<u>Response to comments.</u>

A few months ago, this blog posted “The Debate Over Electron Behavior”. That post looked at different questions about electron behavior inside the polywell. The post was focused on six questions.

1. Electron recirculation – Where are they travelling?
2. Electron recirculation – When are they moving fast? When are they moving slow?
3. The magnetic mirror line - Where do the electrons turn around?
4. The Whiffle ball – Are the electrons creating their own magnetic field?
5. Are the electrons mutually repulsive in the center?
6. Are electrons packing in the cusp points?

There were a number of people on Talk-Polywell responded to that post with critiques of the work. You can view those responses here - http://www.talk-polywell.org/bb/viewtopic.php?t=2691. We promised to get back to them with an intelligent, well written and researched response. The response is given below. One highlight is: we now have a much better understanding for why the Whiffle ball maybe happening.

We realize that our stuff can be filled with mistakes. We want our stuff ripped apart by the most experienced and smartest people out there. We are going to go back and fix errors in the older post. We also aim to keep this approach on all future blog posts. Here are the responses to the comments. Please let us know what you think.

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<u>Response to Dan Tibbet’s comments:</u>

“…a particle does reverse outside the closest or strongest magnetic region of a cusp, it subsequently may not manage to get back inside…”

After consideration, I decided to come at this issue a different way. What you seem to be getting at, is answering the following question: <u>Are there two types of electrons inside the polywell?</u> I will call them “inside” electrons and “outside” electrons.

1. “Inside” electrons are electrons contained within the Whiffle ball. They are contained within the magnetic fields. They bounce around in the center, slowly dissipating energy. They are the electrons which compose the negative point charge in the middle.

2. “Outside” electrons, are electrons which for some reason are outside the Whiffle ball and cannot get back in. They may be corkscrewing along the magnetic lines. They may run into a metal surface. Thomas Ligon stated that these electrons “Pack the cusp loss points”.

Assume all electrons are injected at a given “injection” energy. I imagine that “injection” energy is very close to the “escape” energy. Since the energy to get an electron in there, is very similar to the amount needed to escape. Put another way, the energy needed to get an electron over the magnetic containment lip and into the Whiffle ball – is very close the energy an electron would need to escape the Whiffle ball. If my hypothesis is correct, then right after an electron is injected, would be the best time to lose that electron.

<u>How does an "inside" electron become an "outside" electron?</u>

I thought about this, and I could only think of two general mechanisms for this to happen. Feel free to add if I missed something.

1. Non-uniformities in the magnetic containment field. I drew a picture here to explain this.

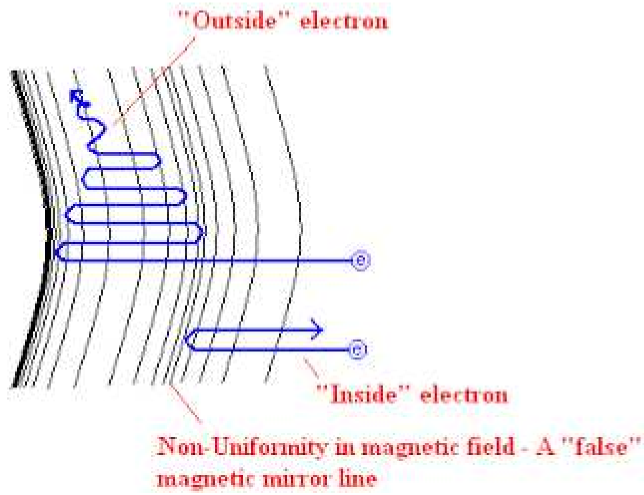

Figure 1: An example of a non-uniform magnetic field.

2. Electrons get some outside boost of energy. This would be an extra kick of energy to knock them over the confining field. As far as I know, there are several ways that this could happen.

"…as the electrons are transported deeper into the magnetic field they are at a lower potential energy…"

I do not understand the statement above. Do you mean as electrons are transported closer to the center or closer to the edges of the Polywell? If they move closer to the edges, I would imagine they would be at higher energies, since the magnetic field is denser at the edges, so the electrons need more energy just to be there, right? If they are moving closer to the center, I would imagine they have lower energy, since there is a zone of no magnetic field in the center, right? Note I am using the board energy term here, and not calling it potential, kinetic, rotational, ect… Since I do not follow that statement it is hard for me to follow what comes after it. Namely, the mechanism, you describe, to remove low energy electron from the machine. When an electron reaches a very low energy level, what happens? Will it "fall out" of the center? Will it sit in the middle? I do not know.

I did follow your upscattering and down scattering mechanism. You called it knocking. I tried to draw a picture to describe this. Please let me know if I have it right.

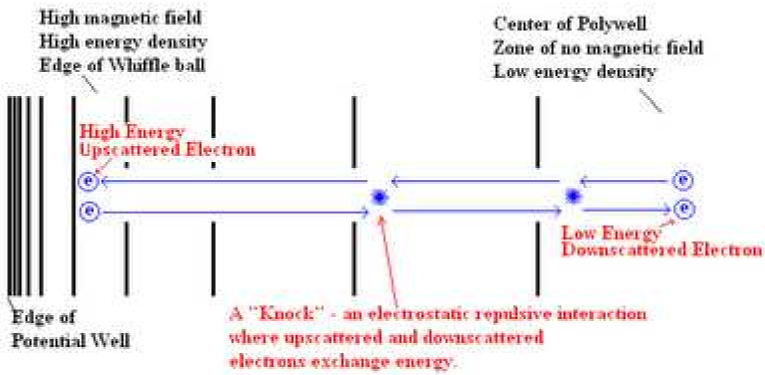

Figure 2: An illustration of electron "knocking" inside a magnetic field.

The black lines represent the magnetic field. They are not drawn correctly as they would be inside the polywell and the electrons would not travel in straight line like that. Still, the picture helps explains the basics of what is going on. The center has a weaker magnetic field. Electrons that occupy the center are at a lower energy. These electrons have been down scattered. They have "knocked" by another electron and lost energy in the collision. The opposite is true of the high energy, upscattered, fringe electrons. As an aside we know that "knocking" really means two electrons coming close enough to have columbic repulsion. They do not need to touch. The distance between them has to fall below the Debye screening length. Then the particles can "see" one another and, repel. These are all really important concepts and connecting them together is significant. The center should have a weaker magnetic field and therefore it contains low energy electrons, electrons which have been down scattered.

To take this picture one step further, somewhere above I would draw in a magnetic mirror line. I would say that, one way, an "inside" electron became an "outside" electron would be if it "knocks" and gains energy enough to pop out of the Whiffle ball. That would be an upscattered electron. It would gain enough energy to cross the magnetic mirror line.

As an addendum to the description above: I would add that unfortunately for us the polywell cannot be described that simply. Though it is good to think of the electrons in the polywell like marbles oscillating in a bowl - the farther from the center the electron flies the more energy it contains - there are exceptions to this convention. As carter pointed out, just because you have dense magnetic fields at the edges – it does not mean you have high fast moving electrons there. What about very late in the polywell's operation, when the electrons and ions have dissipated much of their energy through X-rays? What about some inconsistency in the containment field? Possibly through some imperfection in equipment or an electron motion generated field. This could create a situation where the convention does not hold.

"…The recirculated electrons, are reset to the original energy due to one aspect of Gauss's law…."

What do you mean? Is this a reference to the “edge annealing” process people have been talking about? I know nothing on that concept and am interested in learning more. Gauss’s law states that the electric flux through a closed surface is proportional to the charge contained within [3]. The more charge in a volume, the stronger the field coming out of that surface. The two concepts are related by the permittivity of free space. Mathematically this is expressed:

$$\text{Gausses Law} \Rightarrow \oint_{\text{A Closed Surface}} \text{Electric Field}\ \overline{d\text{Aera}} = \frac{\text{ChargeContainedIn Surface}}{\text{Permittivity Of FreeSpace}}$$

Bussard stated that WB-6 had about a 10 kilovolt potential well with a 12.5 kilovolt drive voltage [7, page 3]. We could use Gausses law to get a really, really, rough estimate of the number of electrons inside WB-6. Here is the calculation:

$$\oint_{\text{A Closed Surface}} \text{Electric Field}\ \overline{d\text{Aera}} = 10{,}000\,\text{volts} = \frac{\text{NetNumberof Electrons}*1.602E-19\ \text{Columbs}}{8.854E\text{-}12\,\dfrac{\text{Columbs}^2}{\text{Newtons}*\text{Meter}}}$$

The units work out and, this estimates that there were roughly 5.5E11 net electrons inside WB-6. Alternatively, we could treat the center of WB-6 like a point charge, and get a different rough estimate of the net electrons inside the machine that way. This would be using Coulomb's law, which is connected to Gausses law.

$$\text{ElectricFieldStrenght} = \left(\frac{1}{4*\pi*\text{Permittivity of FreeSpace}}\right) * \frac{\text{NetNumberof Electrons}*\text{Electric Charge}}{\text{Radius}^2}$$

The radius I used was at 35 cm out from WB-6’s center where I assumed there was no net charge. This method estimates that there are about 8.5E11 net electrons in the polywell’s center. Both methods just give us ballpark numbers.

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<u>Response to Carter’s comments:</u>

“Just because you have a strong field does not mean you have fast particles.”

That is true. However, the case from the post is still correct. It was the following situation. There are two electrons. Both are stationary. One is in a high density field. One is in a low density field. Both electrons are “kicked”. They experience a Lorentz force. The electron in the stronger field, experiences a stronger force.

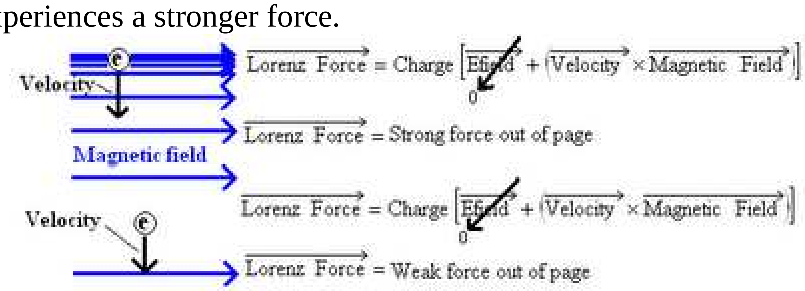


Figure 3: Examining an example of two electrons inside a dense and light magnetic field and looking at the resulting Lorenz force.

Unfortunately, the motion is much more complex. Particles circulate for various reasons. If you are just thinking about the Lorenz force, there a many examples of different movements. Many standard examples of how an ion, an electron and a magnetic field interact. If they have some initial velocity they will circulate in a magnetic field – no initial velocity they will sit. Ions will circulate clockwise. Electrons will circulate counterclockwise. Hypothetically, if an electron or ion moves past a single magnetic field line, it rotates around the line. If the particle has velocity perpendicular to the field, it will corkscrew. There are a collection of equations for this type of motion and the resulting light radiation produced. Electrons and ions can also drift across the field. Lastly, electrons and ions are, themselves point charges. They generate their own electric fields which create motion for other electrons and ions. I have illustrated a few of these hypothetical cases below. There are many others. These figures are just included to show the reader how many wrinkles there are in mapping particle motion inside the polywell

Despite all this, your point is still true. A denser magnetic field merely changes the strength of the Lorentz force. This force accelerates a particle in a given direction. Higher acceleration is not higher velocity. So your statement: “just because you have denser fields does not mean you have faster particles” is true. I will adjust the post. However, I would like to point out that given that there is so much going on inside the polywell, any analysis is going to be flawed somewhere.

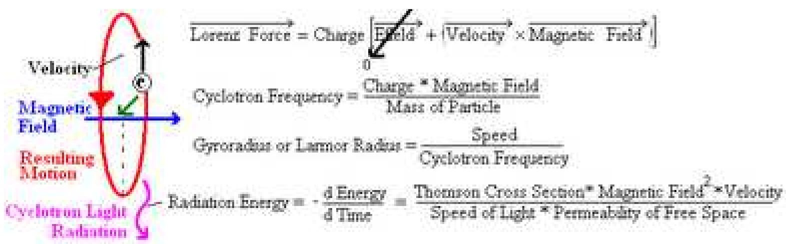


Figure 4: Examining a revolving electron around a magnetic field line and looking at the different equations related to this motion and the light radiation it produces. These are important concepts to connect together – magnetic fields create electron motion. Electron motion generates a second magnetic field. The electron in motion also dissipates energy, in the form of light and there are equations to explain all the motions for this case.

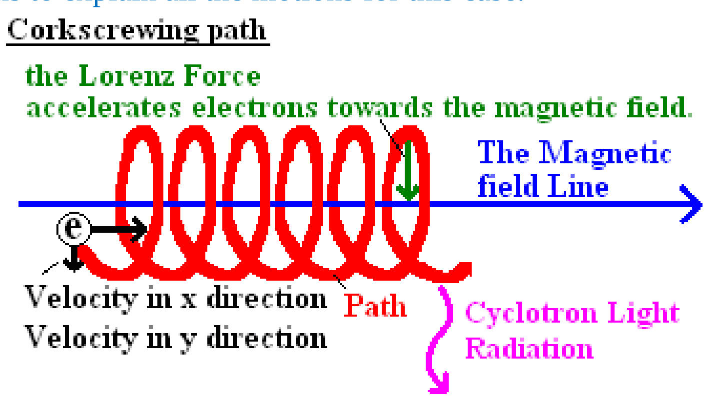


Figure 5: Examining the case of a corkscrewing electron path – one often seen in Indrek’s simulation of the polywell - http://www.youtube.com/watch?v=ao0Erhsnor4.

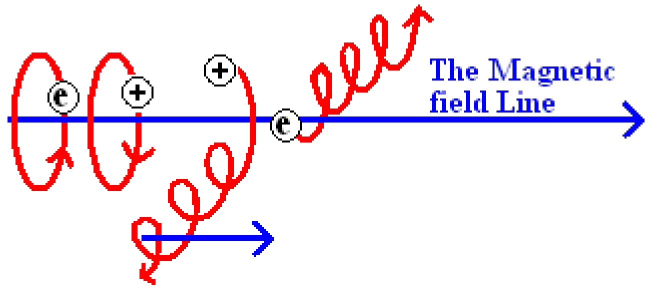


Figure 6: This diagram illustrates electron and ion drift.

"…the magnetic mirror effect has to do with the ratio of velocities perpendicular to the field compared to parallel to the field, as well as the ratio of magnetic field strengths…"

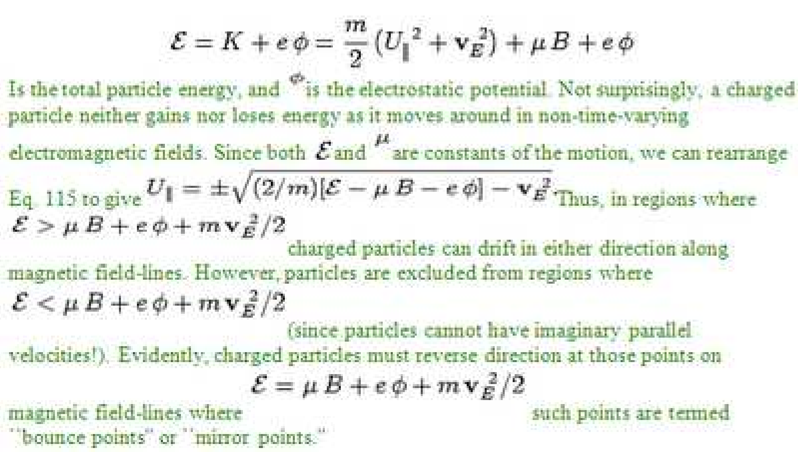
What do you mean by this? Please explain.

"charge times electric field gives force not energy do it does not even have the correct units."

You found an error with in my equation. I called the electrostatic potential, the electric field. One term is in [volts/meter] while the other is in [volts]. My equations came from the link provided - a lecture on magnetic mirrors from the University of Texas at Austin by Professor Richard Fitzpatrick.

http://farside.ph.utexas.edu/teaching/plasma/lectures/node22.html#e2.75

Here is the equation he provided – which is supposed to be an expression for the total particle energy. I turned his expression into one on the blog. In fact most of the rest of that section is lifted directly from these notes. Here are Fitzpatrick's notes - directly from the link:



$$\mathcal{E} = K + e\,\phi = \frac{m}{2}\,(U_\parallel{}^2 + \mathbf{v}_E^2) + \mu\,B + e\,\phi$$

Is the total particle energy, and ϕ is the electrostatic potential. Not surprisingly, a charged particle neither gains nor loses energy as it moves around in non-time-varying electromagnetic fields. Since both $\mathcal{E}$ and μ are constants of the motion, we can rearrange Eq. 115 to give $U_\parallel = \pm\sqrt{(2/m)[\mathcal{E} - \mu\,B - e\,\phi] - \mathbf{v}_E^2}$. Thus, in regions where

$$\mathcal{E} > \mu\,B + e\,\phi + m\,\mathbf{v}_E^2/2$$

charged particles can drift in either direction along magnetic field-lines. However, particles are excluded from regions where

$$\mathcal{E} < \mu\,B + e\,\phi + m\,\mathbf{v}_E^2/2$$

(since particles cannot have imaginary parallel velocities!). Evidently, charged particles must reverse direction at those points on

$$\mathcal{E} = \mu\,B + e\,\phi + m\,\mathbf{v}_E^2/2$$

magnetic field-lines where such points are termed "bounce points" or "mirror points."

As most of the documents I encounter when dealing with the Polywell, that one is hard to follow – so the blog is an attempt to simplify this for everyone who is not familiar with the material. Generally this means "unfolding" all the ideas, adding common analogies and making a passage 2-3 times longer. The blog post is based on the arguments presented above. The passage explains magnetic mirror lines using the particle's total energy. It is basically saying that when a particle lacks enough energy, it cannot travel into a high energy region of a magnetic field. Where it turns around - it has hit a magnetic mirror. Here is the expression that is used in the post – with your correction added. It is the same as Professor Fitzpatrick's except the variable names have been changed.

$$\text{Total Particle Energy} = \frac{\text{Mass Of Particle}}{2}\left(\text{Velocity Parrellel To Magnetic Field Lines}^2 + \text{Velocity parrellel to electric Field}^2\right) + \text{Magnetic Moment} * \text{Magnetic Field} + \text{Electric Charge} * \text{Electrostatic Potential}$$

From this equation professor Fitzpatrick finds three cases. Where the particle can be, where it cannot be, and where it turns around. The post covers these three cases. I used the analogy of a marble moving around a bowl. Showing where the marble can move, where it cannot move and where it turns around. It is all determined by the marbles' total energy and the potential energy of parts of the bowl. The same is true with particles inside magnetic mirrors.

More generally, there seems to be several ways to examine the question: <u>Where do the electrons turn around?</u> One could model the Lorentz force everywhere; using vectors of motion and looking for where the field is too dense for particles to reach. One could examine the magnetic fields and look for magnetic mirrors. One could look at the bulk magnetic field pressure and compare it to the bulk plasma pressure. One could look at the electrons energy and compare it against the confining energy, as Fitzpatrick has done.

Data is needed - there are allot of wrinkles to muddle these kinds of analyses. In an all electron machine these wrinkles include: electrons at different temperatures, electron up and down scattering, imperfect magnetic fields and the diamagnetic Whiffle ball affecting the field. I am sure there are other phenomena – and of course this is before we add ions – which lead to a host of other issues to consider. When ions are in play inside the Polywell, there are X-rays heating and cooling the material, as well as a host of other issues. Data is needed.

Ideally, we need a tool to snap multiple pictures of electron and ion structure inside a working polywell. That would be invaluable. A tool such as that could tell us structure, speed and containment regions for the ions and the electrons inside the machine. It would address so many, many questions. If we knew the structure, we would have strong supporting or refuting evidence for both the Wiffleball and the Virtual Anode. We could tell where the high and the low energy electrons reside. We could tell of the cusp loss points are really packed with electrons, or not. We could roughly estimate what the ions and electron loss rates were for different operating conditions. There probably maybe many more insights yielded by such a tool. <u>A stop motion movie what the electrons and ions actually do inside a working polywell. That would be quite amazing.</u>

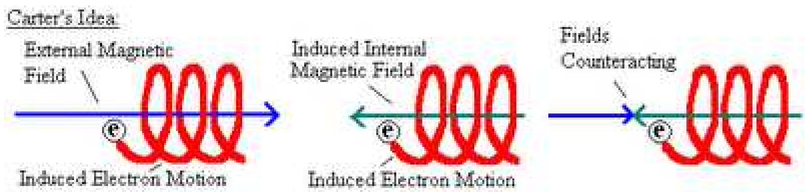
I am only familiar with one method for doing this. That is Thompson Scattering – where light is scattered off electrons or ions to measure plasma structure [5, 6]. I know they do this in other fusion experiments – but this is not at all trivial problem.

"….[The Whiffle ball] is due to the circular motion of the electron in a magnetic field, not the intrinsic spin. There are almost 6 orders of magnitude difference in their effects for a

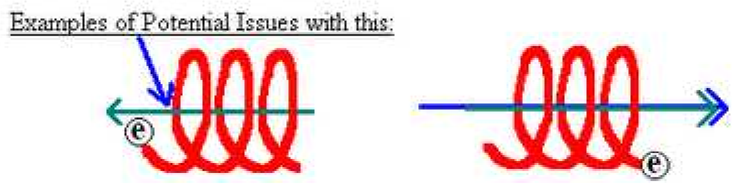
plasma of KT = 1eV. For a fusion plasma at 10keV that is 4 more orders of magnitude difference…"

Carter, you are suggesting that the Whiffle ball comes from a motion generated magnetic field? In other words the electron rotates or gyrates, thereby generating its own magnetic field. These fields add up - and in aggregate, push back the outside field. This creates the Whiffle ball?

This seems like a chicken and the egg scenario. The electrons are moving because of the outside field. The motion makes an internal field. The internal field pushes back on the external field. This would be an interesting idea to explore with respect to one of the magnetic field lines. Below is an illustration of your idea.



Intuitively this idea makes sense to me. It would be analogous to an "internal resistance" that the electron cloud has to the external magnetic field. However, I need to research this concept further. Just reasoning, there would be problems with cases where the electron spirals back the other direction. From Indreks' simulation we would reason this happens roughly half the time. There are also the cases where the electron drifts across the magnetic field. Lastly, this effect would have to align itself against all six of the external magnetic fields.



Can you give me material explaining your '4 orders of magnitude difference' between the induced magnetic field and the intrinsic magnetic moment of an electron. In the appendix below, I try to quantify how strong that little electron magnet could be.

Given everything else going on inside this machine – it seems doubtful that the Whiffle ball could be explained that easily. If the phenomena even occurs. With the spin argument, we have a field that will always be there. The magnetic moment of a free standing electron always exists. It is not created by velocity. A cloud of electrons will have an intrinsic spin. When a strong external field is applied, the electrons line up like little bar magnetics. Their little fields add up. Is the combined magnetic strength of these bar magnetics strong enough to push back the external field? I do not know. In reality, if the Whiffleball is real, it may be a combination of all of these effects - the intrinsic magnetic fields plus the generated magnetic field. We need data to prove this.

Electrons turning in a magnetic field:

Electrons do have an internal spin. This ½ spin comes out of the quantum mechanical model –

and therefore has only discrete values. This spin makes the electron behave like a little bar magnetic. The spin gives the electron a magnetic moment. The magnetic moment of an electron (free standing) is -9.28E-26 Joules/Tesla. See the appendix for more explanation on how I estimated this. If you put an external magnetic field on an electron it's little bar magnetic will cause the electron to turn. Actually the electron experiences a little torque - a force which turns it. You can even find the energy associated with the electron not aligning itself with the external field. When it aligns, it minimizes its energy.

Someone on talk-polywell recently told me I was incorrect in thinking that the electron turns in the field. They cited the Stern-Gerlach experiment as proof. I plan to keep researching this topic. However for right now, I have to respectfully disagree on this particular point. The electron should turn to minimize its energy. I made out an appendix to explain this in more detail. We have a ball park estimate of the magnetic fields used in WB-6: a 1300 Gauss field [8]. In the appendix it is estimated that an electron turning in such a field would lower its energy by 1.21E-26 joules. Remember that this needs to turn an object that only weighs about 9.1E-31 kilograms. This topic is similar to the concept of electron and ion precession in a magnetic field.

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Response to Chrismb's comments:

Brillouin Limit – the Brillouin limit is the maximum amount of electrons you can pack into a given magnetically confined space. It is a limit on electron density. It indicates the limit on the number of electrons you can put inside a Polywell of a given size. It seems likely this would be a concern for focus fusion. Although there is some indication that the polywell may be limited before it hits the Brillouin limit [2] – namely that the loss of an effective magnetic surface can place a more stringent limit on electron density. I do not know a great deal on this topic and I am attempting to learn more. I do agree this should be mentioned in the blog post. It was first described by Leon Brillouin, a professor of physics at Columba University, in 1945 in his paper – "A Theorem of Larmor and its importance for electrons in magnetic fields"[1]. I read his paper.

The Brillouin limit was in fact the hardest topic to research for this post. Nearly two weeks were spent reading papers on this topic. Initially, it seemed that the limit was geometric specific. I found a paper which found the Brillouin limit for tokamaks [9]. I found a more recent paper (2005) which extended the Brillouin limit into stellarators [2]. I found a 1993 paper which appears to investigate the Brillouin limit for the polywell [11]. I also found – your post, Chrismb – from two years ago, which gave a Brillouin limit for the Polywell [10]. My initial approach was to pick out the most relevant equation for estimating the Brillouin limit for a polywell and do that calculation out in this post. However this proved too difficult as no writer seemed to be able to provide me with a good definition of what this limit actually was. Here are some of my favorite descriptions:

"…The theoretical density limit for the confinement of a magnetized, single component plasma occurs when the square of the plasma frequency is one-half the square of the cyclotron frequency…" [13]

"…A maximum achievable density … below which the repulsive and centrifugal forces on the rotating plasma can be balanced by the force due to the confining magnetic field…" [14]

Someone needs to investigate this question. They could treat the Polywell as a multicomponent, non-neutral, non-uniform plasma device. From that starting point, and using the geometry of the machine, they should work to determine if operating a polywell would put it anywhere near the Brillouin electron density limit. If not - then this is not a problem we need to worry about.

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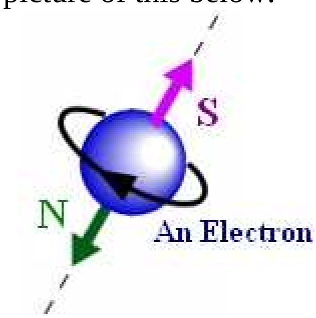
APPENDIX A: WILL ELECTRONS TURN IN A MAGNETIC FIELD?

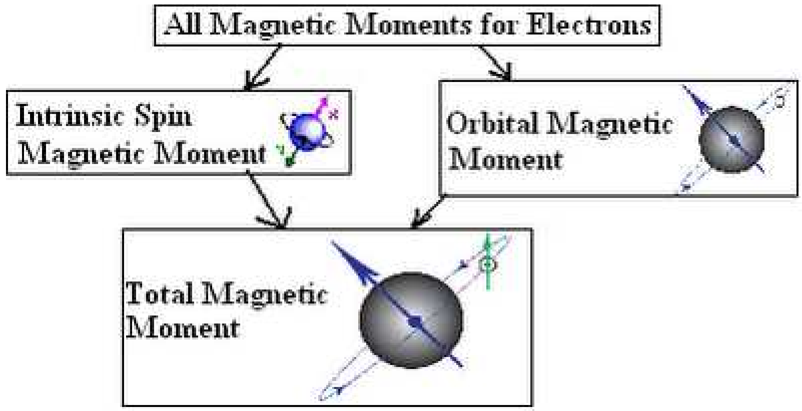
Will an electron turn in a magnetic field?

A few times on this blog I have talked about how an electron moves under a magnetic field. Will a stationary, unmoving, electron turn under a magnetic field? I have said yes, others have said no. I thought I would learn more about this "electron bar magnet" concept. The idea is simple to think about. All electrons spin internally. This spinning creates little north and south poles on an electron. Here is a little picture of this below.



But how strong is this little magnetic?

Magnetic moments are a measure of how magnetic an object is. If you study atomic physics, you will know that there are lots of magnetic moments in the world. There are moments for the electrons, which are different for each place an electron could be found, there are moments for the nucleuses themselves and there are even moments for the protons. The name for this concept is the "spin magnetic moment". It is the magnetic moment created by the electron spinning. If you look this concept up on Wikipedia, you will find a number of mathematical equations for how strong this is. The main confusion is that, normally, there are three different related moments. These are, one for an electron by itself, one for an electron inside an atom, and one which is both phenomena combined. We want the magnetic moment for the free standing electron. I laid out these three moments in a picture below.



Incidentally, you cannot just add these two together to get the total magnetic moment; they are the "quantum mechanical sum" which is a complex problem to solve. There are equations to estimate the magnetic moment for each case. Since we are interested in only interested in the free standing electron – we can pick the equation we need. Here it is [16, 17].

$$\text{Intrinsic Spin Magnetic Moment} = -\text{GSpinFactor} * \text{Bohr Magnetron} * \frac{\text{Angular Momentum Of Electron Spin}}{\text{Reduced Plancs Constant}}$$

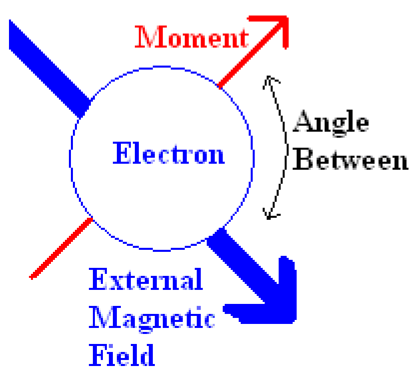
$$\text{Intrinsic Spin Magnetic Moment} = -9.28247\text{E}-26\ \frac{\text{Joules}}{\text{Testla}}$$

<u>What does this moment mean for turning the electron?</u>

The force that turns objects is known as torque. Torque is fundamental concept that can be thought of in many contexts and different situations. Magnetic torque can be found by the following equation [18].

$$\text{Magnetic Torque} = [\text{Magnetic Moment}] * [\text{External Magnetic Field}] * [\text{Sin(Angle Between Vectors)}]$$

You see that when a magnetic moment is not aligned with the external magnetic field, it is at some higher energy state. Thermodynamic says all systems want to minimize there energy, so the electron turns to do this. It turns to lower its' energy. A picture illustrates this below.



Let us look at the strength of this force at the highest energy state possible and at different magnetic field strengths.

(Joules/Testla)	(Testlas)	(Degrees)	(Joules)
Moment	**Magnetic Field**	**Angle**	**Strength of Torque**
-9.28E-26	0.001	90	-9.28E-29
-9.28E-26	0.01	90	-9.28E-28
-9.28E-26	0.1	90	-9.28E-27
-9.28E-26	1	90	-9.28E-26
-9.28E-26	10	90	-9.28E-25
-9.28E-26	20	90	-1.86E-24

It has been stated that WB-6 had about a 1300 Gauss field – although I am skeptical of that number [7]. It is however, probably the right ballpark as Bussard gave typical numbers for copper coiled magnetics at around 1000 Gauss and anywhere below 3,000 Gauss [8]. That puts the field at 0.13 testlas. That ballparks the turning force affecting an electron at an energy of 1.21E-26 joules. This is a tiny amount. But remember this force has to turn a mass about 9.1E-31 kilograms.

Sources:

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