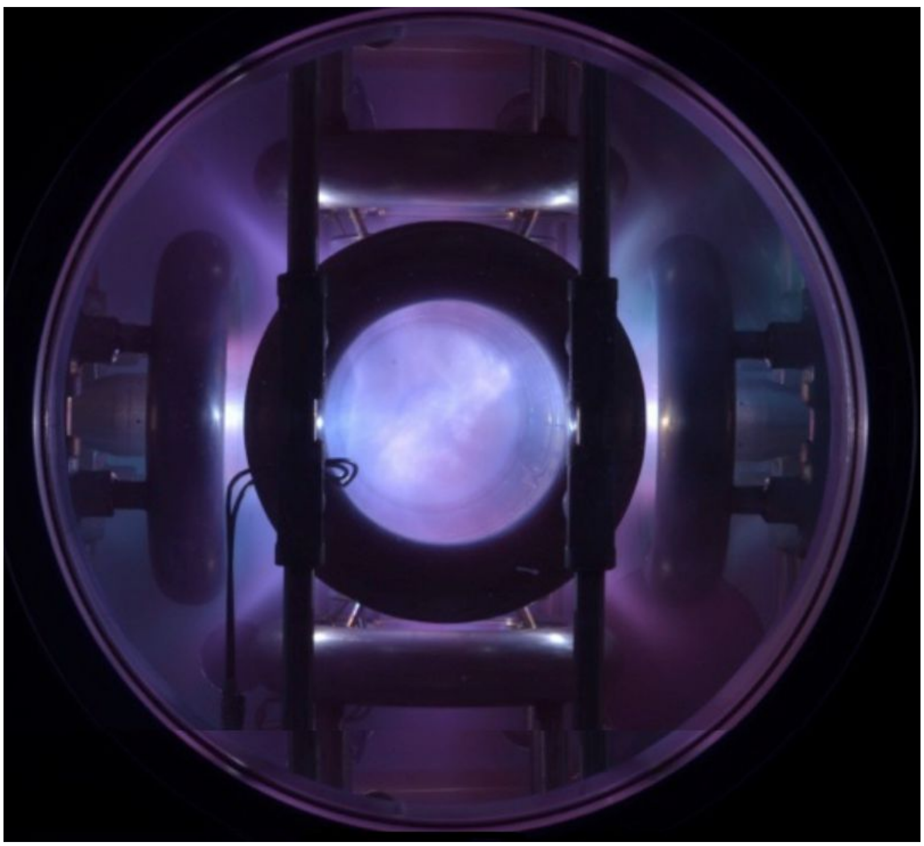
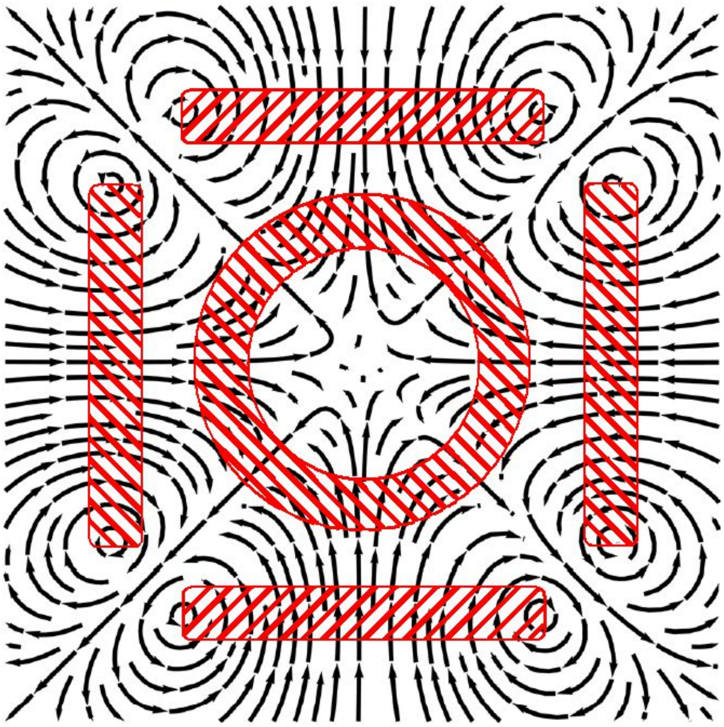
Polywell Fusion In Nine Steps

This is an update on the post "How It Works" from *The Polywell Blog*. That work was written in September 2012 and was based on Robert Bussards' 2005 machine. Bussard reported finding neutrons in that work [3, 22]. If we trust this data - then it is evidence that polywell fusion really works. The newest paper from Dr. Parks' team only provided data for plasma trapping not fusion. Hence, this step-by-step is theoretical at present. If Parks findings are correct it may lead to a ***fusion reactor, which doubles as the worlds' best plasma trap.*** That gets you pretty far down the road to a fusion power. It is still early days, but we see a very promising future for this technology.



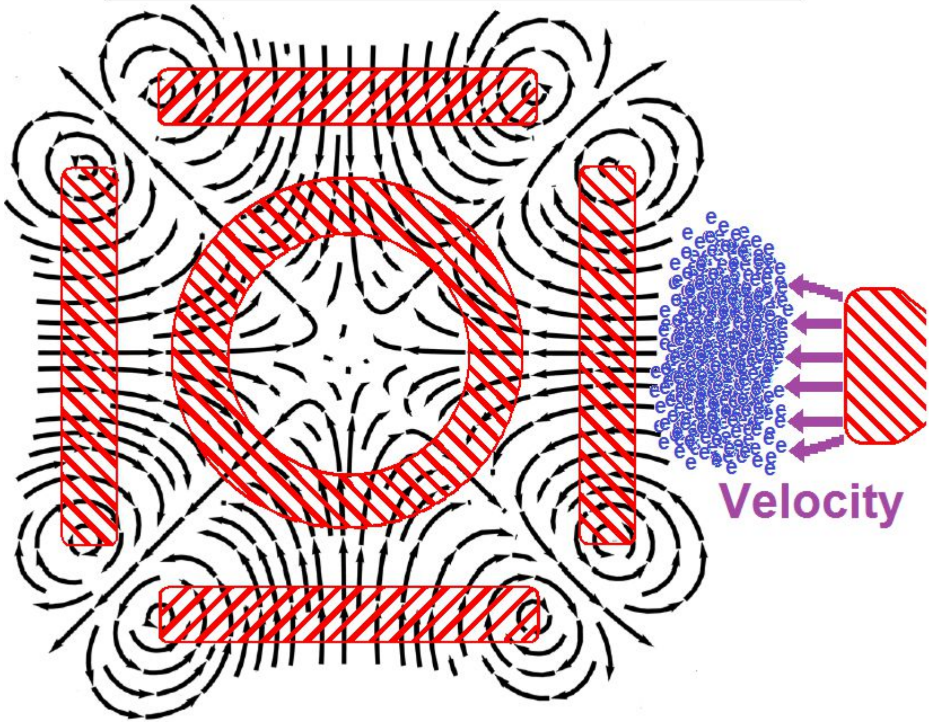
1. Magnetic Field Turned On. The rings inside the polywell are six electromagnets in a box. In WB8, these had 40,960 amp-turns [21]. All of these electromagnets are setup so that their poles point into the center [3, 22]. So that is six north poles facing each other. We do not want those rings to connect with each other - they should be externally mounted. We also want those rings smooth and uniform [25]. At the center there is a pocket of no magnetic field, a null point. All of this is contained inside a vacuum chamber (in WB8 this chamber was held at a pressure is roughly 10 mtorr or less) [24]. The fields are shown below.

1. Magnetic Field Turns On:



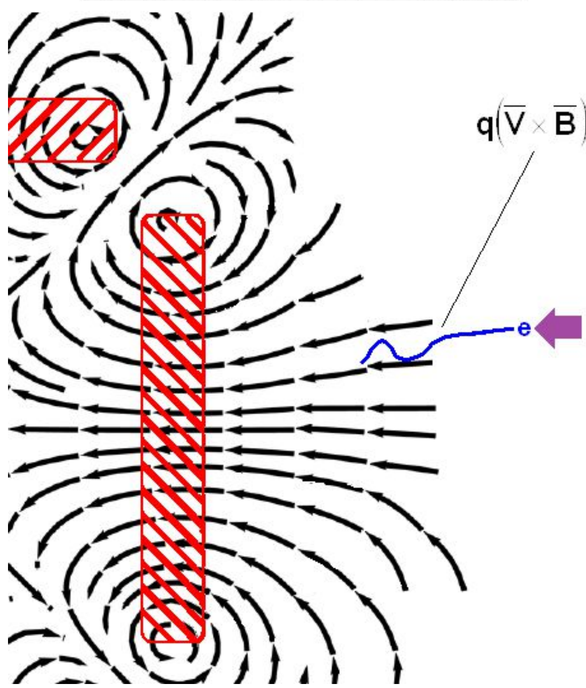
2. Electrons Emitted. Unlike the 2005 work, this new machine did not drive the electrons with any fields [3]. Instead, they just dumped a massive amount of ions right next to the ring structure. I estimated this was ~6E+18 of charged particles, flung out from the emitter at ~1E9 newtons [33]. In a power plant scenario, this material would all be electrons.

2. Electrons Shot Outward:



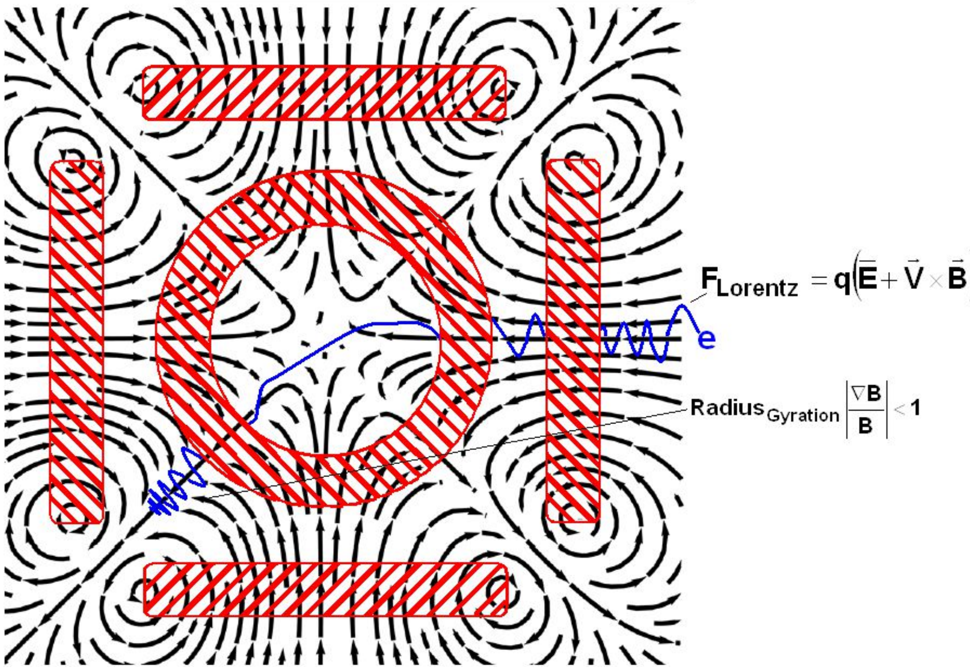
3. Electrons Get Caught By Ring Fields. When the electron gets close it starts to feel the magnetic fields. Specifically, the magnetic component of the Lorentz force starts to drive electron velocity. The electron starts following the magnetic fields generated by the rings. This is different than the 2005 machine, where an electric field was used. The electron oscillates around one of these magnetic field lines, following it towards the center, giving off cyclotron radiation [4].

3. Electrons Get Caught:



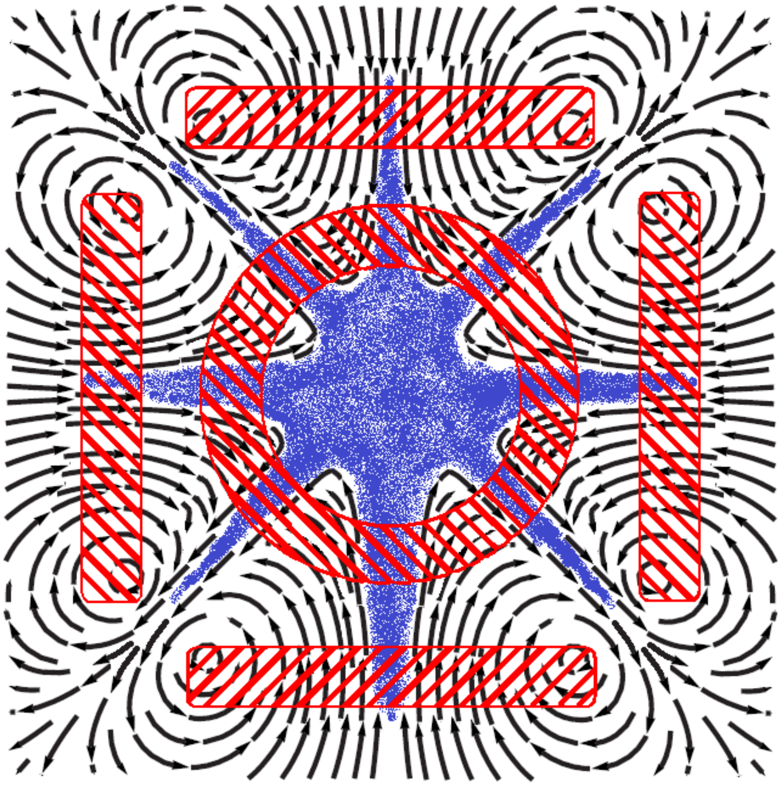
4. Electron Motion Inside Center. When the electron reaches the center, its' motion becomes straighter as it passes through the null point [5]. This is the point of no magnetic fields in the middle of the rings. As it heads out the other side, it starts oscillating again. This oscillation get tighter as the electron gets farther away from the center [11, 8]. The radius of oscillation is the electron gyroradius [6]. The electron follows the magnetic field lines. These lines are drawn together, tighter and tighter at the corners. The field around the electron gets denser. The electron oscillation gets smaller and tighter. At some point, the field gets so tight that the electron hits a magnetic mirror at the cusps [6, 7, 8, 11]. The electron turns around. It heads back toward device center and repeats the motion [8, 11]. An electron should be lost after a given period of time [8].

4. Electron Motion Inside Center:



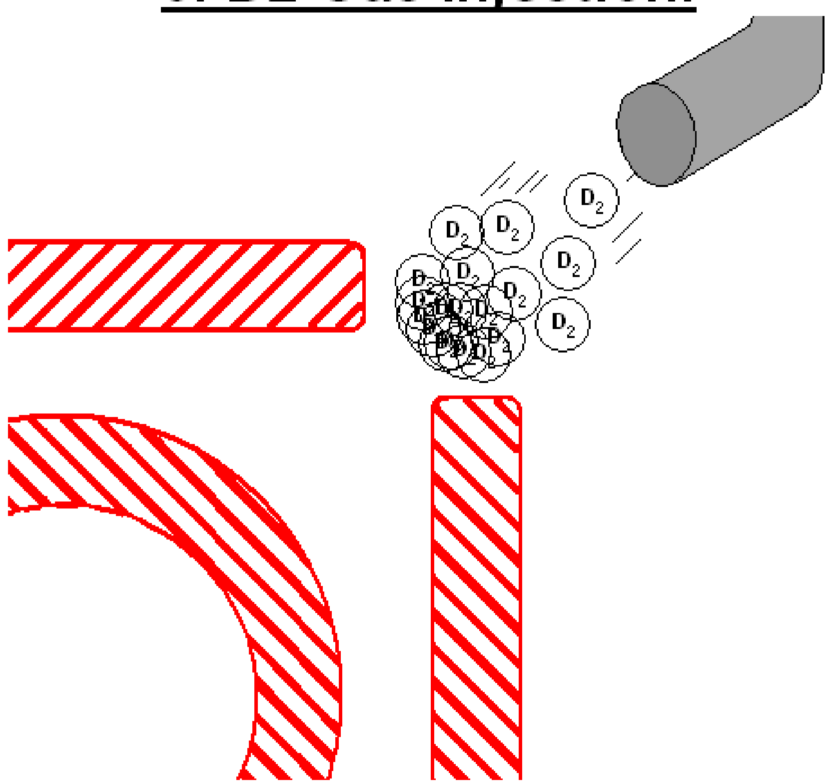
5. Cusp Confined Plasma. The electrons' motion make small magnetic fields [9]. In bulk populations, this gives the plasma magnetic properties, allowing it to go diamagnetic and reject the outside field [29]. Theoretically, the plasma should form a stable system where the plasma pressure balances the magnetic pressure; a beta of one [17, 18, 25-28]. The shape of this cloud would depend on where the pressures find equilibrium, but it is commonly assumed to be a 14 point star. The evidence of cusp confinement was the breakthrough claim of the new EMC2 paper. They provided data (x-ray, visual and flux loop) that this effect has finally been observed in a real physical system [21]. This effect was first predicted in 1954 [3, 5, 25-28]. This is also the trapping mechanism that Lockheed Martins' Skunkworks is chasing [30].

5. Cusp Confined Plasma:



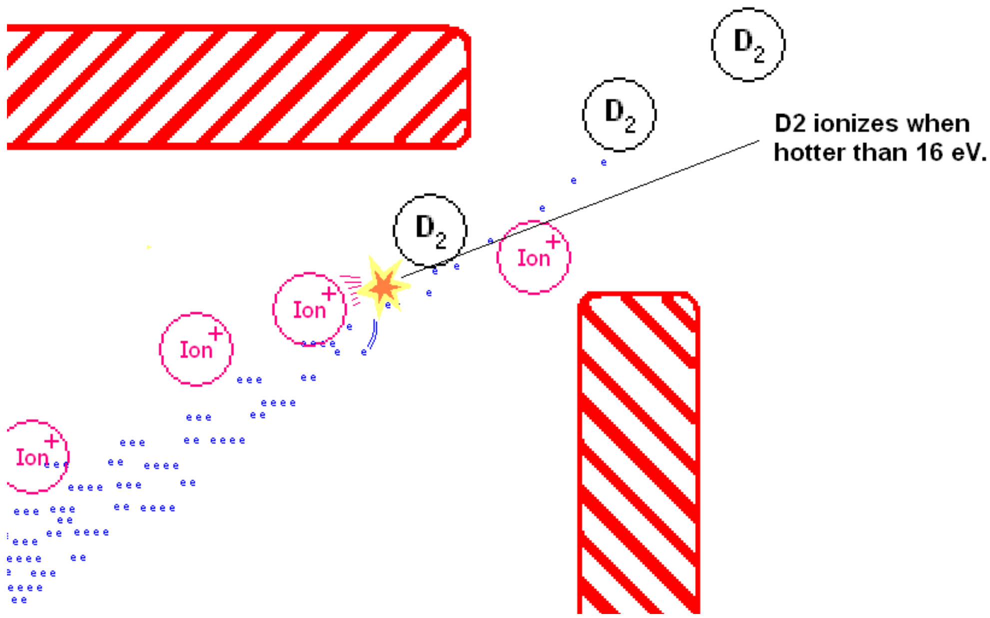
6. Deuterium Gas Injection: The D2 gas is puffed towards the rings [3]. This is the uncharged D2 gas. This means that the gas is less affected by any electric fields. Hence, it can make it to the edge of the rings. Bussard puffed the gas in at the relatively high pressure of 3E-4 torr against vacuum pressure of 1E-7 torr [3].

6. D2 Gas Injection:



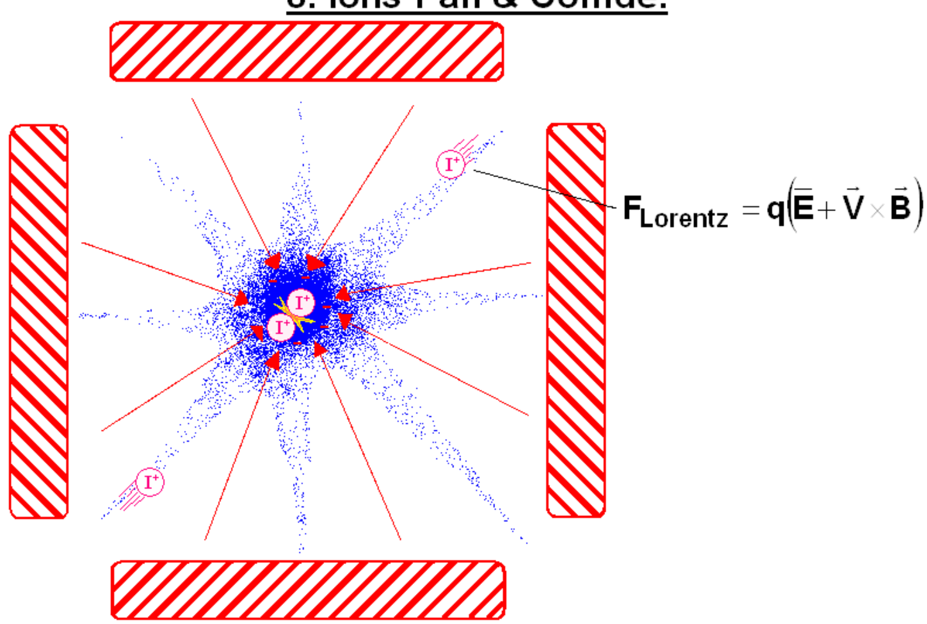
7. The Deuterium Ionizes: When the D2 reaches the edge of the rings it is hit by an electron. If the electron is hotter than 16 eV [1] the D2 will become an ion. Bussard estimated that the typical electron in his device had 2,500 eV [3] at the beta=1 condition [10]. This collision heats up the deuterium and it ionizes. The deuterium loses an electron to become the ion. The ion is positively charged and is attracted to the cloud of electrons in the center. In WB-6, this attraction created a 10,000 volt drop for the ions to "fall down"[3].

7. The D2 Ionizes:



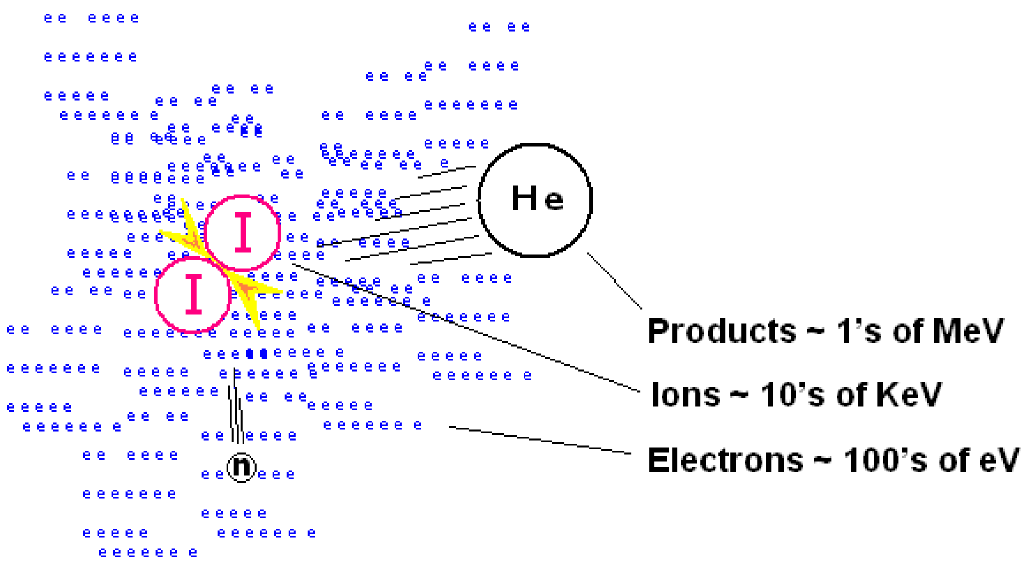
8. Ions Fall & Collide: The charged deuterium is attracted to the electrons in the center. In WB6, it was attracted by the 10,000 volt drop. It “falls down” this hill towards the center [3]. The ion builds up 10,000 eV as it falls. Note that the deuterium ion is about 3,670 times more massive than the electron [12, 1].

8. Ions Fall & Collide:



9. Fusion: If two ions do collide at 10,000 eV, they can fuse. The product will be have on the order of 1 MeV [15] of energy and cannot be held by the electric or magnetic fields. It should therefore rapidly exit the rings. As the voltage increases the odds of fusion typically improves. This is measured by a fusion reactions' cross section [15]. The stated goal of NIF was to get the average plasma temperature over 10,000 eV under confinement [2].

9. Fusion:



Inside WB-6, the deuterium could have collided with 10,000 electron-volts of kinetic energy. This would give a fusion cross section of 1E-4 Barns [15]. This cross section is entered into the volumetric fusion rate equation [16]. This equation is shown below with typical numbers for WB-6 [3, 19, 20]. The ion density is estimated from experimental estimates [3].

$$\frac{\text{Energy From Fusion}}{\text{Hot Volume}} = \left(\frac{\text{Number of Deuterium Atoms}}{\text{Volume of Space}}\right)^2 * \text{Relative Velocity} * \text{Rxn Cross Section} * \text{Ave Energy From Rxn}$$

$$\frac{\text{Energy From Fusion}}{\text{Hot Volume}} = \left(\sim 1E15\ \text{Ion}/\text{M}^3\right)^2 * \sim 1{,}384{,}000\ \text{M}/\text{S} * \sim 1E-32\ \text{M}^2 * \sim 2.92E-13\ \text{Joules}/\text{Ion} = 4.0E-9\ \text{Joules}/\text{Second}$$

Many other things can happen as the ions fall towards the device center. The ion can interact with other electrons or ions. They interact if the distance between these objects falls below the Debye screening length [13]. These interactions can create x-rays, repulsion or collision without fusion [14]. Three main criticisms against this idea are: x-rays sap away too much energy, the electron and ion temperature cannot vary more than 5% and a bell curve of ion energy keeps most of them too cold to fuse [14].

Citations:

1. “Deuterium." *Deuterium*. National Institute of Standards and Technology, 2011. Web. 06 Sept. 2012. <http://webbook.nist.gov/cgi/cbook.cgi?ID=C7782390>.

2. "Development of the Indirect-drive Approach to Inertial Confinement Fusion and the Target Physics Basis for Ignition and Gain." John Lindl. Page: 3937. AIP Physics of Plasma. American Institute of Physics, 14 June 1995.

3. Bussard, Robert W. "The Advent of Clean Nuclear Fusion: Superperformance Space Power and Propulsion." 57th International Astronautical Congress (2006). Web.

4. Bornatici, M. "Electron Cyclotron Emission and Absorption in Fusion Plasmas." *Nuclear Fusion* 23.9 (1983): 1153-257. Print.

5. J. Berkowitz, K. Friedrichs, H. Goertzel, H. Grad, J. Killeen, and E. Rubin, Proceedings of the 2nd International Conference on Peaceful Uses of Atomic Energy (Geneva, Switzerland, 1958), Vol. 1, pp. 171–176.

6. F. Chen, Introduction to Plasma Physics and Controlled Fusion (Plenum, New York, 1984), Vol. 1, pp. 30–34.

7. Fitzpatrick, Richard. "Magnetic Mirrors." *Magnetic Mirrors*. N.p., 31 Mar. 2011. Web. 06 Sept. 2012. <http://farside.ph.utexas.edu/teaching/plasma/lectures/node21.html>.

8. Carr, Matthew, and David Gummersall. "Low Beta Confinement in a Polywell Modeled with Conventional Point Cusp Theories." Physics of Plasmas 18.112501 (2011): n. page. Print

9. "Why Does Moving Electron Produce Magnetic Field?" *Why Does Moving Electron Produce Magnetic Field?* Physics Forums, 3 July 2007. Web. 24 Aug. 2012. <http://www.physicsforums.com/showthread.php?t=184619>.

10. Correll, Don. "Plasma Dictionary." *Plasma Dictionary*. Lawrence Livermore National Laboratory, 12 July 2000. Web. 1 Sept. 2012. <http://plasmadictionary.llnl.gov/>.

11. Mandre, Indrek. "Polywell Simulation 3D." *YouTube*. YouTube, 02 June 2007. Web. 06 Sept. 2012. <http://www.youtube.com/watch?v=ao0Erhsnor4>.

12. "Proton-to-electron Mass Ratio." *Wikipedia*. Wikimedia Foundation, 09 June 2012. Web. 01 Sept. 2012. <http://en.wikipedia.org/wiki/Proton-to-electron_mass_ratio>.

13. Spencer, Ross L. "A Brief Introduction to Plasma Physics." *A Brief Introduction to Plasma Physics*. Brigham Young University, n.d. Web. 6 Sept. 2012. <http://maxwell.byu.edu/~spencerr/phys442/plasma.pdf>.

14. Rider, Todd H. "A General Critique of Inertial-electrostatic Confinement Fusion Systems." Physics of Plasmas 6.2 (1995): 1853-872. Print.

15. Jarvis, O. N. "Nuclear Fusion 4.7.4." *Nuclear Fusion 4.7.4*. National Physical Laboratory, 2011. Web. 30 Aug. 2012. <http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_7/4_7_4.html>.

16. Lawson, J. D. "Some Criteria for a Power Producing Thermonuclear Reactor." *Proceedings of the Physical Society. Section B* 70.1 (1957): 6-10. Print.

17. Simon, Martin. "Diamagnetic Levitation." *Diamagnetic Levitation*. University of California Los Angeles, n.d. Web. 06 Sept. 2012. <http://www.physics.ucla.edu/marty/diamag/>.

18. "Of Flying Frogs and Levitrons" by M.V.Berry and A.K.Geim, European Journal of Physics, v. 18, p. 307-313 (1997).

19 Elert, Glenn. "Kinetic Energy." *Kinetic Energy*. The Physics Hypertextbook, n.d. Web. 10 Sept. 2012. <http://physics.info/energy-kinetic/>.

20. Atzeni, Stefano, and Jürgen Meyer-ter-Vehn. *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*. Oxford: Clarendon, 2004. Print. Page 12

21. Park, Jaeyoung, Nicholas A. Krall, and Paul E. Sieck. "High Energy Electron Confinement in a Magnetic Cusp Configuration." In Submission (2014): 1-12. Http://arxiv.org. Web. 13 June 2014.

22. Should Google Go Nuclear? Clean, Cheap, Nuclear Power. Perf. Dr. Robert Bussard. Google Tech Talks. YouTube, 9 Nov. 2206. Web. 15 Sept. 2010. http://video.google.com/videoplay?docid=1996321846673788606#.

23. Moynihan, Matthew J. "Modeling Plasma Emitters In Polywell Paper." Https://thefusionblog.quora.com/Modeling-Plasma-Emitters-In-Polywell-Paper. Quora, 20 July 2015. Web. 25 Sept. 2015.

24. Private communication, “What was roughly the pressure inside the machine?” Paul Sieck, July 2, 2015

25. University of Maryland, Colloquium & Seminars, "Measurement of Enhanced Confinement at High Pressure Magnetic Cusp System", Jaeyoung Park, September 9th 2014

26. Grad, Harold. "Plasma Trapping in Cusped Geometries." Physical Review Letters 4.5 (1960): 222-223.

27. Haines, M. g. "Plasma Containment in Cusp-shaped Magnetic Fields." Nuclear Fusion 17.4 (1977): 811-58. Web. 18 June 2014.

28. Dolan, Thomas J. Review Article: Magnetic Electrostatic Plasma Confinement. Vol. 1539-1593. Plasma Physics and Controlled Fusion, 1994. Print.

29. Cole, K. D. "Diamagnetism in a Plasma." Physics of Plasmas Phys. Plasmas 4.6 (1997): 2072.

30. McGuire, Tom. "The Lockheed Marin Compact Fusion Reactor." Thursday Colloquium. Princeton Plasma Physics Lab, Princeton. 6 Aug. 2015. Lecture.