Permanent Magnet Spherical Penning trap as a Small Fusion Source

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The Penning Trap as a Fusion Reactor

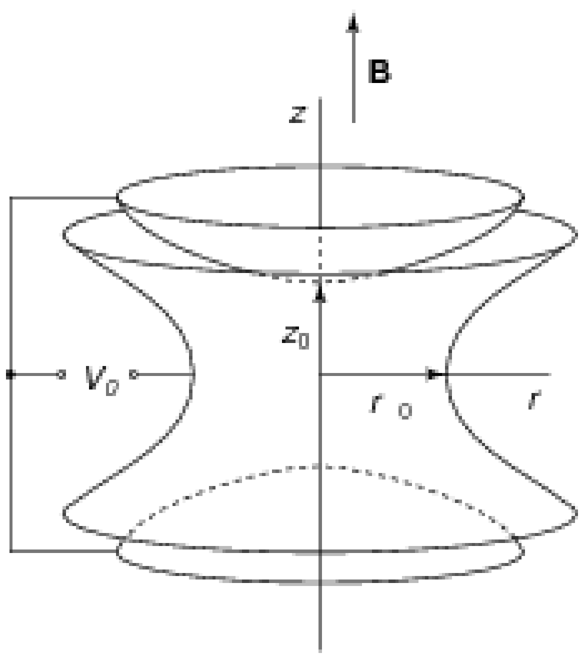
Original concept:

G. Miyamoto, G. Iwata, S. Mori, and K. Inoue, A Possible Fusion Reactor, *Journal of the Physical Society of Japan* **12**(4), 438 (1957).

Detailed Examination by Los Alamos Group:

D. C. Barnes, R. A. Nebel, L. Turner, and T. N. Tiouririne, "Alternate Fusion: Continuous Inertial Confinement," *Plasma Physics and Controlled Fusion* **35**, 929-940 (1993).

The Penning Trap



- Hyperbolic end cap and ring electrodes form a 3D quadrupole electric field.
- Tuning V with B can make the potential well spherical and harmonic.
- Charged particles inserted via a hole in an end cap can be confined in the spherical well.

The Penning Trap as a Fusion Reactor

Overall Scheme:

- A Penning trap with uniform B, harmonic V can be tuned to make a spherical well for electrons.

$$\Phi_{eff} = \frac{V}{3a^2}(r^2 - 2z^2) - \frac{eB^2}{8m} r^2 \qquad (R_0 = Z_0 = a)$$

$$V_0 = \frac{eB^2a^2}{8m_e} \qquad \text{Well depth} = 2/3 \text{ of } V_0$$

- Spherical convergence of trapped electrons produces a central virtual cathode (without the use of grids).
- Ions confined by the central cathode can reach keV energies and undergo nuclear fusion.

(tradeoff between n_i and T_i ; T_i around 10% of V_0)

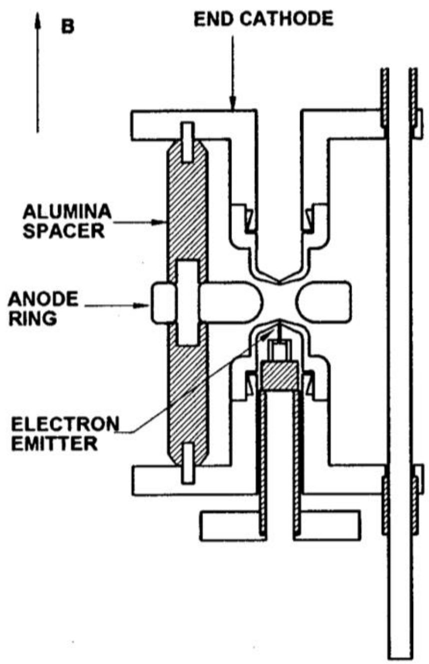
Very Low Power Requirements

- Electrons are loaded into the well over a low potential barrier (a few V) at very low current (uA).
- Scattered electron current to the anode (10’s kV) is very low (10’s uA) (mW power input)
- Contrast with gridded IEC fusion device where grid (10’s kV) current (10’s mA) can approach kW power input levels.

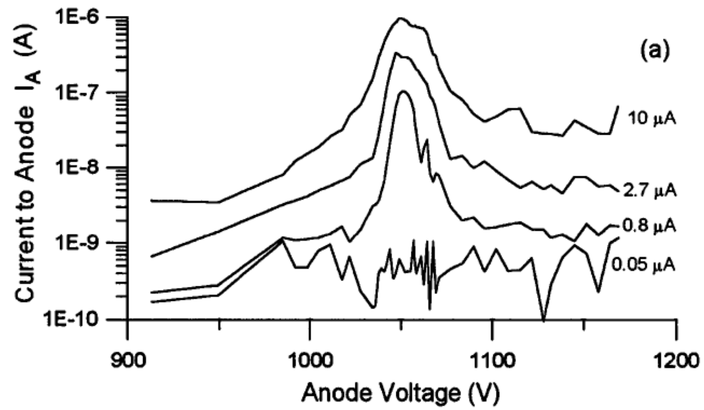
Potential for Fusion with Q ≥ 1, but

- Highest rates require high (hundreds of kV) potentials.
- Very challenging requirements for high voltage standoff.

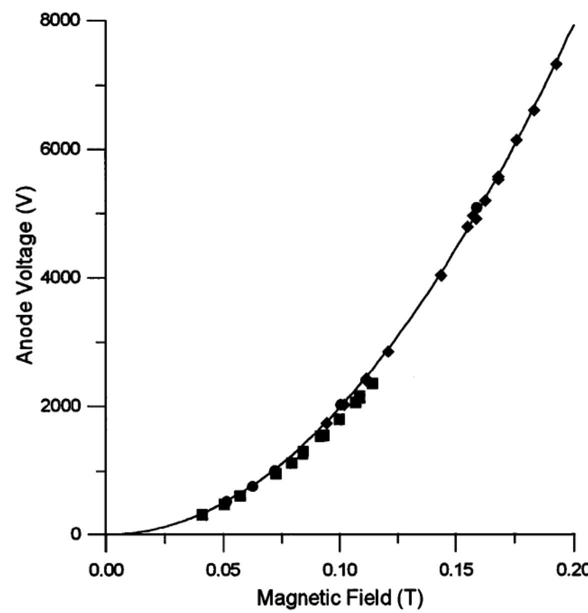
Los Alamos PFX Device, 1997



a = 3 mm



B = 0.076 T.



$V_o = eB^2a^2/8m_e$

T. B. Mitchell, M. M. Schauer, and D. C. Barnes, *Phys. Rev. Lett.* **78**, 58 (1997).

Summary of LANL PFX Work

- Extensive theoretical analysis of the system.
- Observed spherical focus of electrons as predicted by theory.
- Observed electron density 30 times the Brillouin limit.
- Observed 100:1 radial convergence of trapped electrons.
- Acquired data up to 8 kV anode potential.
- Theory predicted possibility of $Q \geq 1$.
- Did not reach the point of actually demonstrating fusion.

Unfortunately, work was terminated due to end of funding.

Penning Traps as Neutron Sources

D.C. Barnes

presented at the
16th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Applications
Madison, WI, October 1, 2014

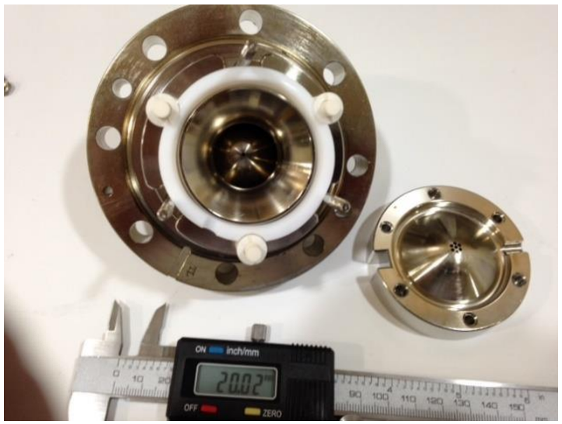
Some summary points:

"Significant Q at mW fusion level."

"Only need modest (but challenging) technology improvements to make Q~1."

"Currently no funding, but ……..a "garage" scale experiment."

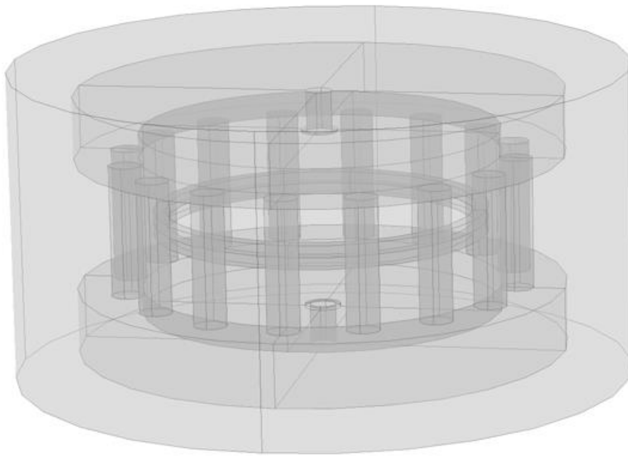
Initial Studies with a Salvaged Paul Trap

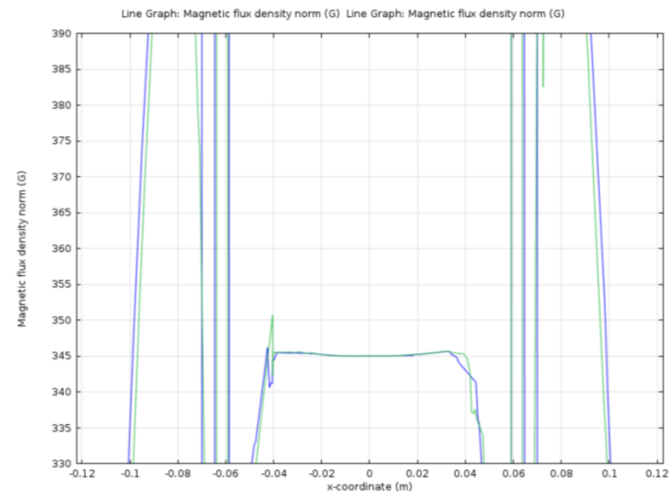


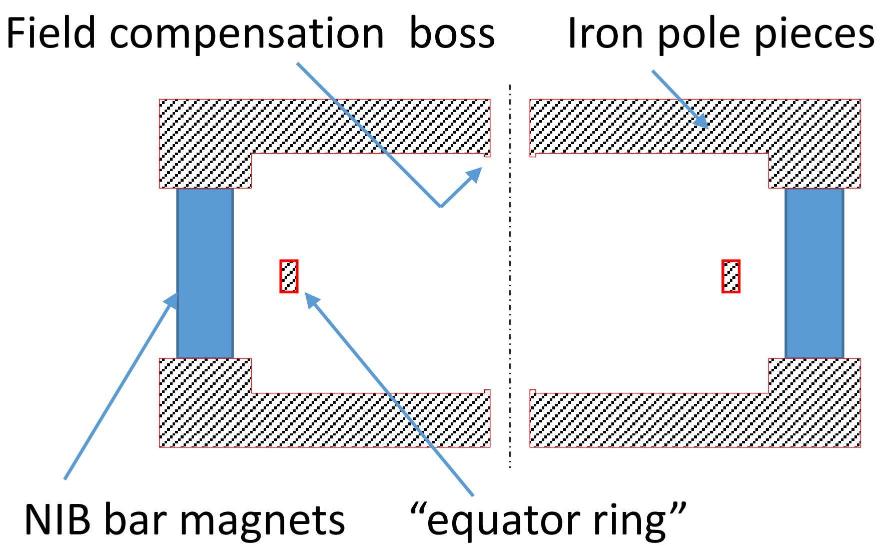
The hyperbolic trap used in the initial experiments was salvaged from an ion trap mass spectrometer.

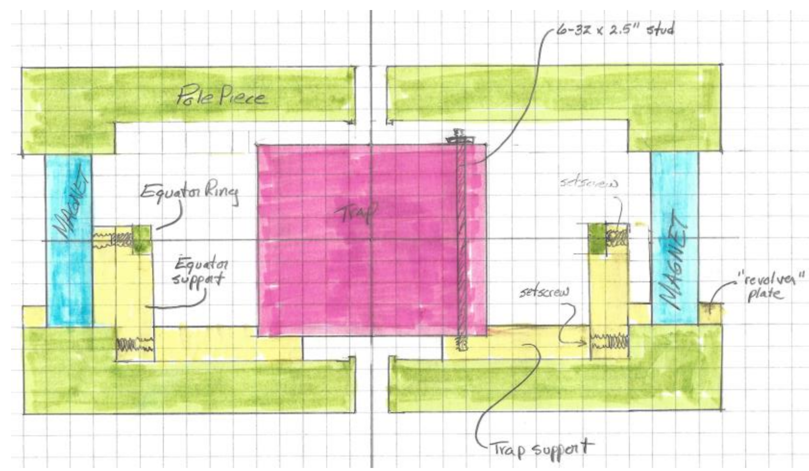
The electron source was an electron microscope hairpin filament.

Permanent Magnet Solenoid

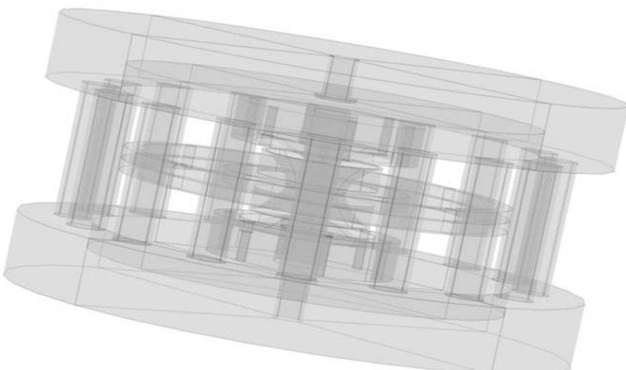


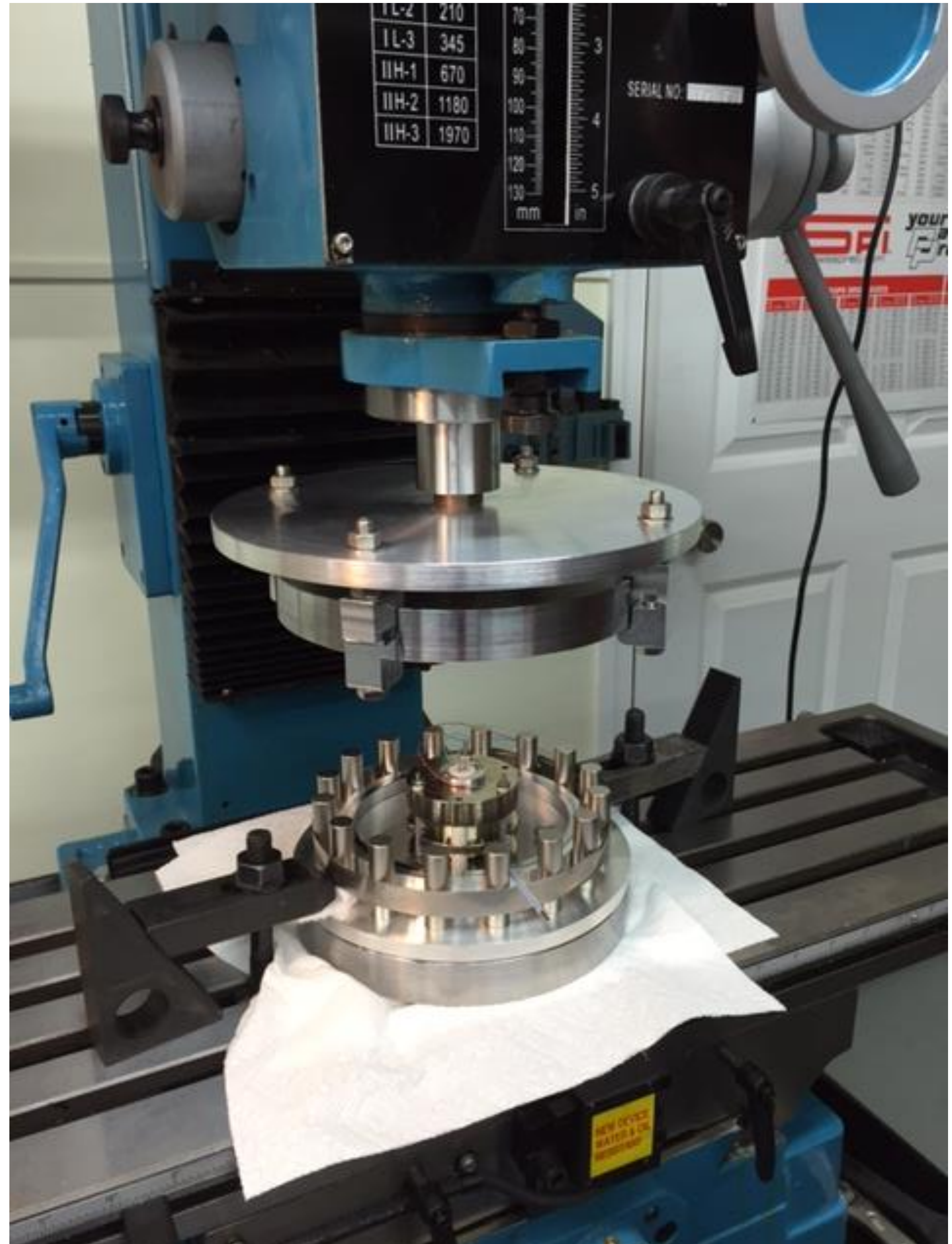




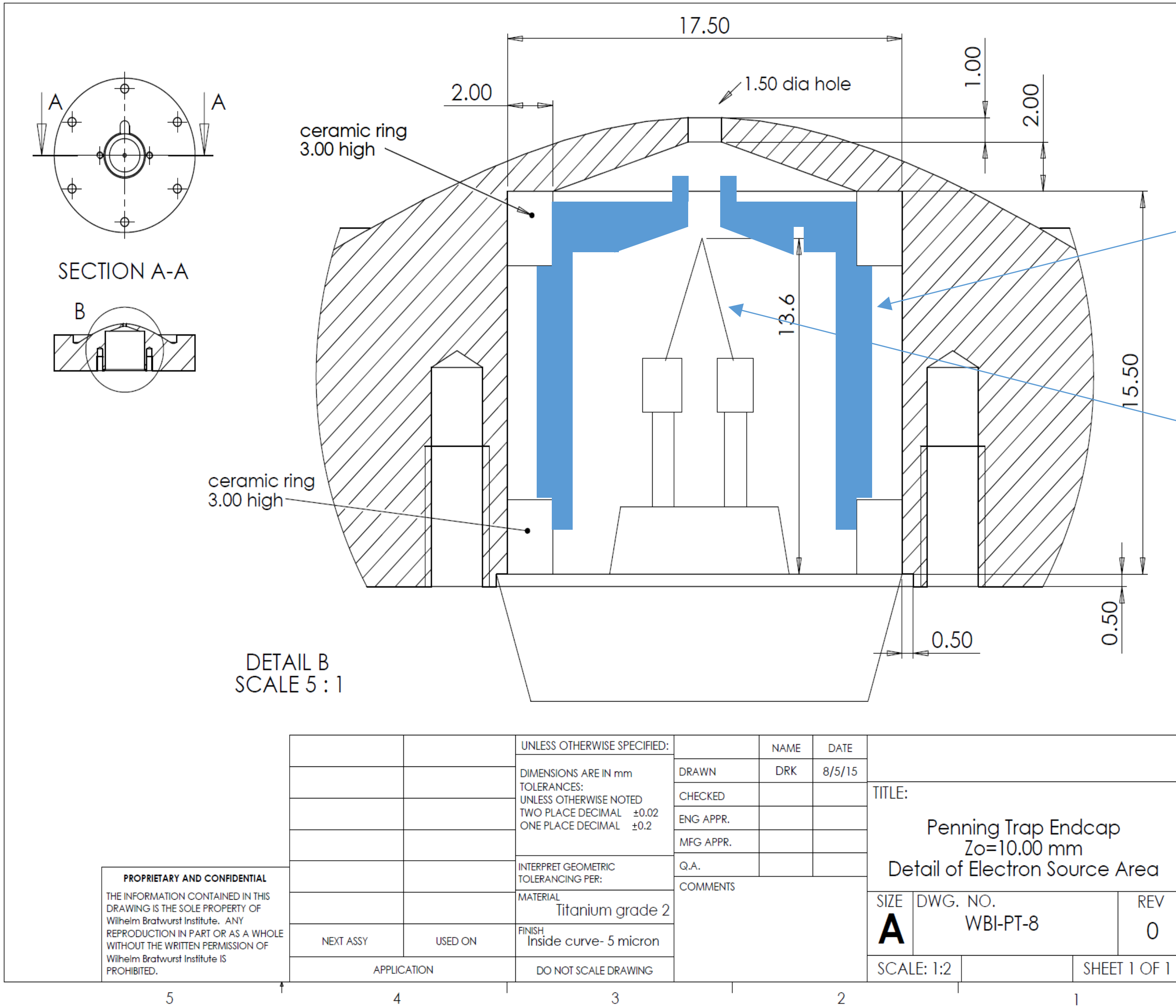


Assembly of Permanent Magnet Solenoid





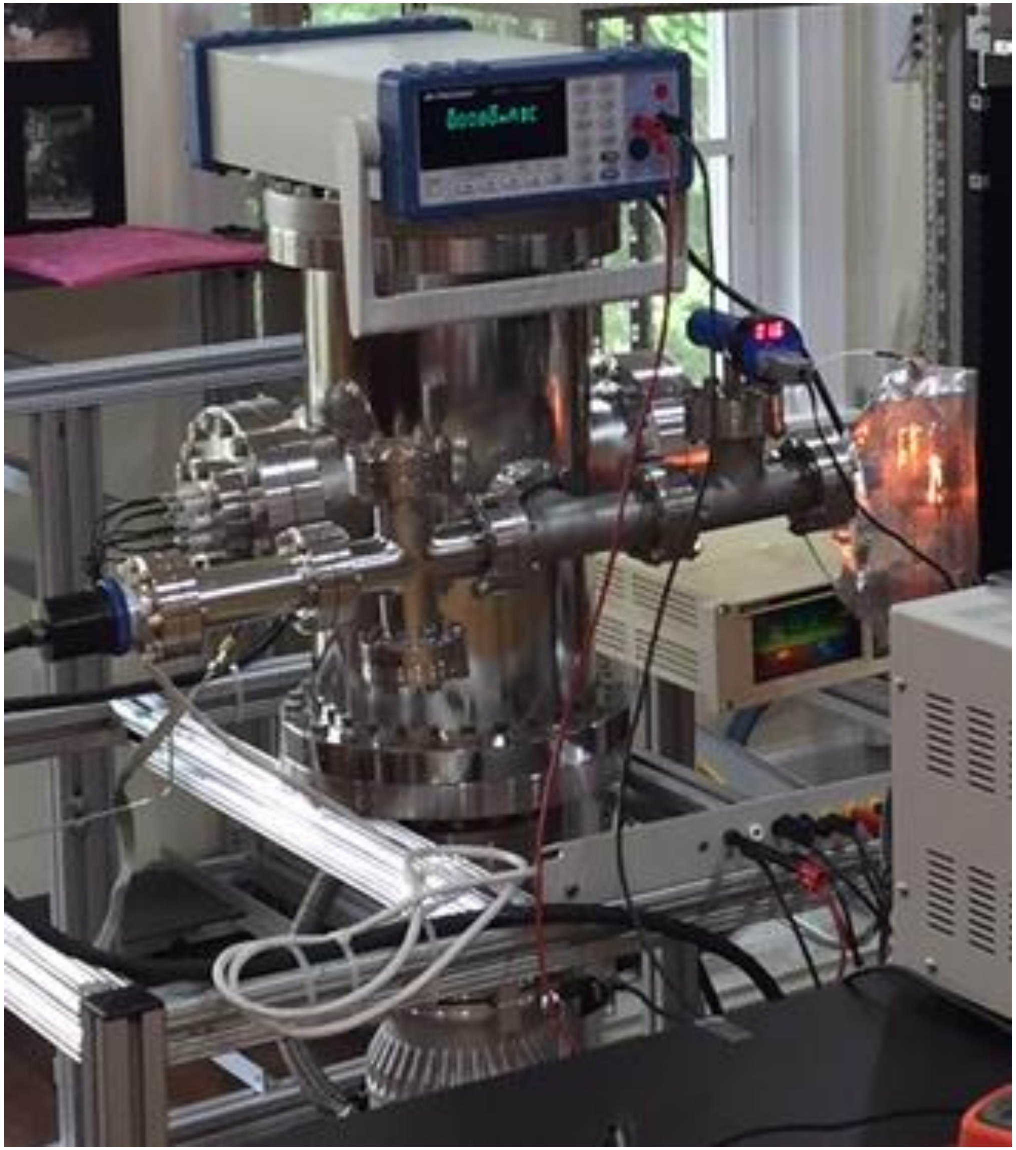
Tungsten Filament Electron Source



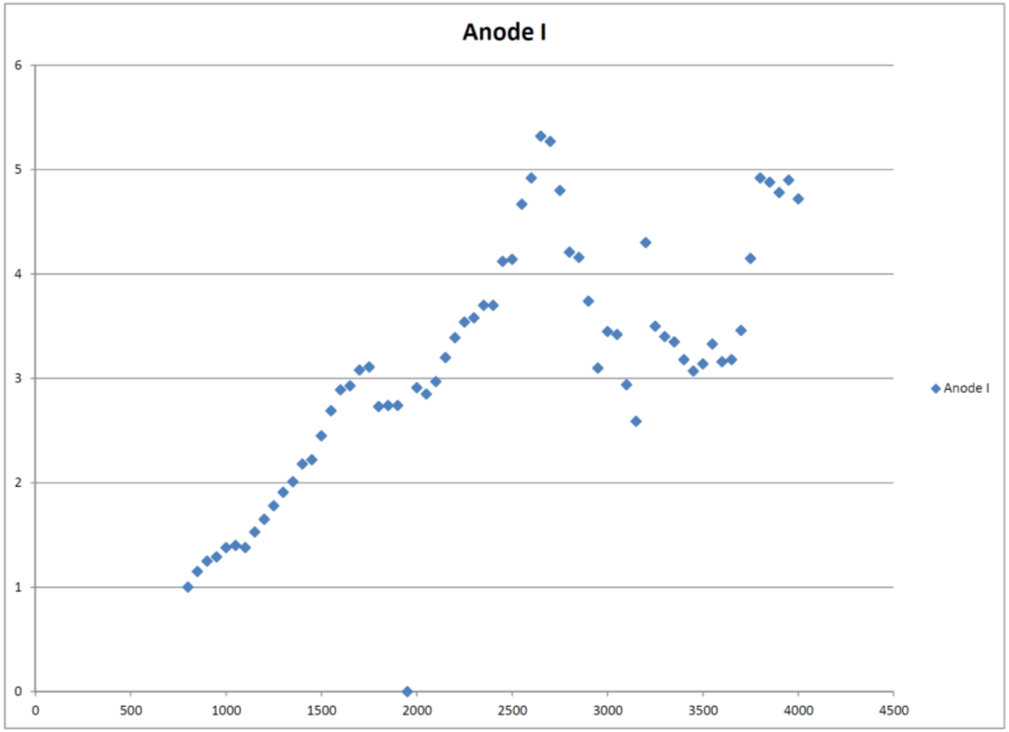
“Wehnelt” electron focus element

Tungsten electron Microscope filament

Vacuum Chamber and Overall System

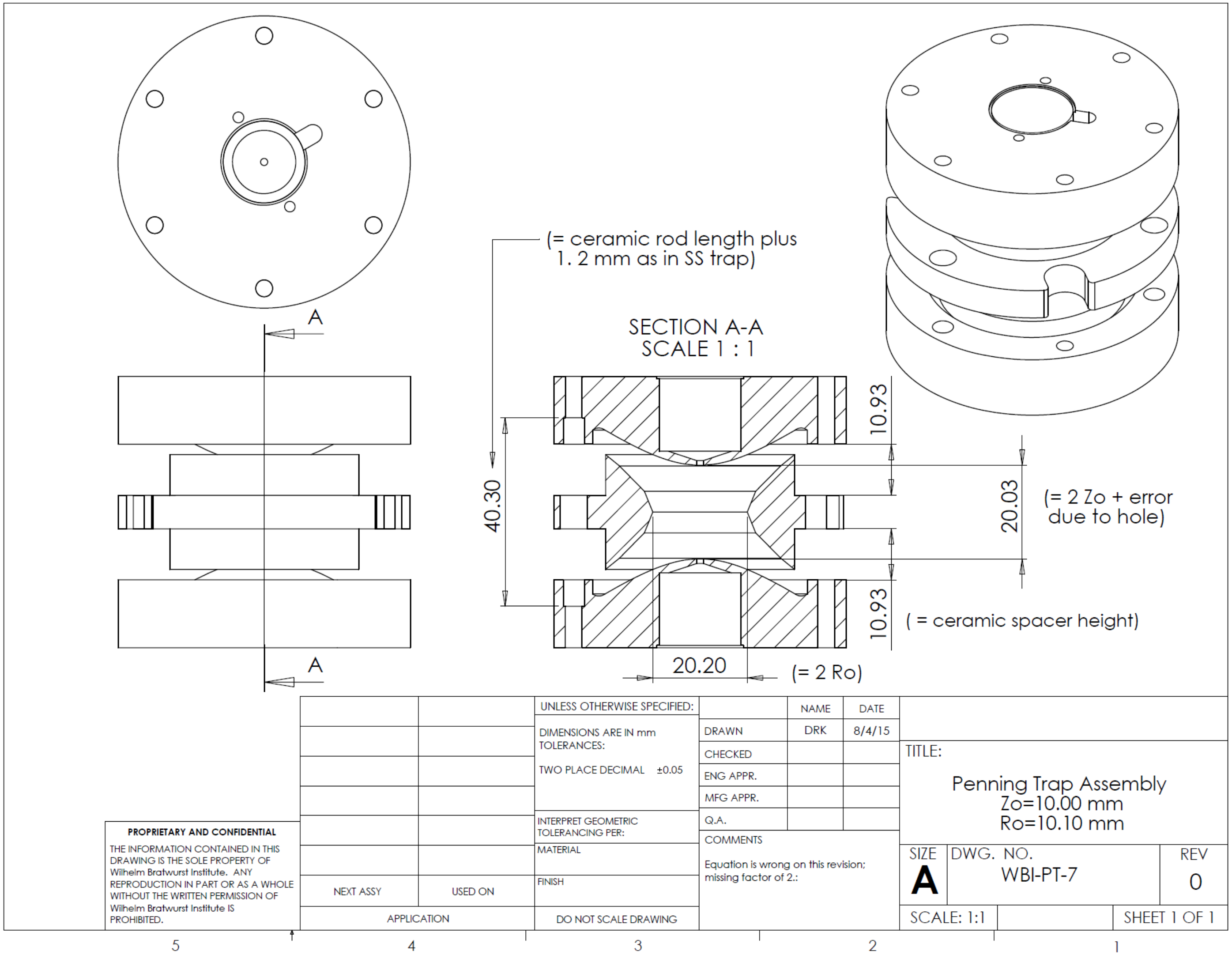


Electron Trapping Resonance in WBI-1 Device

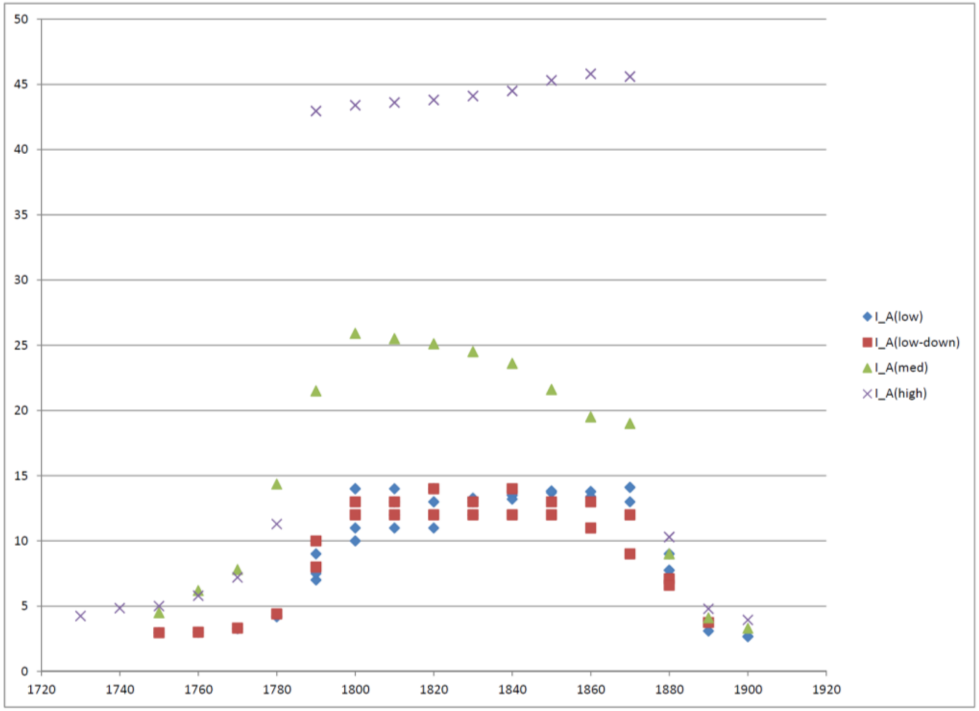


Broad peak not at the theoretically predicted anode voltage

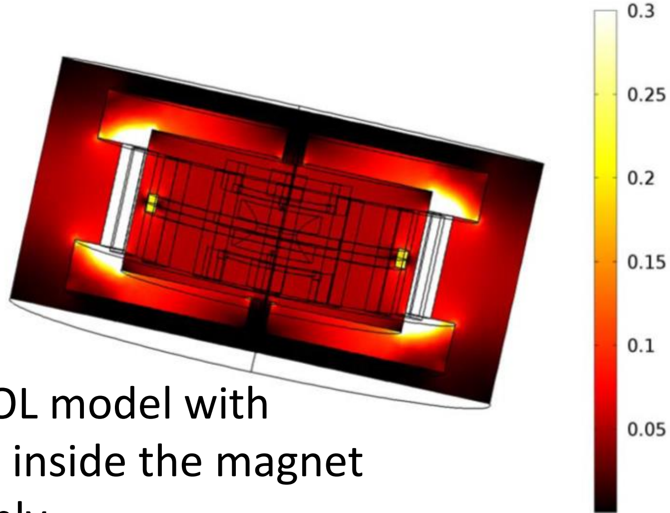
Conversion of the Asymmetric Paul Trap to a=0.707 cm Symmetric Trap



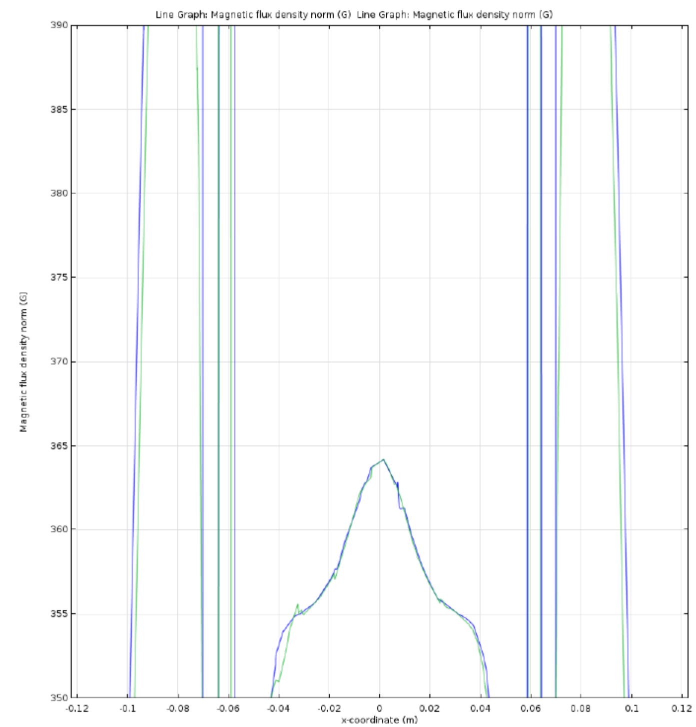
Anode Voltage Scan with Symmetric Trap



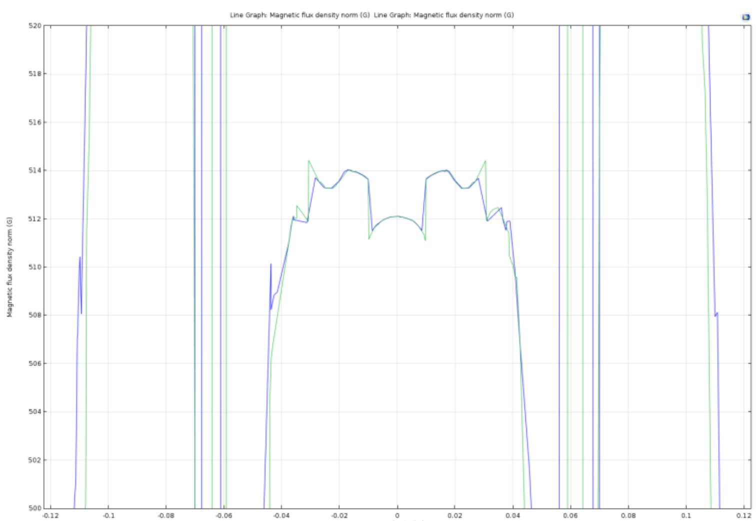
Magnetic Field Distortion in 304SS Trap



COMSOL model with
SS trap inside the magnet
assembly.

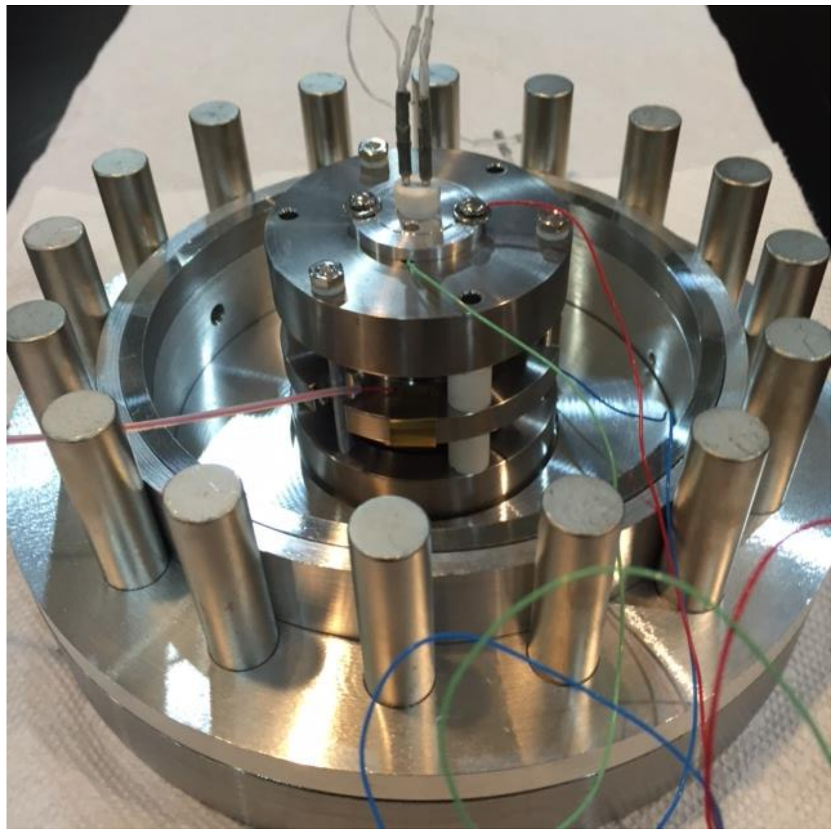


COMSOL field plot showing field distortion
due to Kovar filament pins.



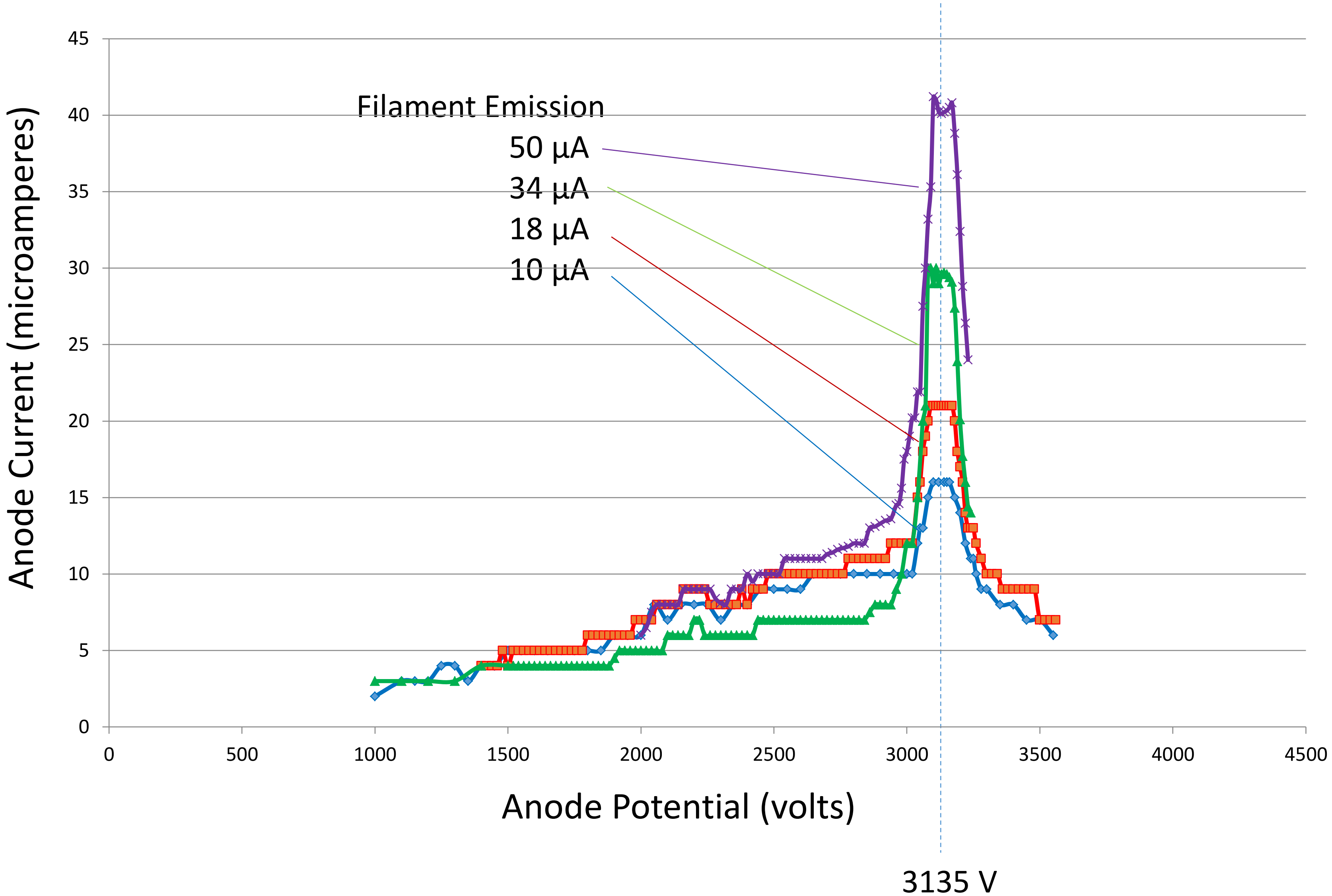
COMSOL field plot for μ = 1.005
304SS trap showing field distortion.

Titanium Trap with Nonmagnetic Electron Source
$R_o = Z_o = 1$ cm

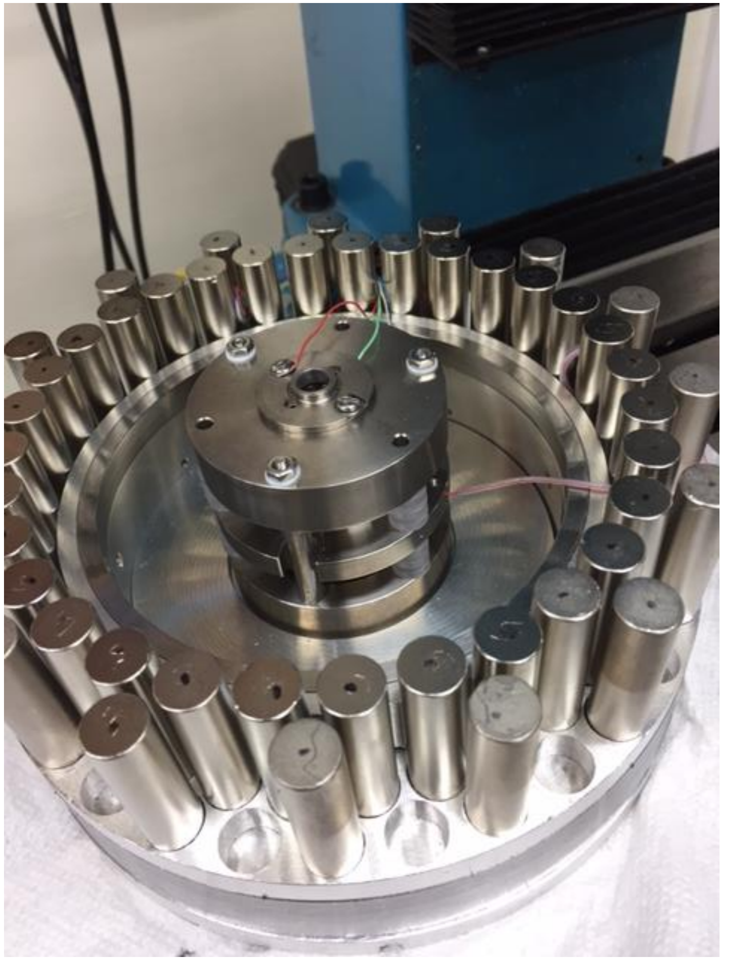


Materials: grade 2 Ti, Al, 316SS, W (filament), ceramics

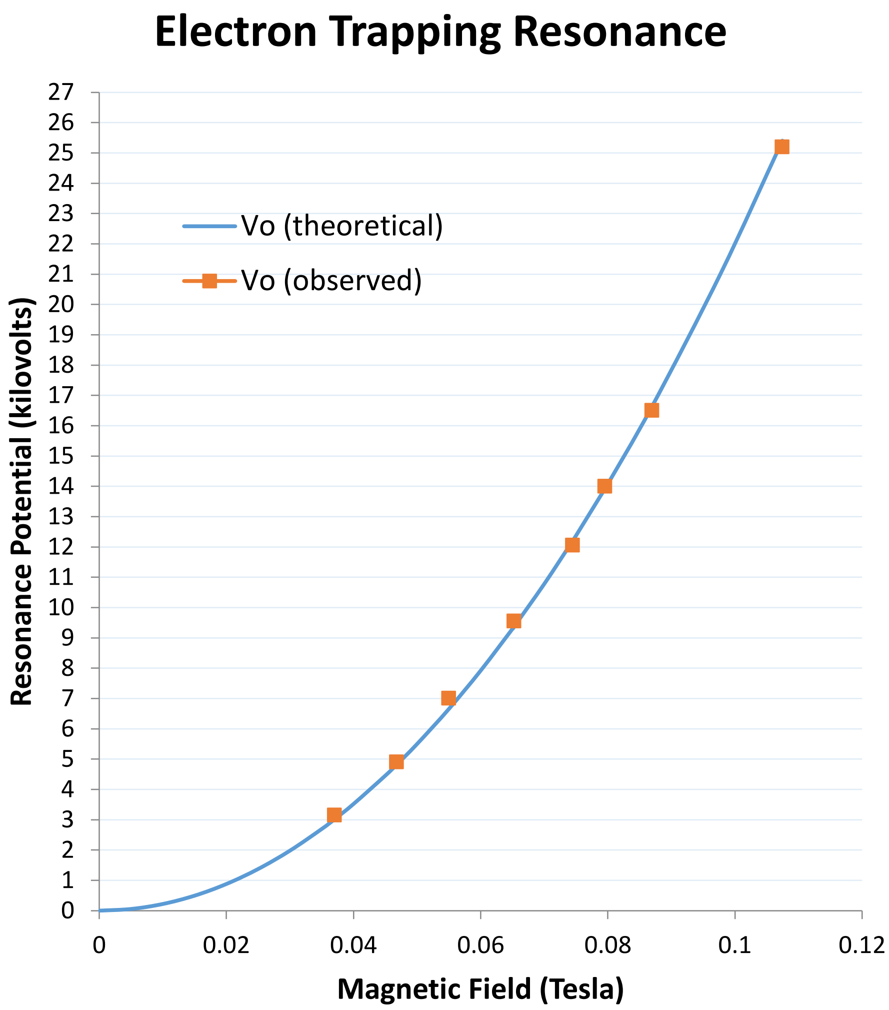
Titanium Trap with Nonmagnetic Electron Source



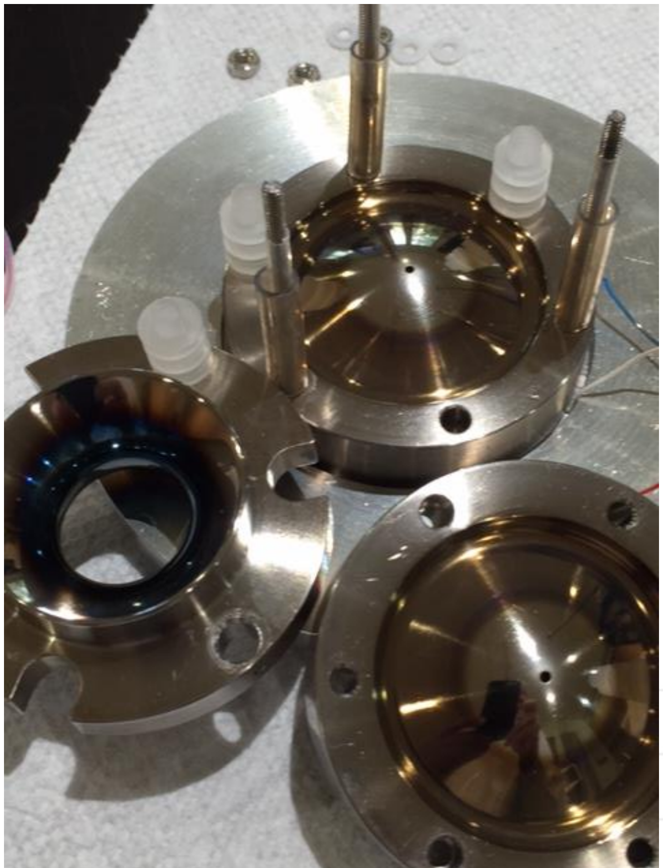
Increased Magnetic Field by Adding Magnets

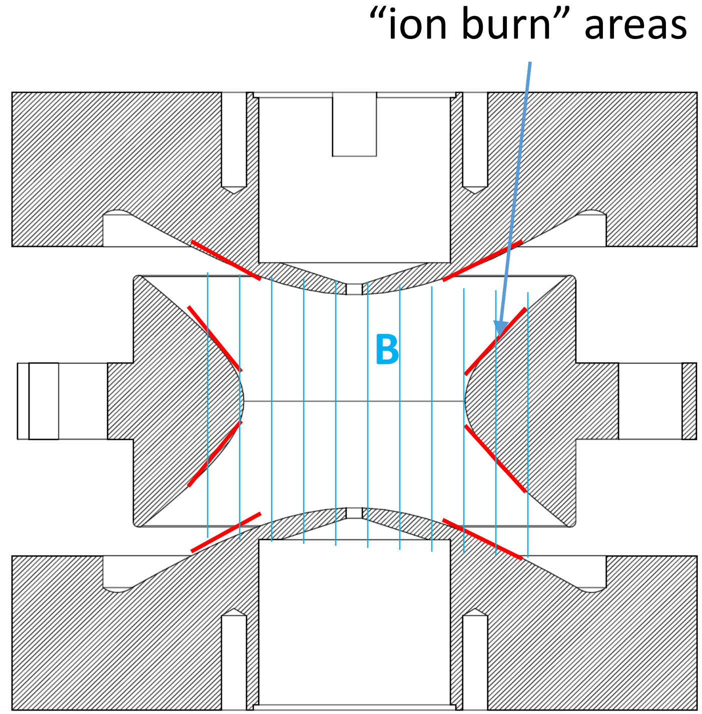


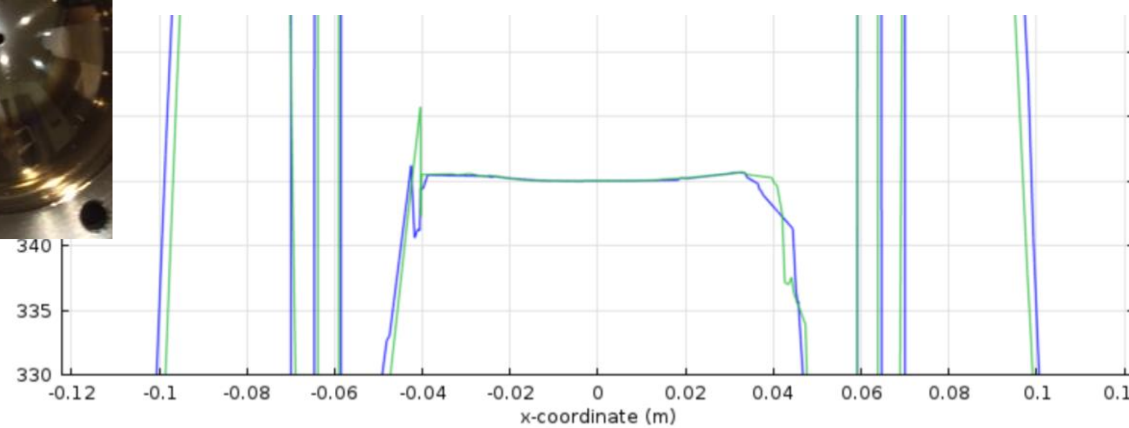
Vo *vs.* B Follows Theoretical Prediction



Operation at Higher B Limited by Discharge







Magnetic field plot

Scaling Model for the Penning Fusion Source

$$\dot{N} \approx 2 \text{ X } 10^{14} \frac{f^2 V^{4.5} C}{[3 \log C + 20.7 + 1/(1 - f)]^{5/2} (1 - f)^{1/2} a}$$

$f = n_{i0} / n_{e0}$	*ca. 0.5 is sufficient*
V = applied voltage (units of 100kV)	*scales strongly with V*
C = convergence (units of 1000)	*ca. linear with C*
a = trap radius (units of cm)	*scales inversely with a*

Neutron production (fusion) rates of $10^9 - 10^{10}$ s^{-1} may be achievable in a 1 cm trap.

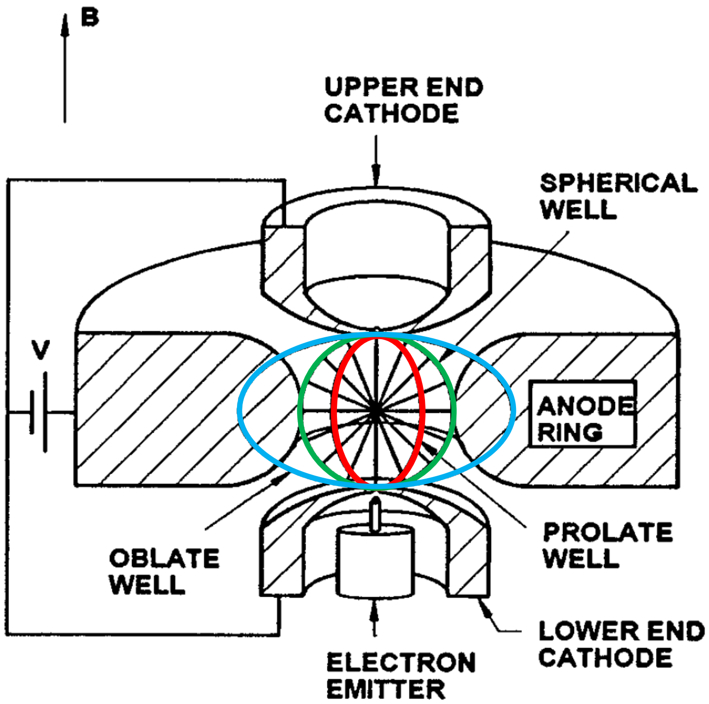
D.C. Barnes, presented at the16th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Applications, Madison, WI, October 1, 2014.

References

1. D. C. Barnes, R. A. Nebel, L. Turner, and T. N. Tiouririne, "Alternate Fusion: Continuous Inertial Confinement," *Plasma Phys. Control. Fusion* **35**, 929 (1993).
2. M. M. Schauer, T. B. Mitchell, M. H. Holzscheiter, and D. C. Barnes, "Electron Penning Trap for the Generation of High Density Non-neutral Plasmas, *Rev. Sci. Instrum.* **68**, 3340-3345 (1997).
3. T. B. Mitchell, M. M. Schauer, and D. C. Barnes, "Observation of Spherical Focus in an Electron Penning Trap," *Phys. Rev. Lett.* **78**, 58 (1997).
3. D. C. Barnes, T. B. Mitchell, and M. M. Schauer, "Beyond the Brillouin Limit with the Penning Fusion Experiment", *Phys. Plasmas* **4**, 1745 (1997).
4. D. C. Barnes, M. M. Schauer, K. R. Umstadter, L. Chacón, and G. H. Miley, "Electron Equilibrium and Confinement in a Modified Penning Trap and its Application to Penning Fusion", *Phys. Plasmas* **7**, 1693 (2000).
5. L. Chacón, and D. C. Barnes, "Stability of thermal ions confined by electron clouds in Penning fusion systems", *Phys. of Plasmas* **7, 4774** (2000).
6. M. M. Schauer, D. C. Barnes, and K. R. Umstadter, "Physics of non-thermal Penning-trap electron plasma and application to ion trapping," *Phys. Plasmas* **11**, 9 (2004).

Extra Slides

Effect of V on Potential Well Shape



$$V_0 = \frac{eB^2a^2}{8m_e}$$

$V < V_0$ Prolate well

$V = V_0$ Spherical well

$V > V_0$ Oblate well

Cross Section of Trap Showing Equipotential Surfaces