New Design Features for Polywell

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Abstract

New design features include a differentially pumped ion source and an electron extractor. Differential pumping localizes the ion birthplace to be at the peak of the electrostatic potential, thus minimizing the ions' energy spread. The electron extractor localizes up-scattered electron losses to occur only in one selected point cusp, thus improving the reactor power balance and the accuracy of simulation. Two-dimensional PIC simulation was used to investigate the scaling of the power-balance with magnet size. Both a two-magnet spindle-cusp design and a six-magnet Polywell design were simulated with D+D fuel. The Polywell design demonstrated much superior power balance compared to the spindle cusp. Even so, scaling to break-even leads to an impractically large reactor size. Thus, it now appears that resistive magnets will not work with advanced fuels. Super-conducting magnets will be required to reach break-even. Simulation also suggested favorable bremsstrahlung scaling with size. This gives hope for future reactor designs utilizing $p+B^{11}$ fuel.

The above abstract was read by the author in a 25-minute talk before 27 attendees at the 15th annual Workshop on IEC Fusion at Kyoto University. Following the Workshop, a preliminary version of the talk was posted on the Workshop website (http://www.iae.kyoto-u.ac.jp/beam/iec2013/). This more recent final.pdf file contains corrected slides and notes. The notes are the actual verbatim text as read by the author at the Workshop.

Lockheed-Martin Inc. T4 Reactor

- Quoting Wikipedia "High Beta Fusion Reactor"
  - "A cylinder with very few open magnetic field lines.
  - "Very good arch curvature of the field lines.
  - "The system has a beta of about 1."
- Could this be a spindle cusp IEC reactor?

Last February, Charles Chase of Lockheed-Martin Corporation spoke at a Google Solve-for-X seminar. His 14-minute talk was filmed and broadcast on YouTube*. He showed these two photos in his talk. Chase identified the tall man in the white shirt as Tom McGuire, inventor of (quote) "our brand new concept." McGuire received his Ph.D. from M.I.T. about 6 years ago. Ray Sedwick, who is in attendance today, was McGuire's thesis supervisor back at M.I.T.

Describing the photo on the right, Chase said (quote), "What you can see on the right is during an experiment inside our chamber. You can see the plasma and one of the magnetic coils inside. You can see the plasma following the magnetic field lines exactly as predicted." (end quote).

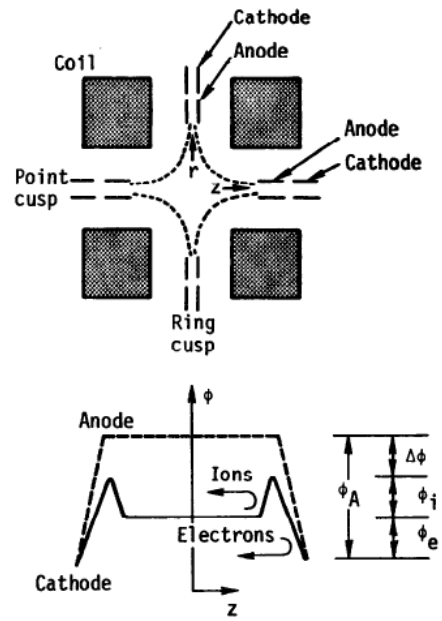
Presumably the "prediction" Chase spoke of was a PIC simulation done by McGuire. McGuire became an expert in PIC, when he did an extensive simulation using OOPIC-Pro as part of his Ph.D. Thesis.

Guessing that perhaps the Lockheed device is similar to the old spindle-cusp reactors, I did the the following simulation.

* http://www.youtube.com/watch?v=JAsRFVbcyUY

History of Spindle-Cusp Reactors

Fig. 17D1. Plugging electrodes and magnetic field lines (dashed curves) in a spindle cusp, and the corresponding axial variation of electrostatic potential in vacuum (dashed curve) and with plasma (smooth curve). Potential barriers ϕ_i and ϕ_e confront electrons and ions, with the applied voltage ϕ_A. The potential at the center of the anodes is depressed an amount $\Delta\phi$ by Debye shielding. From T.J. Dolan, "Design study of electrostatically plugged cusp fusion reactor", UCRL-52142 (1976), Figs. 2 and 3.



T.J. Dolan, “Fusion Research”, Pergamon Press, copyright 1982; and Thomas James Dolan, “Fusion Research (corrected)”, copyright 2000, 937 pages.

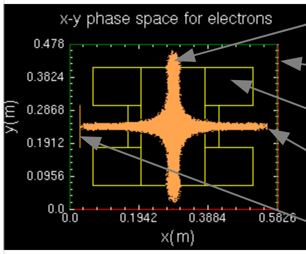
Led by Russian researchers, spindle-cusp reactors were investigated extensively in the closing decades of the 20th century. The slide shows "cusp plugging," implemented by installing "Cathode" and "Anode" electrodes in the 2 magnet bores and also in the ring cusp between the magnets. Experiments* in Canada showed ion densities remained too small to make a practical power reactor. Ions were found to flow freely to the anodes where they were lost. Research publications on spindle-cusp reactors ended with Dolan's 1994 review article.

The design being reported here is a hybrid of Bussard's Polywell concept married to the old spindle-cusp design. Instead of the interior electrodes shown in this slide, the hybrid design uses the surrounding vacuum tank as a cathode and the magnet containers as anodes. Electrons originating at the tank wall enter the enclosed volume as beams along the point-cusp lines through the magnet bores.

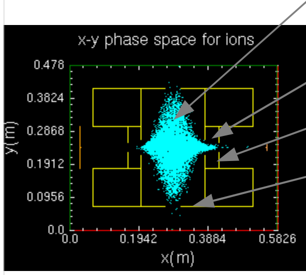
The confined electrons form an electrostatic potential well similar to that shown in the slide. Hills at the outer edges of the confinement volume confine both ions and electrons. Ions turn around at the inner slope of the hills, just inside the magnets. Electrons leave through the cusps, slow down, and turn around near the tank walls.

* P.Couture and B.L.Stansfield, "Confinement in a double-cusp electromagnetic trap", Plasma Phys. Vol. 25, 1001 (1983)

PIC Simulation of Reactor Features



- 40K e-Macroparticle Positions
  - Cylindrical Vacuum Tank Outline
  - Coil Magnets Biased @ 100kV
  - Electrons Entering along a Point Cusp
  - Extractor Electrode Blocking e-Losses
- 10K Ion-Macroparticle Positions
  - D^+ Ions Born from e's in D_2 gas cell
  - Pumping Apertures Confine D_2 gas
  - Ring Electrode Biased @ 100kV
- Central 2D Slab is Simulated



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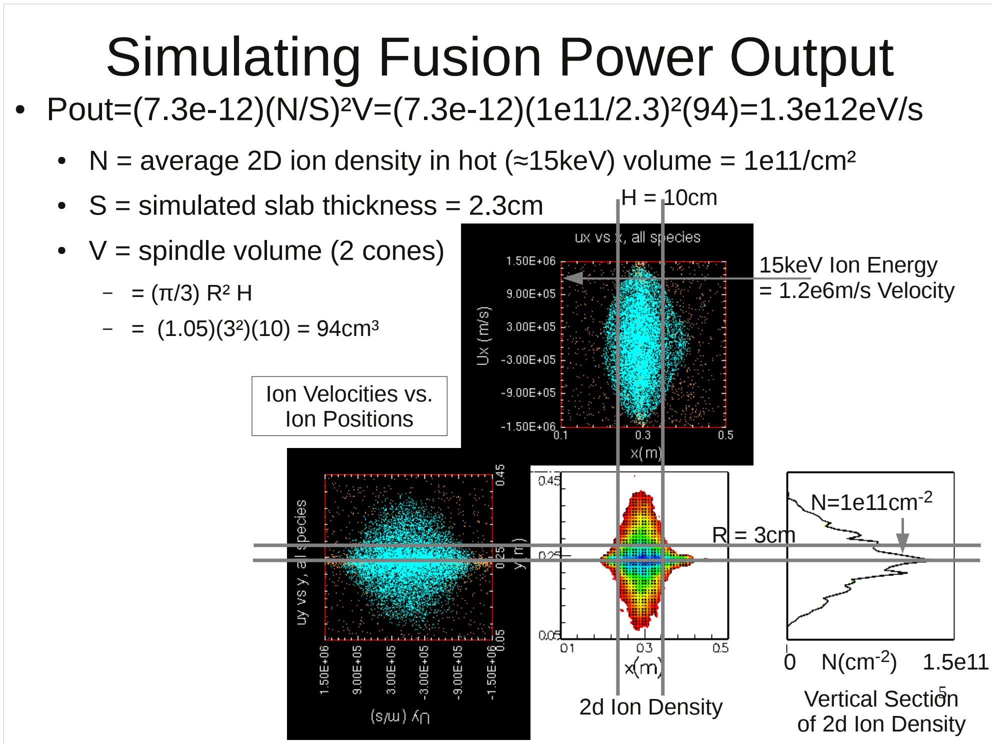
The most important new feature of the modified spindle-cusp reactor is the "Extractor Electrode," shown located a short distance inside the left tank wall. With this electrode in the simulation, electron losses occur only on this one electrode, not through the opposite point cusp, not through the ring cusp, and not on any of the internal structures, such as the magnets.

Electrons make many passes in and out from center until they gain enough energy to hit the electrode. As a given electron gradually gains energy, it turns around further and further from center before returning on each pass. The electrode is at a lower voltage than the tank walls; therefore, electrons tend to hit it first. A requirement was imposed to make all the electrons hit the electrode. The voltage difference between electrode and wall was made slightly larger than the up-scattered energy gain per pass. The distance from wall to electrode was found by trial and error to be that shown in the slide.

To make the simulation manageable, the volume simulated is two-dimensional, not three-. A slab of plasma is located at the center of a hypothetical three-dimensional reactor. The slab thickness is big enough to contain the point cusps, even in the third dimension. By symmetry, the width of the cusps is the same in the slab and perpendicular to the slab. This feature makes the power loss in the one slab equal to the power loss in three dimensions, a useful simplification.



The spindle-cusp reactor power output, Pout, was computed from the simulated ion density, slab thickness, and plasma volume as shown in the slide. By examining the diagnostic plots of ion velocity vs. position, the vertical and horizontal extent of the hot, fusing ions was determined to be the area delimited by the lines. The three-dimensional ion density was computed from the two-dimensional simulation by dividing the integrated counts by the area and by the slab thickness S. DD reactivity and DD energy yield were taken from the NRL Plasma Formulary. The slab thickness S was derived by imposing the condition that the three-dimensional density at the plasma surface be related to the B-field at the surface by the formula β=1. The same method was later used to compute the slab thickness for the cubic Polywell reactor. The details of the method of determining S are deferred to the discussion of the Polywell power balance later in the presentation.

Spindle-Cusp Reactor Power Balance

- Power Balance $Q \equiv$ (Power Out) / (Power In)
- Fusion Power Out, $P_{out} = \frac{1}{2} n^2 \langle \sigma v \rangle V E$
  - n = ion density = (2d ion density)/(slab thickness S)
  - $\langle \sigma v \rangle$ = DD fusion reactivity at 15keV = 4e-18cm^3/s
  - V = spindle volume (inside which D-energy ≈ 15keV)
  - E = energy liberated by one fusing DD pair = 3.7MeV
  - Pin = Power carried away by electrons hitting the catcher electrode plus ions hitting the cylindrical tank
- Q = Pout / Pin = 1.3e12 / 8e22 = 1.6e-11
  - Compare this to Polywell with Same Magnets.

To be useful for power generation, Q must be greater than unity. The simulation shown here computes Q for a small scale model reactor, one which can be fabricated with off-the-shelf copper magnets and DC power supplies.

Q increases as the size of the scale model is increased. The size of a break-even(Q=1) reactor was predicted by extrapolation, using an empirical fit to the theoretical, exponential relationship between magnet size and Q. In what follows we will discover that the model Polywell reactor has a much bigger Q-factor than the model spindle-cusp reactor. A bigger Q-factor extrapolates to a smaller net power reactor. Designing the smallest net-power reactor is the main purpose of my work.

We now leave the discussion of the spindle-cusp reactor and move on to analyze the simulation of the cubic Polywell reactor.

Cubic Polywell Reactor Simulated

(a) Grounded Vacuum Tank with Ports on 6 Faces

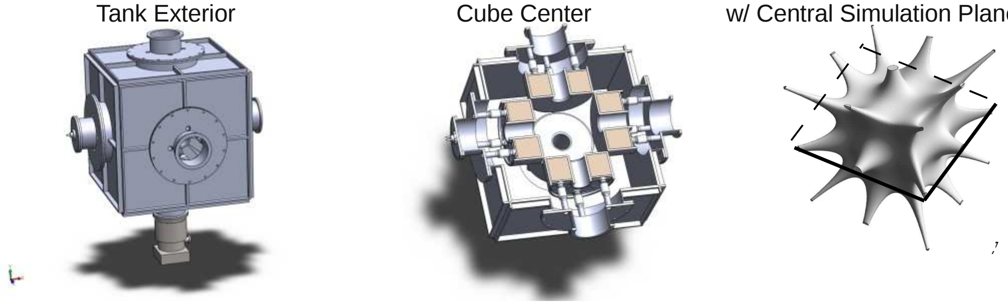
- Vacuum Pumps and Electron Emitters Attach to Ports.

(b) Six Coil-Magnets Mounted on Insulating Legs

- D_2 Gas Flows into Gas Cells through Hollow Legs.

(c) B-field of 26 cusps, 8 in the central plane

(a) Cubic Vacuum Tank Exterior — (b) Tank Cut-away thru Cube Center — (c) Magnetic Field Iso-Contour w/ Central Simulation Plane



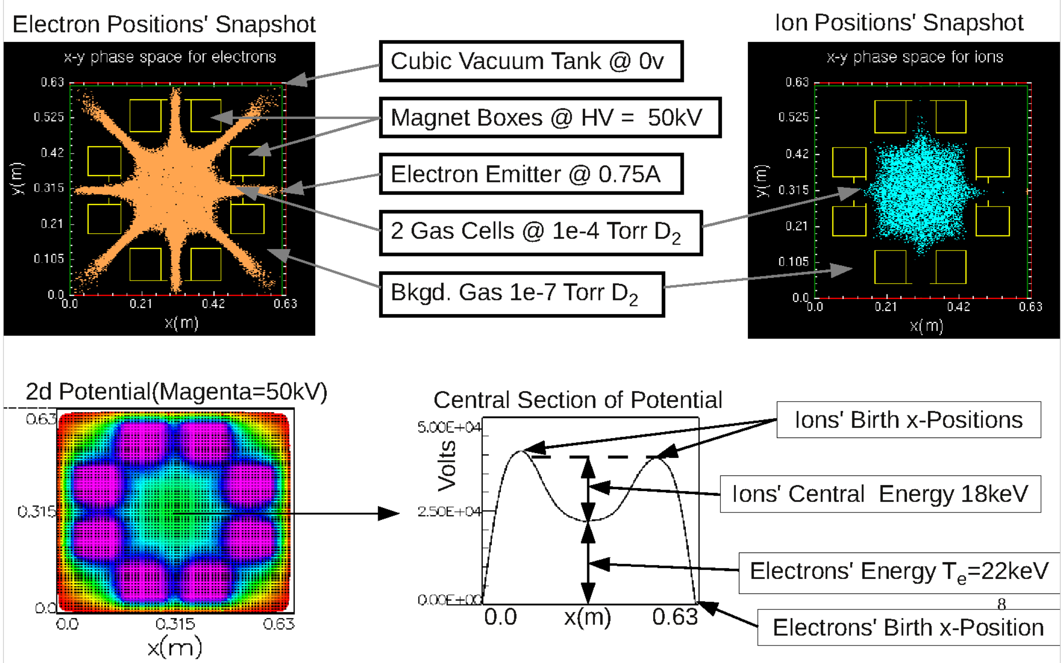
The inside diameter of the vacuum tank was chosen to fit the size of commercial, off-the-shelf magnets, which have 35cm outside diameter. The high voltage bias level on the magnets was chosen to optimize the DD reactivity. This optimum energy turns out to be 15keV. The applied voltage was made 50 kilovolts, about three times the desired ion energy. This level of bias voltage seems reasonable, but a rigorous optimization was not performed.

The middle image, with the tank half-cut away, shows the 8 square cross sections of the 4 magnet coils intersecting the mid-plane of the cube. On the right is shown the B-field surface from six such magnets. The surface, computed analytically and published two years ago by the University of Sydney group*, has 26 cusps.

For simulating the plasma in the central plane, an approximation to the three-dimensional B-field was made. Six circular current loops in the analytic formulation were replaced by 8 straight wires in the simulation. This provides a good approximation to the B-field in the central plane. Contributions to the B-field from the omitted portions of the current loops, above and below this plane, tend to cancel each other by symmetry arguments.

* Matthew Carr, David Gummersall, Scott Cornish, and Joe Khachan, "Low beta confinement in a Polywell modelled with conventional point cusp theories", Phys. Plasmas, **18**:11 (2011)

Cubic Polywell Reactor Features



The upper images show snapshots of the electron and ion particle positions. The eight magnet sections are shown as yellow squares. The 8 current-carrying wires are located at the centers of the squares. The wire currents and magnet sizes were taken from the advertised specification of a typical copper magnet.

Electron beams were generated from small emitters located at two opposing points on the left and right magnet axes. The DC electron current leaving the emitters was adjusted by trial and error to stabilize the confined electrons' charge. Steady-state was reached after about 500 microseconds of simulated time.

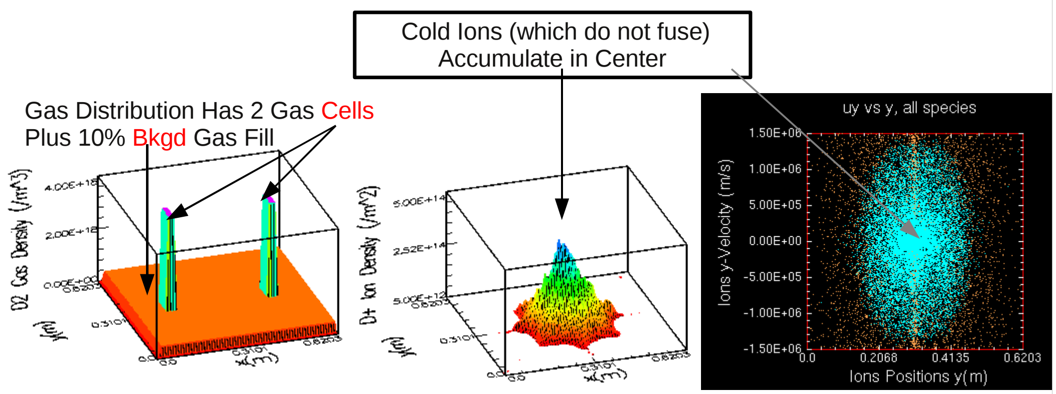
Ions were produced continuously by the electrons' ionizing deuterium gas in two gas cells. The gas was confined by apertures with small holes to let the electron beams pass through the cells. The holes were made as small as possible to reduce the gas leakage rate through the holes. The smaller the gas leakage rate, the smaller the exterior pressure. This technique of reducing the pressure by choking the flow using apertures is called "differential pumping."

The rate of ion formation by gas ionization is proportional to the gas pressure in the cells. This pressure was adjusted by trial and error to stabilize the steady-state ion charge and make the electron central density equal the ion central density.

The electron current and gas pressure are the knobs used to stabilize the densities. The simulation produces diagnostic plots from which the steady-state power balance was computed.

The Need for Differential Pumping

- Gas inside gas cells produces E≈15keV, hot ions.
- Background cold ions dilute and pollute hot ions.
- Diagnostics show 10% bkgd. is already too big.
- Much smaller background is needed.



Ions born in the 2 gas cells gain the maximum energy from falling into the potential well. However, not all the gas stays in the gas cells. Gas leaking out through the apertures forms a uniform pressure everywhere outside the cells. Ions born outside the magnets fly immediately to the tank walls. Ions born inside are trapped, but with defective energy. The simulation was used to investigate the maximum background gas pressure which can be tolerated. This information is needed to determine how much vacuum pumping capacity must be provided. Vacuum pumping is the most expensive sub-system of the reactor design.

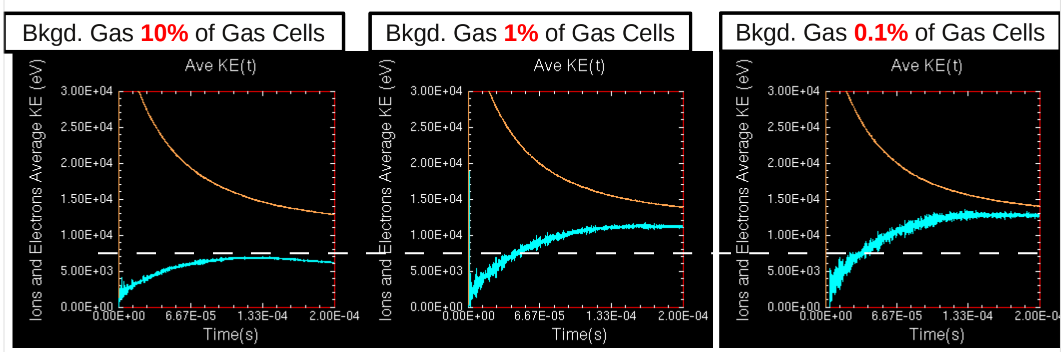
The simulation source file contained a block of code called "MCC," which stands for Monte Carlo Collisions*. An analytic function specifies the initial gas pressure at each cell throughout the two-dimensional simulation volume. The function has 2 peaks, located at the gas cells, plus a uniform background everywhere else. At each time step the simulation throws a weighted random number to determine which electrons ionize an atom. Ions and secondary electrons are tracked from the time and place of their birth. They move under the influence of the electrostatic potential. They are tracked using Maxwell's equations, just like the primary electrons from the electron emitters.

Simulations were run for 10% background density, shown here, as well as 10-times and 100-times smaller backgrounds..

* C.K.Birdsall, "PIC Charged-Particle Simulations Plus MonteCarlo Collisions...", IEEE Trans. Plasma Sci., **19**:2, pp.65-85 (1991)

200μs of Start-up Plasma Generation

- Ion kinetic energy(shown in blue) peaks then falls.
- Av. energy > 7.5keV(dashed) is needed to fuse.
- 10% Background (below left); energy is too low.
- 1% and 0.1% both have enough energy to fuse.



Three different simulations were run with different initial levels of background-gas. The slide shows the electron energy in orange and the ion energy in blue. The Time scale shows the simulated time in seconds, measured from the time the electron beams were turned on. Over the first 200 microseconds, the electrons' average energy falls from 50keV to about 15keV, which is its desired steady-state value. The final electron energy is very nearly the same for all 3 levels of background gas. It is determined mainly by the bias voltage which was the same in all 3 simulations.

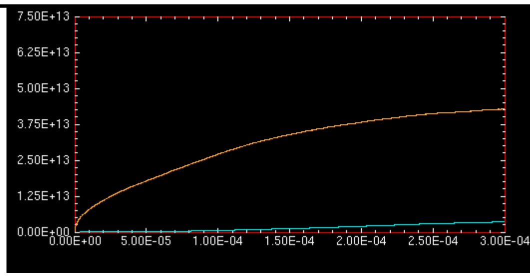
The ion energy, shown in blue, rises with time until around 200 microseconds, then declines. Comparing the three runs, we see that reducing the background gas level causes the ion energy to peak at larger and larger values. The optimum ion energy, as dictated by DD reactivity, is 15keV. If the average ion energy doesn't make at least half this level, indicated by the dashed line, the central ion energy is too small to make a useful fusion yield.

These diagnostics show that the background gas pressure must be kept 100 to 1000 times smaller than the pressure in the gas cells. The remaining simulations were done with a background gas level of 0.1%. This produced the biggest power output, but at the cost of more pumps. In a practical reactor, the extra fusion power might not be worth the extra cost of the pumps. The lower the background gas pressure, the more pumps would be needed to maintain the pressure.

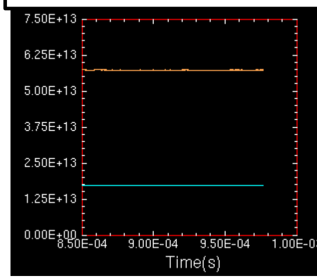
Start-Up out to 1ms ≈ Steady-State

- Energy/density optimized by adjusting knobs:
  - Magnets' bias adjusted to ≈ 3X desired ion energy
  - Electron(e) density maximized by adjusting e-current
  - Ion density(≈ central electrons') by adjusting pressure
- After adjustment, densities level off by time 1ms.

Initial Electron(orange) and Ion(blue) Average Densities



Final Electron & Ion Densities

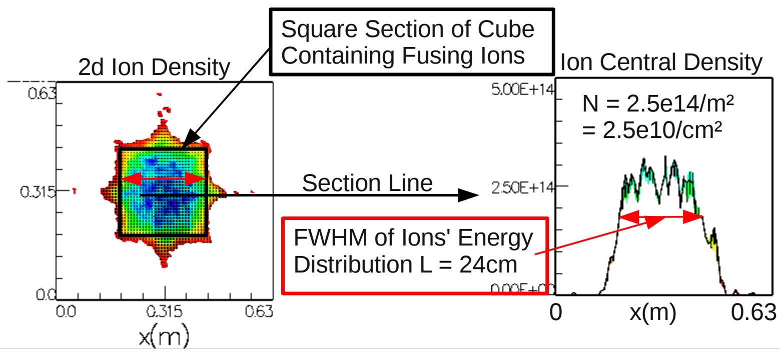


The initial phase of reactor operation starts at time zero when the electron emitters are turned on. A constant 50-kilovolt bias on the magnet boxes pulls in the electrons and accelerates them. Electrons immediately form a central potential well which accelerates ions born in the gas cells. The depth of the potential well determines the central energy of the trapped ions. The ion density rises to eventually neutralize the central electron density. As the ion density rises, the depth of the potential well shallows until it reaches the optimum 15 kilovolts. The graphs in this slide show the final electron and ion densities averaged over the simulation volume. An excess of electrons trapped in the cusps causes the electrons to outnumber the ions by about 3-to-1 when averaged over the whole volume.

These diagnostics were produced by simulating magnets of diameter 26cm. Later, I performed a second simulation with magnets twice as large. Then the ratio of electrons to ions was smaller, only 2-to-1 with the larger magnets. We can infer that the ratio of electrons to ions will continue to fall as the size of the model reactor increases toward net power.

Polywell Reactor Power Balance Q

- Q = Ratio of Fusion to Drive Power ≡ Pout / Pin
  - Pout = ½ $(N/S)^2$ <σv> V E_{DD}, where:
    - 2D Density N determined from diagnostic plots shown below
    - Slab thickness S & cube volume V(≡L^3) from next slide
    - <σv> & E_{DD} taken from Plasma Formulary pgs. 45 & 44
  - Pout =½$(2.5e10/1.6)^2$(2.8e-18)$(24)^3$(3.7e6)=1.7e13 eV/s



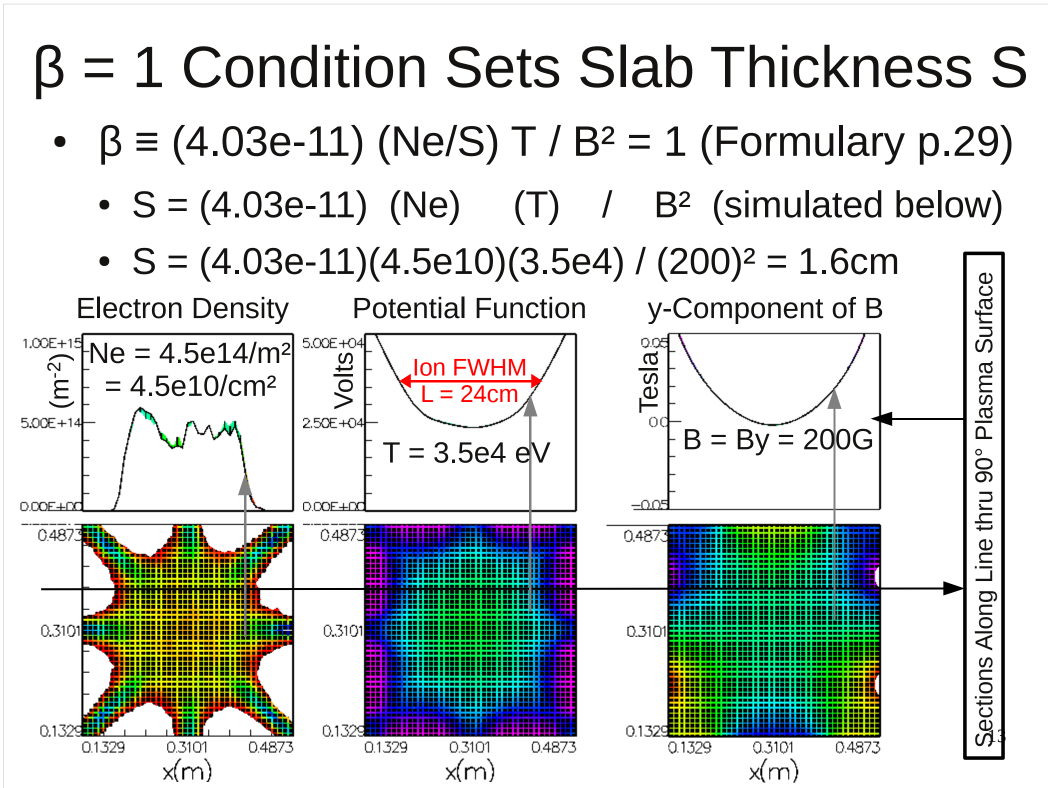
Power balance for the cubic reactor was computed for comparison to the spindle-cusp reactor. The power output, Pout, is the numerator of the power balance Q. Pout is proportional to the square of the ion density times the volume of the hot ions confined in the plasma.

The ion density is the slab's two-dimensional density N divided by the slab thickness S. N and S were determined from diagnostics as will be shown in the next slide.

The volume V of hot ions was taken to be the volume of a cube made small enough to exclude the slow ions at the surface of the plasma cloud. The value of L was taken to be the width of the potential well at its half-maximum-value. This is the length of a hot ion's trajectory, measured between the points where the ion loses half its central energy on its periodic transit back and forth across the well.

The main factor differing between spindle-cusp reactor and cubic reactor is the volume of hot ions. L-cubed is a much larger volume than the corresponding conic volume of the cones in the spindle cusp. The two reactors incorporated the same sized magnets.

Including all factors, the cubic Polywell would produce about 100 times more power than the spindle-cusp reactor.



The two-dimensional simulation was used to predict the performance of a hypothetical three-dimensional cubic reactor. The two dimensions of the simulation are x and y, as shown in this slide. The three-dimensional reactor can be thought of as containing a stack of identical slabs with densities the same as the slab simulated. We need to know the slab thickness S to compute the three-dimensional density in the power balance expression, shown in the previous slide.

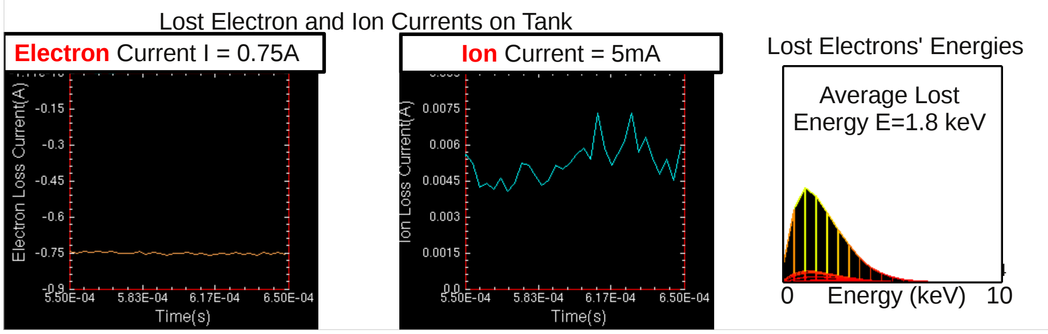
This slide shows how S was computed. The magnets confine the electrons inside a 26-cusped surface shown previously(slide-7). The central section of this surface contains the 8-cusped two-dimensional surface shown in the lower-left panel. This two-dimensional surface exhibits a sharp boundary where the inside electron density drops to zero in crossing the surface, inside to outside. The condition that relates plasma to field at such a magnetically confined plasma's surface is that the outward pressure exerted by the electrons equals the inward pressure exerted by the magnetic field. The formula for the ratio of these pressures, called Beta, is given in the plasma Formulary.

The "Beta equals one" equation was solved for S and evaluated at a convenient surface point, shown by the horizontal line. The resulting value, S=1.6cm, turns out to be equal to twice the width of one cell of the PIC simulation. The simulation thus describes a central slab of plasma 72 cells wide by 2 cells thick.

The same technique was used to calculate S for the spindle cusp.

Power Losses from Electrons & Ions

- Ion power loss << electron power loss(see below)
- Pin ≈ Electron-Amps(I) x Volts(E) in slab S
- Pin = 0.75A x 1.8kV = 1.35kW = 8.4e21 eV/s
- Q = Pout / Pin = (1.7e13) / (8.4e21) = 2e-9
- Cube's Q(2e-9) >> Spindle-Cusp's Q(1.6e-11)



The input drive power maintains the plasma density, charge, and particles' energies. Due to energy conservation, the input power is equal to the kinetic-energy loss-rate of electrons and ions escaping the plasma. The simulation keeps track of these losses by following the particles which hit the magnets, apertures, and tank wall. Power loss by each type of particle is the product of the particles' loss rate times average energy.

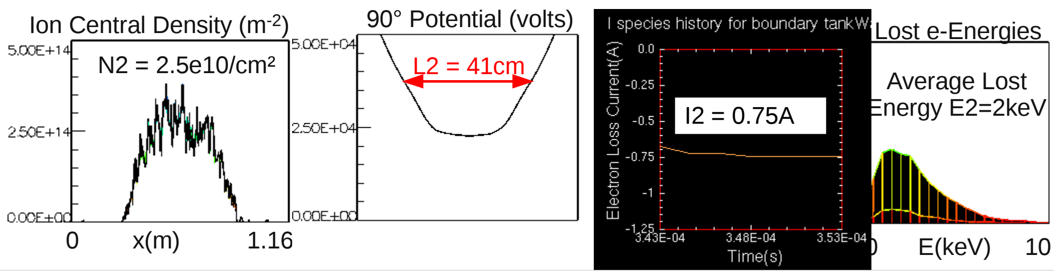
The left and center diagnostics show the current of electrons and ions hitting the tank wall at steady-state conditions. Except for statistical variations, the currents are constant at 0.75A and 50mA. By charge conservation the electron loss current is forced to be equal to the emitter input current, as specified in the input file. The right-hand diagnostic shows the energy spectrum of electrons hitting the tank walls. The electron power loss, as shown in the slide, is the product of current times energy. Expressing the electrons' energy in volts, the loss power has the units of watts.

Similar analysis was performed for particles hitting the magnets and apertures. Other losses were found to be negligible compared to the electron losses through the cusps to the tank walls. Using the Extractor Electrode, only a single cusp had losses.

Using this method, the cubic reactor's power balance is predicted to be about 100 times bigger than the spindle-cusp's. No further consideration need be given to spindle-cusp reactors.

Simulating Break-Even Size(D_b)

- Factors independent of size cancel out of Q2/Q:
  - $Q \sim (N/S)^2 L^3/Pin \sim [N^2 S^{-2} L^3 / (I E) \sim N^2 S^{-2} L^3 / E$
  - $Q2/Q = (N2/N)^2 (S/S2)^2 (L2/L)^3 (I/I2) (E/E2) = (D2/D)^n$
    - $= (2.5/2.5)^2 (1.6/1.06)^2 (41/24)^3 (.75/.75) (1.8/2.0) = 10.2$
  - $n = \log(Q2/Q)/\log(D2/D) = \log(10.2)/\log(.52m/.26m) = 3$
- $Db = D/Q^{(1/n)} = 0.26m / (2e\text{-}9)^{(1/3)} = 200m$ **Ouch!**
  - And this even ignores magnets' resistive power loss!

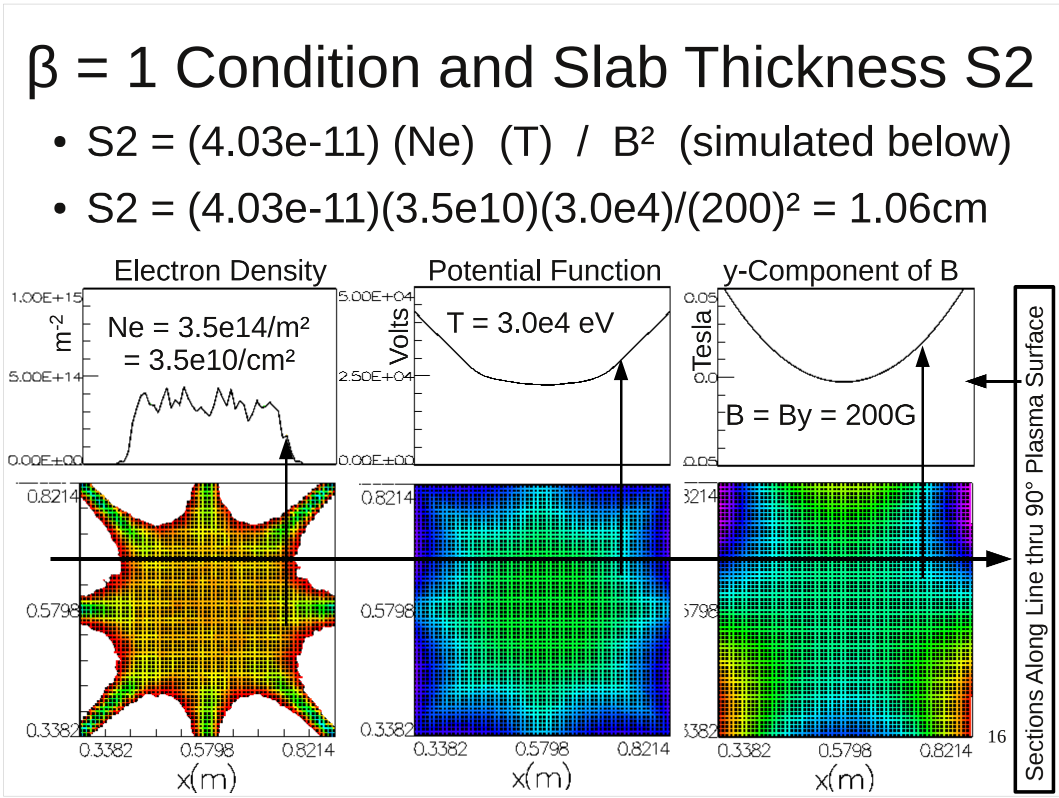


In his 2006 IAC publication, Bussard gave analytical arguments that the power balance Q should increase as the 5th power of magnet size. Instead of accepting the analytical arguments, we fit an exponent, n, to the simulation. The best-fit exponent turned out to be n=3, not n=5 as Bussard would have had it.

This exponential extrapolation to break-even size predicts a magnet size of 200 meters, not very practical.

A number of factors combine to make the fitted exponent less than expected. Bussard predicted the ion density factor should increase by factor of 16 when the magnet size was doubled. The simulation says it increases only by a factor of 2. The volume should increase by a factor of 8. It only increased by a factor of 5. These factors multiplied together lead to a power output much reduced from what Bussard predicted. Fortunately, the power input, taken to be equal to the losses, also decreased. However, this reduction only partially compensated for the reduction in output power. Thus, the power balance Q decreased.

If the exponent had turned out to be 5, as Bussard said, the predicted break-even reactor size would be 16 meters. Such a small break-even size would have been very competitive with tokamak reactors, for example, ITER. However, this would be too good to be true, especially considering that the Polywell design, so far, used copper magnets and D+D fuel, instead of super-conducting magnets and D+T fuel as in ITER.



This slide shows the calculation of the slab thickness from diagnostics with a two-times-larger magnet. The two-dimensional density N and electron energy at the plasma surface are found to be smaller for the larger magnets. The B-field is found to be the same at the plasma surface, even though the applied B-field at the magnets is 2 times larger. This surprising reduction in the surface B-field occurs because the size of the plasma cube shrinks relative to the magnet size. As the magnet size increases, the cube surface moves into a weaker field region, deeper inside the magnets. This reduces the surface density of electrons matching the B-field via the β=1 condition.

Why the plasma size shrinks relative to the magnet size can be understood from the following argument: The magnetic field at the surface of the magnets increases in proportion to the magnets' size. This is a feature of copper magnets related to their cooling requirements. As the size of the magnets increases, the injected electrons' energy stays the same, set by the constant high-voltage bias on the magnets. With fixed injected-electron energy, the stronger magnetic field squeezes the plasma to a smaller size relative to the magnet size.

The second simulation used 144 cells across a 1.16-meter tank. It is desirable to simulate a still larger size, but this would require using more cells, extending the computing time. Computing time for the 2-times-larger-magnet case already took more than 100 hours on a 3 GHz Intel E8400 processor.

Superconducting Magnets

- Size reduction relative to resistive magnets:
  - Reduction Factor = (.115m/.16T)* / (.052m/3T)† = 40
    - * Simulated so far has been GMW Inc. Model 3472-70 magnet.
  - S/C magnet would reduce predicted Db → 200/40 = 5m

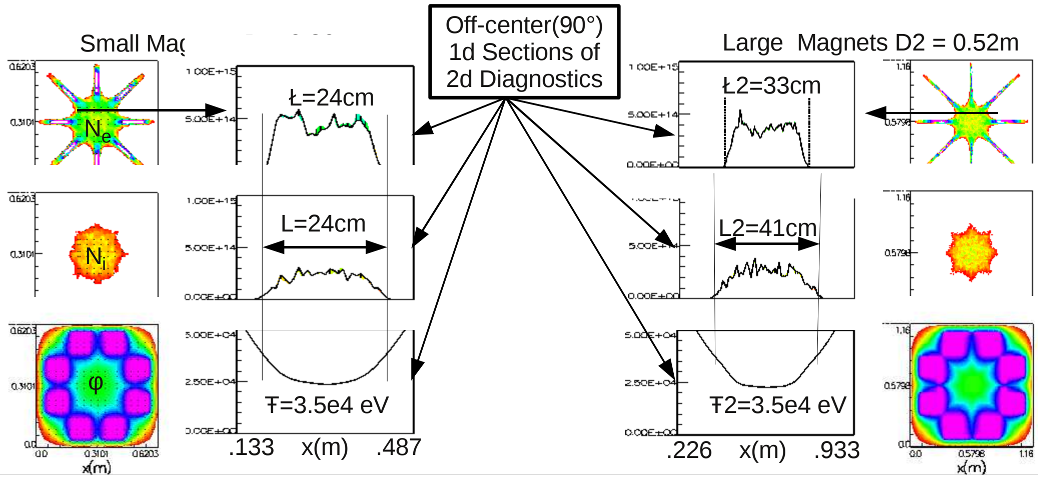
† Cryomagnetics Inc., Model S60-200-050
Split-Pair Configuration with 52mm Warm Bore.
6T in aiding mode, 3T peak-to-peak in opposing mode

CRYOMAGNETICS, INC.
INNOVATIVE TOOLS FOR SCIENTIFIC RESEARCH

Detailed simulations have not yet been undertaken for super-conducting magnets. A rough scaling factor was estimated by taking the ratio of size-to-field as a measure of the expected size reduction. The copper magnets simulated in this presentation were based on a particular standard magnet from GMW Associates. This magnet has a bore diameter of 11.5 centimeters and a mid-bore field of 0.16 Teslas. For comparison, a magnet of approximately the same size was selected from the Cryomagnetics catalog. This magnet has a bore of 5.2 centimeters and mid-bore field of 3 Teslas. Taking the ratio of these factors gives a combined-factor of 40 as the expected decrease in break-even size. Applying this factor to the simulated size of the copper magnet system results in a tentative size-estimate of 5 meters for the super-conducting Polywell. This tentative size estimate for Polywell is quite small compared to ITER's 20m magnet size.

Energy Loss to Bremsstrahlung

- Pb ~ $\iiint dxdydz\, N_e/S\, N_i/S\, T_e^{0.5}$, Formulary pg. 58
- Pout / Pb ~ $L^3/Ł^3$, shrinks as magnet size increases.
- Bremsstrahlung becomes less important as D→Db.



The power lost to bremsstrahlung was estimated from the simulations with the two sizes of copper magnets. The formula for radiated power is a three-dimensional spatial integral of electron density times ion density times the square-root of electron energy. A useful simplification is to replace the integral with the product of average values times the width of the one-dimensional distributions of electrons and ions. The ratio of bremsstrahlung power to fusion power then becomes proportional to the ratio of widths of the one-dimensional diagnostics shown for electrons to ions.

A surprising feature of the simulation was that the diameter of the electron cloud grows more slowly than the diameter of the ion cloud as the size of the reactor increases. This feature increasingly shrinks the ratio of bremsstrahlung power loss to fusion power output.

The ratio of electron-size to ion-size, L-bar(Ł) divided by L, fell from 1.0 to 0.8 as the magnet size increased by a factor of 2. The fractional power loss to bremsstrahlung is proportional to the 3rd power of this ratio. Thus, the fractional power lost to bremsstrahlung improves substantially with increasing magnet size.

Conclusions

- Polywell-Q >> Spindle-cusp-Q (forget it!)
- Electron extractor confines electron losses to a single point-cusp out of the 18 cusps in Polywell. This improves power balance in cubic Polywell.
- Background-gas pressure must be at least 100X less than gas-cell pressure to obtain net power.
- Resistive magnets will not work for net power.
  - Superconducting magnets are a viable alternative.
- Bremsstrahlung becomes relatively less important as reactor size increases. This might rescue $p+B^{11}$ as a viable reactor fuel.

These are the 5 important conclusions from my simulation work: (1) cubic reactors are better than spindle-cusp reactors; (2) an electron extractor reduces electron losses and simplifies simulation; (3) background gas pressure must be kept at least 100 times smaller than gas-cell pressure; (4) super-conducting magnets will be needed to build a practical net power reactor; and (5) bremsstrahlung becomes less important as reactor size increases. This last conclusion gives hope for an aneutronic reactor design based on $p+B^{11}$ fusion.

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