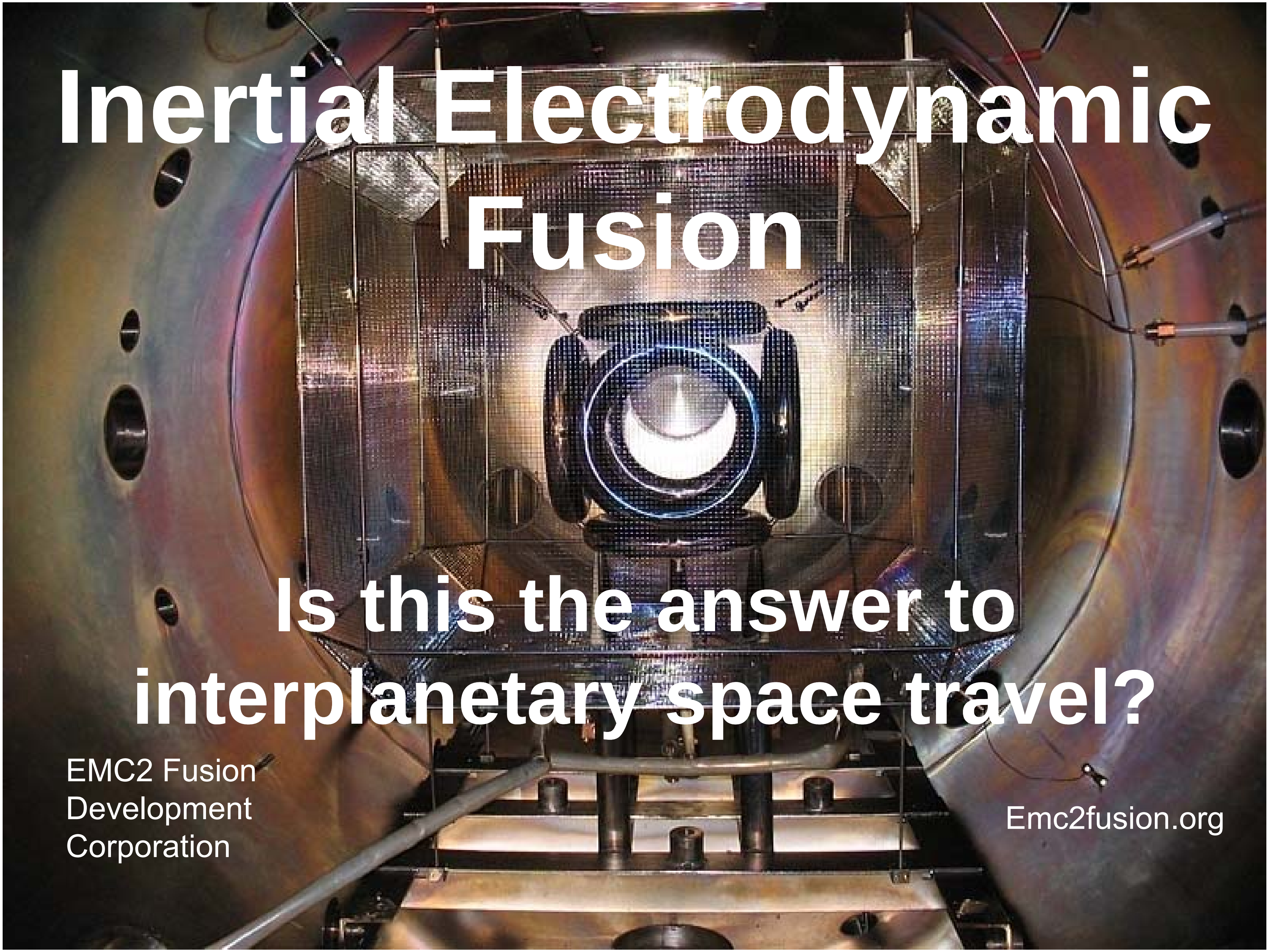
Inertial Electrodynamic Fusion
Is this the answer to interplanetary space travel?
EMC2 Fusion Development Corporation
Emc2fusion.org

# Energy/Matter Conversion Corp's Main Players…

- Dolly Gray, President
- Dr. Robert W. Bussard
- Dr. Nicholas A Krall
- Lorin Jameson
- Michael Wray
- WB6 Construction Team:  Mike Skillicorn, Ray Hulsman, Noli Casama

# Proof of Concept?

- November 2005:  successful fusion tests
- Subscale device, not a net power demo
- Four test runs replicated the fusion rate
- Runs agreed with rate predicted by theory
- Theory projects a very strong scaling with increased size ($B^4R^3 \approx R^7$)
- Net power predicted at 1.5 to 2 m radius

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# Applications to Spaceflight

- This technology projects reactors of multiple gigawatts
- The intended fuel, p-B11, allows direct conversion of fusion energy to high voltage DC.
- Lightweight, high density electrical source for various electric thrusters.

# IEC Background

- Fusion reactions were discovered using electrostatic particle accelerators
- P. T. Farnsworth conceived of spherical accelerators as practical fusion reactors
- Robert Hirsch, working for Farnsworth, demonstrated practical devices in the 1960's.
- DOE never funded the research.

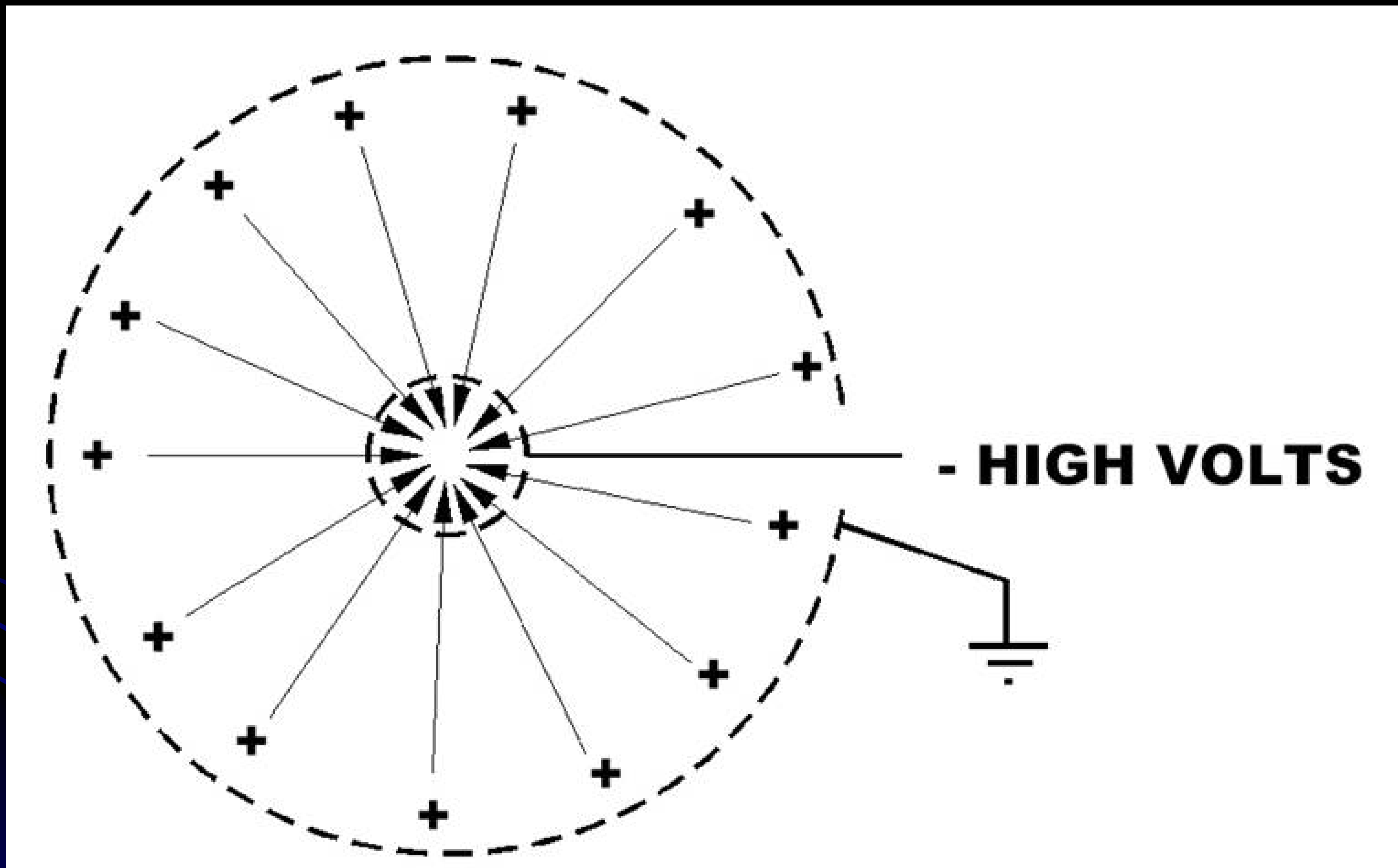
# This is a "Hot Fusion" Technology

- Actually, temperature is not the important factor, and temperature does not appear in the fusion rate equation
- $= n_1 \ n_2 \, \sigma_f \ v$
- Achieve velocity by electrostatic acceleration. All particles reach center at fusion energy instead of a Maxwellian mix.
- May calculate temperature: 11604 Kelvins per electron volt

# High-School-Science Simple

- "Farnsworth fusors" are being built by amateurs (fusor.net)
- At least eight high-school science students have achieved fusion.  Michael Li won 2nd place in the Intel Science Talent Search, 2003, and a $75k scholarship.
- But the Farnsworth fusor cannot hit breakeven due to grid limitations.

# Hirsch/Farnsworth Fusor




"Inertial-Electrostatic Confinement of Ionized Fusion Gases", Robert L. Hirsch, *Journal of Applied Physics*, v. 38, no. 11, October 1967.

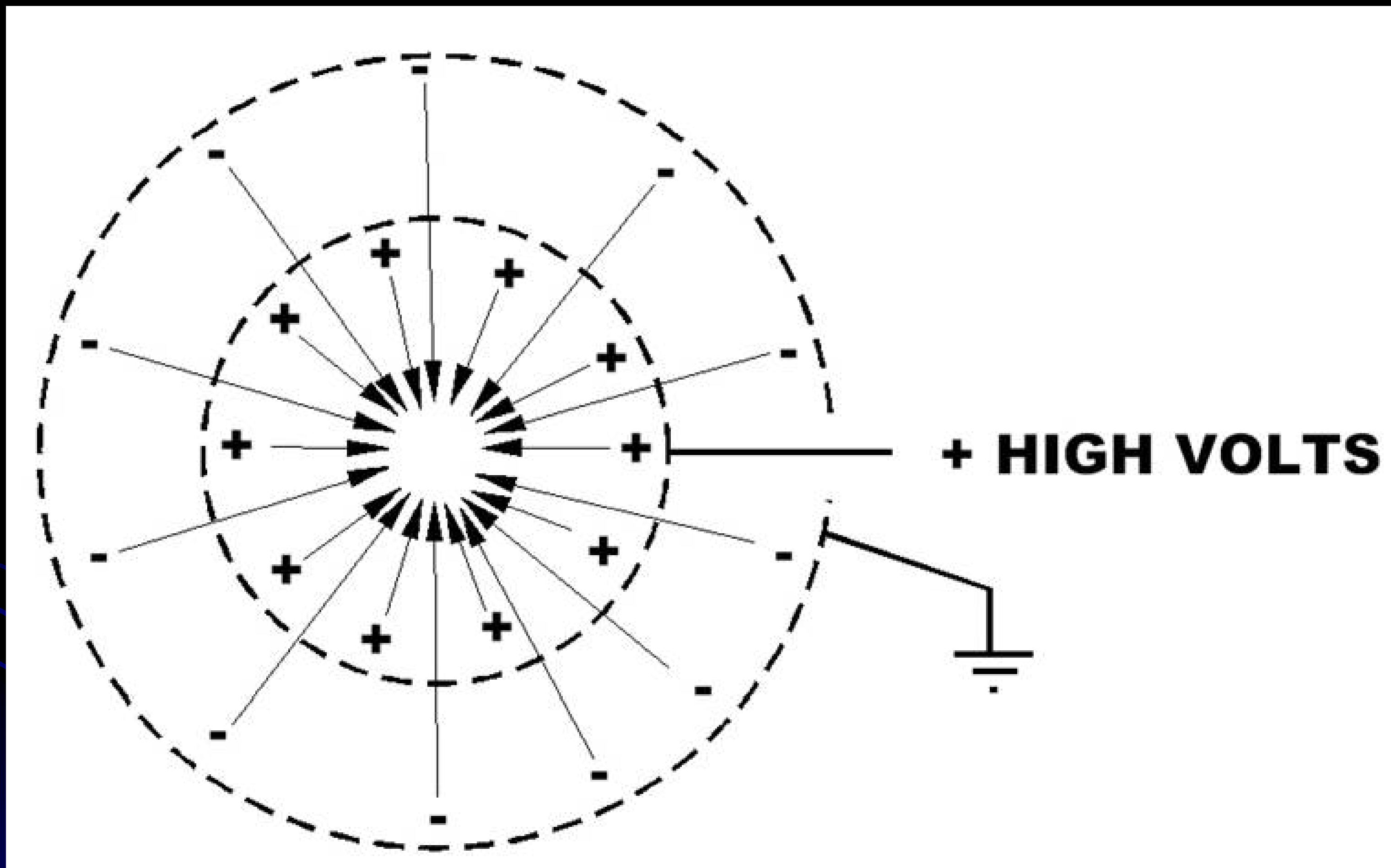
# Grid Transparency Limitation

- Grids typically about 92-95% transparent, limit probably 98%.  Thus, unlikely a typical ion will exceed 50 transits of the center of the machine.
- Orders of magnitude better ion life is required.

# Elmore Tuck Watson Machine

- Grids accelerate electrons rather than ions.
- Electron potential well accelerates the ions.
- The ions experience no grid losses.
- But the electrons experience high grid losses. Net power still hopeless.
- Both electron and ion confinement is dynamic, so this is Inertial "Electrodynamic" fusion, (IEF)

# Elmore Tuck Watson Machine

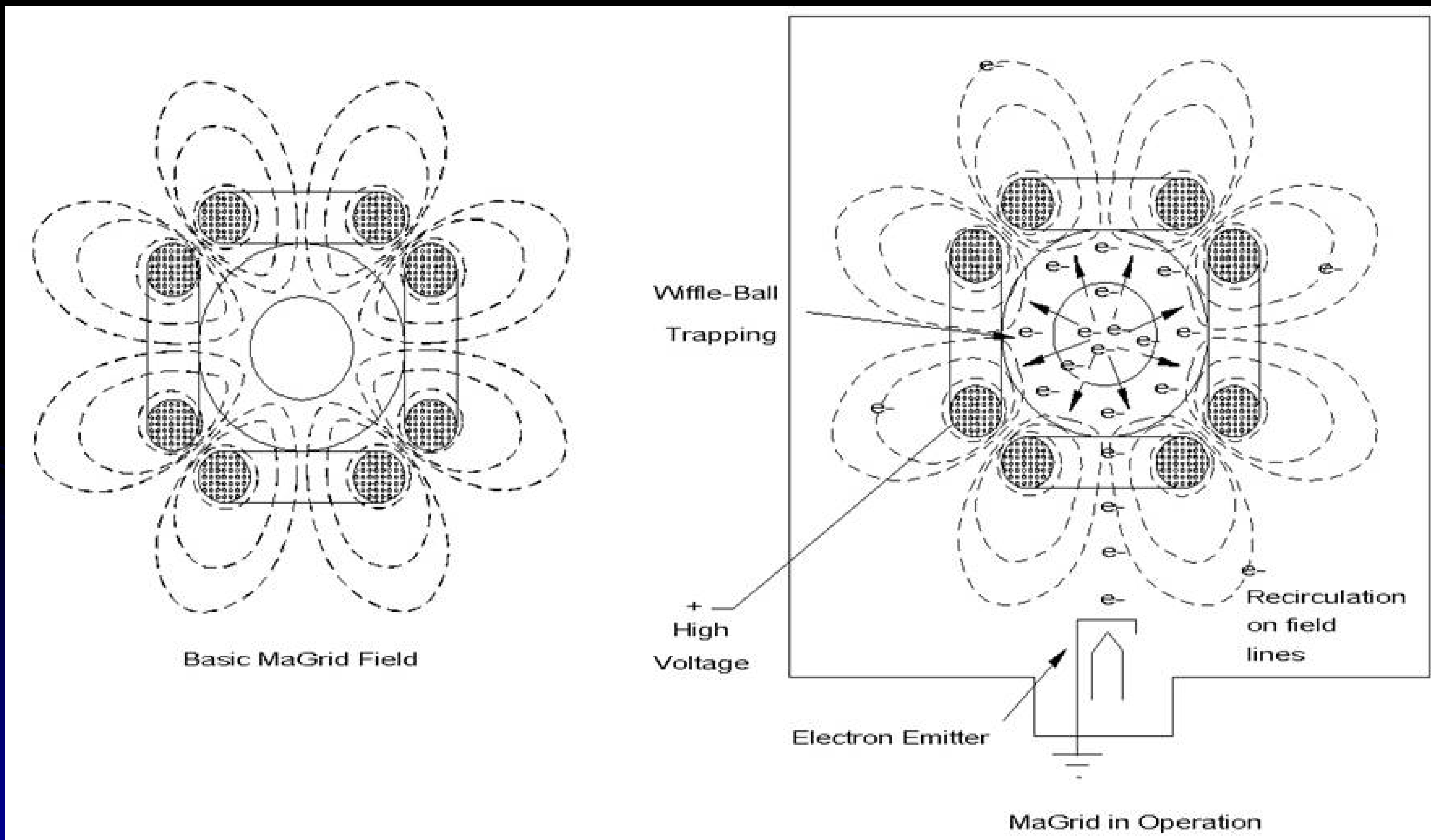



"On the Inertial-Electrostatic Confinement of a Plasma", William C. Elmore, James L. Tuck, Kenneth M. Watson, *The Physics of Fluids*, v. 2, no. 3, May-June 1959.

# Bussard's IEF Approach

- Electron grid of ETW machine replaced with magnetically-insulated "magrid"
- Electrons several thousand times lighter than fusion fuel ions … fields that can't hold ions easily confine electrons.
- Remember, this is *dynamic* confinement, and both electrons and ions are in constant, vigorous motion.

# WB6 Schematic



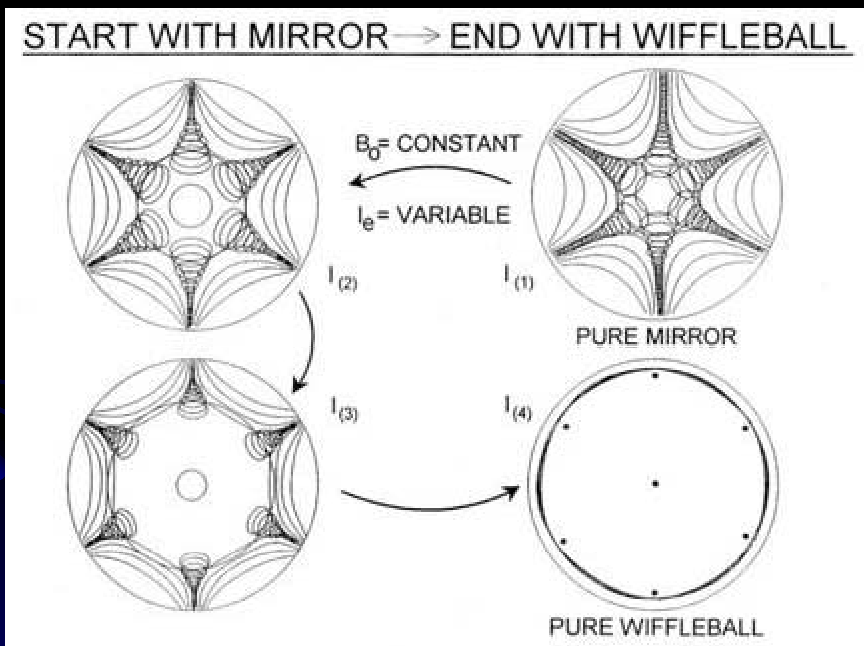
# Wiffleball

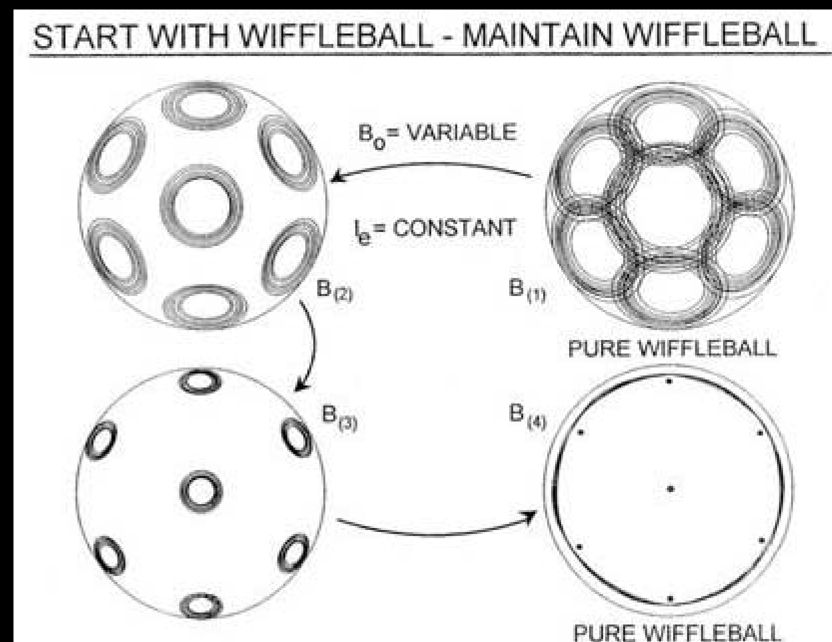
- Magnetic phenomenon that looks like child's toy ball
- Magrid field pushed back by huge electron flux exhibiting diamagnetic behavior
- Quasi-spherical, cusp holes scrunched down to small effective diameter
- Electrons escape every few thousand transits of center, but retained by fundamental magrid recirculation behavior

# Forming a “wiffleball”

**One look at these, and the nickname was obvious …**

The enormous flux of electrons at the center exhibits “diamagnetic” properties (it excludes magnetic fields). This pushes back the magnetic field and constricts the cusp holes.



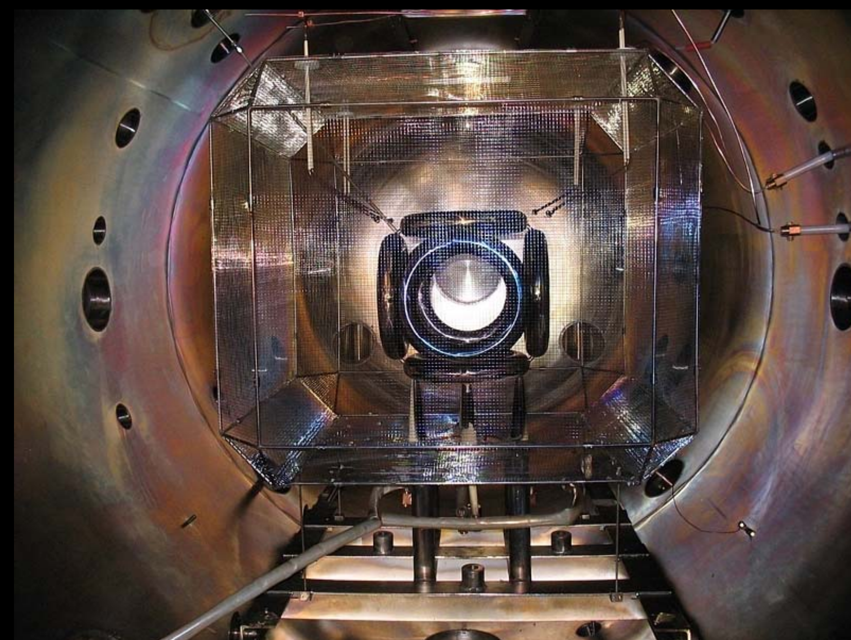




With apologies to the Wiffle Ball™ Corporation … the resemblance of this phenomenon to their marvelous toy is apparent, and we hope they don’t mind the association with a project to save the world.

# WB6

- This is the device that finally worked
- Truncated cube (6 magnets, open faces and corners)
- Magnets spaced slightly apart to avoid “funny cusp” losses.
- Magnets are simple copper solenoid coils, all with the same pole pointed in.
- Wiffleball trapping plus MaGrid factor gives electron lifetimes of around 100,000 transits

# WB6



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# What did WB6 accomplish?

- Finally confined electrons as the computer models said it should.
- Demonstrated the importance of two fine details of magrid constructions that prior devices had ignored.
- Worked about a thousand times better than previous models.
- Four replicate fusion runs before it fried

# WB6 Operation

- Pulsed due primarily to limitations of available power supplies.  Ran on capacitors for high voltage.
- The fusion was produced in sub millisecond bursts just when a deep potential well was present.
- Deuterium, 2-3 neutrons counted per test, $1.3 \times 10^4$ neutrons/count, 2 fusions per neutron.
- Resulting rate between 1e8 and 1e9 fusions per second … at a potential well depth of only 10 kV!

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# Compare to Farnsworth Fusor

- Hirsch achieved such reaction rates with DT running at 150 kV.
- DD fusors have gotten close to this at 120 kV and above.
- But a fusor at 10 kV barely makes detectable fusion. WB6 was *screaming*, running at a very high rate for such a low voltage.

# What terminated the runs?

- Pulse ended with a Paschen discharge (neon sign glow discharge) that drained the capacitors. This was due to excess gas, not some intrinsic limit of the concept.
- This does demonstrate what happens if excess fuel is introduced: the machine will "choke". This is an intrinsic safety feature.
- Further work should incorporate an improved ion source.

# Piston Engine Analogy

- Early engine with eye-dropper fuel metering rather than a carburetor
- Would a few cycles of firing just be a noisy waste of good booze?
- Would a cracked piston after four tests mean the technology was doomed?
- Or would you build an improved engine with fuel metering, cooling, oil system?

# The Next Steps ..

- WB7: robustified WB6, intended for longer runs, better endurance, better fuel metering.
- WB8: Truncated dodecahedron, same size as WB7, to see if less-quasi, more spherical geometry improves performance as expected.
- Aim for much better-quality data, quasi-continuous operation.

# WB8, Truncated Dodecahedron

Why?
Less quasi,
More
spherical!

Artwork by Tony Rusi
and Skip Baker

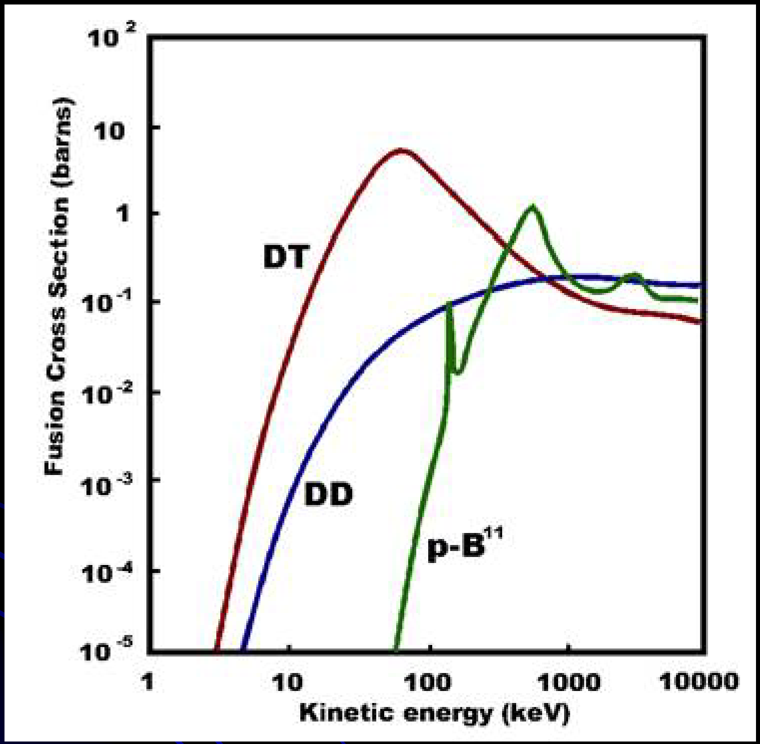
# And then net power?!!

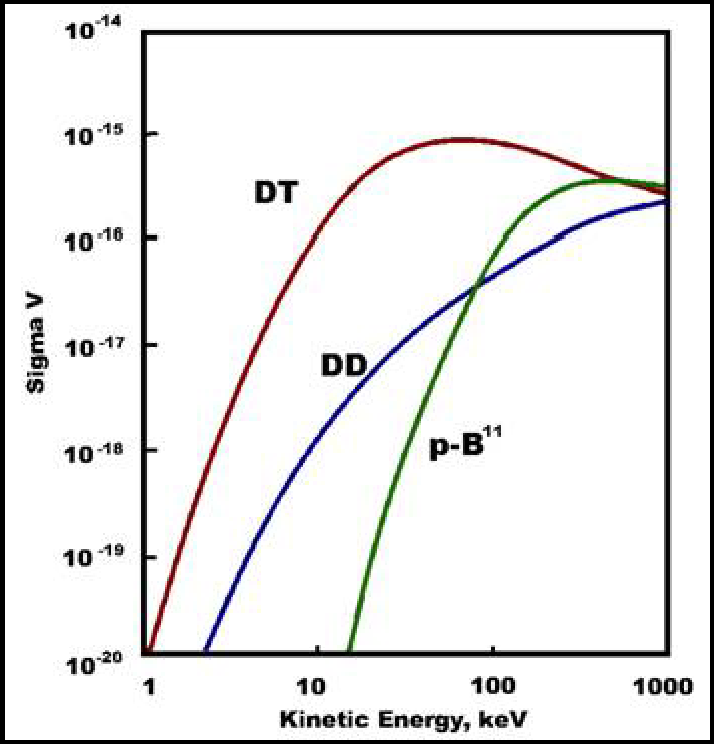
- Sure is ambitious, even audacious
- You could aim for a series of intermediate sizes as a “risk mitigation” measure
- Dr. Bussard thinks intermediate sizes are a waste of time and money.  The scaling strongly favors larger size.  1.5 m = net power for $150 M
- And there appears to be no reason why a p-$B^{11}$ reactor could not be built (2 m, $200 M)
- If the p-$B^{11}$ reaction proved impractical, that reactor would still run DT or DD.

# P-$B^{11}$

- Can't be run in a tokamak … initiation energy far too high
- Relatively easy in an electrodynamic machine … circa 100 kV potential well depth
- Almost all reaction energy comes off in 3 alpha particles.  No neutrons, no radioactive byproducts, allows direct conversion

# Fusion Cross Sections




http://fds.oup.com/www.oup.co.uk/pdf/0-19-856264-0.pdf

# Direct Conversion

- Possible when reaction energy is kinetic energy of charged particles, especially when energies closely grouped
- The opposite of putting kinetic energy in with electric fields.
- Decelerate against electric fields to make high voltage DC.
- p-$B^{11}$ may allow close to 95% recovery

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# Terrestrial Power

- High efficiency means less cooling requirements, reduces costs
- HV-DC output converts to AC using existing technology
- A p-$B^{11}$ system has no radioactive waste, fuel abundant and cheap
- Should eventually dominate electric power market, contribute to fuel production, market maybe $5 T per year?

# Space Power

- NSTAR/DS1: 2.3 kW, 93 mN,
  $I_{sp}$ 2000-3000 sec

- ESEX 27 kW arcjet,
  $I_{sp}$ 500-1200 sec

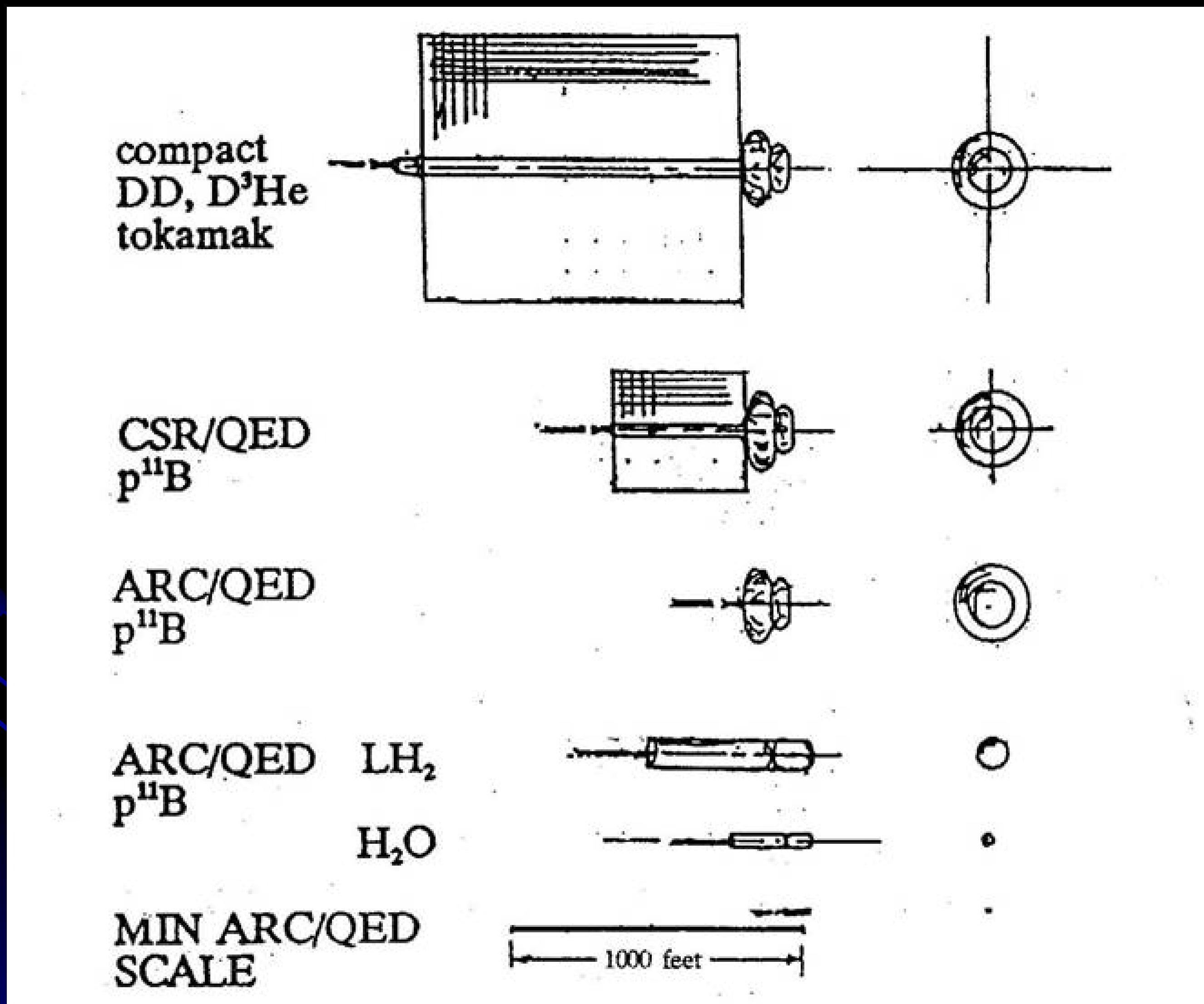
- 180 HP light aircraft: 134 kW

- SSMEs : 18 GW, 1.7 MN, $I_{sp}$ 460 sec

# Dr. Bussard's Propulsion Systems

- QED: Quiet Electric Discharge.  Typically use relativistic electron beam heating of reaction mass (the arcjet from hell).  Lower $I_{sp}$, higher thrust, for shorter missions.
- DFP: Diluted Fusion Product.  Some inert reaction mass added to fusion product directly from reactor.  Very high $I_{sp}$, lower thrust, for long-range missions.

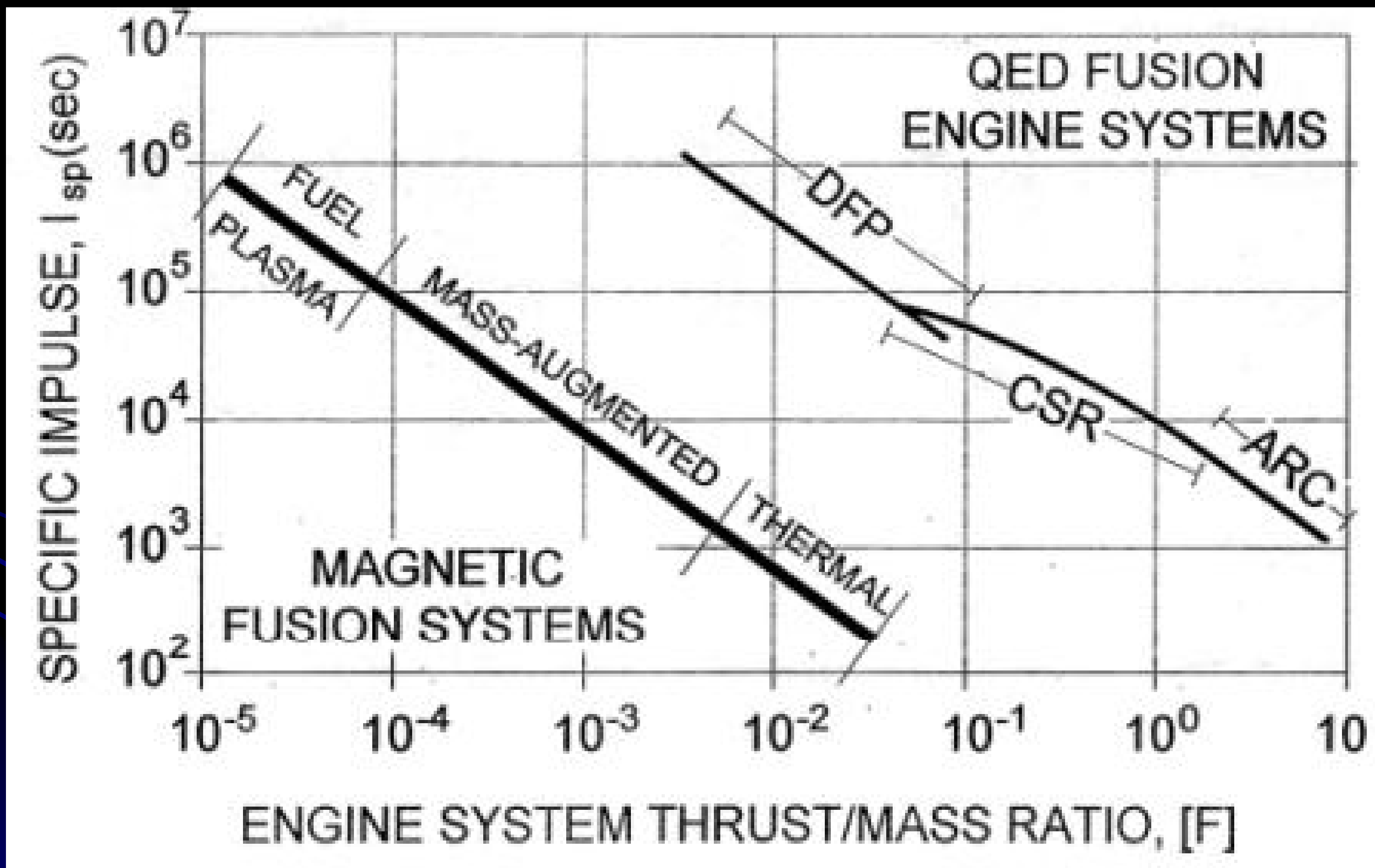
# Tokamak vs QED Radiators



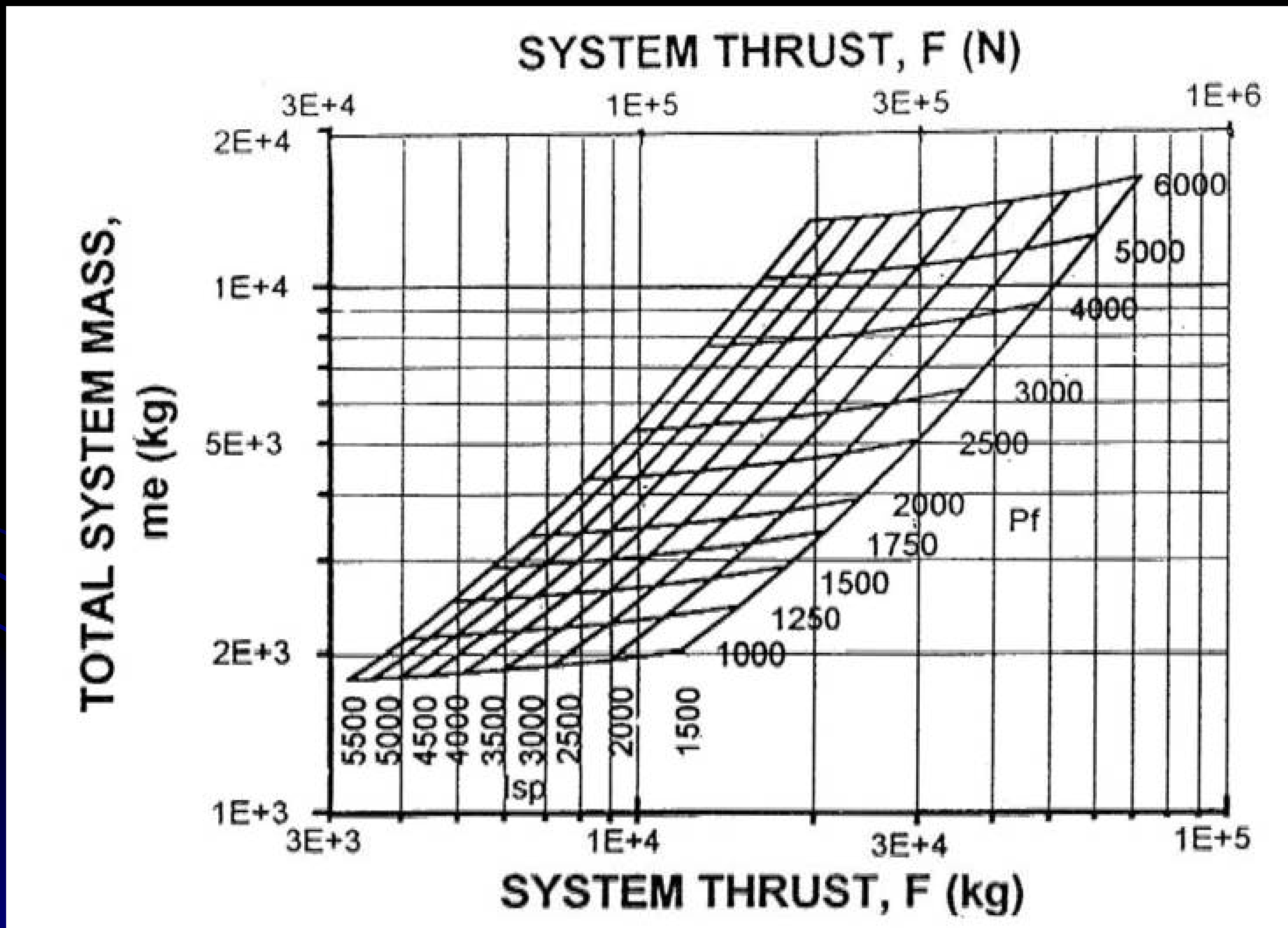
# QED Engine Variants

- QED/ARC: All Regenerative Cooling. Reaction mass used as the coolant, so fairly high flows required. Low $I_{sp}$, high thrust. Good for launches, landers, short missions.
- CSR: Controlled Space Radiation. Radiators required. Higher $I_{sp}$, but less thrust and more "junk in the trunk".

# Relative Performance



# QED/ARC Performance



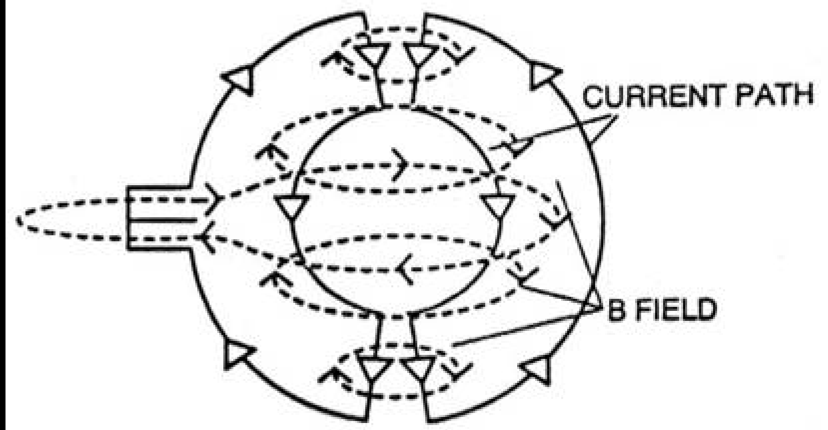
# QED/CSR Types

- CSR-A: Limited regenerative cooling, REB heating of reaction mass, typically water. Smaller radiators than CSR-B, but lower $I_{sp}$ and higher thrust.
- CSR-B: Very low reaction mass flow, so larger heat radiators required. High $I_{sp}$, low thrust. Expected to use an ion accelerator rather than REB heating.

# For the outer solar system …

"Diluted Fusion Product" (DFP)

- Low thrust, high $I_{sp}$: 50,000 sec to > $10^6$ sec
- Radiators required

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# Spacecraft Based on These Systems

- SSTO
- Landers
- Short range
- Intermediate range
- Long range

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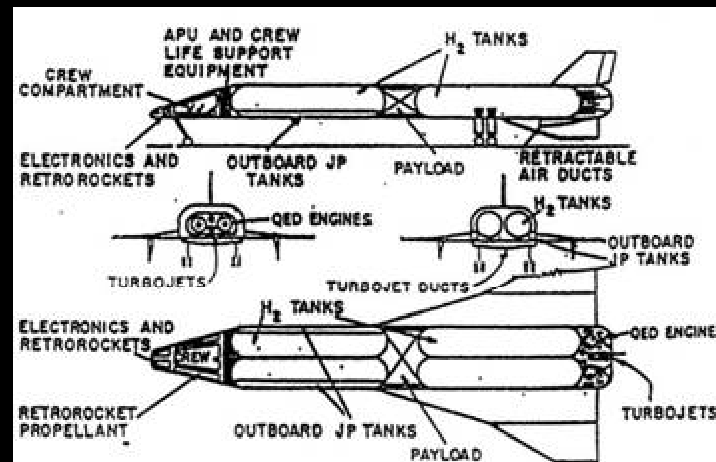
# SSTO: Air-Breathing!

- QED/ARC
- Air-breathing at low altitude (like scramjet)
- Hydrogen reaction mass at high altitude
- $I_{sp}$ 1538-3062 sec
- Thrust 208.6-83.2 T
- Wet 250 T, Dry 155 T
- Payload 35 T
- $27/kg to LEO




System Technical and Economic Features of QED-Engine-Driven Space Transportation, Robert W. Bussard

33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit

- Inertial-Electrostatic-Fusion Propulsion Spectrum: Air-Breathing to Interstellar Flight, R. W. Bussard and L. W. Jameson, Journal of Propulsion and Power, v. 11, no. 2, pps 365-372.

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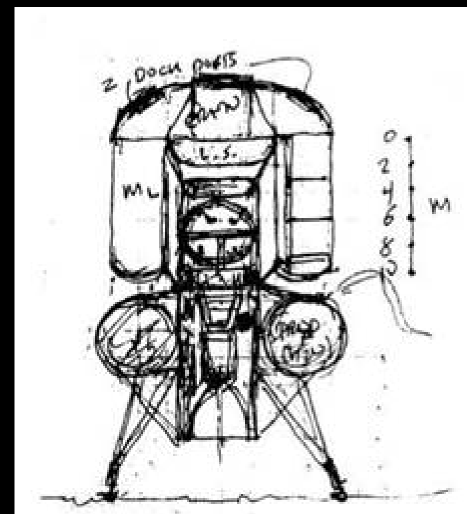
# LEO to Luna Transport/Lander

- QED/ARC, water reaction mass
- $I_{sp}$ 1590-2760 sec
- Thrust 75.5-43.5 T
- 250 T wet, 105 T dry
- Payload 35 T
- $\Delta V$ 15.8 km/sec
- $24.20/kg



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# Mars: LEO to LMO

- QED/CSR-A preferred (ARC will work)
- Water reaction mass
- Lander similar to lunar transport/lander
- $I_{sp}$ 7800 sec
- Wet 500 T, dry 171 T
- Payload 78 T
- ΔV 59 km/sec
- $232.60/kg

System Technical and Economic Features of QED-Engine-Driven Space Transportation, Robert W. Bussard

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# LEO to Titan

- DFP preferred, CSR-B usable
- $I_{sp}$ 70,000 sec (almost continuous thrust)
- Wet 400T, Dry 148 T
- Payload 45 T
- ΔV 354.5 km/sec
- $331.20/kg


R. W. Bussard and L. W. Jameson, "From SSTO to Saturn's Moons: Superperformance Fusion Propulsion for Practical Spaceflight," 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 27-29 June, 1994, AIAA 94-3269.

System Technical and Economic Features of QED-Engine-Driven Space Transportation, Robert W. Bussard

33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit

# Colonizing the System

- Estimates include transportation costs of the people, a generous allowance of equipment and supplies for each, and regular trips home.
- Estimates do not include the cost of the equipment and supplies, just the transport thereof.
- Estimates expect 10 years, many trips.
- Spacecraft development costs not included, but life cycle costs included.
- Estimates made in 1997

# Lunar Colony

- 4000 people
- 25 tons of stuff each
- $12.48 B

R. W. Bussard, "System Technical and Economic Features of QED-Engine-Driven Space Transportation," 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 6-9 July, 1997, AIAA 97-3071.

# Mars Colony

- 1200 people
- 50 tons stuff each
- $15.64 B

R. W. Bussard, "System Technical and Economic Features of QED-Engine-Driven Space Transportation," 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 6-9 July, 1997, AIAA 97-3071.

# Titan Colony

- 400 people
- 60 tons stuff each
- 16.21 B

R. W. Bussard, "System Technical and Economic Features of QED-Engine-Driven Space Transportation," 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 6-9 July, 1997, AIAA 97-3071.

# 1200 people on Mars for the cost of a few Apollo landings?!!

- Economics driven by exceptional performance
- High payload fractions
- Low trip times, so many flights
- Craft highly reusable
- Fuel cheap and light
- Reaction mass from native materials wherever possible
- Each part of the system improves the economics of the rest.

# References

- NPO:  emc2fusion.org
- Askmar:  http://www.askmar.com/Fusion.html
- Valencia report
  - Many earlier papers referenced, available at Askmar
- Google Talk
- Fusor.net (original *Analog* article, many refs)
- Additional references posted on display board, but these websites above should contain all.