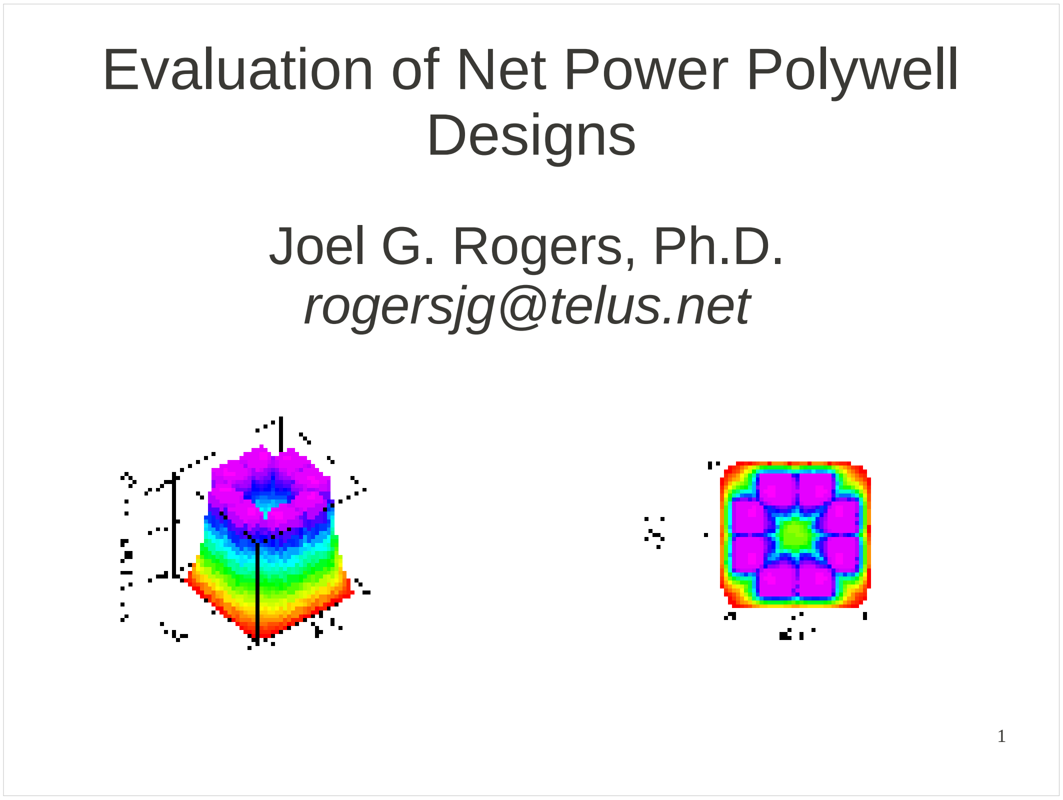

Evaluation of Net Power Polywell Designs

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Abstract of the Presentation

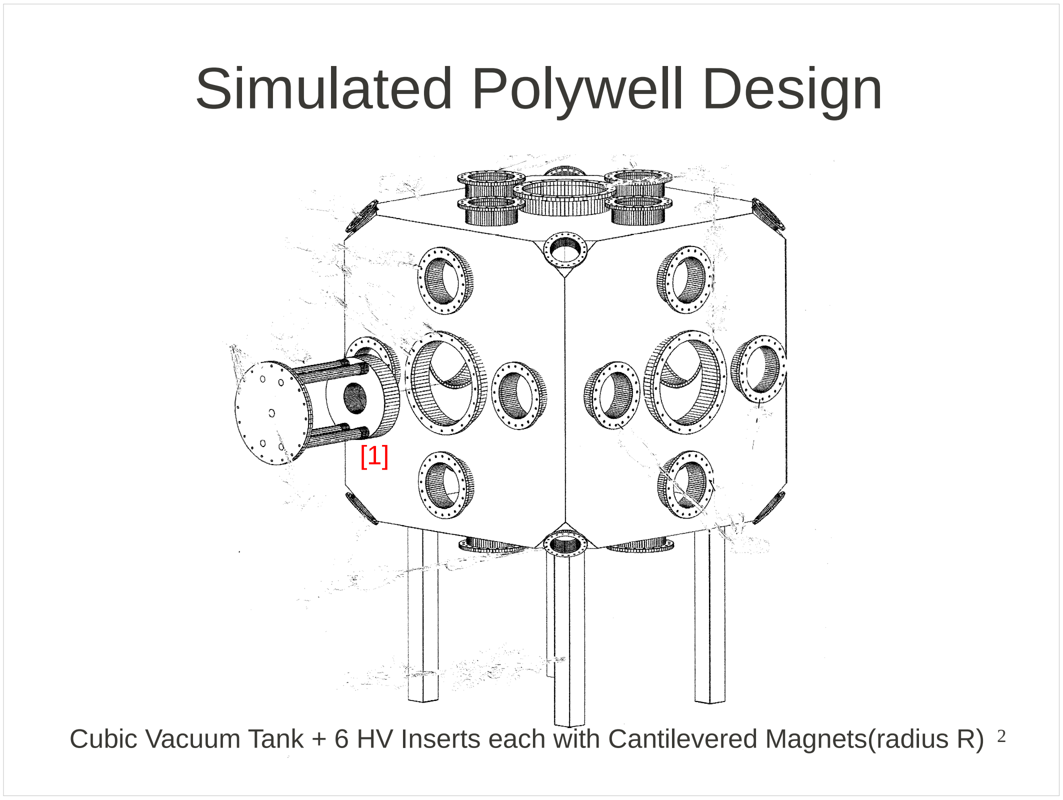
PIC simulations[1] presented at last year's IEC-2009 Workshop, held at the Univ. of Wisconsin, have continued to improve. The objective of this year's work was to more accurately predict the performance of a net power cubic Polywell fueled by DD fusion.

In steady-state, fuel ions must be continuously supplied inside the potential well which confines the ions long enough for fusion to occur. A scale-model potential well is shown above in a perspective view on the left and in a projection view on the right. Three possible fueling scenarios were simulated: ion guns outside the well, ion guns inside the well, and gas ionization inside the well. External ion guns were ruled out immediately; ion beams reflected off the outside of the potential barrier and did not enter the interior of the well. A detailed consideration of pros and cons seems to favor internal ion guns over gas ionization.

Simulations of Polywell fueled by internal ion guns were done for two different scale models, differing by a factor-of-two in size. These showed Bussard's[2] theoretical 5th power scaling law for Q with R was too optimistic. Without doubt, simulations point to a scaling exponent less than 5, implying a larger value for break-even radius than predicted by Bussard[2].

[1] OOPIC-Pro(2D) and Vorpal(3D) are from Tech-X Corp. of Boulder, CO, USA (txcorp.com).
[2] R.W.Bussard, 57th IAC(2006), reprint available on askmar.com/Fusion.html

Note added in proof: This 18-page PDF file was prepared as a verbatim record of a 20-minute lecture given by the author at the 12th US-Japan Workshop on Inertial Electrostatic Confinement Fusion, October 21, 2010.

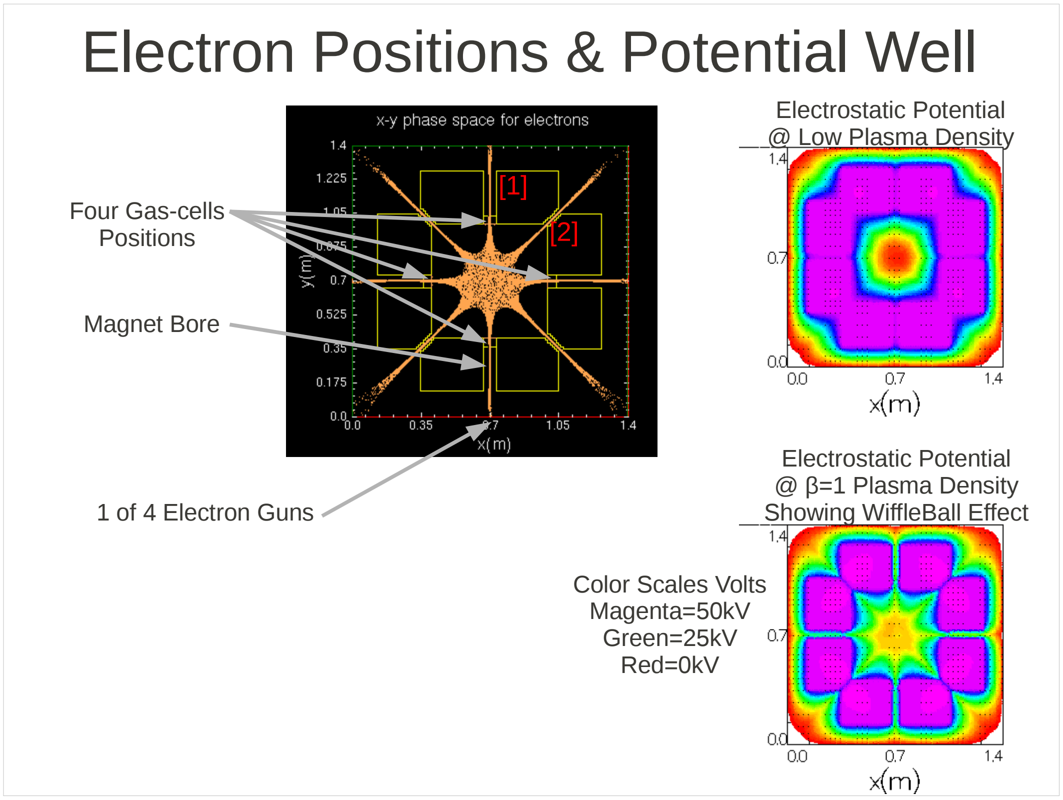


Simulated Polywell Design

Cubic Vacuum Tank + 6 HV Inserts each with Cantilevered Magnets(radius R)

“This shows the reactor simulated. Six inserts hold six coil magnets in a cubic arrangement. A square coil shape was simulated rather than the round coil shown in the slide[1].

“The design is scalable, meaning that larger sizes predictably produce larger amounts of power. One important objective of the simulation is to predict how big a reactor would have to be to produce net power. Simulations were done on small models for computing speed, then power-gain was extrapolated to full-scale net-power size.”



Electron Positions & Potential Well

Four Gas-cells Positions

Magnet Bore

1 of 4 Electron Guns

Electrostatic Potential @ Low Plasma Density

Electrostatic Potential @ β=1 Plasma Density Showing WiffleBall Effect

Color Scales Volts
Magenta=50kV
Green=25kV
Red=0kV

“Here are 3 snapshots of plasma diagnostics from the simulation. The black square shows electron positions in orange as a function of their x- and y-coordinates. Coil magnets are represented by yellow squares[1]. Magnet bores are shown as the rectangular openings between squares. Edges of the coils are chamfered[2] to allow close packing of the magnets at their almost touching corners. Electrons are emitted from 4 electron guns, shown as orange bars on the green/red vacuum tank walls.

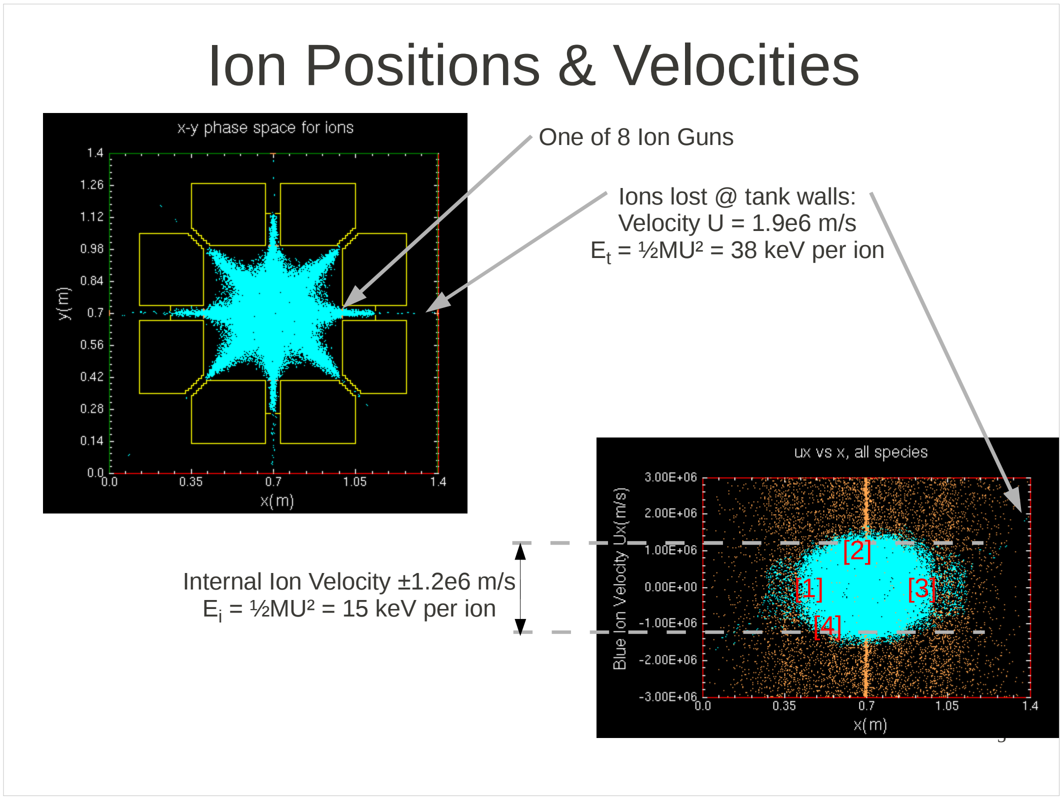
“The 2 Figs. on the right show the electrons' electrostatic potential well which confines ions. The upper snapshot was made at an early time during the start-up of the reactor, when the electron density was low. The diameter of the well, and therefore the volume of the plasma, expands as the plasma density rises. The lower Fig. shows a snapshot made at a later time during start-up. The expansion of the potential well is one of the characteristics of the WiffleBall effect, as predicted by Bussard.”

R = 35cm Model Specifications

- Electron Current[1]: 5.0A from each electron gun
- Magnet Bore[2] & Corner Spacing[3]: Minimized
- Magnet Bias Voltage[4]: 50kV
- Corner-cusp[5] & Face-cusp[6] B-fields: ±0.9T
- 2 Alternate Ion Source Designs:
  - Four deuterium gas cells OR ...
  - Eight 250mA ion guns

“This slide shows the specification of the larger of 2 scale models. In addition to magnet size R, the 6 mechanical and electrical parameters shown in this slide[1-6] were varied to optimize the performance of the reactor.

“Two different types of ion fueling were simulated; EITHER ionization of neutral gas confined in gas cells, as shown in the previous slide; OR 8 ion guns mounted on either side of each magnet bore, as shown in the next slide.”



Ion Positions & Velocities

One of 8 Ion Guns

Ions lost @ tank walls:
Velocity U = 1.9e6 m/s
$E_t = ½MU^2 = 38$ keV per ion

Internal Ion Velocity ±1.2e6 m/s
$E_i = ½MU^2 = 15$ keV per ion

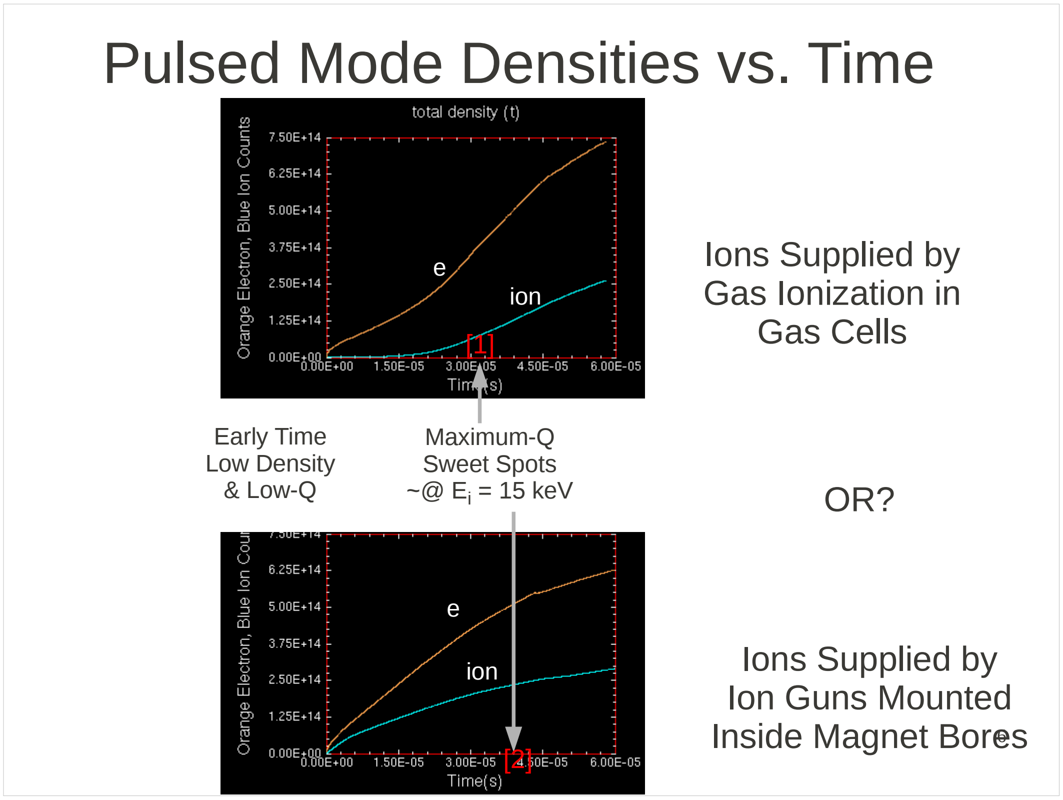
“In this slide, 2 snapshots of moving ions are shown in blue. In the upper Fig., 8 ion guns are shown as orange bars inside the magnet bores. Ions emitted by the ion guns initially fall toward center then bounce back and forth in the electrostatic potential well until they either fuse or until they leak out along one of 8 cusp lines.

“The lower Fig. shows ions in position-velocity space. In the on-line display the ions circulate clockwise. Ions are emitted at the edge of the well with zero velocity[1]; they accelerate toward center[2], decelerate on the other side of the well[3], and cycle back toward their birthplace[4]. Due to the scalloped shape of the well boundary, each bounce an ion makes takes it on a different path through center.

“Some ions are lost by up-scattering. The lower pair of arrows point to lost ions just before they hit the left tank wall.

“Though fusion is not simulated, ions which fuse would produce charged particles, including trions, alphas, and/or protons. By design, charged fusion products would be guided to the tank walls by the magnetic field. Their kinetic energy would be converted to electricity by direct conversion, using a Venetian Blind type of electrode[1].”

[1] “Direct Energy Conversion in Fusion Reactors”, Ralph W. Moir, *Energy Technology Handbook*, McGraw Hill, 1977, pp. 5-150 to 5-154; linked on askmar.com/Direct_Energy.html



Pulsed Mode Densities vs. Time

Ions Supplied by
Gas Ionization in
Gas Cells

Early Time
Low Density
& Low-Q

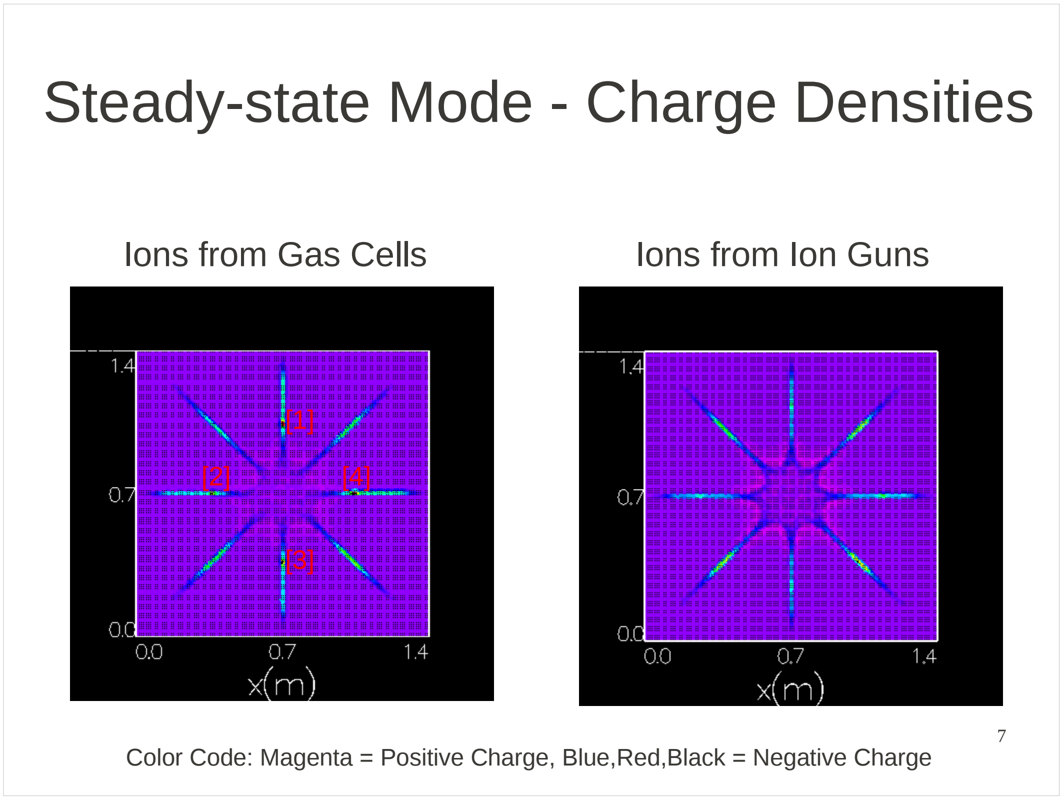
Maximum-Q
Sweet Spots
~@ E_i = 15 keV

OR?

Ions Supplied by
Ion Guns Mounted
Inside Magnet Bores

“In this slide are shown graphs of the time evolution of electron density and ion density during start-up. The simulation starts with an empty tank at Time=0. The densities rises in 10's of microseconds as electrons and ions flow into the potential well. At selected times, shown by arrows, initial pulsed operation is converted to steady-state. The time chosen should be the time at which the fusion power gain reaches its maximum value. A more convenient criterion was substituted, namely when the confined ion energy reached the optimum fusion energy, 15keV.

“The time of converting to steady-state differed depending on whether ions were supplied by gas ionization[1] or by ion guns[2]. The gas ionization process produces an extra electron inside the well which adds to the electrons' portion of the plasma pressure and lowers the ion density compared to ion-gun fueling.”



Steady-state Mode - Charge Densities

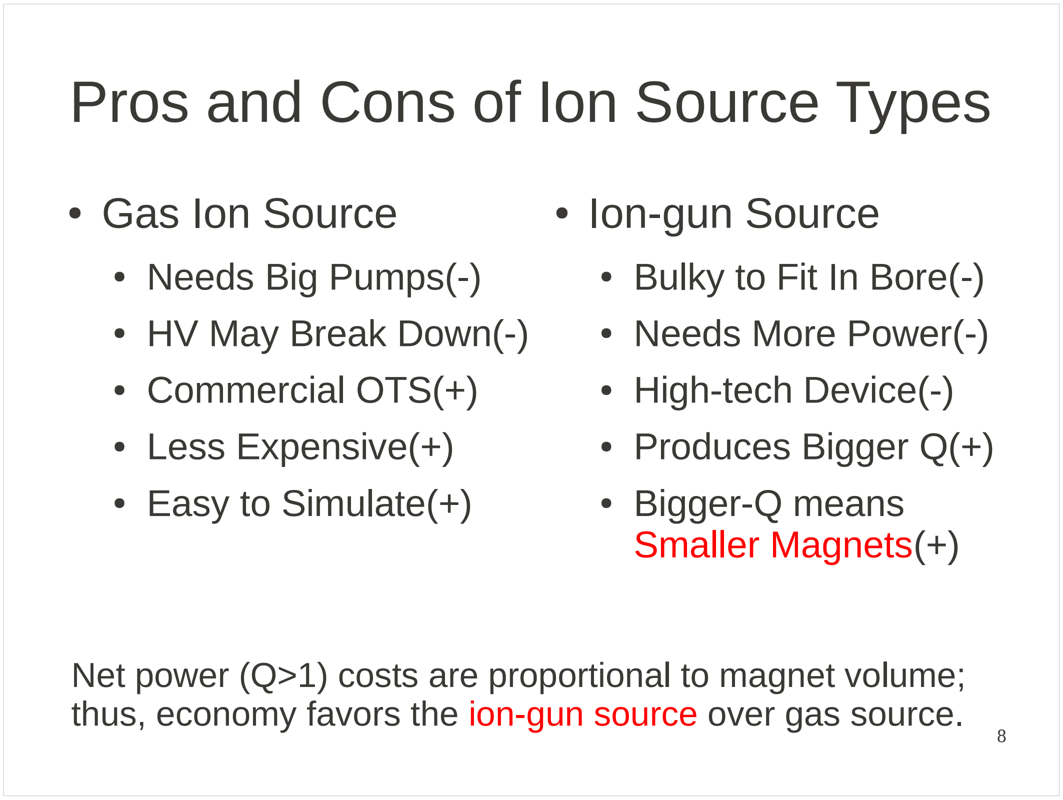
Ions from Gas Cells

Ions from Ion Guns

Color Code: Magenta = Positive Charge, Blue,Red,Black = Negative Charge

“This slide shows charge densities for the 2 fueling options. Similar features include positive charge at the center surrounded by negative charges around the outside. The main differences between fueling scenarios are spikes in negative(electron) density at the positions of the 4 gas cells[1-4]. These spikes are caused by cold electrons trapped at these positions after their matching ions have been drawn into the well.

“The extra negative charge in the left Fig. causes a reduction in the ion density, shown in magenta, compared to in the right Fig. This reduction in ion density is the most serious drawback of the gas source compared to the ion-gun source.”



Pros and Cons of Ion Source Types

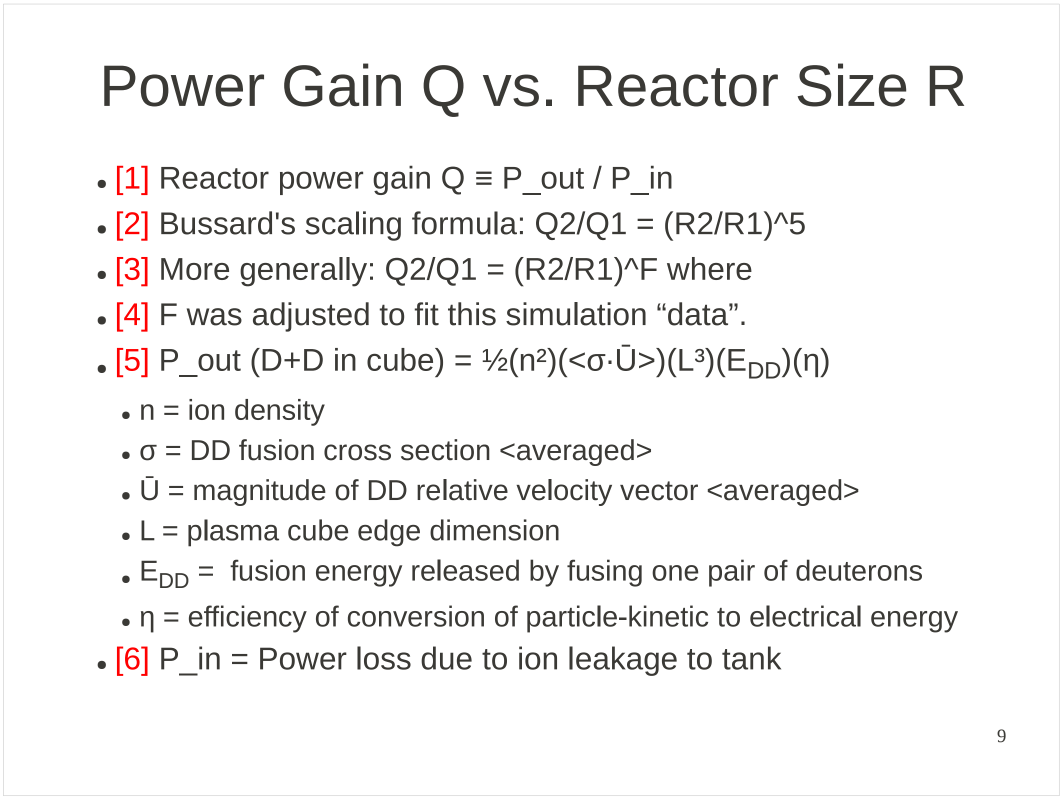
- Gas Ion Source
  - Needs Big Pumps(-)
  - HV May Break Down(-)
  - Commercial OTS(+)
  - Less Expensive(+)
  - Easy to Simulate(+)
- Ion-gun Source
  - Bulky to Fit In Bore(-)
  - Needs More Power(-)
  - High-tech Device(-)
  - Produces Bigger Q(+)
  - Bigger-Q means Smaller Magnets(+)

Net power (Q>1) costs are proportional to magnet volume; thus, economy favors the ion-gun source over gas source.

“Though not simulated, pumps are required to maintain low pressure between the magnets and the tank wall. If the pressure exceeds about 0.1mTorr the bias voltage will break down and short out the magnet bias power supply. The pumping equipment needed for gas ionization is available 'off the shelf'(OTS), which means the gas ionization source requires less engineering development than the ion-gun solution. In addition, the OOPIC-Pro simulation software includes the tools to simulate gas ionization from basic principles, making the present conceptual design of the gas source more reliable than the ion guns.

“Commercial ion guns are too bulky for the small scale models and have a maximum current limitation of 10mA or so, much less than required. These limitations will need to be addressed before ion guns will be practical for net power. This makes the ion guns a 'high tech' solution to fueling, compared with the 'low tech' of the gas sources.

“Despite these drawbacks of the ion-gun solution, it has the overwhelming advantage of smaller magnet size. Subsequent simulations of net power scaling were done with simulated ion-gun sources.”



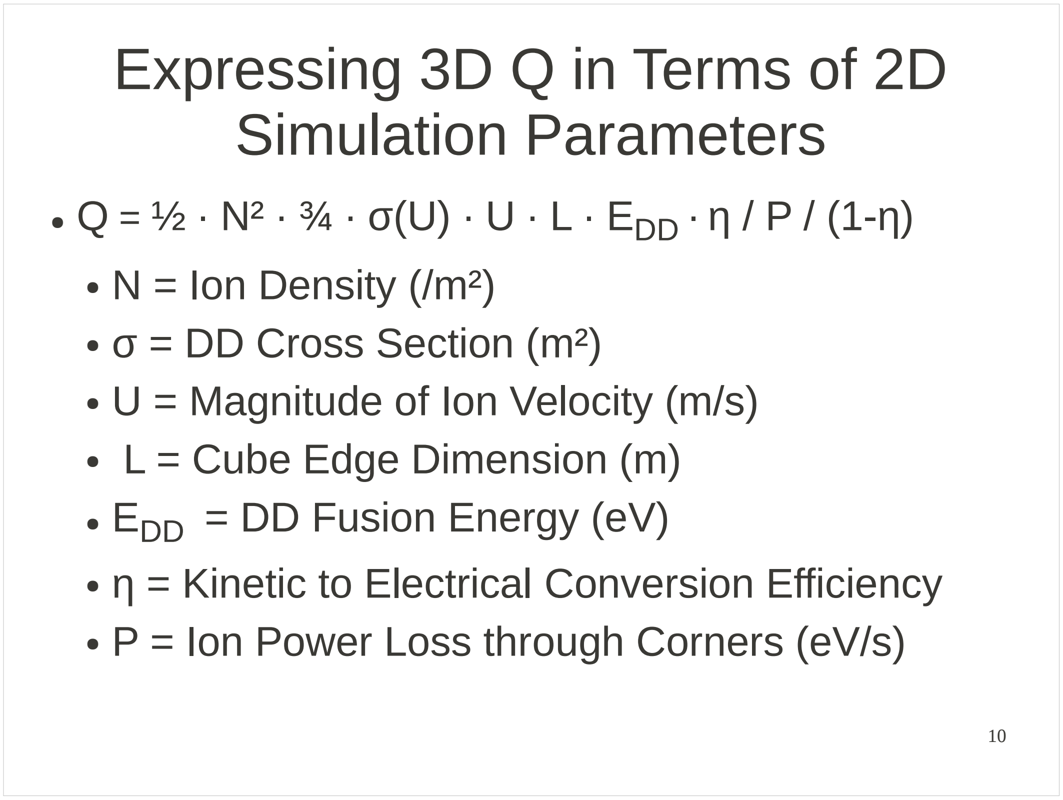
Power Gain Q vs. Reactor Size R

- [1] Reactor power gain Q ≡ P_out / P_in
- [2] Bussard's scaling formula: Q2/Q1 = (R2/R1)^5
- [3] More generally: Q2/Q1 = (R2/R1)^F where
- [4] F was adjusted to fit this simulation “data”.
- [5] P_out (D+D in cube) = ½(n^2)(<$\sigma\cdot\bar{U}$>)(L^3)(E_{DD})(η)
  - n = ion density
  - σ = DD fusion cross section <averaged>
  - $\bar{U}$ = magnitude of DD relative velocity vector <averaged>
  - L = plasma cube edge dimension
  - E_{DD} = fusion energy released by fusing one pair of deuterons
  - η = efficiency of conversion of particle-kinetic to electrical energy
- [6] P_in = Power loss due to ion leakage to tank

“The crucial Figure of Merit for reactors is the power gain(Q). Q increases with reactor size R according to a scaling formula. The definition of Q[1] is the ratio of fusion power-out to drive power-in. Bussard said[2] that Q scales as the 5th power of radius R. To accommodate the simulation results, we generalize the scaling formula to be a power law[3] with adjustable exponent F[4].

“The textbook formula[5] for fusion power output contains the product of density(n), times cross section(σ), times relative velocity($\bar{U}$), times volume(L^3), times energy-yield(E_{dd}), times efficiency(η).

“Finally the power-input, P_in[6] was found to be equal to the power loss of ions hitting the tank. This and other possible loss mechanisms, like electrons hitting the magnets, were analyzed by tracking individual particles in the simulation.”



Expressing 3D Q in Terms of 2D Simulation Parameters

- $Q = \frac{1}{2} \cdot N^2 \cdot \frac{3}{4} \cdot \sigma(U) \cdot U \cdot L \cdot E_{DD} \cdot \eta / P / (1-\eta)$
    - N = Ion Density (/m²)
    - σ = DD Cross Section (m²)
    - U = Magnitude of Ion Velocity (m/s)
    - L = Cube Edge Dimension (m)
    - E_{DD} = DD Fusion Energy (eV)
    - η = Kinetic to Electrical Conversion Efficiency
    - P = Ion Power Loss through Corners (eV/s)

“This slide shows how the preceding textbook 3D formula for Q can be expressed in terms of the 2D simulation parameters. The simulation models the central slab of a cubic 3D plasma volume. The thickness of the slab is approximately the Debye length(λ_D), which must be much smaller than the edge dimension of the cube. The exact slab thickness is unimportant as long as it is small compared to the size of the cube.

“To express Q in terms of the simulated 2D parameters, the cube is envisioned as a stack of identical slabs of plasma, stacked to span the cube dimension, L. The number of such slabs in 3D is the cube dimension divided by the slab thickness, L/λ_D. The 3D density is the 2D density divided by the slab thickness, N/λ_D.

“The lost power, P_in, includes the effects of all the cube's 12 line cusps. The simulation only accounts for ions which enter one of the 4 corner cusps from inside the slab. These ions enter the corner cusps at a polar angle approximately parallel to the slab. Accounting for the extra losses occurring inside the other slabs in the stack, and also from a range of polar angles including all the slabs in a stack, multiplies the slab power loss, P, by a factor of the square of the number of slabs. The resulting $(L/\lambda_D)^2$ factor in the denominator of Q cancels a factor of $(L/\lambda_D)^2$ in the numerator arising from the n^2 and L^3 terms in the textbook formula. This cancellation makes Q independent of the slab thickness.”

Fitting Q vs. R Exponent F to “Data”

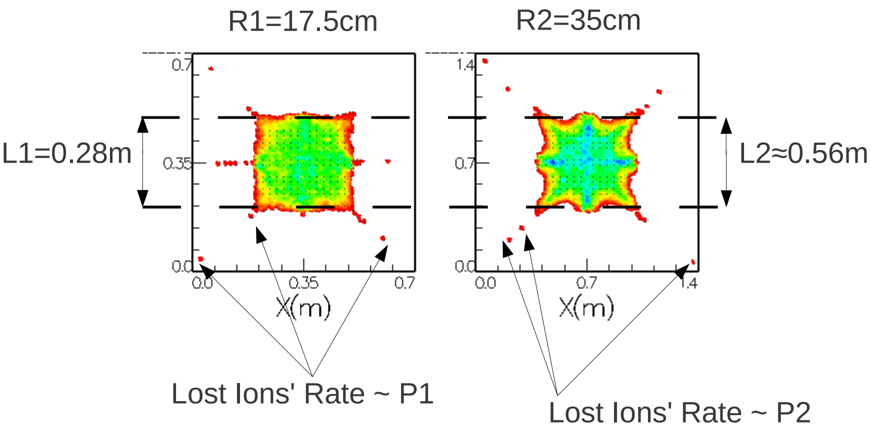
- [1] Q2/Q1 = (R2/R1)^F
- [2] Simulate reactors at R1=17.5cm and R2=35cm
- [3] From β=1 and $n=N/\lambda_D$ conditions, N2/N1 ≈ 2
- [4] From diagnostic plot in next slide, L2/L1 ≈ 2
- [5] Also from the next slide, P2/P1 ≈ 1
- [6] $F = 2*\log_2(N2/N1) + \log_2(L2/L1) - \log_2(P2/P1)$
- Combining last 4 lines, F ≈ 3
- F ≠ 5 (as Bussard said it was in IAC 2006)

“The scaling of Q with R was represented as the power-law form shown in this slide[1].The exponent F was fitted to simulated 'data' at the radii R1 and R2[2]. R1 is approximately the size of Bussard's WB-6 device and R2 a factor-of-two larger. The expression for Q contains factors which do not depend on radius and therefore cancel out of the ratio Q2/Q1. The factors which remain are the 2D density N[3], cube edge dimension L[4], and slab power loss P[5].

“Substituting the simulation values in the expression for F[6] gave F=3. This says Q scales as the 3rd power of R.

“This value of scaling exponent disagrees with Bussard's theoretical value F=5. This disagreement has serious consequences on the prediction of break-even radius, as we shall see.”

Snapshots of Two Ion Densities



R1=17.5cm

R2=35cm

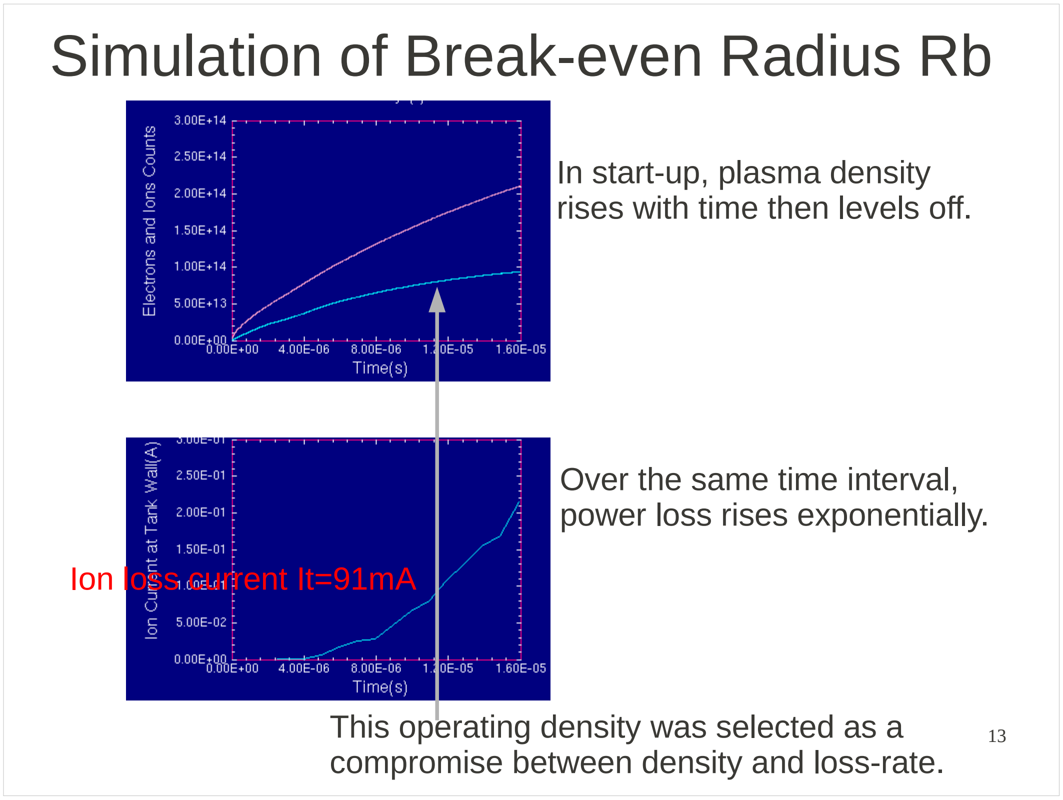
L1=0.28m

L2≈0.56m

Lost Ions' Rate ~ P1

Lost Ions' Rate ~ P2

“These snapshots of ion densities determine the ratios of the L's and P's used in the previous slide. The dimensions of the square distributions determine the L-ratio. The loss-rates of ions through the corner cusps determine the P-ratio.”



Simulation of Break-even Radius Rb

In start-up, plasma density rises with time then levels off.

Over the same time interval, power loss rises exponentially.

Ion loss current It=91mA

This operating density was selected as a compromise between density and loss-rate.

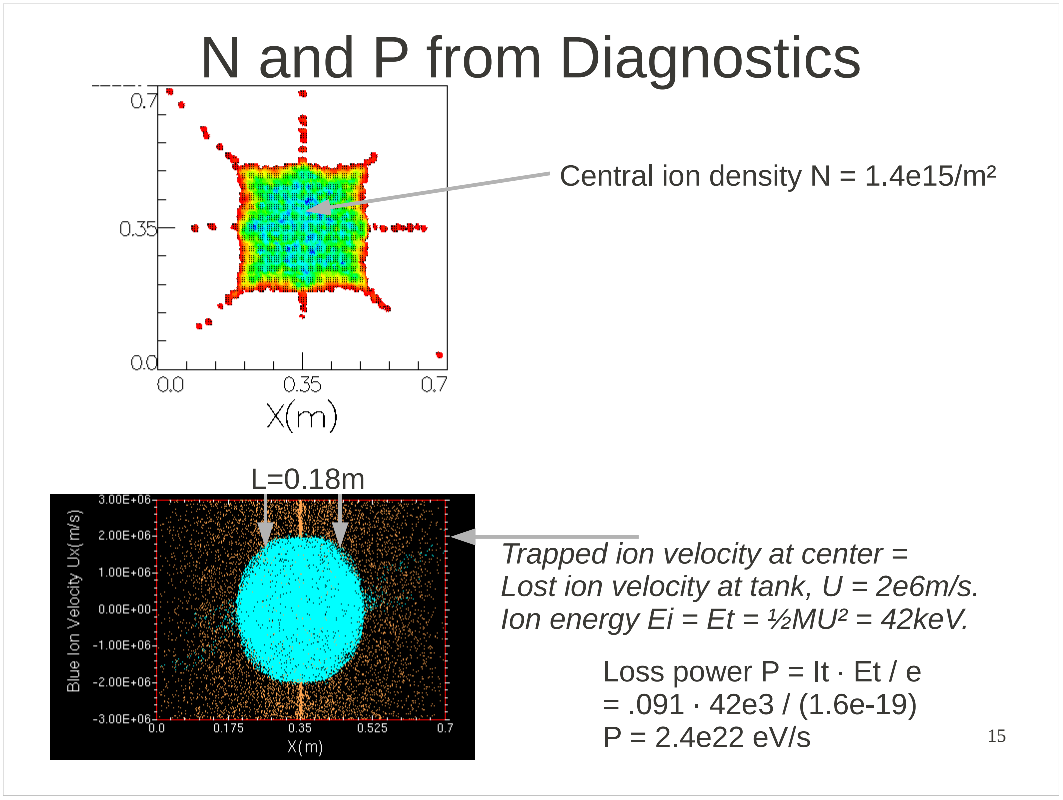
“The 3rd power scaling law just derived was used to estimate break-even radius, Rb. An operating point was selected by choosing a particular time to stabilize the density. This choice fixed the steady-state ion density at the value shown by the arrow in the top graph, and also fixed the steady-state current of lost ions at the value shown by the arrow crossing the blue curve in the bottom graph. The loss current shown in the bottom graph, It=91mA, is simply related to the loss power, P; P is just this current times the lost ions' average energy. The lost ions' average energy, E_t, was determined by tracking several lost ions, like those indicated by the arrow in the lower Fig. of Slide#5; converting their velocities to energies; and finally averaging the resulting energies.

Formula for Break-even Radius Rb

- [1] Rb=R/Q^(1/3) where:
  - R ≡ R1 = 0.175m, LN2 cooled, resistive magnet radius
  - [2] $Q \equiv ½ N^2 ¾ \sigma U L E_{DD} \eta / P / (1-\eta)$, from slide#10 where:
    - N = 1.4e15/m^2, central area density from next slide
    - σ = 6.5e-30m^2, fusion cross section (@ $½MU^2$ = 42keV)
    - U = 2.0e6m/s, ion central velocity next slide
    - L = 0.18m, ion plasma cubic edge dimension from next slide
    - E_{DD} = 10.24MeV, He^3-catalyzed fusion yield per DD pair
    - η = 0.70, kinetic-to-electrical direct conversion efficiency
    - P = 2.4e22eV/s, slab power loss [It · Et / e] from next slide
- [3] Substituting for R and Q, Rb = .175m / (1.7e-9)^(1/3)
- Rb = 150m (OUCH. This design still needs work!)

“The formula for break-even radius, Rb[1], was determined by inverting the 3rd-power scaling law just derived and then evaluating it at Q1=Q, R1=R, Q2=1, and R2=Rb. The simulation parameters determining the 3D power gain Q[2] were varied to maximize Q. From the form of the Rb expression[1], maximizing Q also minimizes Rb.

“Even so, the estimated reactor size[3] is impractically large, Rb=150m.”



N and P from Diagnostics

Central ion density N = 1.4e15/m^2

L=0.18m

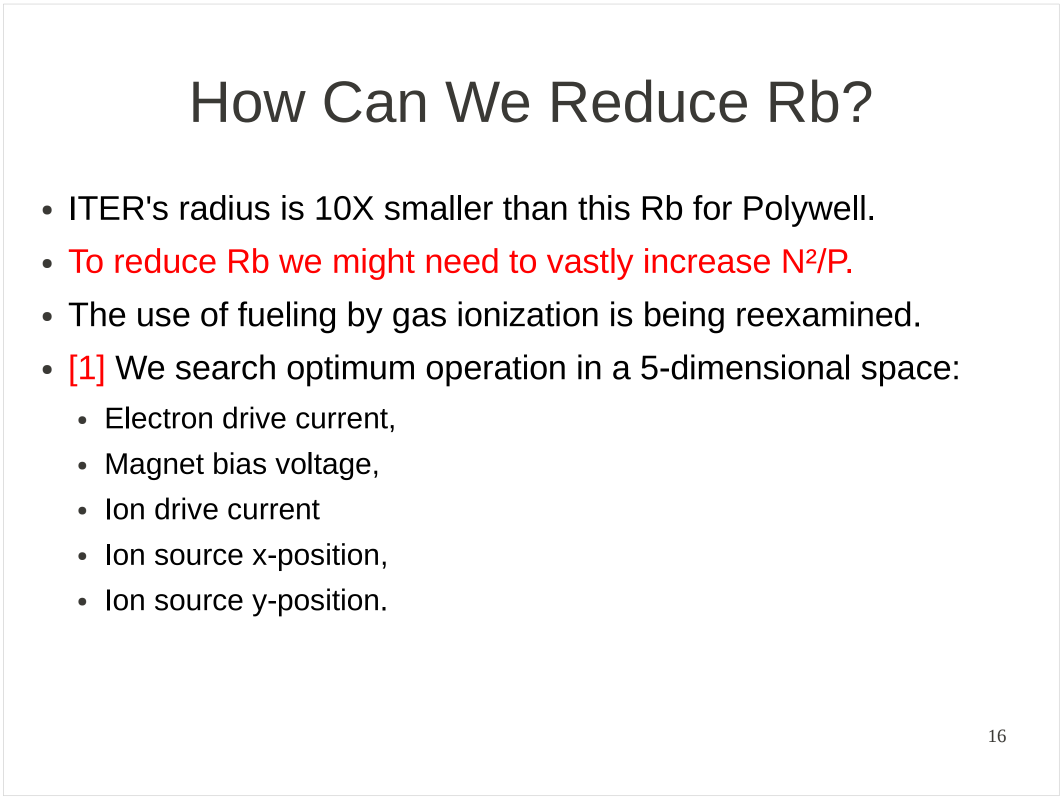
Trapped ion velocity at center =
Lost ion velocity at tank, U = 2e6m/s.
Ion energy Ei = Et = $\frac{1}{2}MU^2$ = 42keV.

Loss power P = It · Et / e
= .091 · 42e3 / (1.6e-19)
P = 2.4e22 eV/s

“The diagnostic plots shown in this slide, along with the ion loss current, It, from the slide before the last, determined the parameters needed to compute Rb according to the formula of the previous slide. The top Fig. above is a snapshot of 2D ion density at the selected steady-state operating point. Its central value is the plasma density N substituted in the previous slide.

“The lower Fig. is a snapshot of ion velocity vs. position. The cubic edge dimension L was reduced from the full-width-at-half-maximum density, color coded yellow in the upper Fig., because only fast ions can contribute to fusion power. When the ions slow down to turn around at the edge of the well, they temporarily stop fusing because the fusion cross section at low velocities is negligible.

“The lower Fig. also determines the central and lost ion velocities which determine σ, U, and P in the Rb formula.”

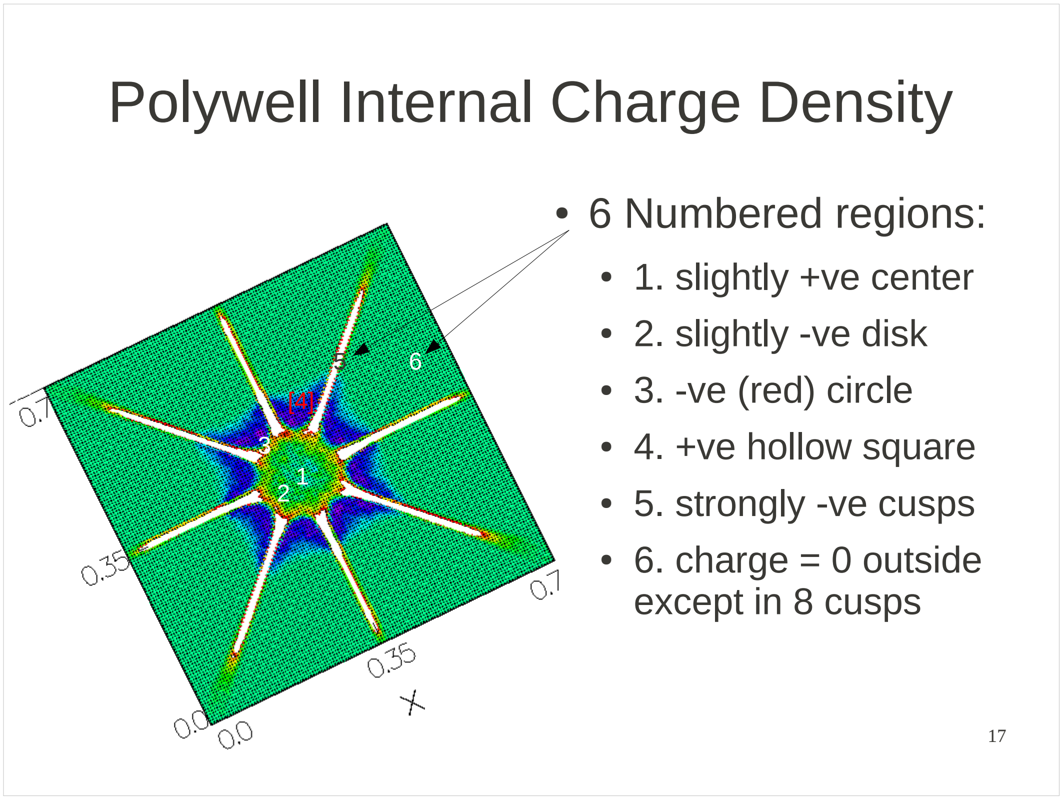


How Can We Reduce Rb?

- ITER's radius is 10X smaller than this Rb for Polywell.
- To reduce Rb we might need to vastly increase N^2/P.
- The use of fueling by gas ionization is being reexamined.
- [1] We search optimum operation in a 5-dimensional space:
  - Electron drive current,
  - Magnet bias voltage,
  - Ion drive current
  - Ion source x-position,
  - Ion source y-position.

“One way to reduce Rb would be to find a point in the 5-dimensional knob space[1] of steady-state values where N^2/P is vastly increased from its value at the simulated operating point. It seems unlikely such a point exists for the small scale models.

“On the other hand, Bussard predicted closing of the cusp holes as a feature of the WiffleBall effect. Such cusp closing hasn't been seen in simulation. If cusp closing exists at larger magnet sizes and higher densities, the WiffleBall effect might break the 3rd power scaling law. Breaking this scaling law seems to be required to make steady-state Polywell practical for net power.”



Polywell Internal Charge Density

- 6 Numbered regions:
  - 1. slightly +ve center
  - 2. slightly -ve disk
  - 3. -ve (red) circle
  - 4. +ve hollow square
  - 5. strongly -ve cusps
  - 6. charge = 0 outside except in 8 cusps

“Polywell seems to be more complex that Bussard thought. The blue colored region of positive charge density[4] is ineffectual for fusion. Only a central core, about the size of the disk contained in the red circle, contains fusing plasma. The blue region could be reduced in diameter by reducing the ion energy to be much less than the well depth. This might reduce ion loss(P) at the available densities, but it would also reduce the volume(L^3) of the confined plasma.

“How to inject lower energy ions is not yet clear. Preliminary efforts to move the ion guns inside the magnets have resulted in excessive losses from circulating ions hitting the ion source structure. There does not seem to be any obvious way to lower the ion energy below the edge of the well.”

Polywell Simulation Summary

- Potential well depth ≈ 80% of magnet voltage.
- Quasi-neutral plasma core is confined at center,
- Surrounded by borders of positive/negative charges.
- Electrons outnumber ions two-to-one.
- Excess electrons circulate through magnet cusps.
- P_in equals ion power lost to vacuum tank walls.
- Power gain Q scales as R^3.
- Net-power + steady-state would need huge magnets.
- Ongoing simulation aims to reduce predicted Rb.