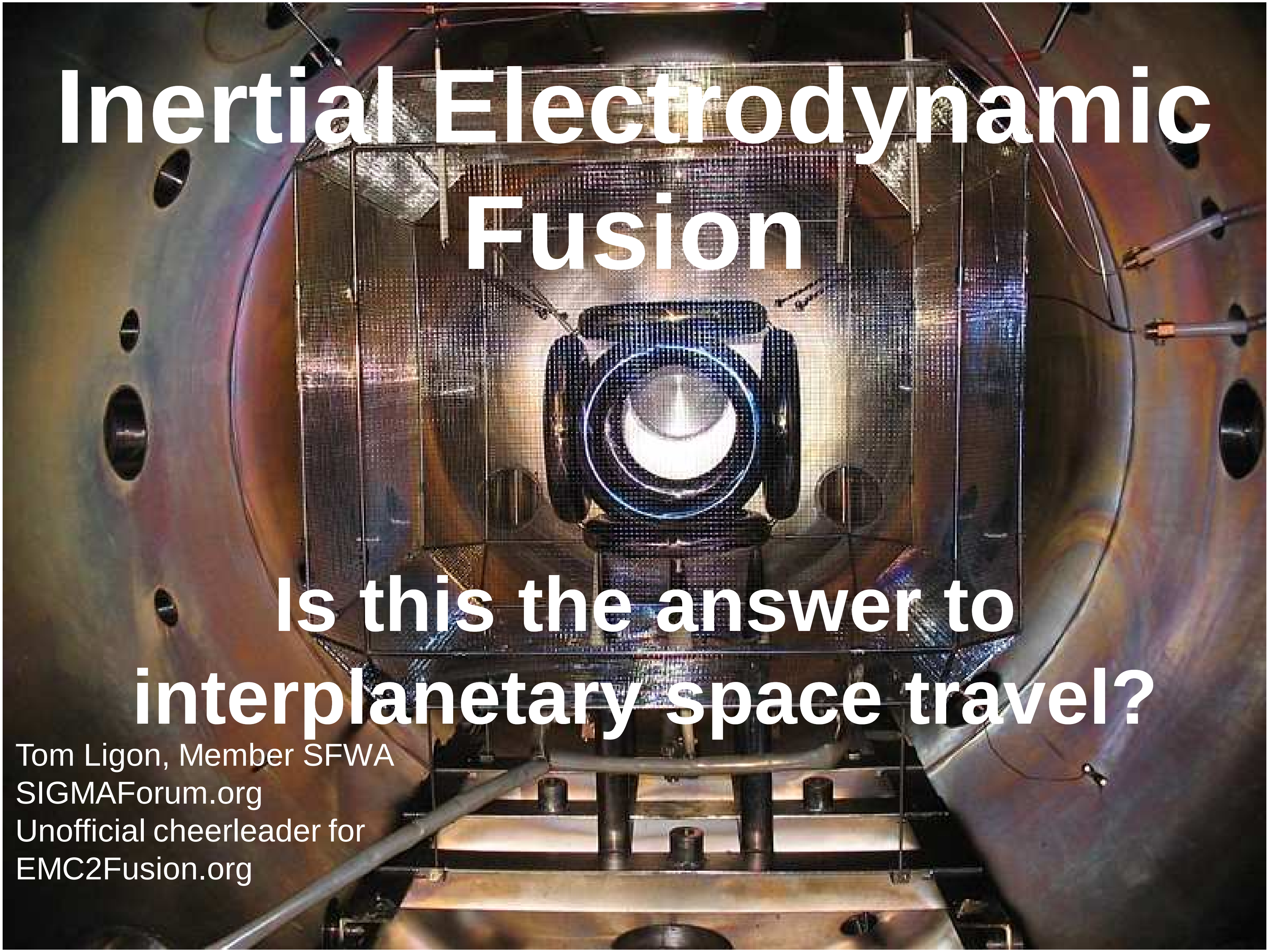
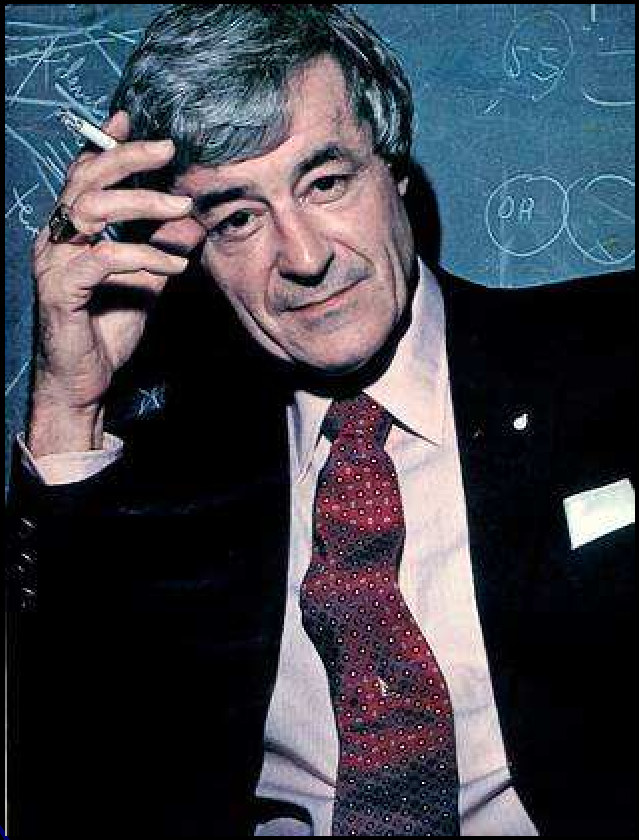


Inertial Electrodynamic Fusion

Is this the answer to interplanetary space travel?

Tom Ligon, Member SFWA
SIGMAForum.org
Unofficial cheerleader for
EMC2Fusion.org

Robert W. Bussard, 1928-2007



Bussard Factoids

- Bussard Ramjet, circa 1960. "I guess I'll never live that down."
- Proposed Rover nuclear rocket, 1953. Built, tested, worked!
- Wrote the book(s) on nuclear rocket propulsion with R. D. DeLauer http://en.wikipedia.org/wiki/Bussard
- An architect of the US fusion research program: "It was a scam."
- "Nuclear weapons are addictive. Once you set one off, you feel like a god, and you want to do it again."
- Space enthusiast from early childhood, believed we must go to space for our continued survival.
- Watch "The Google Talk" to see his personality.

Askmar.com/fusion.html

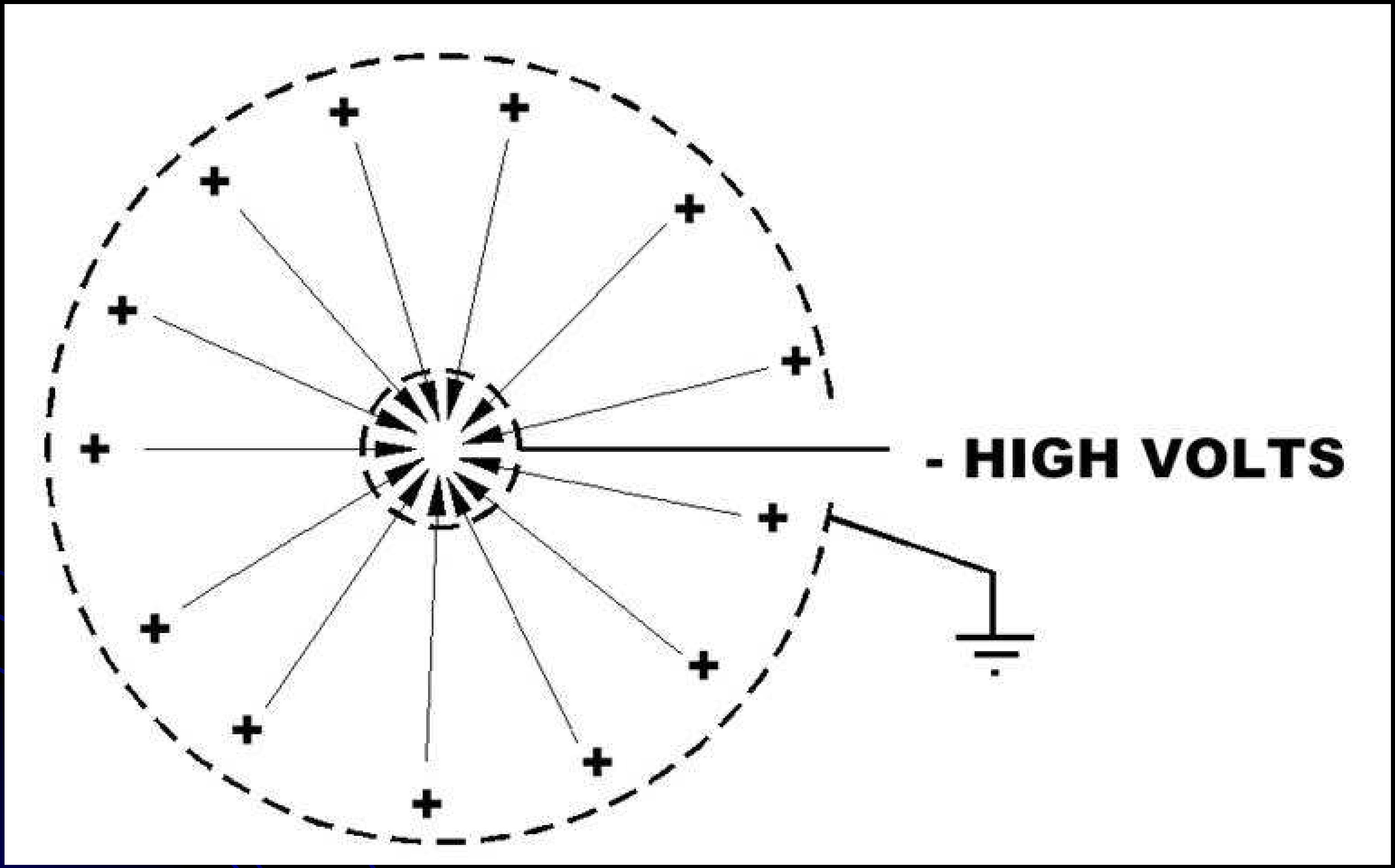
IEC Background

- 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

Hirsch/Farnsworth Fusor

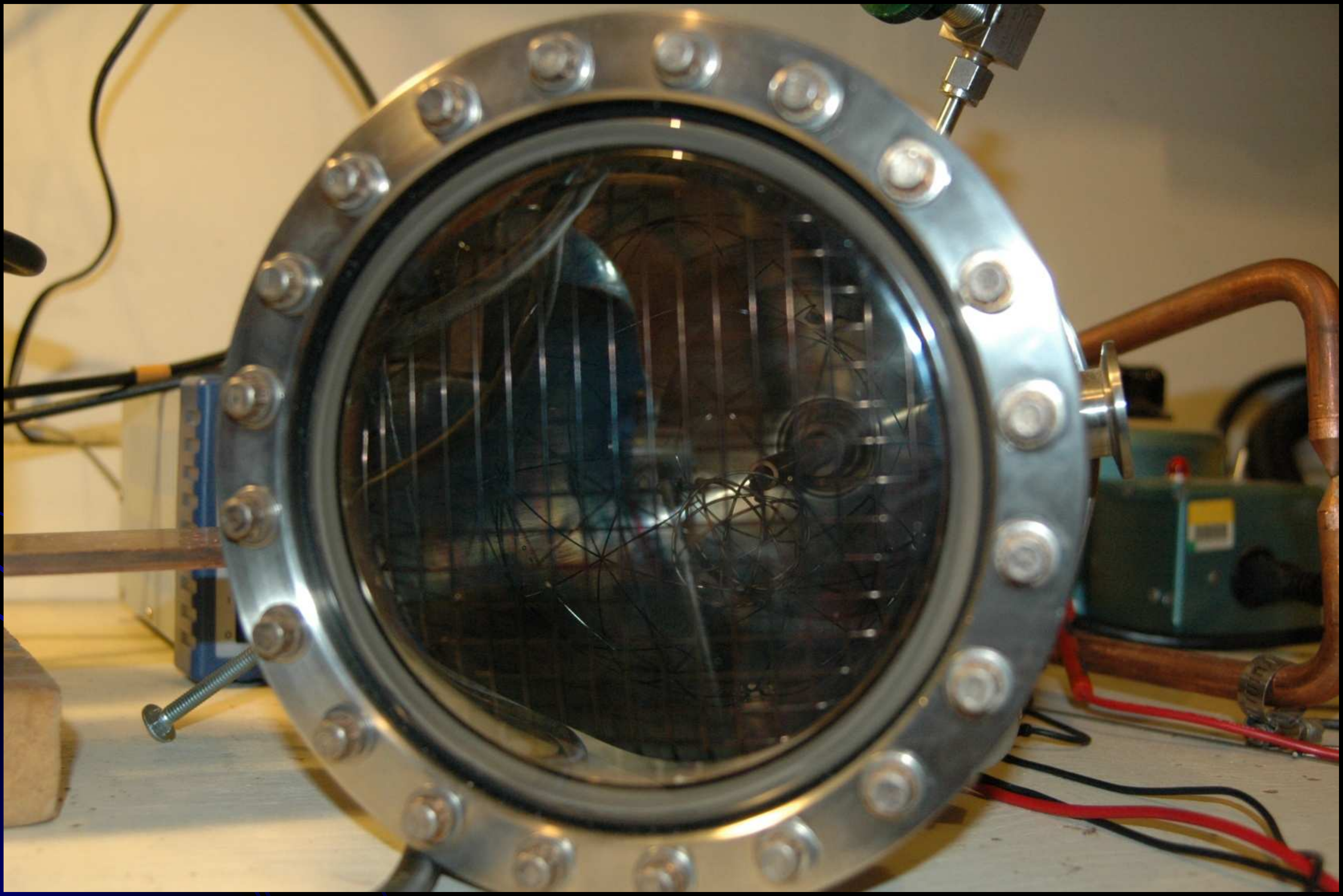


"Inertial-Electrostatic Confinement of Ionized Fusion Gases", Robert L. Hirsch, *Journal of Applied Physics*, v. 38, no. 11, October 1967.

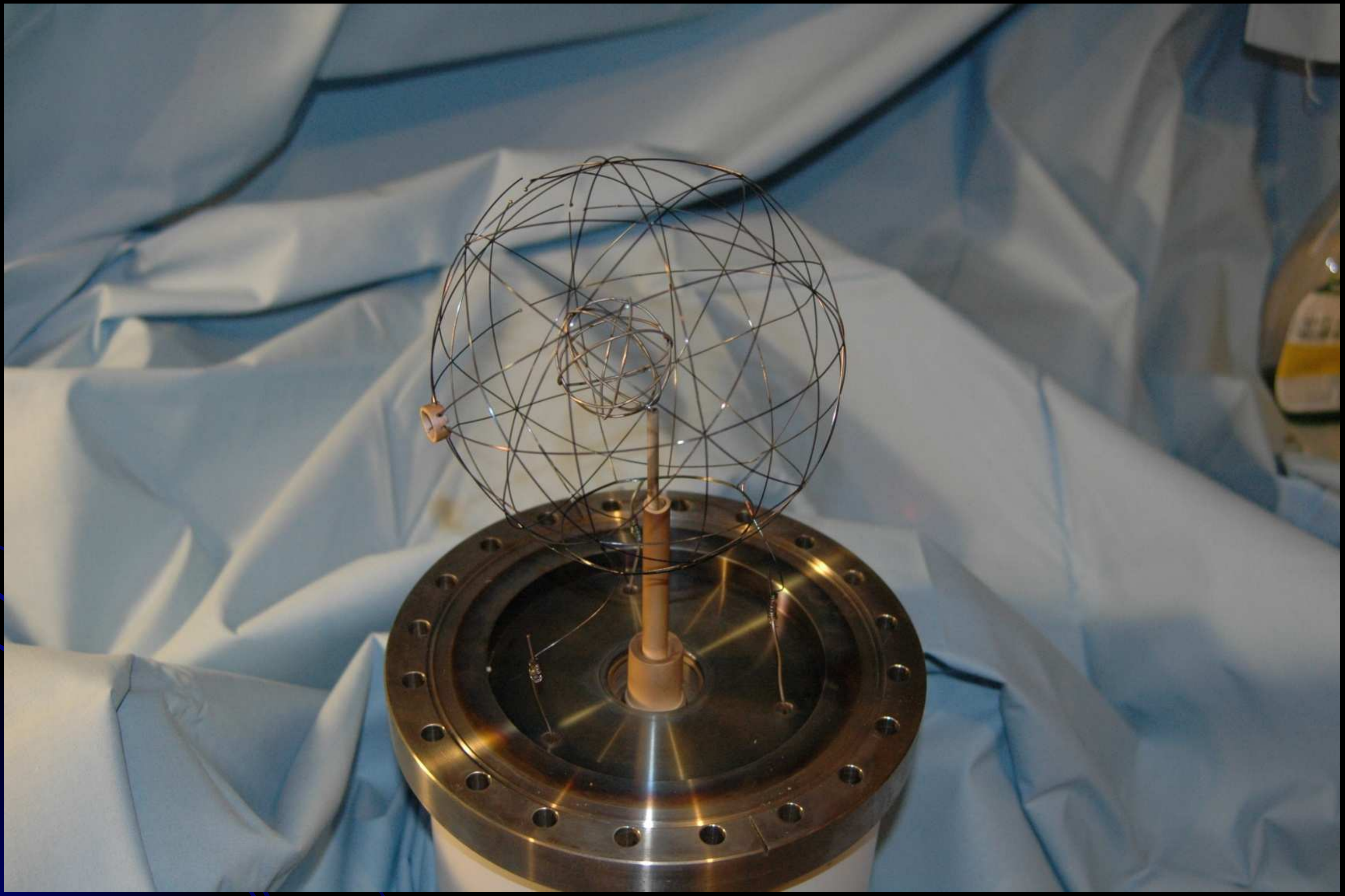
Dog and Pony II

- D&P I was built in a plastic desiccator and only lasted 2 weeks, but launched the amateur fusion movement.
- D&P II has actually made sustained DD fusion (3000 fusions/second at 18 kV for up to 45 minutes at a time), but was badly beat up from many road trips.

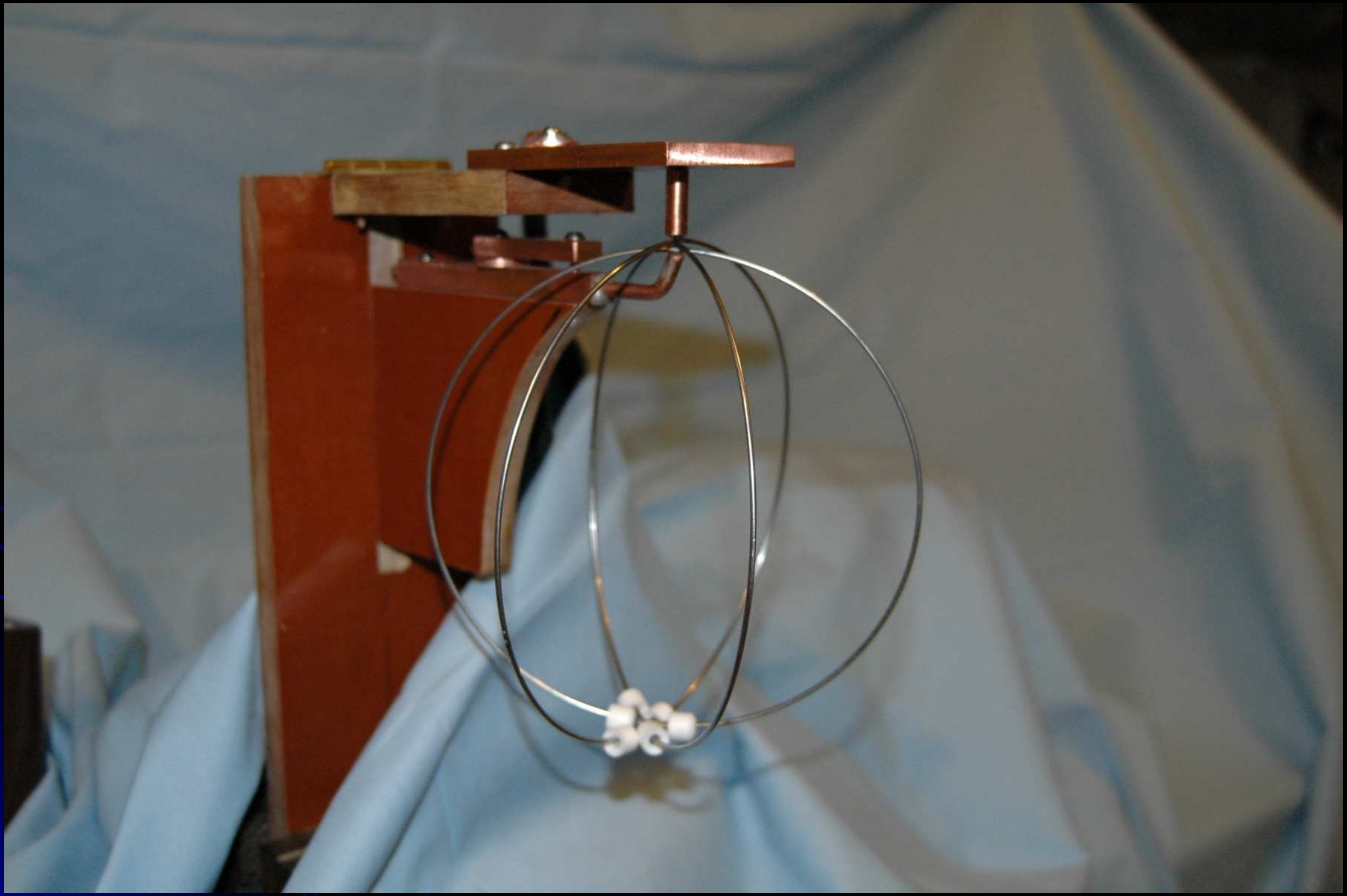
D&P II before rebuild



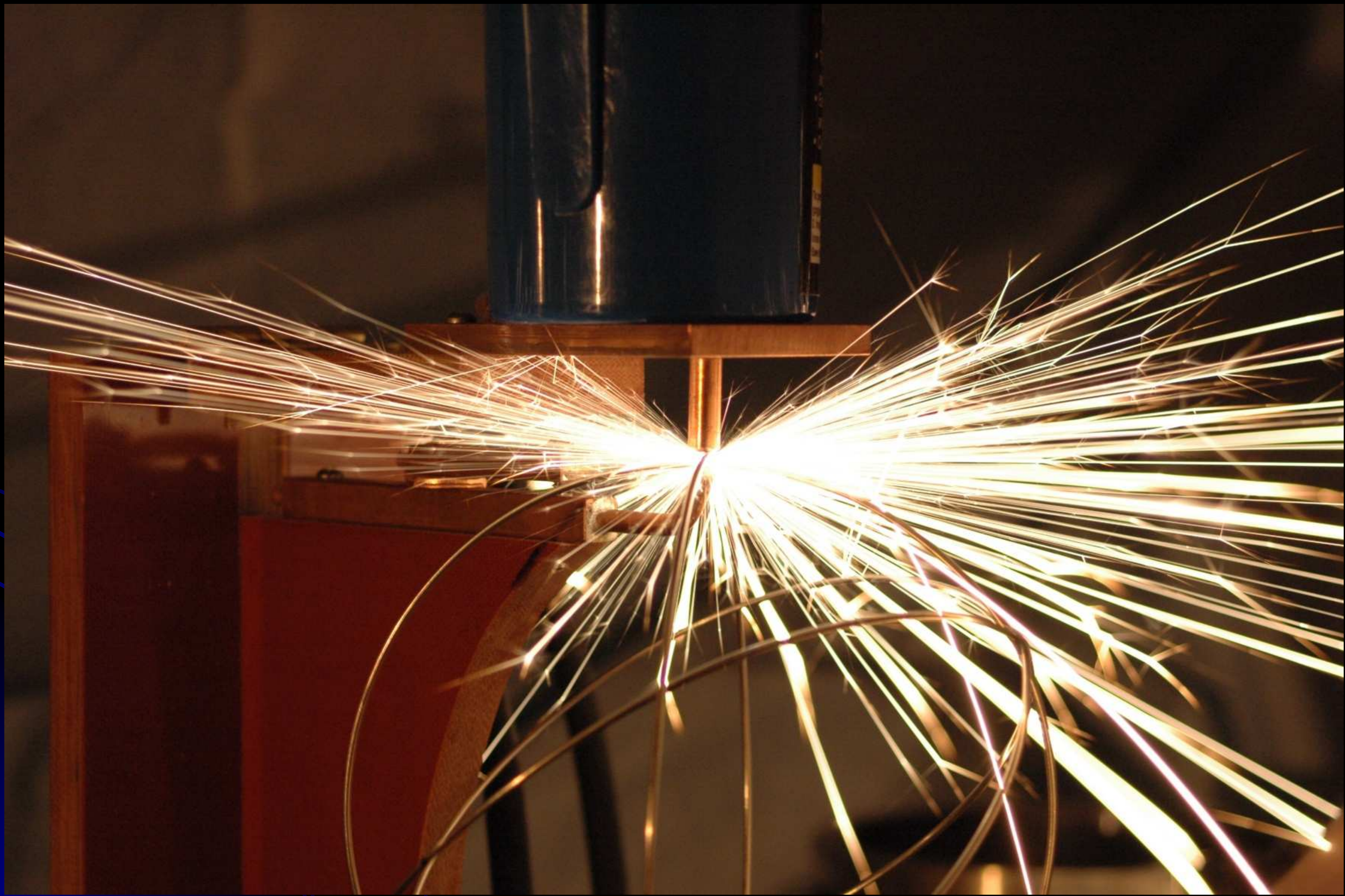
D&P II Old Grids
(suffers from inner grid ED)



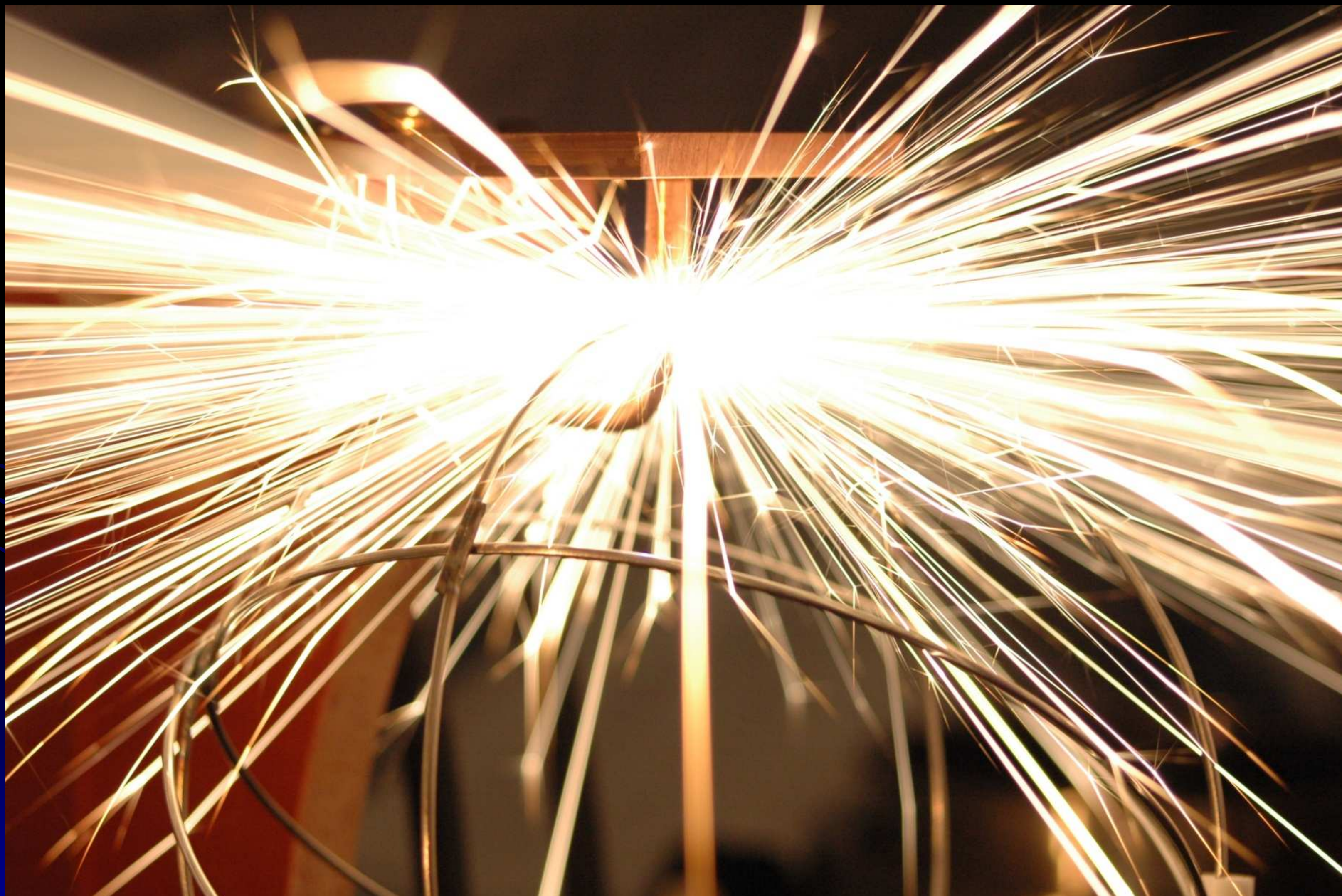
New Outer Grid Construction



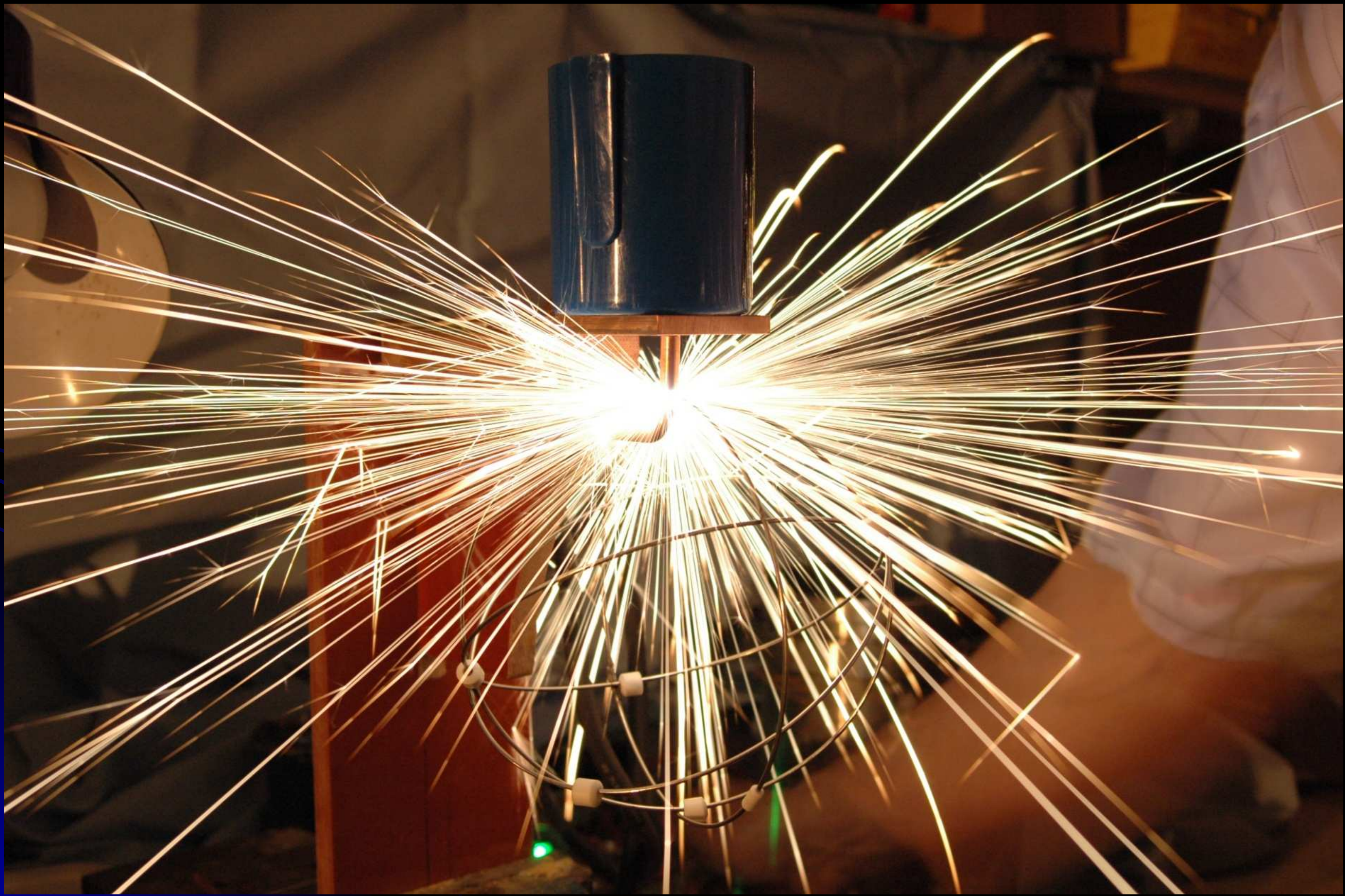
Spot Welding is Fun!



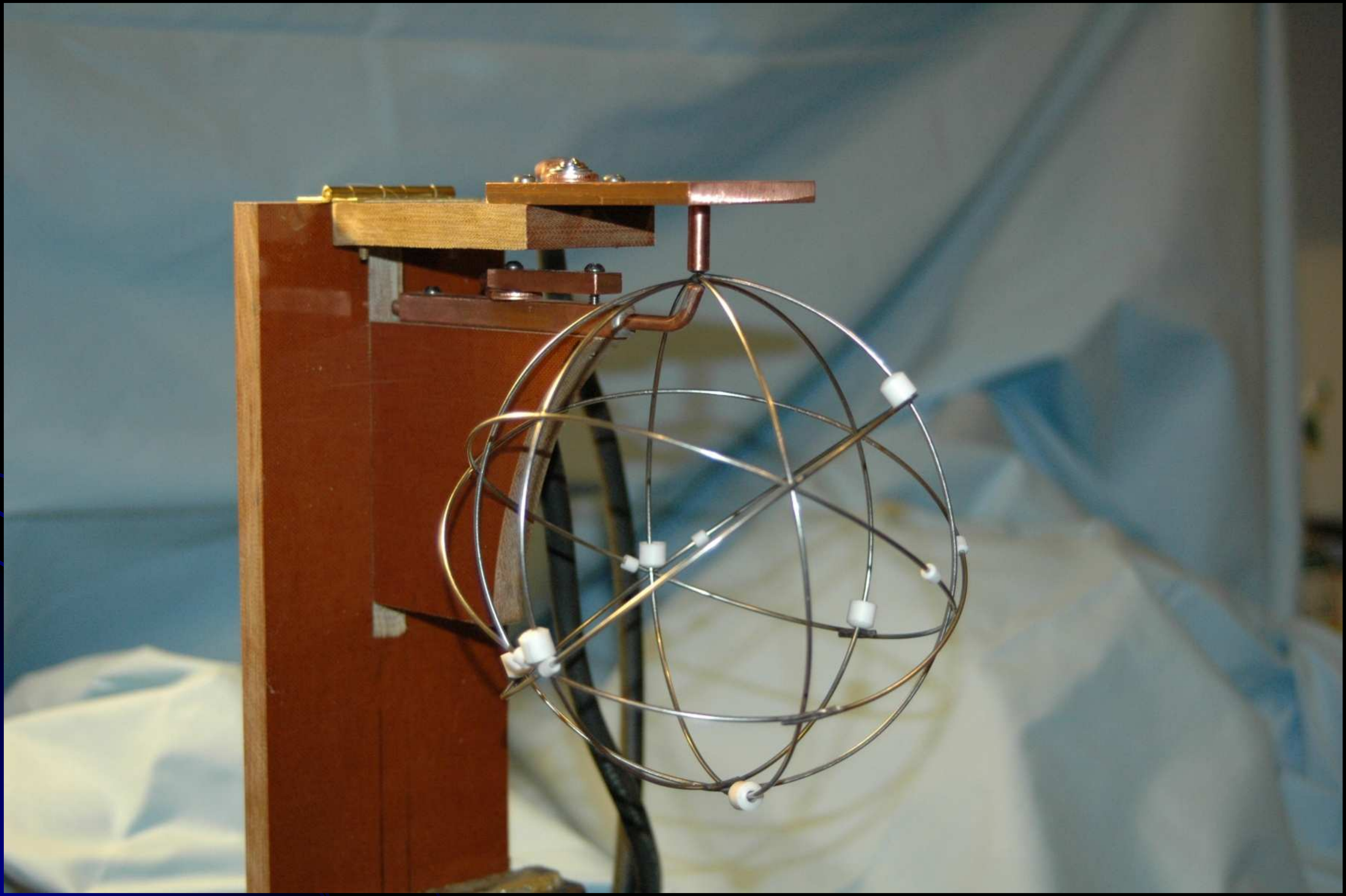
Lots of fun!



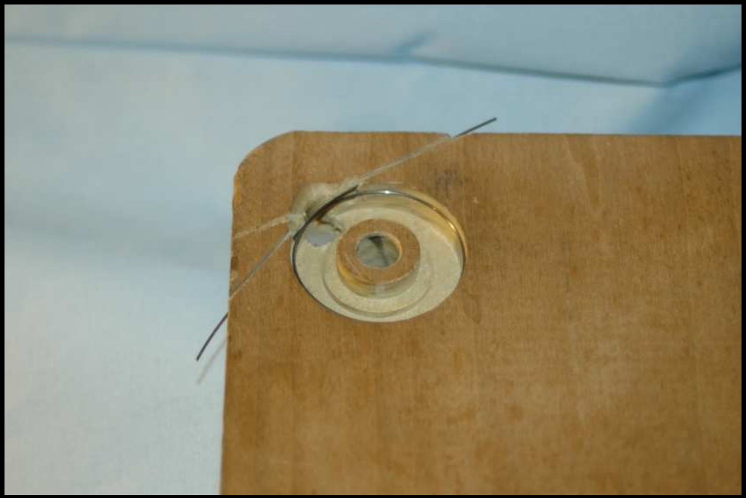
Coming together …

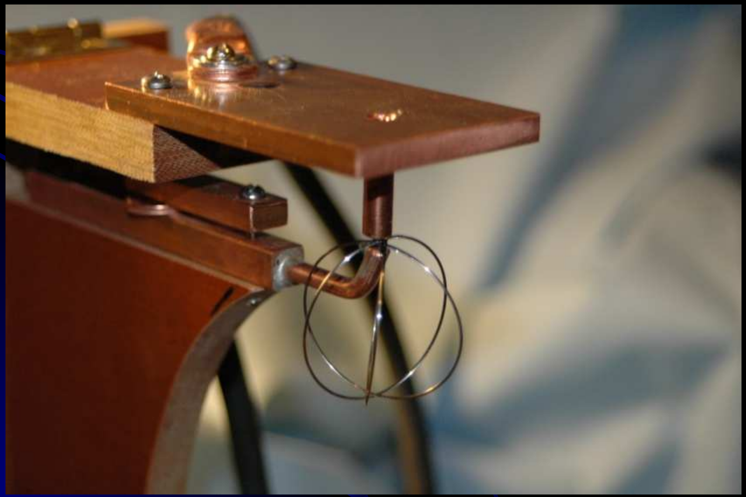


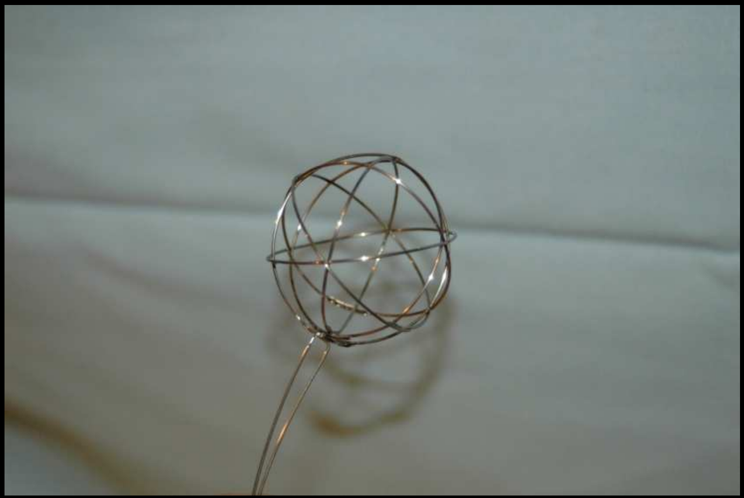
An outer grid is done!



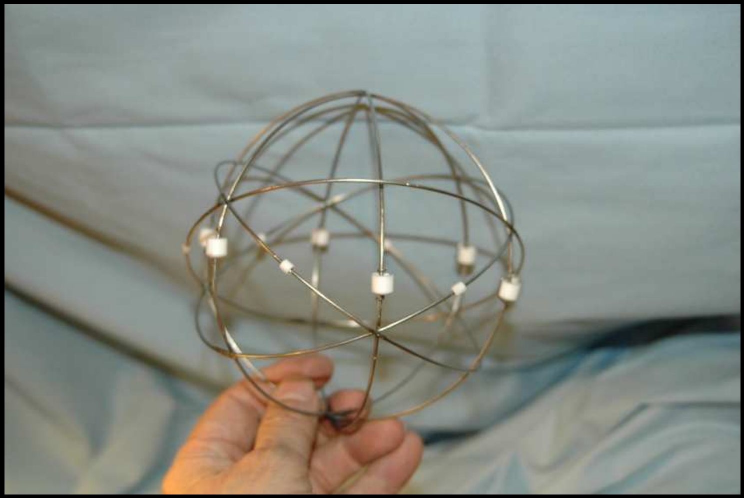
Inner Grid Construction

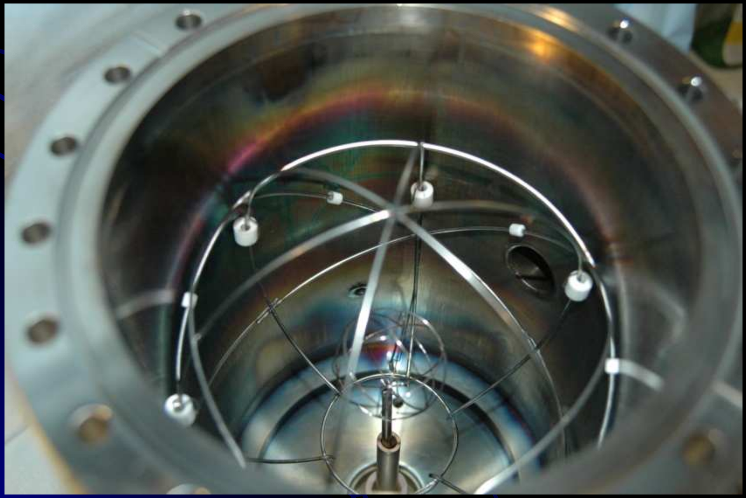




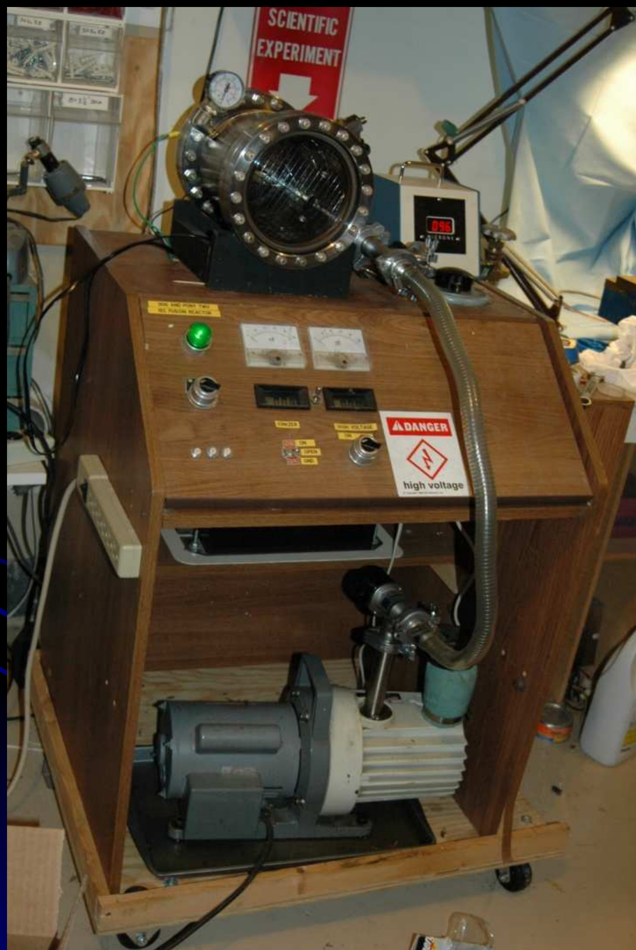


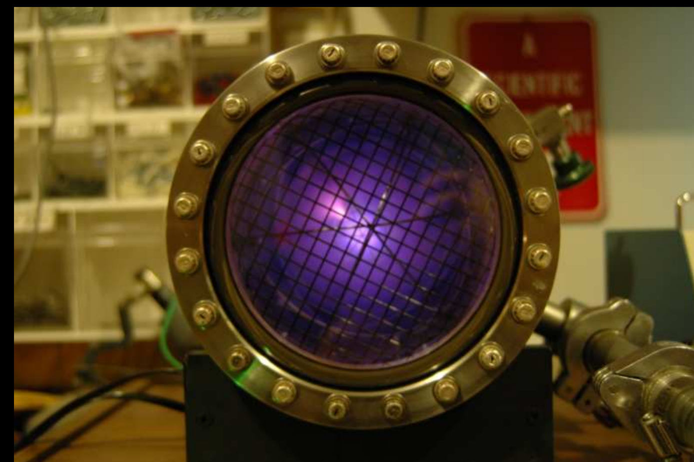
Going Back Together



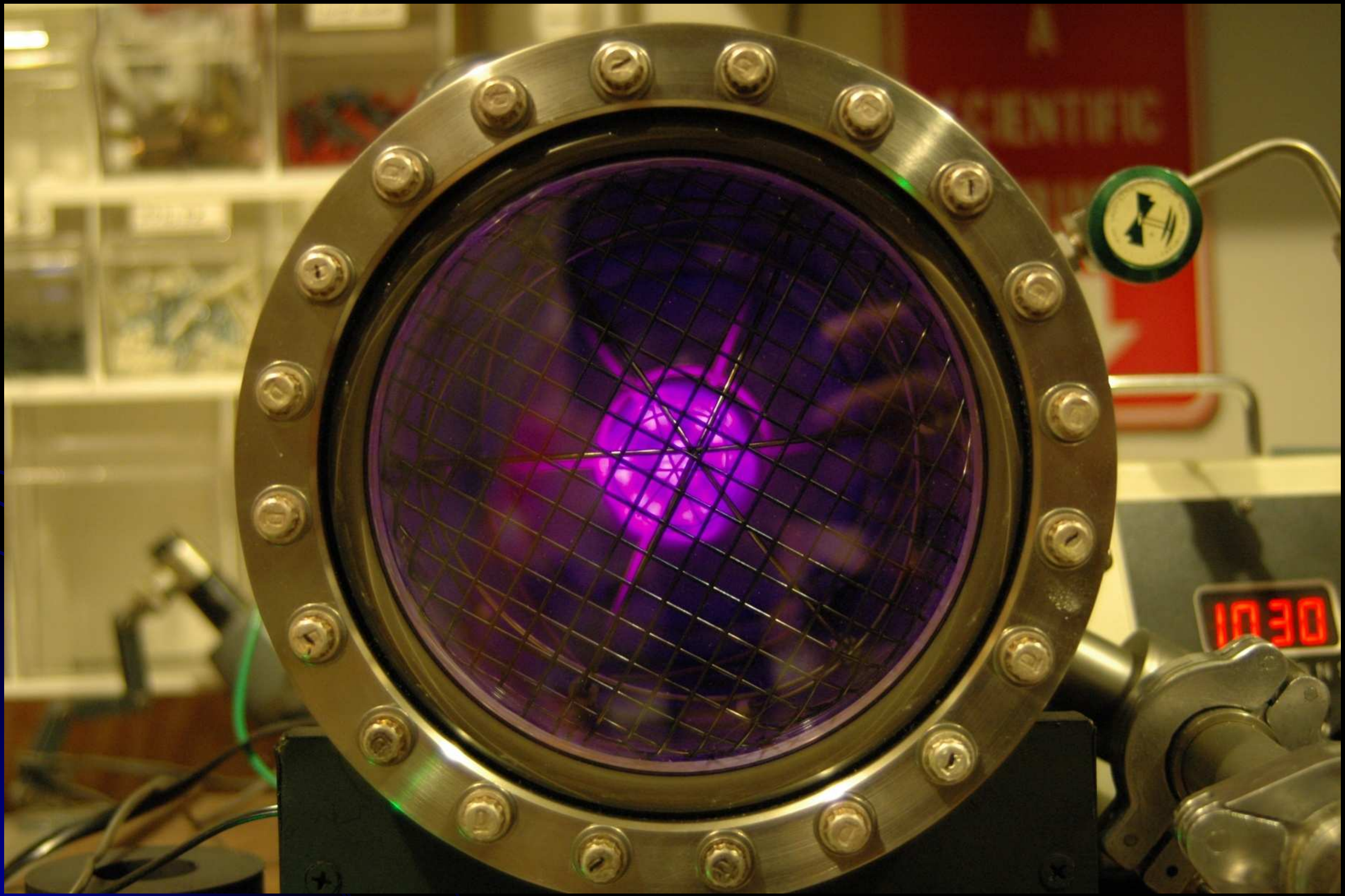



Back in Operation

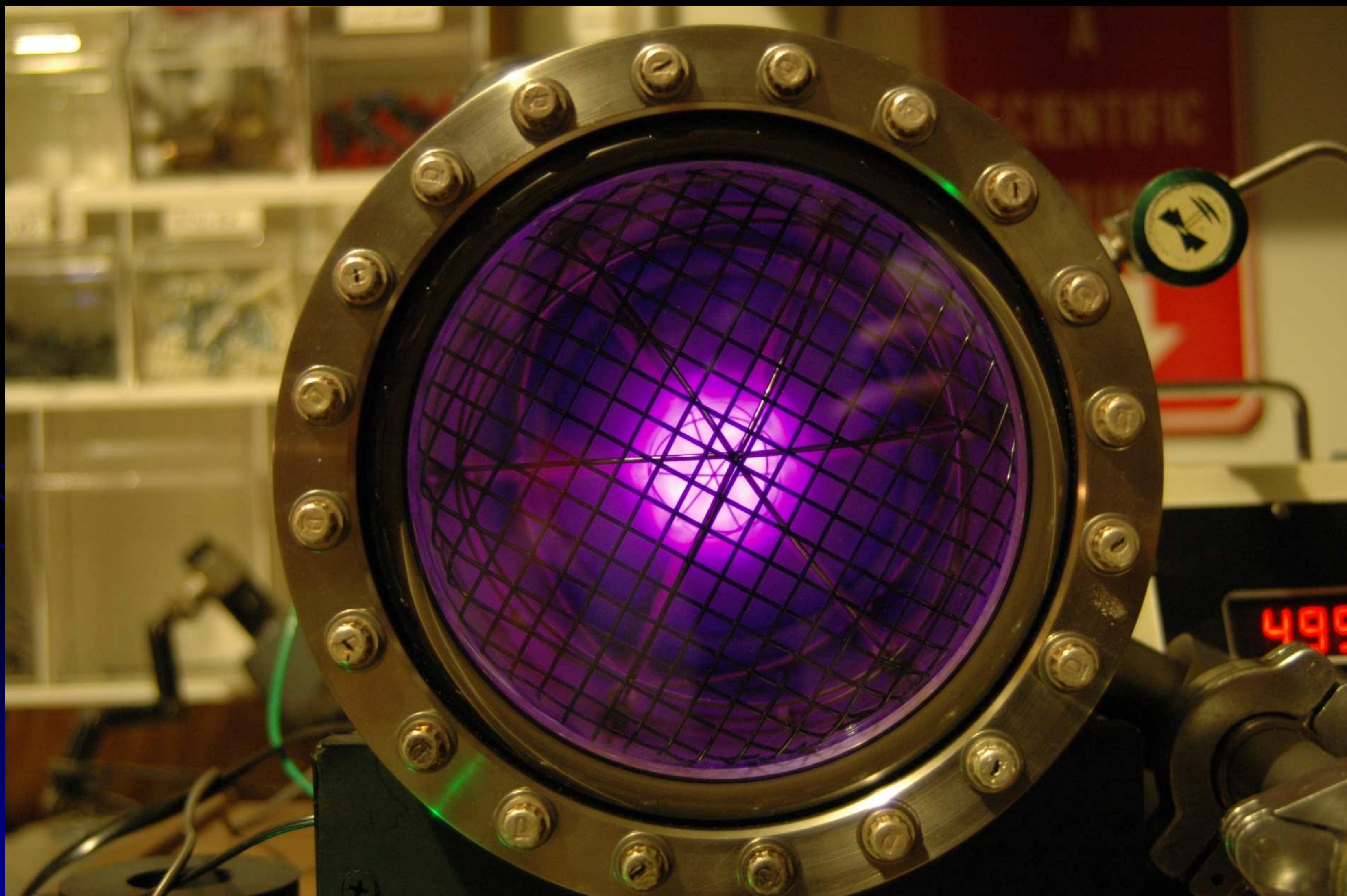




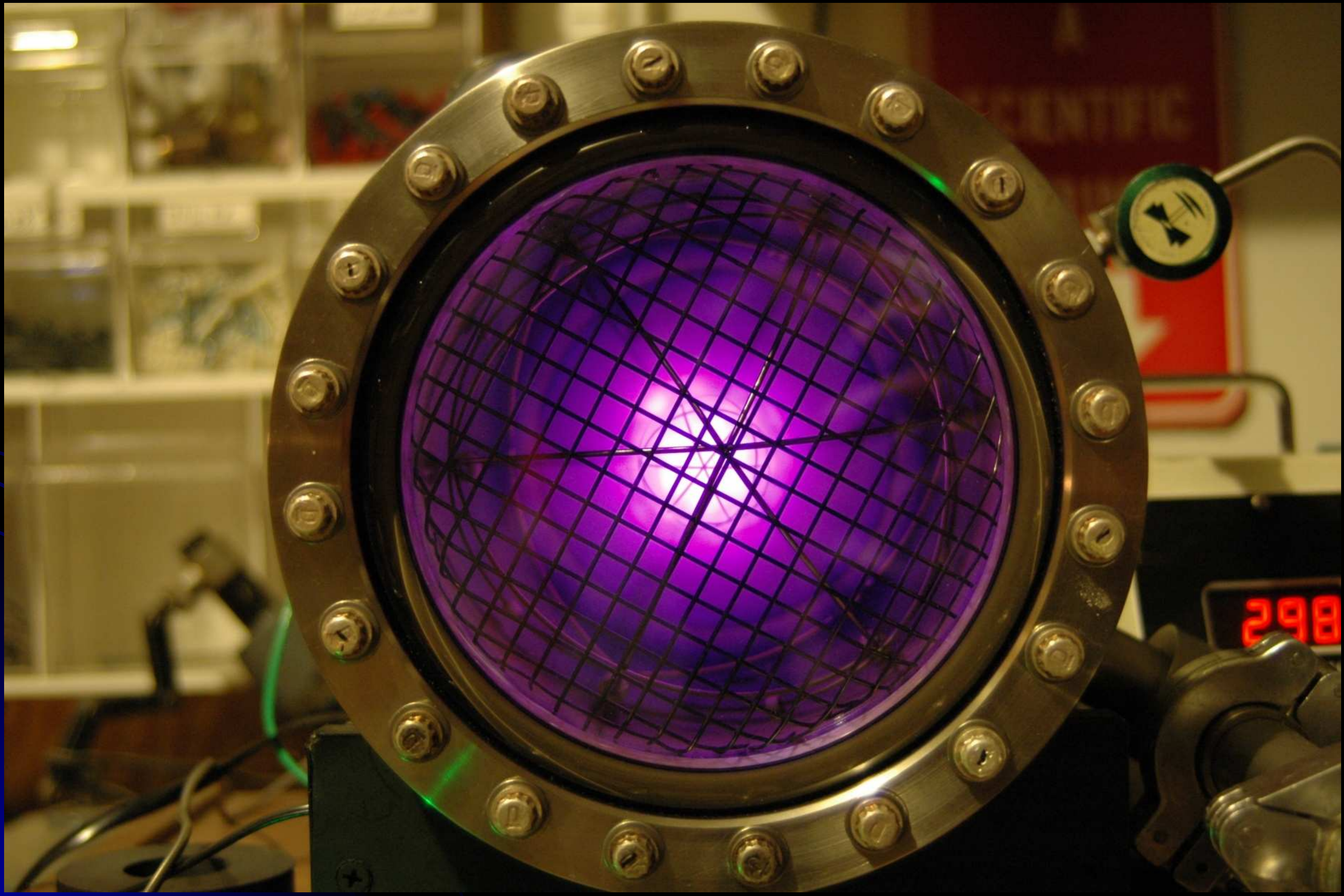
1030 mtorr, 400 V



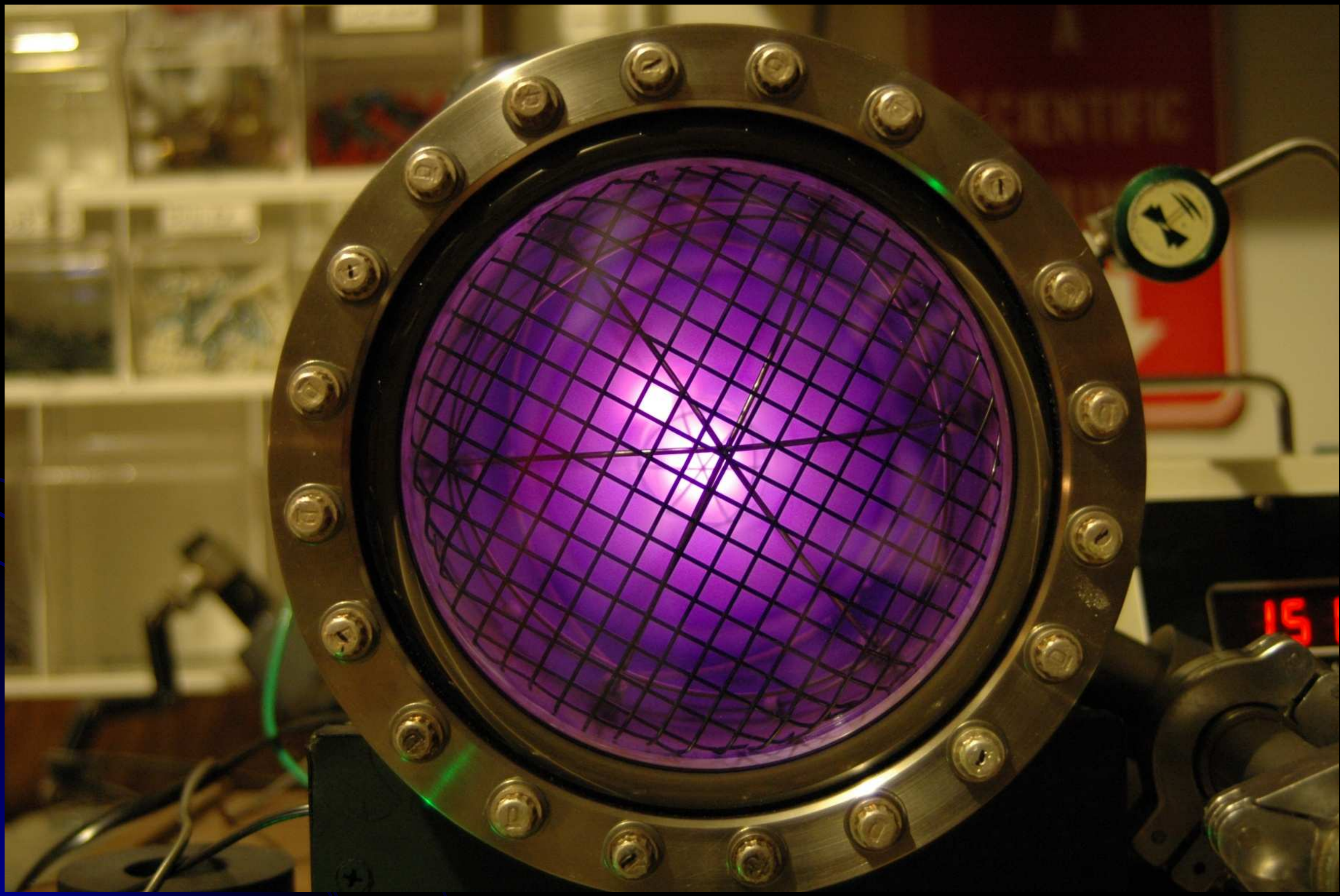
500 mtorr



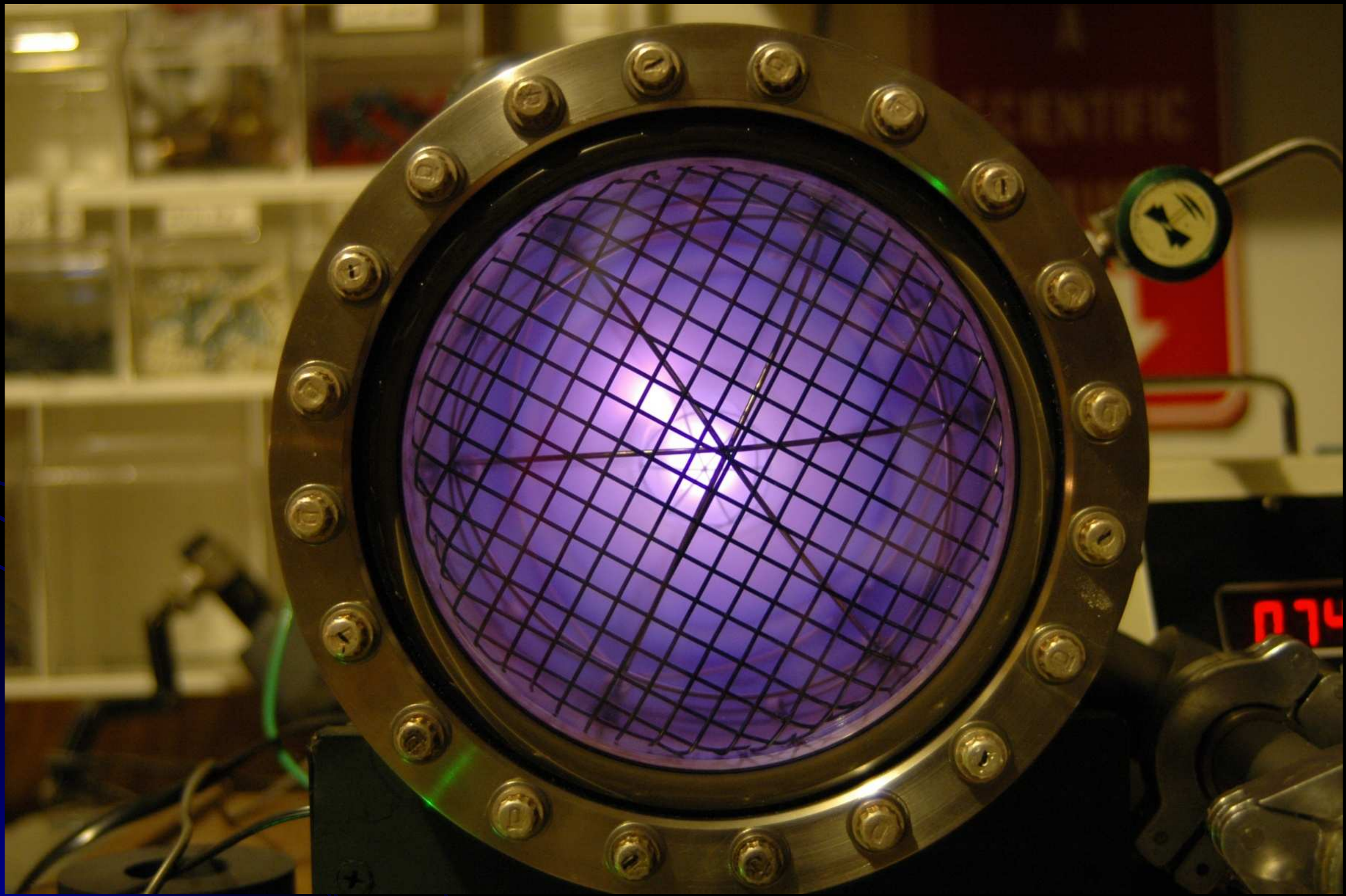
300 mtorr



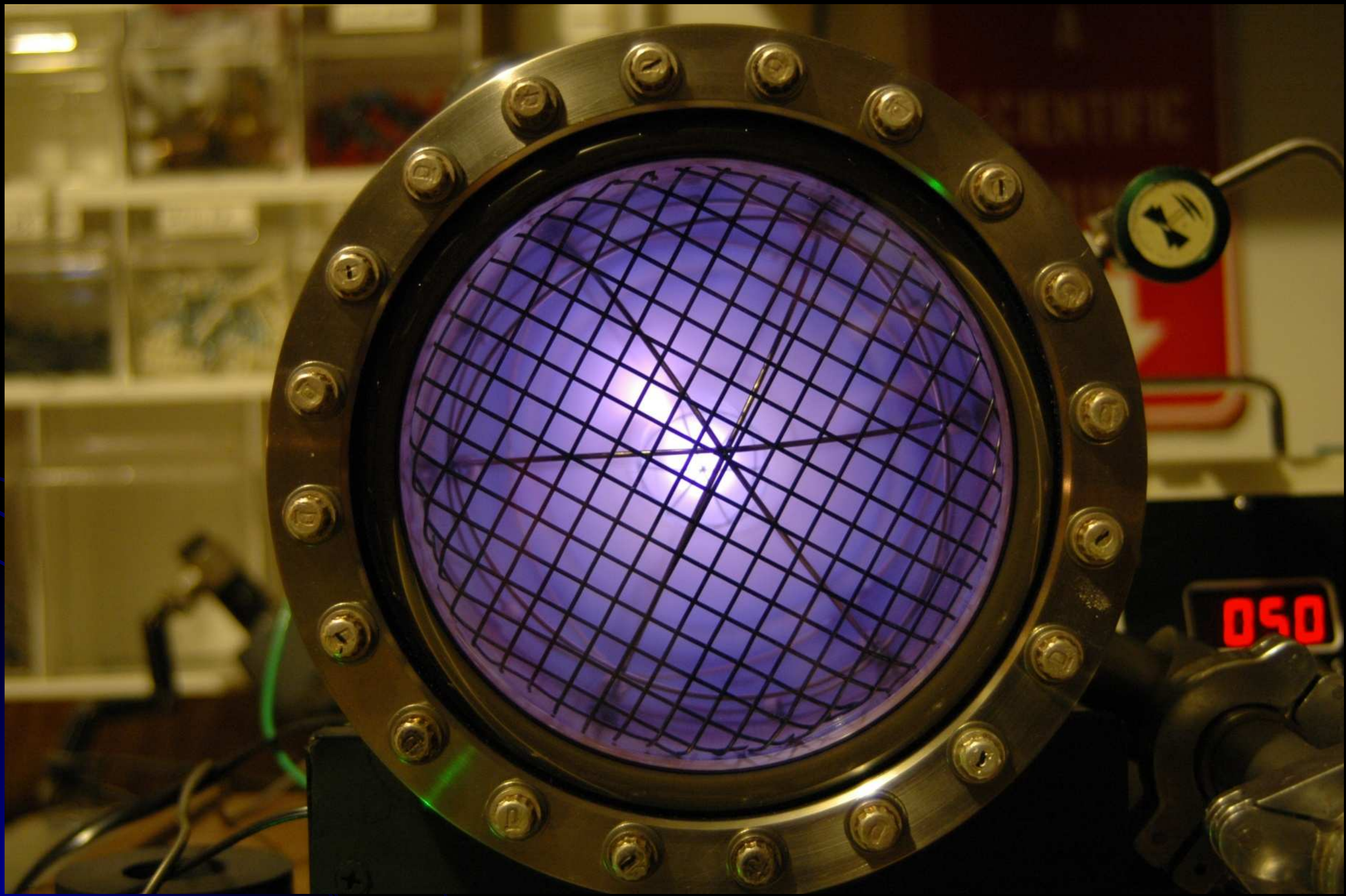
150 mtorr



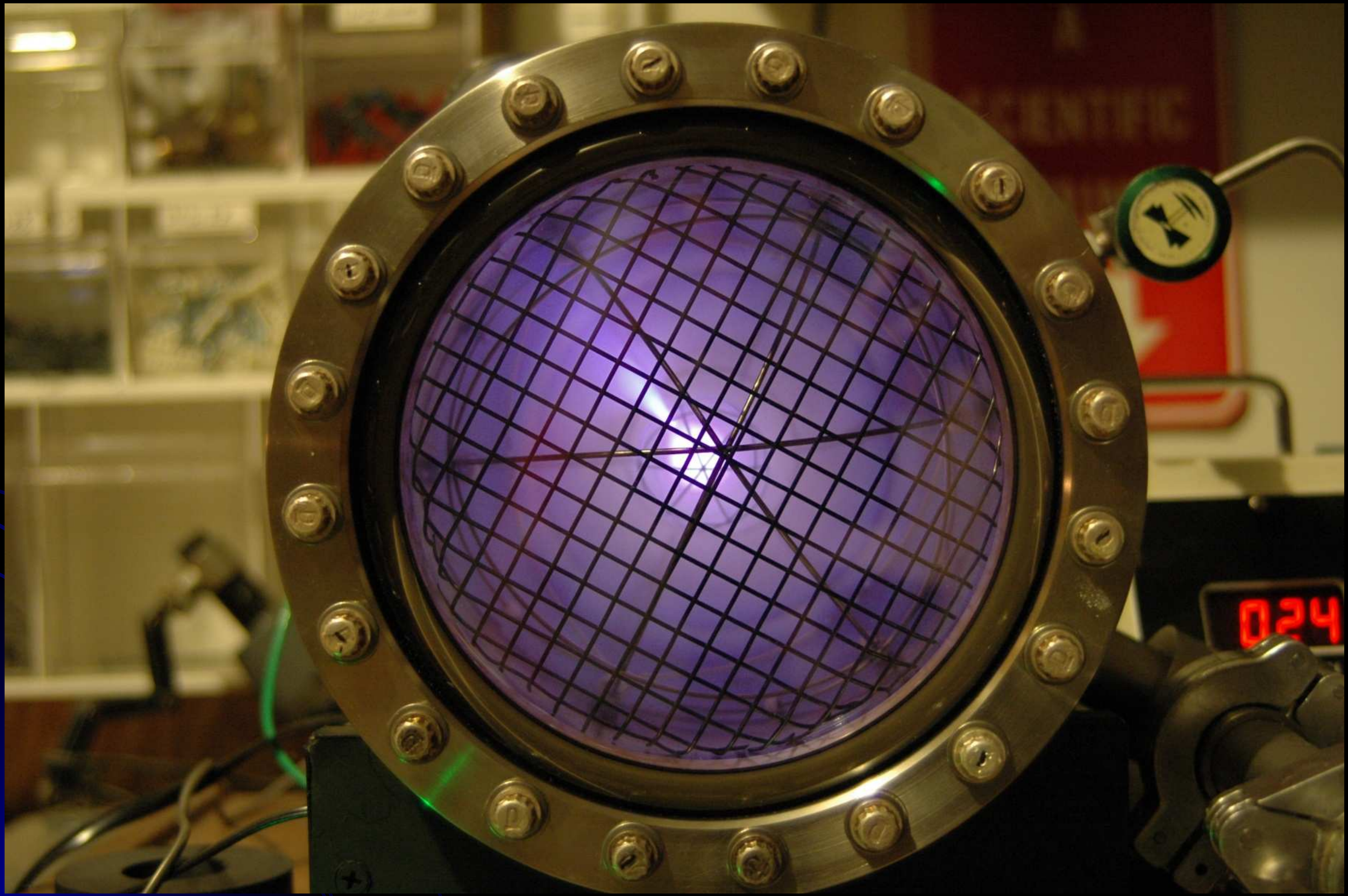
75 mtorr



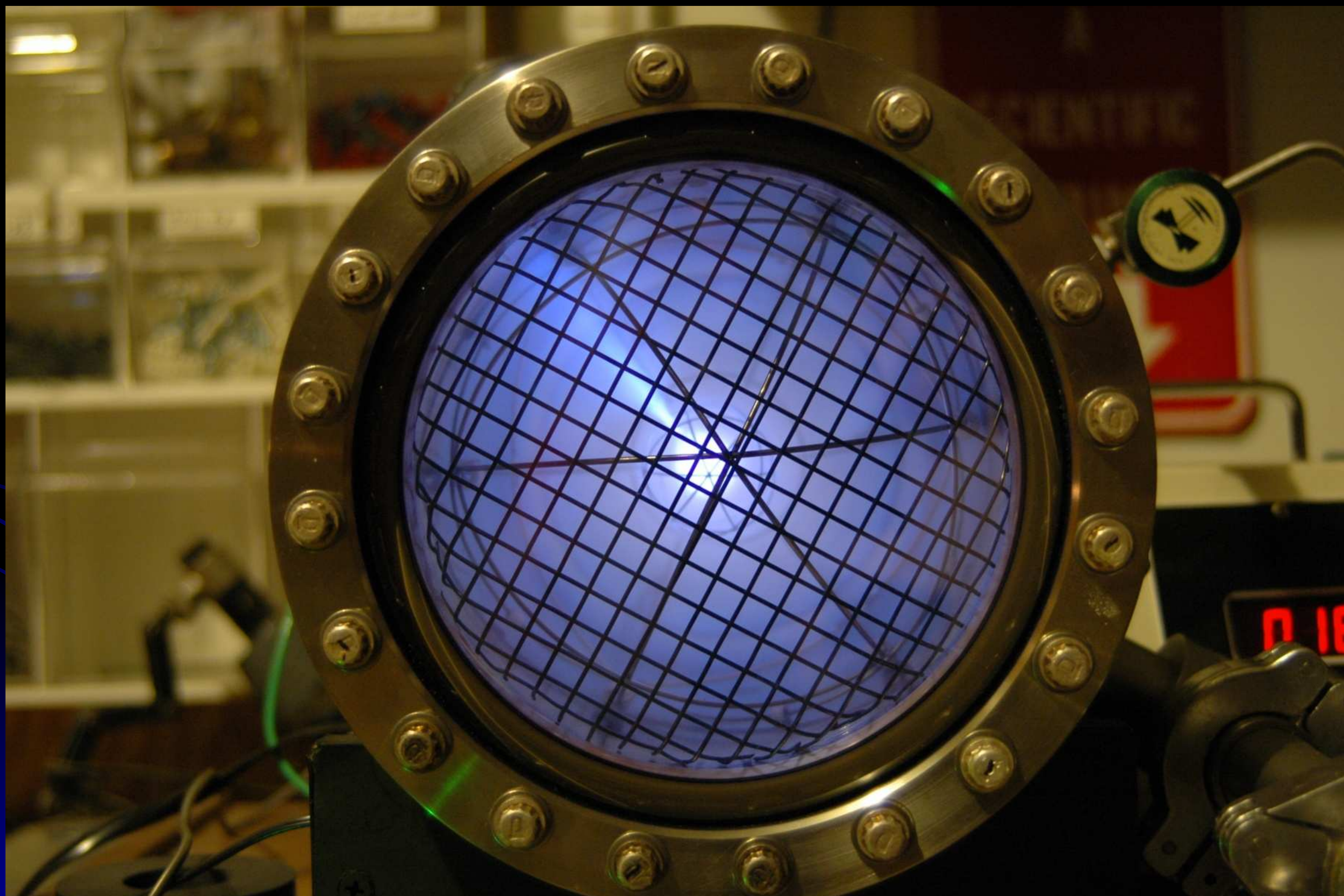
50 mtorr



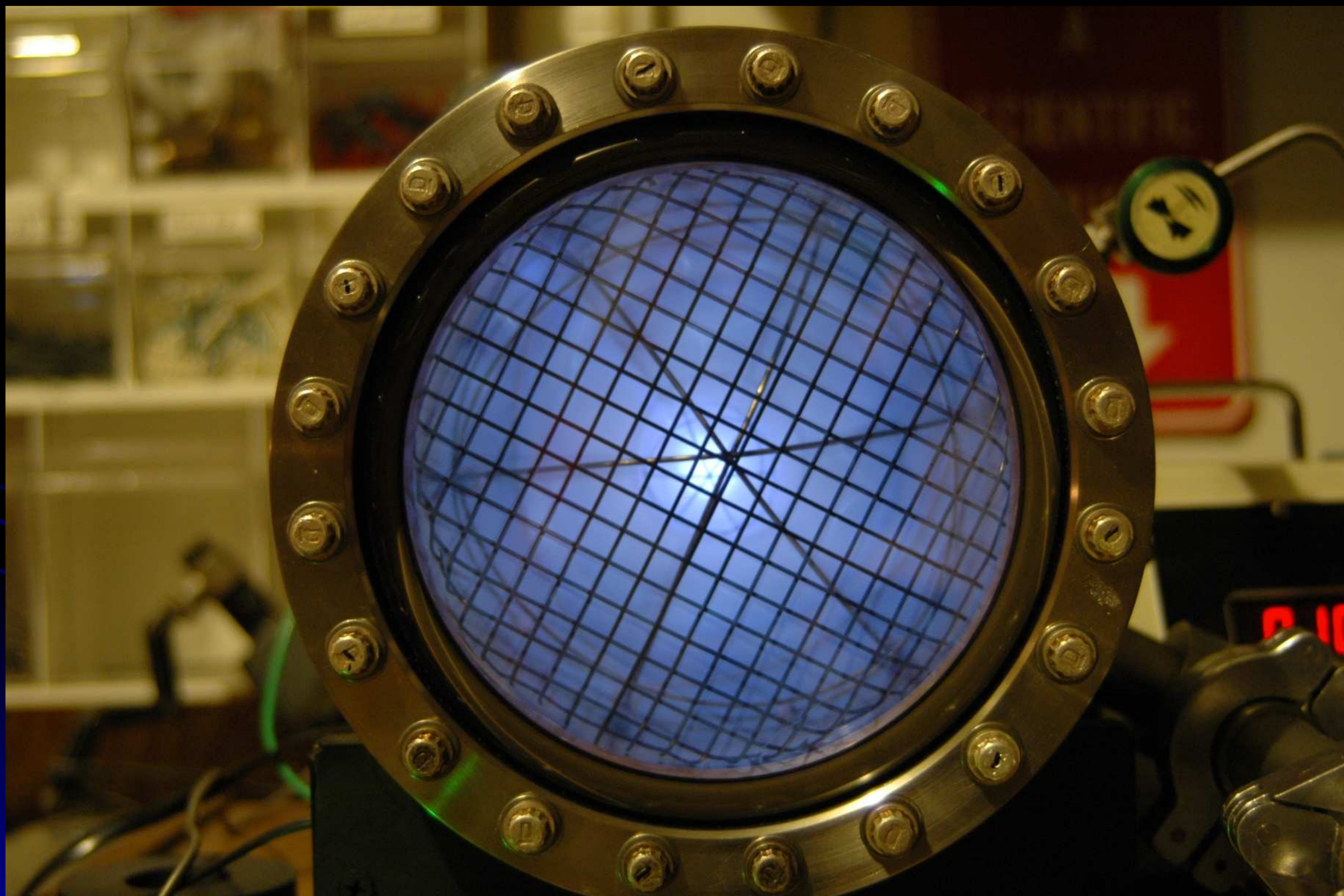
25 mtorr



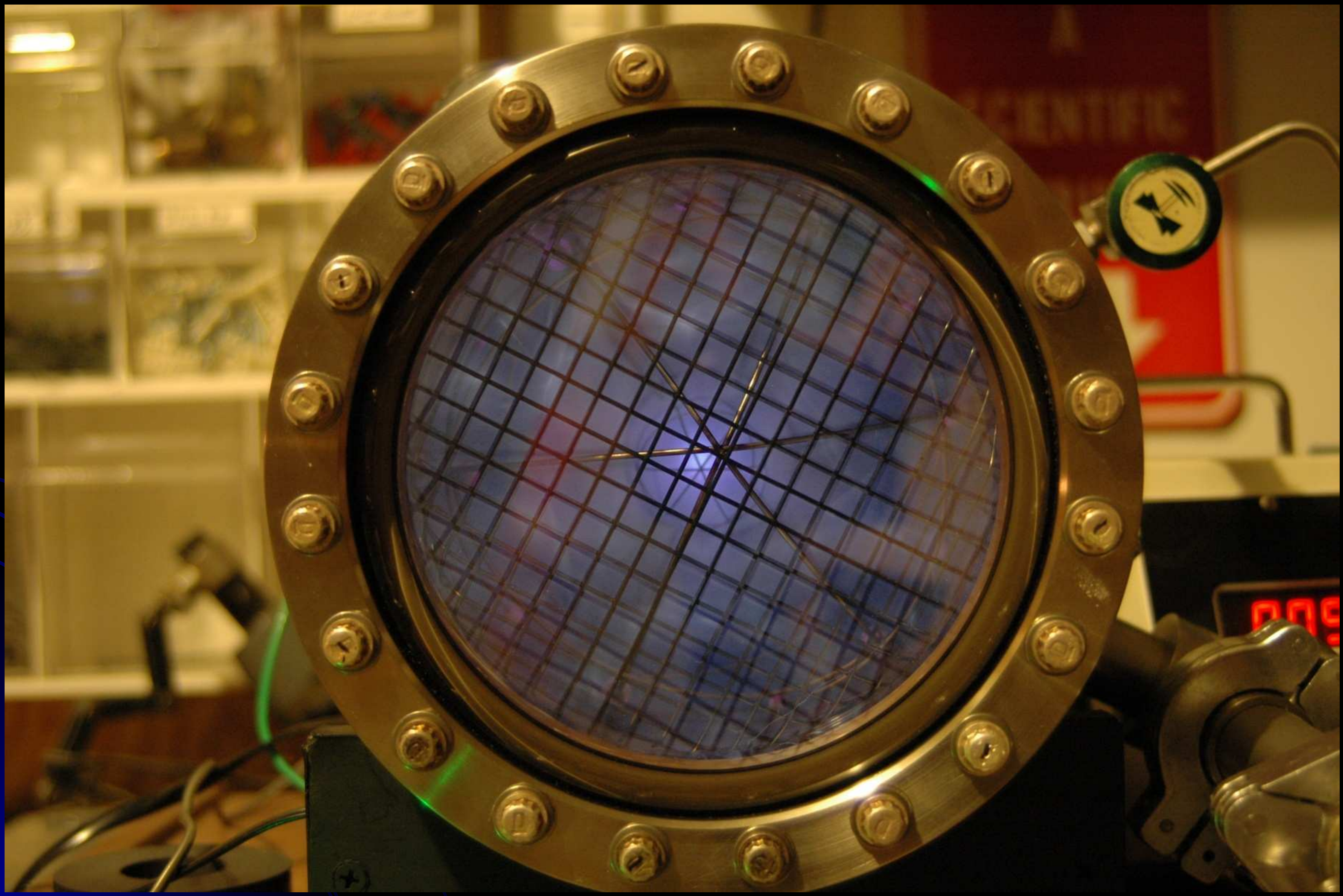
16 mtorr



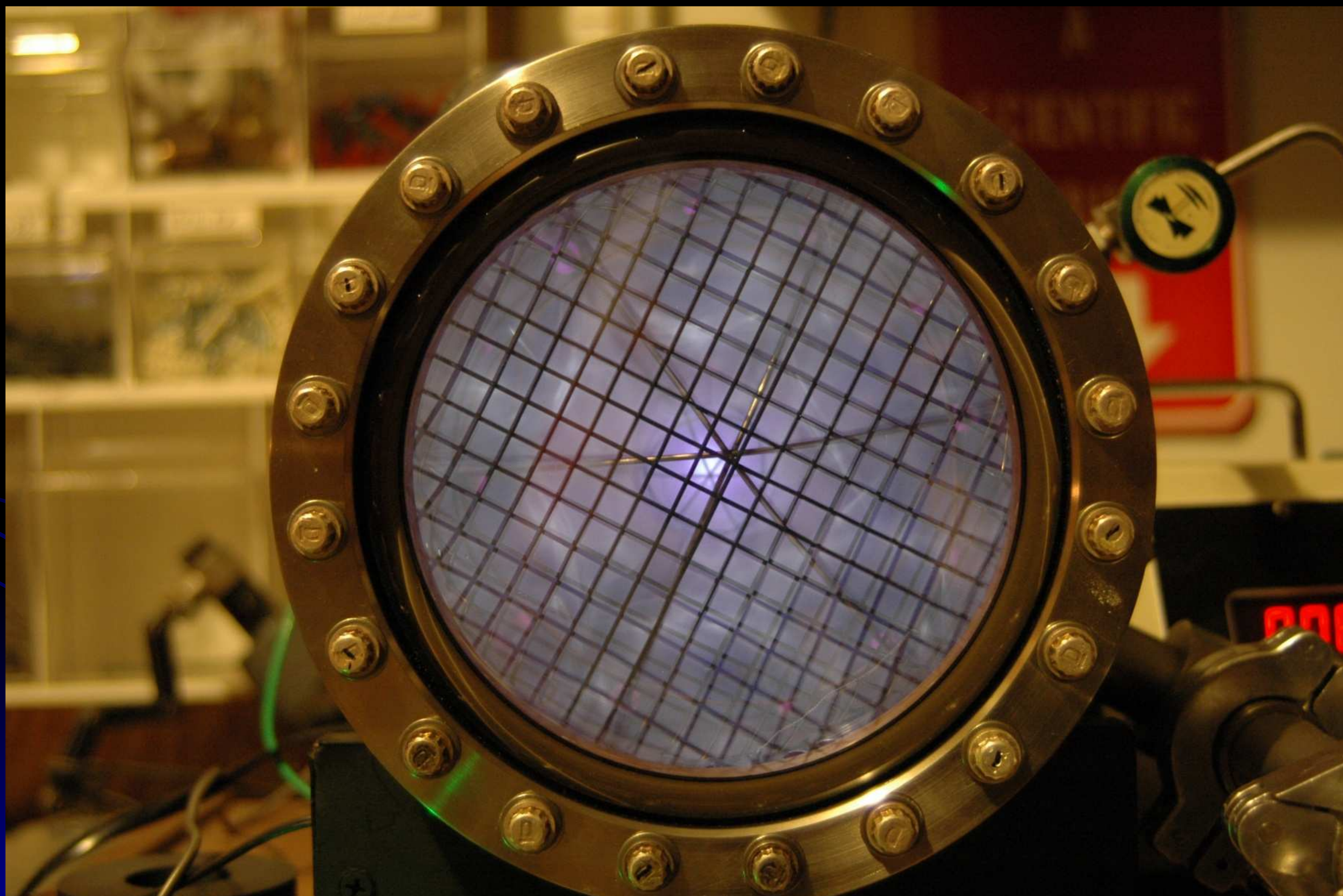
10 mtorr



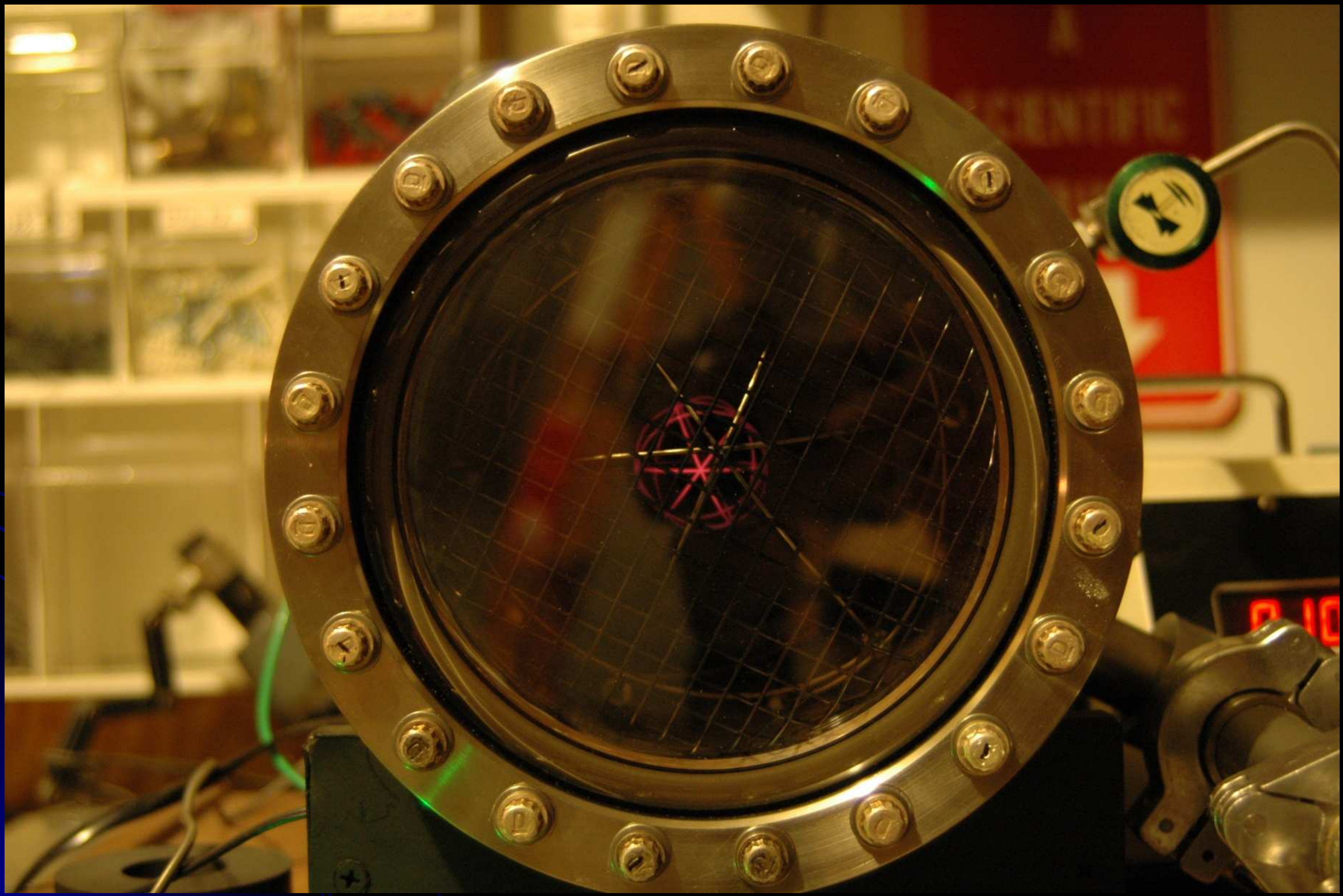
8 mtorr



7 mtorr, High Voltage



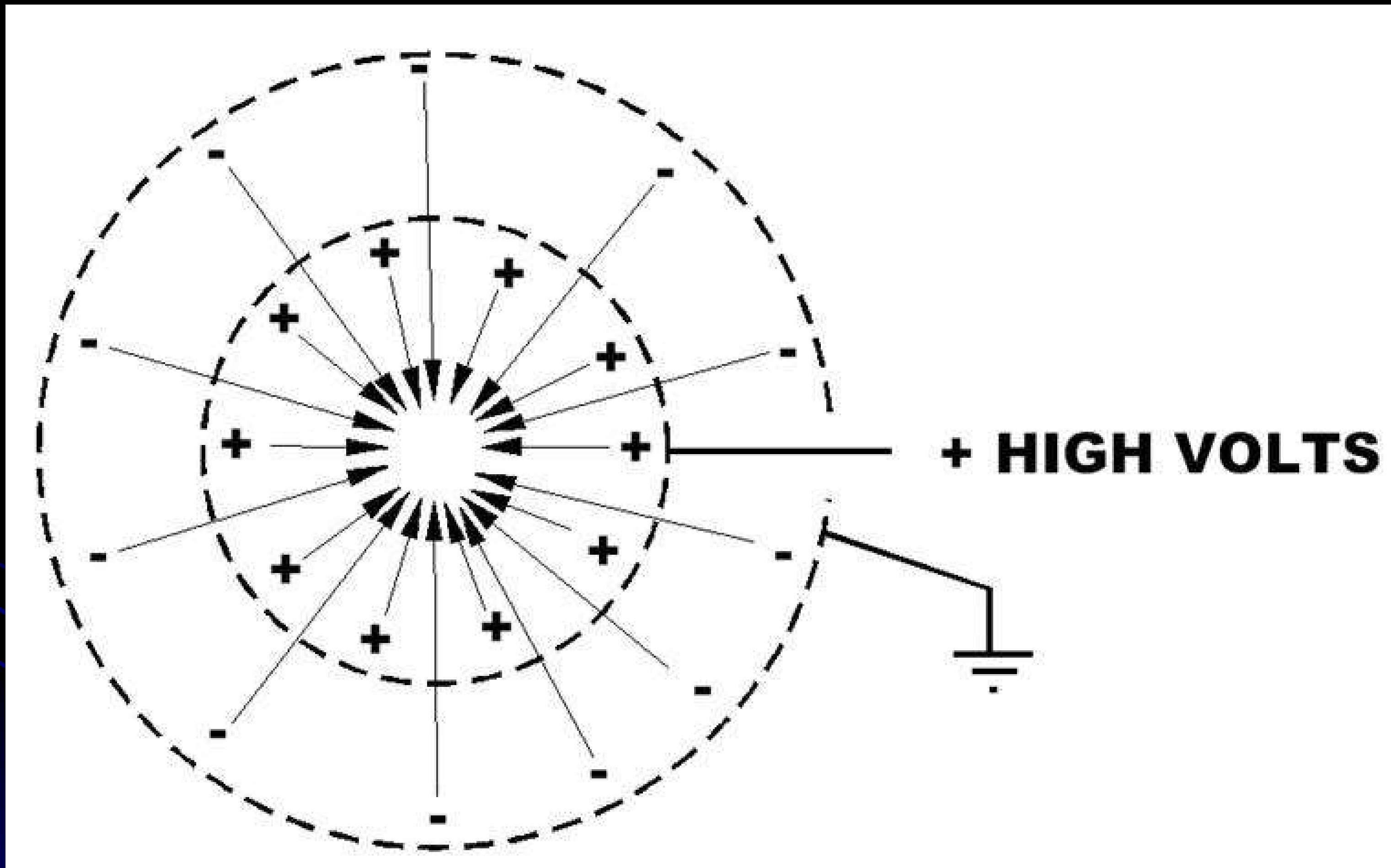
Extinguished



Fusors Cannot Make Net Power

- By a very large margin!
- Great educational tools
- Useful as neutron sources
- Easy: many high school students have built them.
- North Korea claims to have a fusion reactor … maybe they are catching up with Free World high school students?

Elmore Tuck Watson Machine



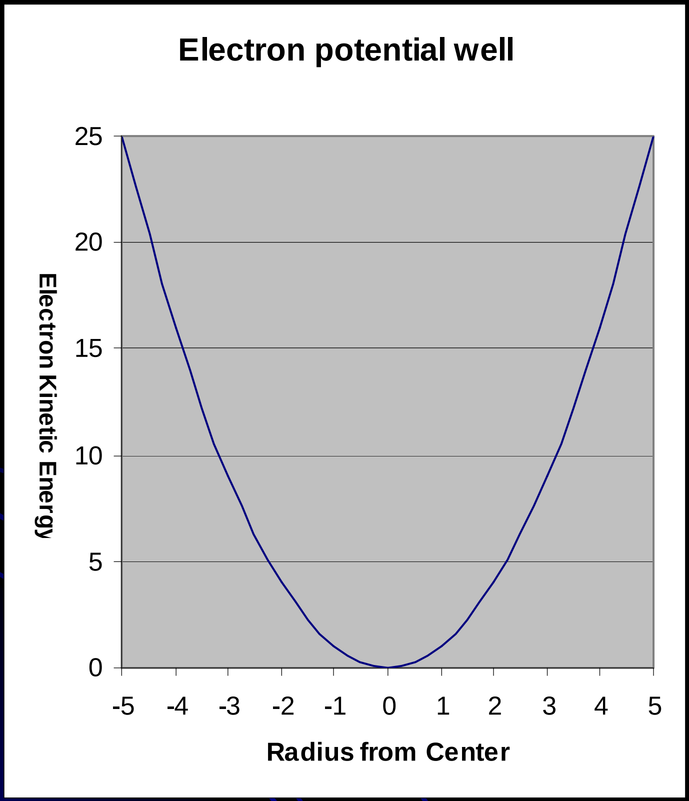
"On the Inertial-Electrostatic Confinement of a Plasma", William C. Elmore, James L. Tuck, Kenneth M. Watson, *The Physics of Fluids*, v. 2, no. 3, May-June 1959.

ETW is the opposite of a Fusor

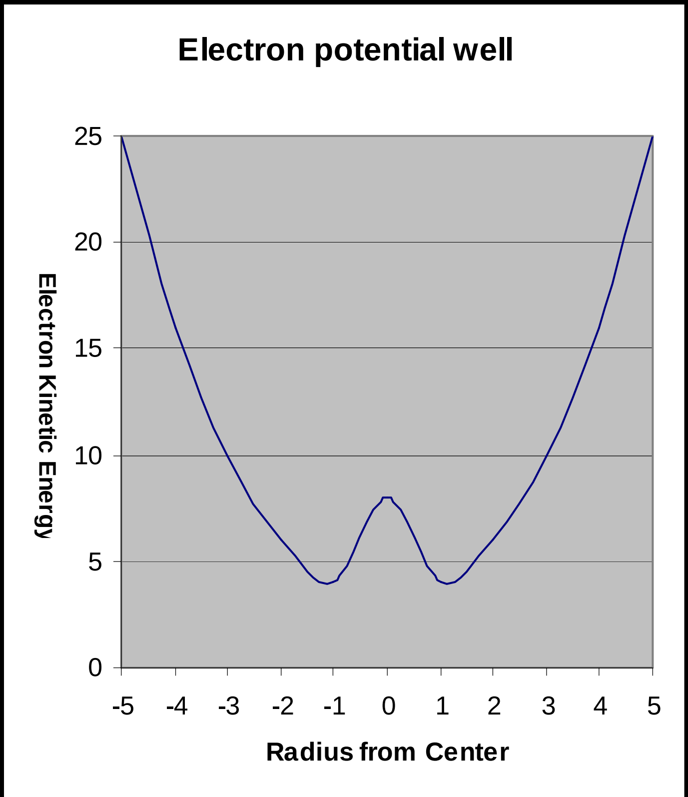
- Grid polarity reversed.
- Accelerate electrons to the center.
- Use the electrons (negative charge) instead of a negative grid to trap ions
- Hopeless electron losses for a net energy machine, but they would make some fusion.

Potential well

Just Electrons



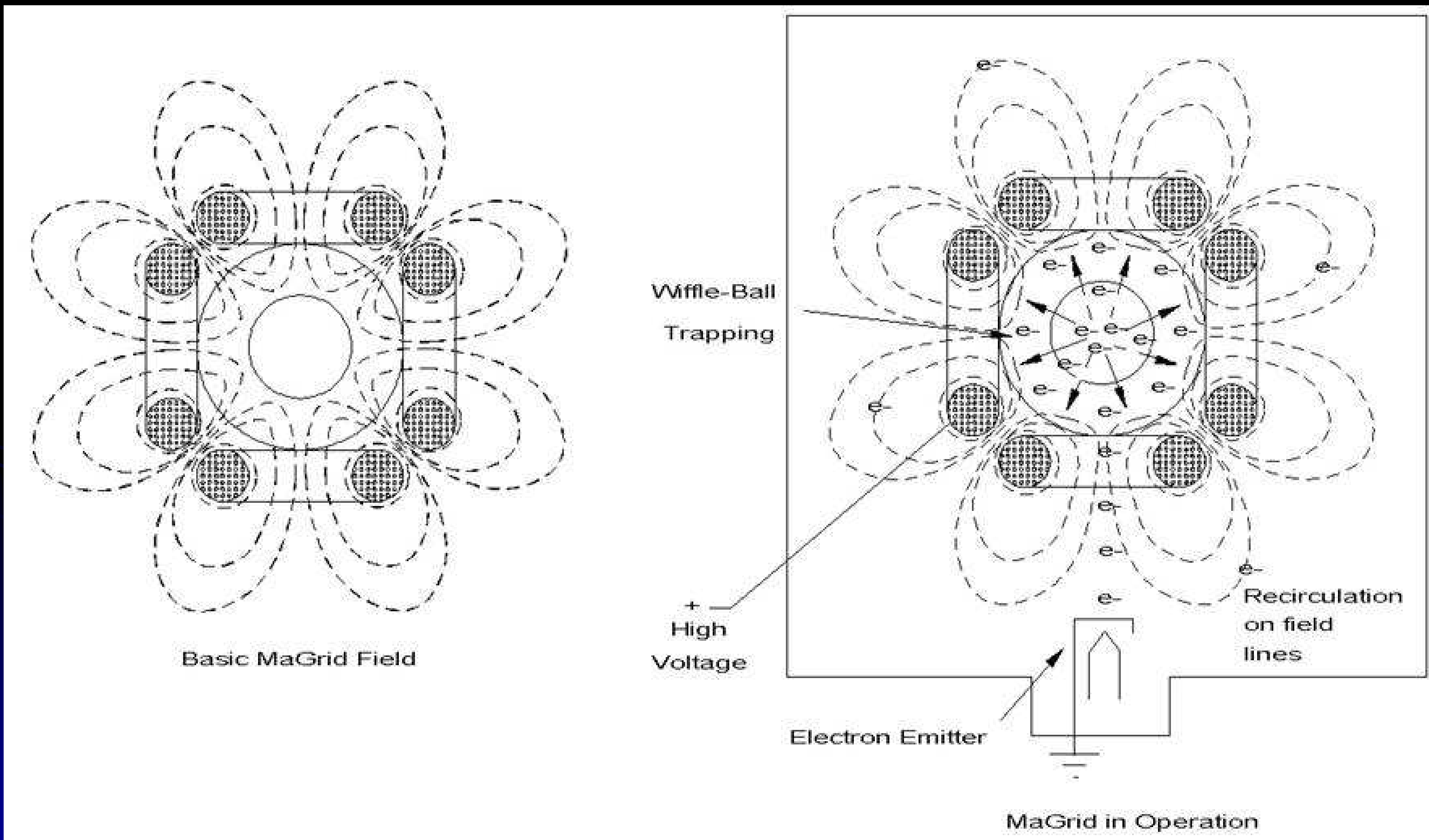
Electron Well with Converging Ions



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 or repel electrons.
- Remember, this is *dynamic* confinement, and both electrons and ions are in constant, vigorous motion.

WB6 Schematic



Energy/Matter Conversion Corp's Main Players, San Diego, WB-6

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

WB-6: Proof of Concept?

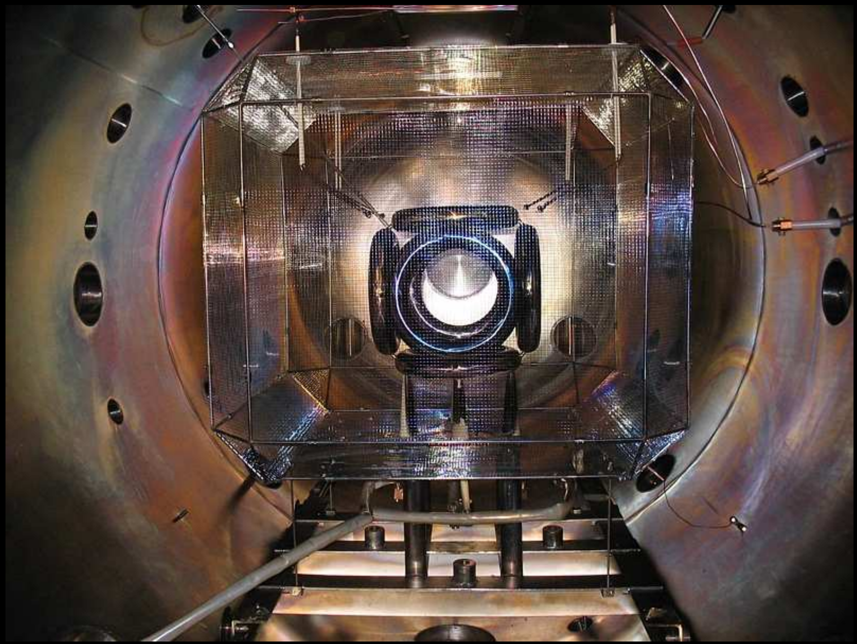
- November 2005: successful fusion tests
- Subscale device, not a net power demo
- Four test runs replicated the fusion rate
- Runs agreed with rate predicted by theory
- Theory projects a very strong scaling with increased size ($B^4R^3 \approx R^7$)
- Net power predicted at 1.5 to 2 m radius

Emc2fusion.org

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.
- Suffleball trapping plus MaGrid factor gives electron lifetimes of around 100,000 transits

WB6



Emc2fusion.org

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, 1.3×10^4 neutrons/count, 2 fusions per neutron.
- Resulting rate between 1e8 and 1e9 fusions per second … at a potential well depth of only 10 kV!

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

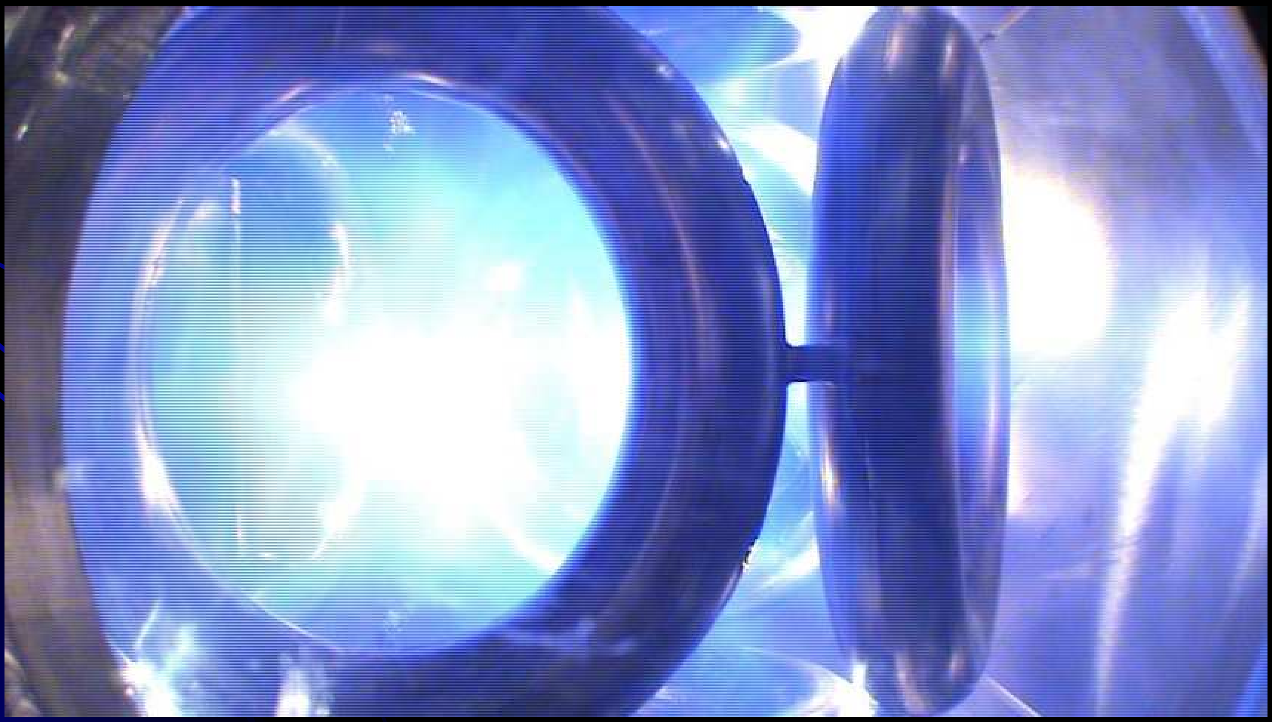
- Early engine with eye-dropper fuel metering rather than a carburetor
- Would a few cycles of firing just be a noisy waste of good booze?
- Would a cracked piston after four tests mean the technology was doomed?
- Or would you build an improved engine with fuel metering, cooling, oil system?

Main Players, Santa Fe, WB-7

- Rick Nebel (Theory)
- Jaeyoung Park (Lab work)
- Both “on loan” from Los Alamos, very experienced in IEC fusion research
- Mike & Kevin Wray (Computer/Physics)
- Mike Skillicorn (Mech. Design)

WB-7: Confirming Study

- Runs consistently and reliably “Like a watch”
- “Produces results we like”
  - (The results are, however, “nuanced”)
- Results have been peer reviewed.
- But project back under *&%$ embargo



WB7.1 under construction

- Larger scale, less than a net power size
- Attempt to burn p-B11?
- Funding around $8M?

Proposal for full-sized WB-D reactor

- Highly speculative at this point, beyond the scope of funded work
- EMC2FDC soliciting donations to pursue preliminary design work

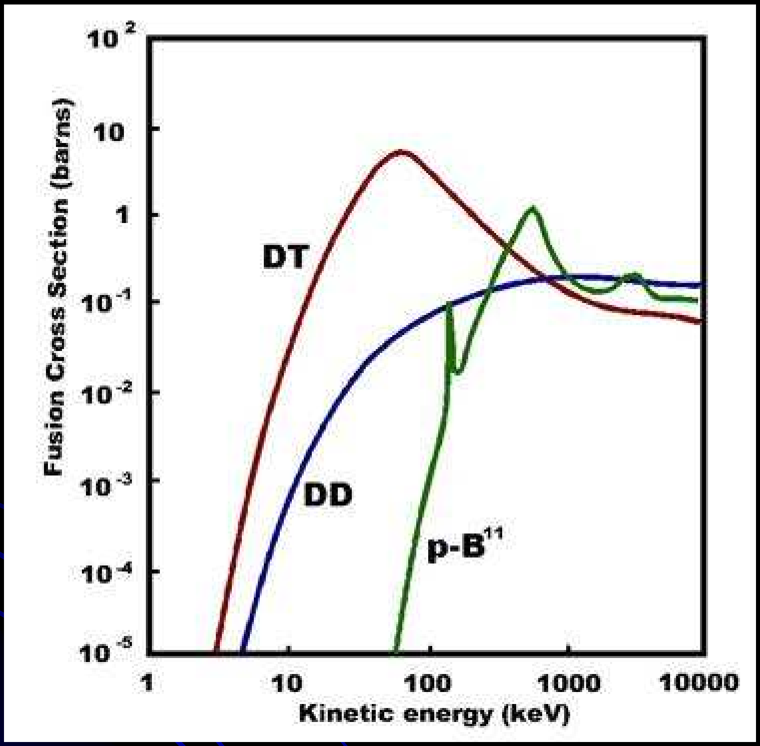
And then ….

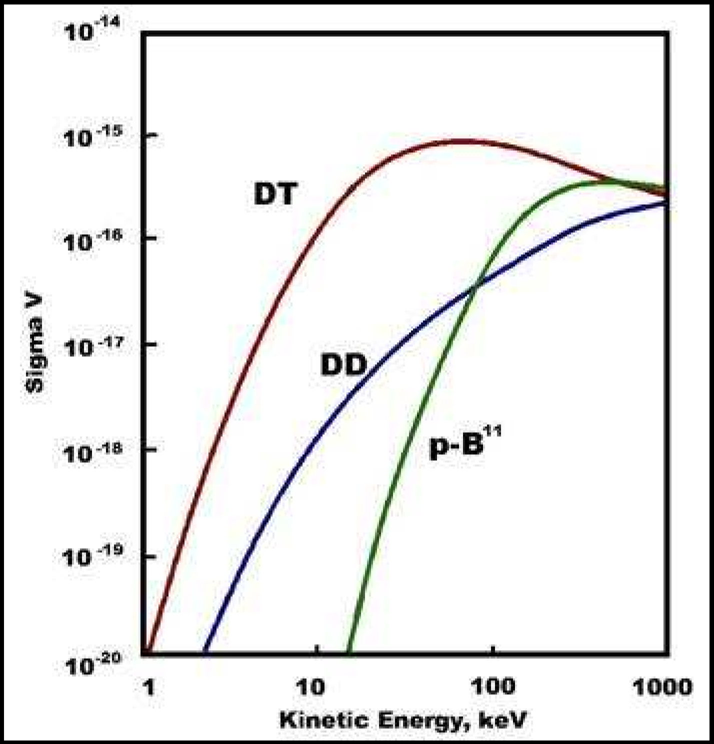
- OK, let’s suppose they build a p-B11 net power reactor ….
- …. And then save the planet with cheap, clean power ….
- …. And make a lot of money so we can do what we really want to do …

p-B^{11}

- Can’t be run in a tokamak … initiation energy far too high, bremsstrahlung losses excessive.
- 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
- Brem losses mitigated by restricting the central virtual anode height (keep electron energy low) and running hydrogen-rich (keep average Z low)

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.
- $p\text{-}B^{11}$ may allow 85 - 95% recovery

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
- By 2015, world installed generating capacity projected at over 5000 gigawatts, so a nice market exists

US Energy Information Administration, Report #:DOE/EIA-0484(2010)

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.

Find papers at Askmar.com

Space Power

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

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

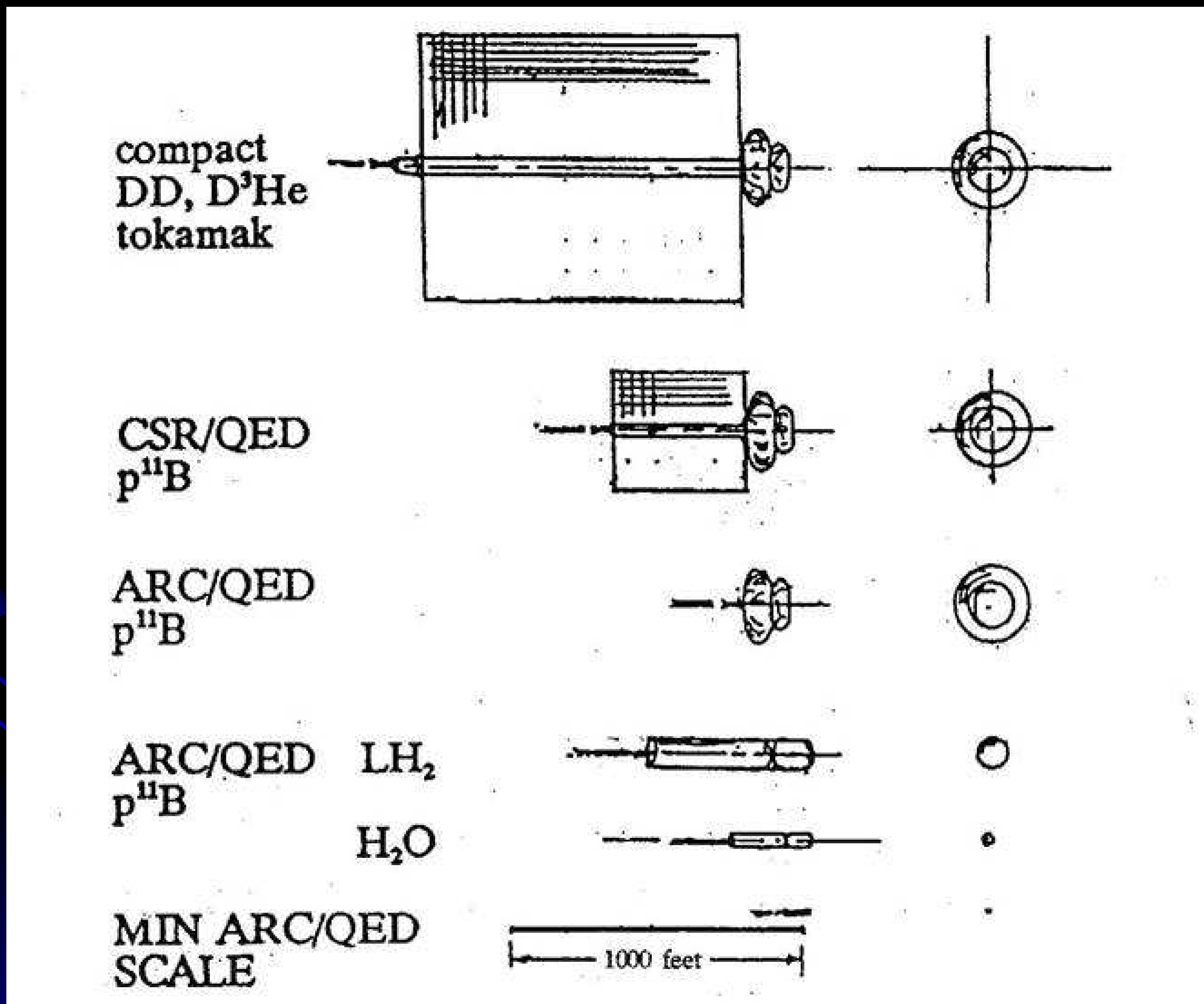
- 180 HP light aircraft: 134 kW

- 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”.

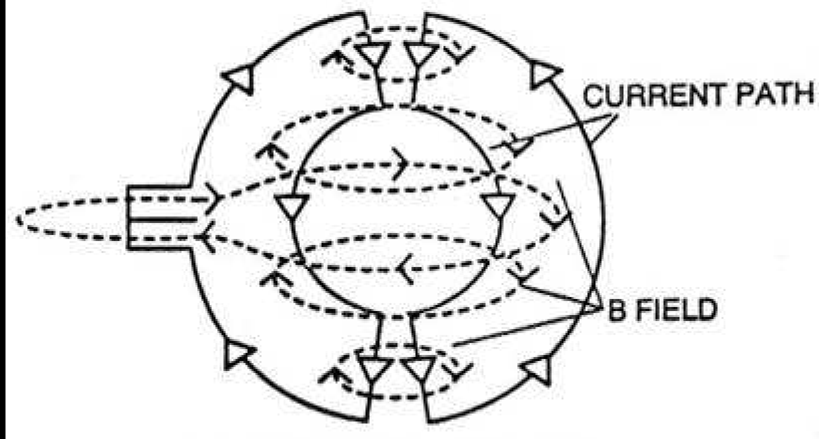
QED/CSR Types

- 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



Emc2fusion.org

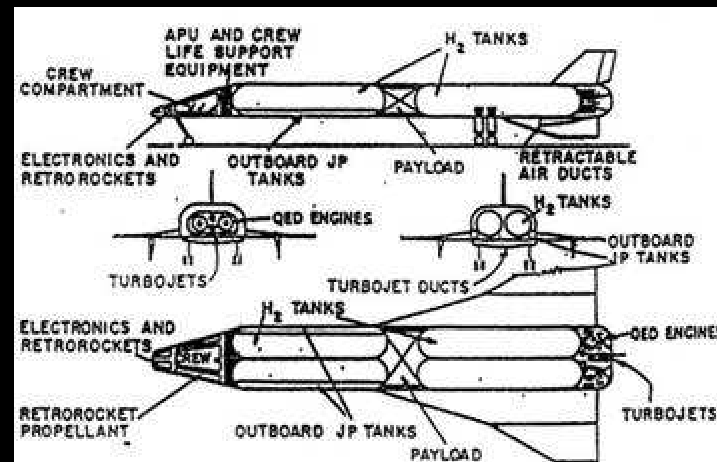
Spacecraft Based on These Systems

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

Emc2fusion.org

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

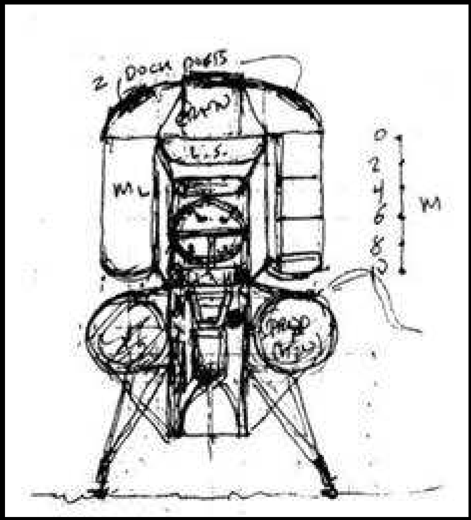
33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit

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

See Askmar.com for paper

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
- ΔV 15.8 km/sec
- $24.20/kg



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

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

Figure: an RWB original!

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

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

See Askmar.com for paper

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

See Askmar.com for paper

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.

See Askmar.com for paper

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.

See Askmar.com for paper

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.

See Askmar.com for paper

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
- Open-Source discussions: talk-polywell.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)
- en.wikipedia.org/wiki/Polywell
- cosmiclog.msnbc.msn.com/ (news updates)
- Handout available after the talk