{d\text{Time}}$$

$$\frac{\text{Ion Cooling Rate}}{\text{Volume}} = \frac{3}{2} * \text{Temperature}_{ion2} * \text{Density}_{ion1} * \text{Density}_{ion2} \langle \text{CrossSection} * \text{Velocity} \rangle \quad (7,8)$$

He is looking specifically at the ion two, population. He balances the two expressions and integrates over space and density, coming to this expression for the cold ion's temperature.

$$T_2 = T_1\left[1 + \frac{7.4E-6 * \langle CrossSection * Vel \rangle * (\#ofProtons_2 * T_2 + \#ofProtons_1 * T_1)^{3/2}}{\sqrt{\#ofProtons_1 * \#ofProtons_2} * Z_2^2 * Z_1^2 Ln[\Lambda_{1-2}]}\right]^{-1} \quad (9)$$

Where T stands for temperature and the Ln [] term is the Coulomb logarithm. The Coulomb logarithm is a way to find the mean free path for an ion in a big cloud of ions. Let us say you have a cloud of ions. You know the density, the charge, the temperature of this cloud. You throw in a test ion. The coulomb logarithm is a way to tell how for that test ion could go without smacking into other ions. The Z is the atomic number it would be 1 for deuterium and 1 for tritium. By including Z, Rider has made his nice equation work for lots of fuel combinations. *From this Rider calculates that the cold ion temperature would be within 5% of the hot ion temperature. If that were true, then Rider argues you could only keep the two cloud temperature separated by a maximum of 5%.*

D. Can you keep ions at 2 different temperatures? Case II:

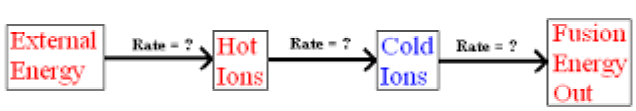
Rider looks at another method of maintaining two different temperatures, a hypothetical case. Assume you keep the cold ions cold, artificially; how much cooling would you need to pull this off? To figure this out, Rider needs to know the velocity of the collisions between the ions. He assumes all collision velocities are

$$\text{Velocity of ion } 1 \approx \sqrt{\frac{3 * \text{Temperature}_{Ion1}}{\text{Mass}_{Ion1}}} \qquad \text{Velocity of Ion } 2 = 0 \quad (10)$$

This is an estimation based on the statistics for such a case. There will certainly be collisions at much higher and lower energies. If this is true then all the energy transferred from the really hot ions to the really cold ions will be via collisions. Rider can then use his ion to ion heating equation, equation seven. Is Rider missing any energy flows? I do not know. Rider divides the energy transfer rate by the fusion power rate to arrive at equation 11.

$$\frac{EnergyTransferTo\ Hot\ Ion2}{FusionPower} = 1.2E-13 * \frac{Mass_C}{Mass_H} * \frac{Z_C^2 * Z_H^2 * Ln[\Lambda_{Hot-Cold}]}{CrossSection * EnergyReleased * Temp_H} \quad (11)$$

What Rider is actually doing by this is comparing how fast we can fusion energy out, to how fast energy would transfer from one cloud to the other. The idea is, if one cloud can be heated, would it lose energy to the cold cloud faster, than fusion energy comes out of the reactor? In addition, there is another rate to consider: the rate it takes to heat the hot cloud in the first place.



It is important to point out that Rider's analysis do contain some simplifications. First of all, there are the assumptions on collision velocity and his estimation on the Columbic logarithm value. These are somewhat reasonable. Next, Rider is only looking at two rates, *ion to ion* energy transfer and fusion rate. There are, electron to ion energy transfers (albeit small), x-ray heating and cooling, ion annealing, Cyclotron radiation and fusion products reheating the cloud; just to name a few other phenomena which could effect ion temperature.

Rider is correct that if one could maintain a temperature difference this would vastly improve Polywell performance. For instance, in the P-B11 reaction, the reaction everyone wants to do, it is helpful if we keep the borons cold and the protons hot. Ideally we would maintain this temperature difference and run the reaction at 620,000 eV - to take advantage of the peak cross section for the reaction. I have read5 that the optimum voltage for pB11 was 550,000 eV; this needs to be figured out. Rider plugs in the numbers for this situation, into his equation and comes up with this comparison.

$$\frac{\text{Energy Transfer To "Hot" Ion2}}{\text{Fusion Power}} \approx 1.4 \qquad (12)$$

This argument makes a Polywell operating like this: an energy loser. What he is saying is: in this case you would always need to put in energy faster then you can get it out. This is, of course, a hypothetical case. *Based on these calculations Rider will, from now on, assume all clouds of ions have the same average temperature*. Rider accurately points out that even if you had a big cloud of ions in the center, in which each individual ion was at the same temperature, not all the ions would collide correctly. It is these kinds of calculations that make me want actual, real, data about polywell operation.

Rider also points out that even if you could keep all the protons inside the polywell exactly at one temperature, and all the borons exactly at another temperature, you would still have them colliding at odd angles. Odd angle collisions are not collisions at full velocity. As a consequence, even in this hypothetical case, you would still have many collisions not resulting in fusion.

E. Ion Thermalization: How fast will the ions go to a bell curve?

Imagine a test ion. It gets injected into the polywell, towards a mass of ions and electrons in the center. First, let us ignore electron-ion interactions. An electron is about 1,836 times less massive then an ion. When electrons and ions do hit, they can create x-rays. This is a problem and, Rider will address it later. For ion-ion collisions, when one ion hits another, one of the following four things can happen:

1. Ions can bounce off one another. This is called a coulomb collision.
2. Ions can bounce off one another and, a photon is created.
3. Ions can fuse.
4. Ions can pulverize one another. This happens in atom smashers.

Rider assumes that the test ion would spend only a short amount of time in the core. This is a valid assumption for Rider, because for his model, the core is ~0.0001% of the total cloud of ions. Because of this, Rider uses an “effective density” for the entire polywell, the core, mantle and edge. Put another way, since a test ion flies across the whole device it makes sense that a device-wide “effective density” is used. Rider is assuming the core, mantle and edge model remains fixed throughout, which he argues would not be true in reality. This can best be explained by a picture of ion density throughout the ion cloud in the polywell.

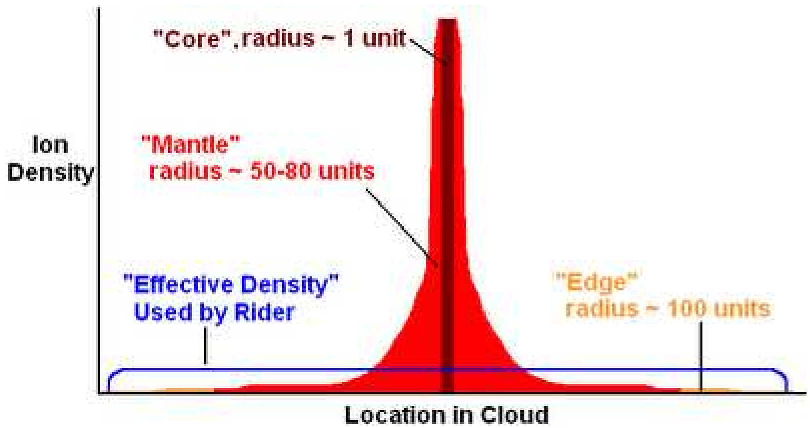
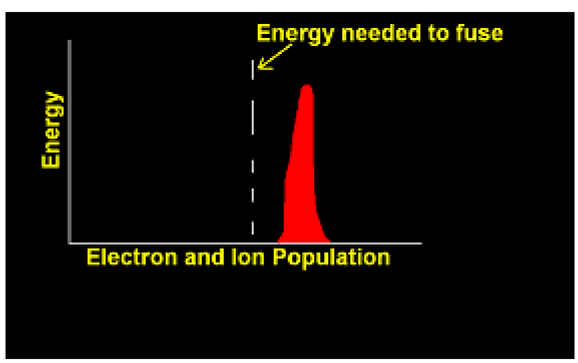


Figure 5: This is a graph of the ion density inside the polywells’ edges, mantle, core and the “effective density” rider uses for his model. The core has a flat density, the mantle density scales down by 1/r^2 and the edge is constant. This is not to scale. This graph is adopted from Kralls’ 1991 paper. Rider assumes that this distribution does not change over time. Rider states that this would not be the case in reality. The core is supposed to degrade and spread out in space14. Rider bases this on a private communication with W M Nevins. More research is needed to understand this core spreading question, how fast density spreading occurs, and how it is related to electric and magnetic field strength.

Thermalization is when the energy distribution goes to a bell curve. Do not confuse this with the density distribution (figure 5a). This concept is illustrated in figure six.



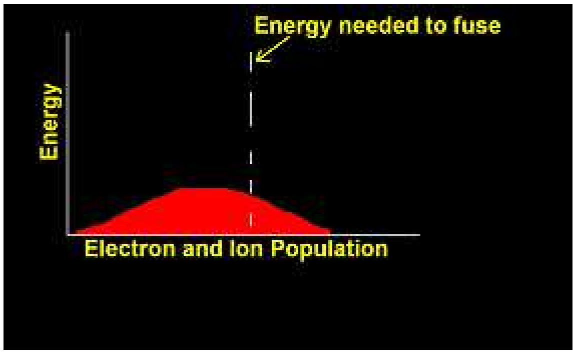
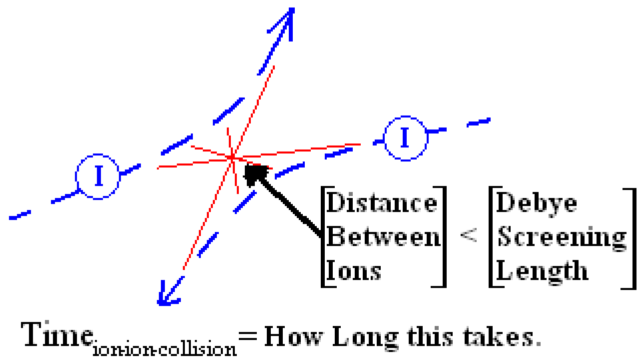


Figure 5a: Thermalized verses monoenergetic energy distributions. On the left is a cloud of ions at one temperature. Ideally all the ions injected would be at the same energy. Over time the ion energy spreads out. Some ions heat up, some cool down. This is called thermalization and is shown on the right. Rider needs to determine how long this takes.

Rider argues that the time it would take this cloud to go to a bell curve, is some multiple of the ion-ion collision time. It should be noted that if Bussards' diamagnetic Whiffle ball and virtual anode are true, then the ion density would look slightly different then the picture above in figure 5. Bussard believed that the Whiffle ball would increase the amount that the Polywell can contain electrons by a factor of about 1000 11. It is hard to foresee exactly how this would change the ion density picture. The virtual anode would mean a dense concentration of ions in the core, with a slight dip in density at the exact center. This anode was space charge limited - the idea is that the ions in the core are mutually repulsive forcing them to space apart. This means the ion density would dip exactly in the center. Bussard estimated that this anode could have a charge of about 15% of the well depth11. Additionally, someone needs to figure out if the Whiffle ball and the virtual anode existed, how they would effect core spreading. *All of these claims, the existence of the Whiffle ball and virtual anode, all need to be verified.*

F. Finding the ion-ion collision time:

The time for an ion-ion collision is found in equation 13. What equation 13 tells you is how long it takes for an ion to change direction, when it encounters another ion. This does not mean the two ions have to touch. If the distance between the two ions falls below the Debye length, the columbic force causes them to repel. Equation 13 tells you how long this process takes. This math works only for plasma which is uniform or isotropic. That means this equation works for plasma which is uniform in density, energy and charge distribution. Rider got this formula, by modifying one found in "Plasma Physics for Nuclear Fusion" page 96. It should be noted that the Polywell does not contain an isotropic plasma. If you think about it, equation 13 and equation 4 should be connected. This is illustrated is figures 5b and 5c below.



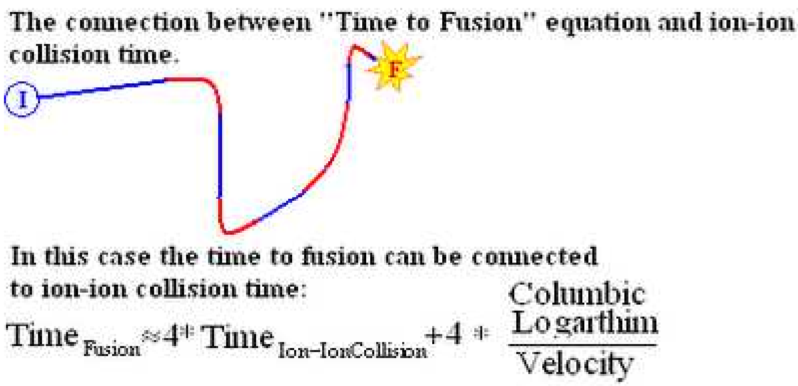


Figure 5b: This figure explains what ion-ion collision time is. It is the time during which the two ions are close enough to experience the columbic force. During that time the ions may or may not collide. *Figure 5c: I am unsure on this, and would appreciate an experts' opinion here. It seems that one can relate the ion-ion collision time, the columbic logarithm and the time to fusion equations. Since to fuse, two ions must collide, then it would seem that "time to fusion" should be some multiple of "ion-ion collision time". Say an ion has 300 collisions with other ions, and on the last collision it fuses – in that case the "time to fusion" should be roughly 300 times the "ion-ion collision time". That relation should hold, except there are times when an ion is moving alone. That time should be the ion speed divided by the mean free path. Of course, many ions will not fuse because they lack enough energy.*

Rider assumes that ion upscattering, loss and thermalization, are all proportional to the ion-ion collision time. This is shown in equation 14.

$$\text{Time}_{\text{ion-ion-collision}} = \frac{3\sqrt{3} * \sqrt{\text{Mass}_{\text{ion1}}} * \text{Temperature}_{\text{ion1}}^{3/2}}{8 * \pi * \text{Charge}_{\text{ionA}}^{4} * e^{4} * \text{EffectiveDensity}_{\text{Ion1}} * \text{Ln}(\Lambda_{\text{Ion1Ion2}})}$$

$$\text{Time}_{\text{Upscattering\&Lost}} \propto \text{Time}_{\text{Thermalization}} \propto \text{Time}_{\text{ion-ion-collision}} \qquad (13, 14)$$

The Ln( ) in equation 13 is the columbic logarithm, which is used to calculate the mean free path for an ion in a cloud. The mean free path is how far an ion can travel before it smacks into another ion.

Rider also points out: ions can collect lots of energy, through collisions. They can get so energized; they can fly away and, get lost. This "upscattering and loss" time is relative to "ion-ion collision time". Upscattering losses will be treated in section H. Rider now compares thermalization time to fusion time.

$$\frac{\text{Time}_{\text{Ion-Ion-Collision}}}{\text{Time}_{\text{Fusion}}} \approx 0.01 - 0.001 \qquad (15)$$

This is a similar conclusion found in other fusion reactors. If someone just saw the above statement, it would easy to conclude that the polywell would thermalize much faster then it could produce fusion. The importance of this argument cannot be understated. It is central to the heart of the argument against the polywell. *Once the polywell thermalizes, it will fail.* This is what most of the rest of Rider's paper will show. I would point out that ion-ion collision time is not the same as thermalization time. Maybe it takes 100 or 200 collision times for a polywell to thermalize. That could put the times on par with one another. *There are also a number of assumptions that went into this calculation, such as one single collision velocity, quasineutrality, uniform density throughout the reactor and the consideration that scattering is density and volume independent. At the same time Rider has not considered ion annealing, the effect fusion products ions reheating cold ions and, x-ray reheating of the plasma cloud. Additionally it is unclear how the virtual anode and the Whiffle ball would affect this behavior.* It is these kinds of assumptions that make me want hard data to verify this calculation.

G. Will The Ions Inside The Core Collide In One Dimension?

Rider devotes a section to countering an idea by D.C. Barnes from Los Alamos National Laboratory, that the ions in the center will behave anisotropic. Mr. Barnes' idea is shown graphically below.

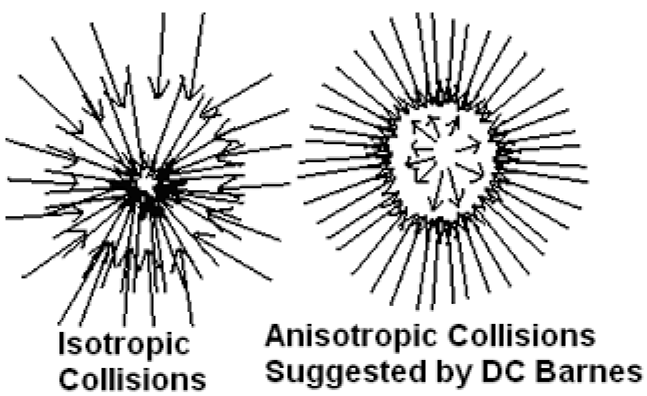


Figure 6: This is a graphical representation of ion behavior inside the center of the polywell. On the left, the ions behave isotropic, all the ions fly into the center and hit at all angles. On the right, the ions get rejected from the center, possibly due to a virtual anode. The ions slam into one another head on. All these collisions would, effectively, be in one dimension or anisotropic.

Here, Rider simply presents a series of arguments against this, with no math. Here are Rider's arguments against this happening, explained:

1. The ions need to bounce straight back from the center. He sees this as unlikely.
2. Rider argues that the more likely situation is that the ions would sideswipe the core. This is shown graphically below.

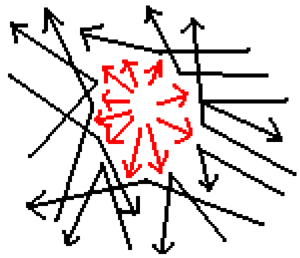


Figure 7: Rider argues that ions would more likely sideswipe the polywell's core.

3. Rider argues that the incoming ions are higher energy and will push there way into the lower energy ions, so that collisions will be isotropic anyways. This is shown graphically below. I have an issue with this critique. The density of the core is much higher than the mantle. Bussard claimed that the virtual anode, the core, is space charge limited - the idea is that the ions in the core are mutually repulsive forcing them to space apart. This means ions would have some space to move in the center. It should be remembered that high and low energy ions are all from the same cloud of ions, not the two different temperature clouds of ions discussed in section D. It would be wonderful if Dr. Nebels' team in San Diego could measure the internal density, temperature and, structure of the plasma cloud inside the polywell.

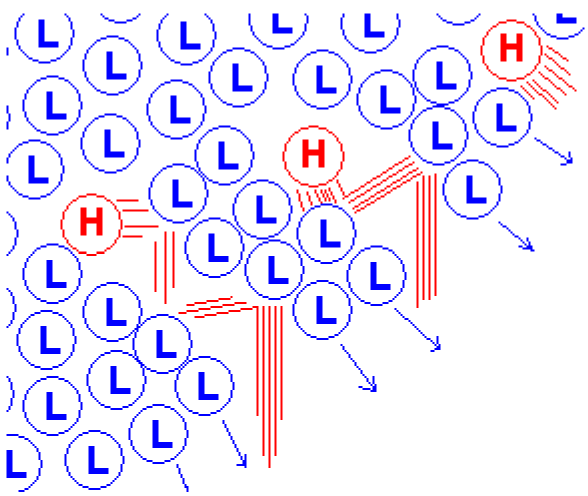


Figure 8: Rider argues that high energy ions would penetrate the polywell's core.

4. Rider points out that even if Mr. Barnes' suggestion was maintained, a number of remaining instabilities 6 still need to be dealt with.

H. How big is the issue of Ions being lost inside the Polywell?

From this point on, Rider assumes that all the ions inside the polywell are thermalized and have a bell curve. We know, from this point, the polywell should fail. Bussard, Rider, Krall and many others agree on this point. It would be interesting to see if pulsing the reactor, would get around this problem. Running it and seeing how long it would actually take to thermalize. Most of the rest of this paper shows how the polywell fails, once thermalized.

Rider now focuses his attention on the ion distribution inside the polywell. There are actually a number of considerations Rider puts into his ion distribution. These are shown graphically below.

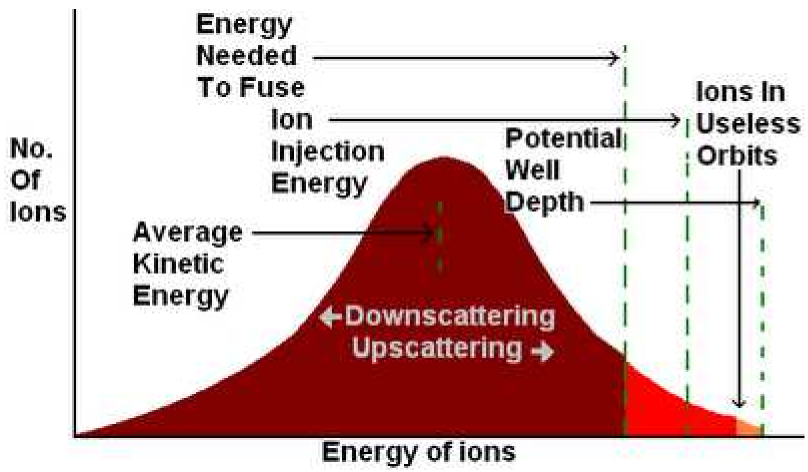


Figure 9: Rider's purposed distribution of ions inside the polywell. If the polywell's ions are thermalized, then they must have a bell distribution. The bell curve is cut at the high energy end. These ions have so much energy they can escape the magnetic field and are lost; hence the bell curve is cut. Just below these ions are high energy ions, pushed into useless orbits. The scale is exaggerated, *I do not know of any useless orbits inside the polywell. As I understand it, all the ions ride the magnetic fields back into the center, however Thomas Ligon described a phenomenon where electrons would get caught in the funny cusp loss points. Could the same phenomenon exist for ions? More research or explanation on this is needed.* Next comes, the ion injection energy, the energy the ions are injected into the polywell. Ions should be injected above the energy needed to fuse and below the "escape energy". The minimum energy needed to fuse comes next. You will notice that the bell curve is slightly uneven around this fusion energy cut off (fewer ions on the right then you would expect). This is because to the right of this minimum material fuses and leaves the cloud. *How far can the fusion minimum be from the potential well depth? I do not know, this a question that needs to be solved.* Next up, is the average kinetic energy or average temperature of the ions inside the polywell. Statistically, this would be 2/3 times the injection energy of the plasma. Up scattering is when injected ions move up in energy, through collisions; while down scattering is when ions move down in energy, through collisions.

Rider wants to compare the time it takes for the ions to escape the well, with the time it takes for the ions to fuse. This is a good way to determine if upscattering is a problem. He does this with a test ion. Imagine a test ion entering ions inside the Polywell. These ions have a bell distribution like the one seen above.

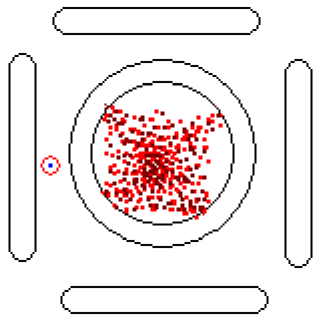


Figure 10: This is a cartoon of a test ion (circled in red) enter a polywell populated with two types of ions (this is A + B fusion reactor). The ions each have a bell curve of energies. This picture is not an accurate representation of the spatial distribution of the ions might be. Rider wants to test how long it will take the test ion to be lost from the system. The ion will get lost when it has as much energy as the well depth.

It should be noted here, that it matters what kind of ion this test ion is. For example boron will see a much deeper well then deuterium because boron has charge of five and deuterium has a charge of one. Boron is also five times bigger and more massive, which could have some effect. As the ion bounces around inside the polywell, it gets upscattered. Upscattering is when the ion gains energy inside the polywell. The ion will get lost when it has the same energy as the well that it is in. Mathematically, this amount of energy is shown below.

$$\text{Energy of Ion Loss} = \text{Elementary Partical Charge} * \text{Potential Energy Of Well} * \text{Electron Charge} \quad (16)$$

Fortunately, for Rider, someone has already figured out an expression for how fast particles upscatter in an inertial electrostatic device, such as a Fusor. *The expression he is going to use is for a general IEC device filled with all the same species of ions, NOT a polywell.*

$$\begin{aligned} &\text{Value} = \left(\frac{\text{Energy}_{\text{Loss}}}{\text{Enegy of Ion Injection}_{A}}\right) \\ &\text{Time To Lose A Ions To Upscattering} = \exp(|\text{Value}|) * [1 - \exp(-|\text{Value}|)] * \\ &\qquad \left[\frac{\sqrt{\text{MassOfIonA}} * \text{IonATemperature}^{3/2}}{4\sqrt{2\pi}\text{ParticleChargeIonA}^{4} * \text{ElectronCharge}^{4} * \text{DensityOfIonA} * \text{ColumbLogarthim}}\right] \end{aligned} \quad (17)$$

Rider does not have a similar expression for a two species system. He derives one. He uses an equation for how a test particle would slow down in a cloud with two kinds of ions, where each ion has the same amount of energy and the cloud is uniform in all directions. This is the Sivukhin expression. It is similar to, but not the same as the Sivukhin diffusion coefficient. This is a coefficient used to calculate how an ion moves when it is being scattered electrostatically in a cloud of electrostatic ions. I only bring up the diffusion coefficient as a way to educate the reader. By combining these two mathematical expressions – the single species expression, and the Sivukhin expression - Rider arrives at a way to estimate how fast ions will be upscattered and lost in the polywell, for a two species system.

$$\text{Value} = \left(\frac{\text{Energy}_{\text{Loss}}}{\text{Enegy of Ion Injection}_{A}} \right)$$
$$\text{Time To Lose A Ions To Upscattering} = \exp(|\text{Value}|) * [1 - \exp(-|\text{Value}|)] * \left[\frac{\sqrt{\text{MassOfIonA}} * \text{IonATemperature}^{3/2}}{4\sqrt{2}\pi \text{ParticleChargeIonA}^{4} * \text{ElectronCharge}^{4} * \text{DensityOfIonA} * \text{ColumbLogarthim}} \right] \quad (18)$$

Rider creates a bunch of parameters for his imaginary polywell. He puts these parameters into the above equation for an estimation of ion upscattering loss time against time needed for fusion. These results are presented in table two. His results reinforce statements from both polywell proponents and critics: that if the polywell thermalizes, it will fail. *According to Riders' estimates, ions would be lost very quickly inside the reactor, if it thermalizes.*

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