Coronado
Consulting

MUSC
MEDICAL UNIVERSITY
of SOUTH CAROLINA

WILHELM BRATWURST
INSTITUTE
FOR
APPLIED PHYSICS
RESEARCH

Spherical Penning Trap as a Small Fusion Source

Daniel C. Barnes [1] and Daniel R. Knapp [2]

[1] Coronado Consulting, Lamy, New Mexico, and Wilhelm Bratwurst Institute
Charleston, South Carolina, USA

[2] Medical University of South Carolina and Wilhelm Bratwurst Institute
Charleston, South Carolina, USA

IEC2018, College Park, MD

Overview

Purpose - This work is directed toward reproducing and extending previous work at the Los Alamos National Laboratory on use of a Penning trap as a small fusion reactor.

Methods - A permanent magnet solenoid was designed and constructed to house a 10 mm. radius symmetric hyperbolic electrostatic trap with an electron source.

Results - Electron trapping was demonstrated by plotting anode current (from scattered electrons) *vs*. anode potential and observing a resonance peak at the predicted anode potential. Observation of resonance peaks at fusion relevant anode potentials has been hampered by runaway discharge in the trap.

Conclusions – Electron trapping was observed as predicted by theory, but we have not

yet been able to reach potentials capable of achieving fusion.

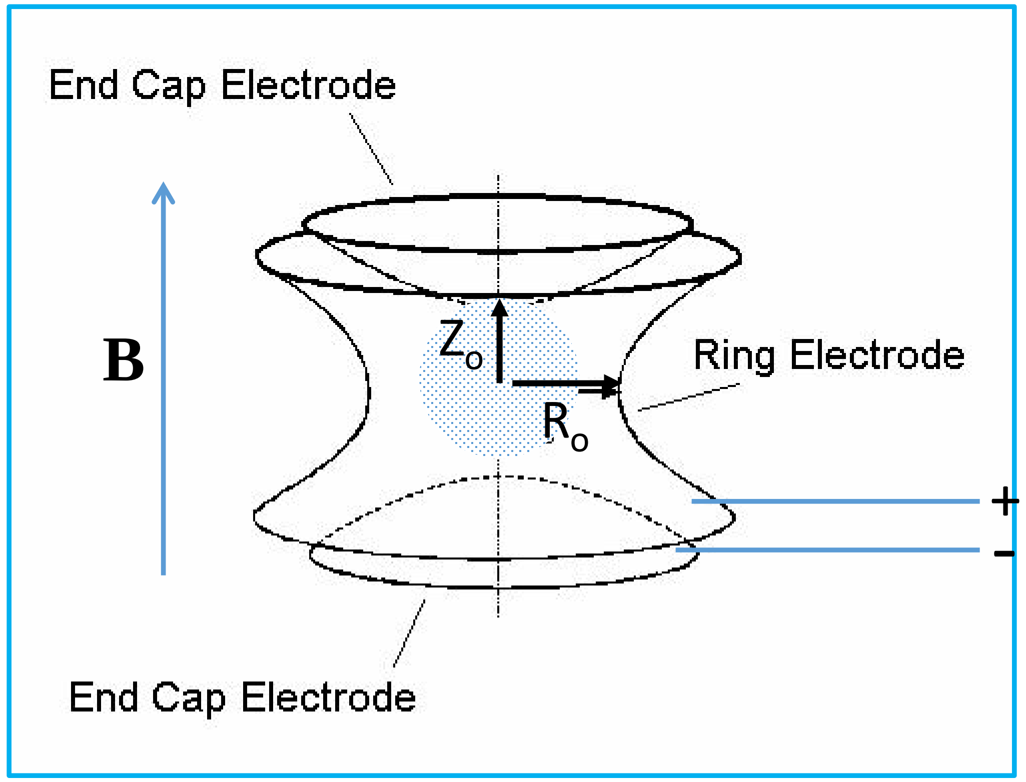
Future Work – The solenoid magnetic field strength will be increased to increase the resonant anode potential to levels required for a potential well capable of yielding nuclear fusion of deuterium ions attracted to the trapped electron cloud. We will explore new approaches to suppressing the runaway discharge including alternative trap designs (e.g. Malmburg-Penning trap). Nuclear fusion will be observed by detection of product neutrons using a ^{3}He detector.

Present work: Avoid discharge using pulsed operation. Neutrons detected but need to improve electrical noise rejection.

Future work: Continue investigation of pulsed operation at higher voltages. Improve noise rejection of ^{3}He detector system

The Penning Trap as a Fusion Source

- A Penning trap with uniform B, harmonic E can be tuned to make a spherical well for electrons without the use of grids.
- Electrons are maintained IEC beam-like by appropriate boundary conditions.
- Spherical convergence produces a central virtual cathode.
- Ions confined in the central cathode can reach keV energies and produce neutrons.



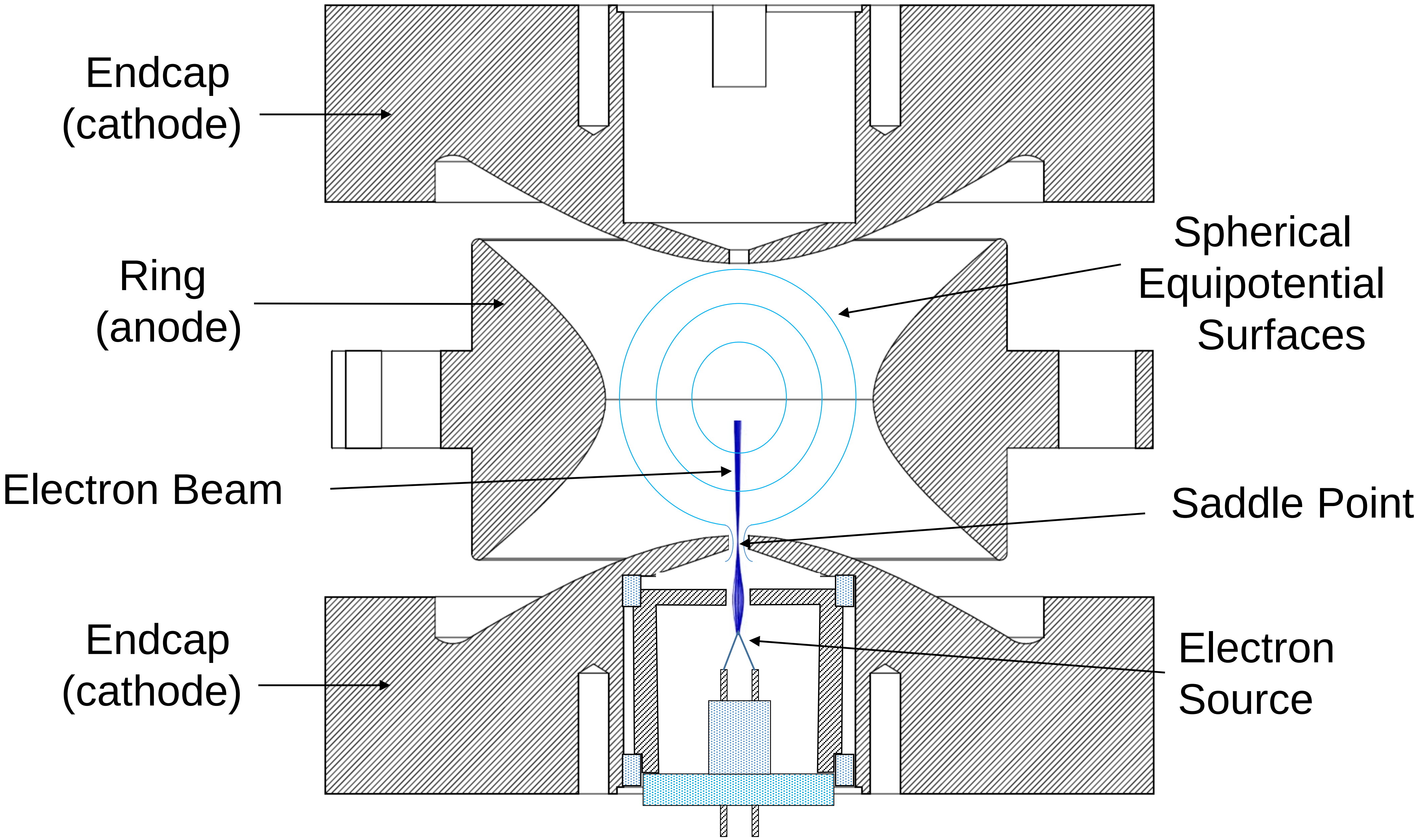
$$\Phi = \frac{2V}{3}\left(\frac{r^2/2 - z^2}{a^2} + 1\right)$$

The Penning Trap

- The Penning trap uses hyperbolic end cap and ring electrodes to form a 3D quadrupole electric field.
- Electrons are “dropped” off the low radius part of an end cap cathode (zero angular momentum – Brillouin flow).
- Tuning V with B can make the potential well spherical and harmonic.
- Geometry is such that electrons don’t hit the anode.
- Electrons are recollected at low energy at the cathode.

Wilhelm Bratwurst Institute for Applied Physics Research

Cross Section of Trap Showing Equipotential Surfaces


Endcap (cathode)

Ring (anode)

Electron Beam

Endcap (cathode)

Spherical Equipotential Surfaces

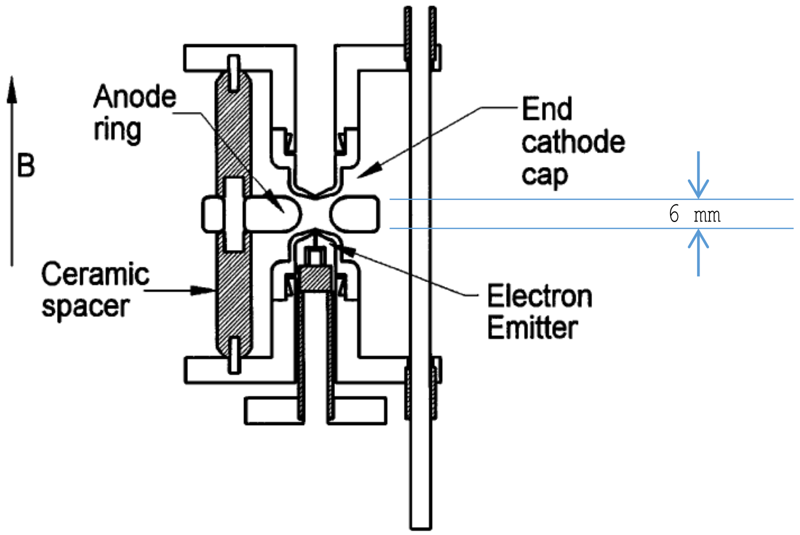
Saddle Point

Electron Source

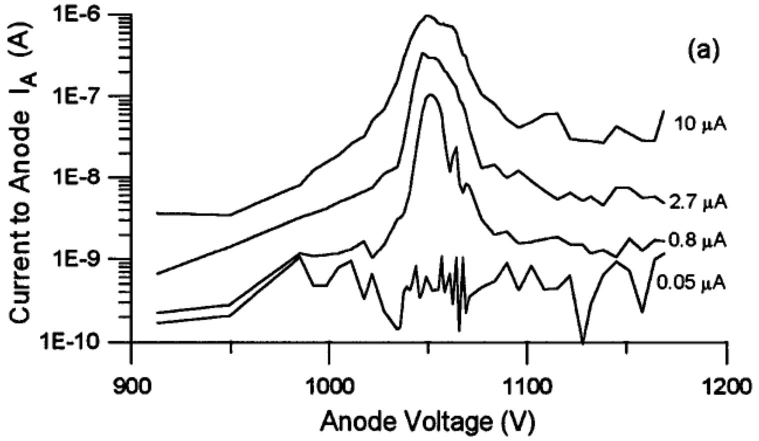
The potentials for the electron source elements were determined by SIMION modeling. The low potential of the saddle point over which the electrons are injected into the trap results in a very low power requirement for electron loading of the potential well.

WILHELM BRATWURST INSTITUTE FOR APPLIED PHYSICS RESEARCH

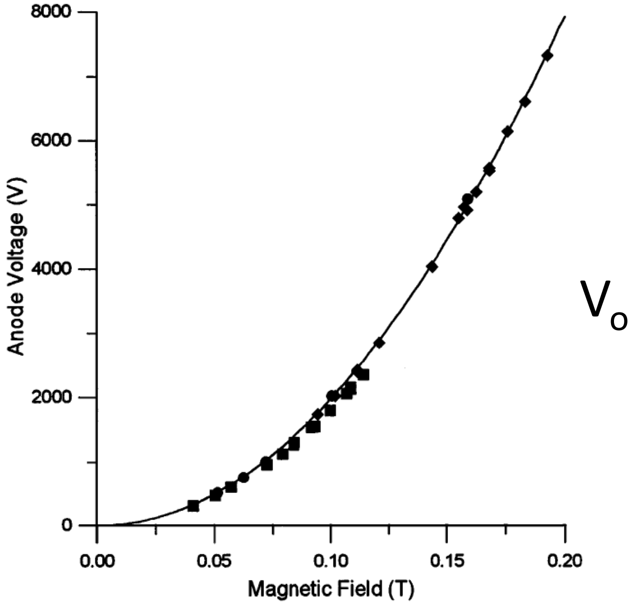
Cold-bore, Spherical Penning Trap (Los Alamos PFX) [2]



The Penning trap used in the Los Alamos PFX experiment. $R_o = Z_o = 3$ mm. The trap was inserted in the cold bore of a superconducting solenoid. B was varied from 0.05-0.22 Tesla. The corresponding anode voltage for electron trapping ranged from around 500V to 10kV.



Observed anode current vs. anode voltage near the spherical point for B = 0.076 T. showing the resonance peak.

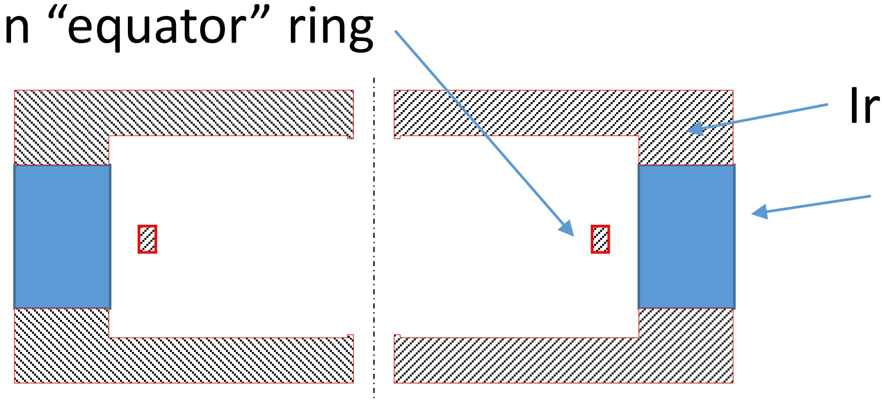


$$V_o = eB^2a^2/8m_e \quad (1)$$

Plot of the anode voltage vs. magnetic field at the maximum anode current points showing the curve matches the theoretical spherical condition defined by equation (1).

Wilhelm Bratwurst Institute for Applied Physics Research

Permanent Magnet Solenoid

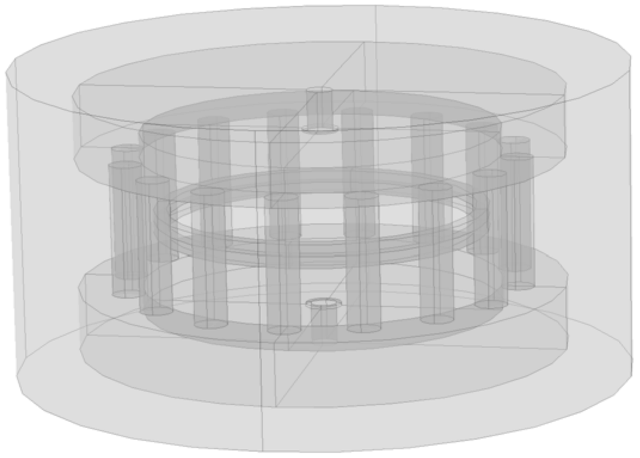


Iron “equator” ring

Iron pole piece

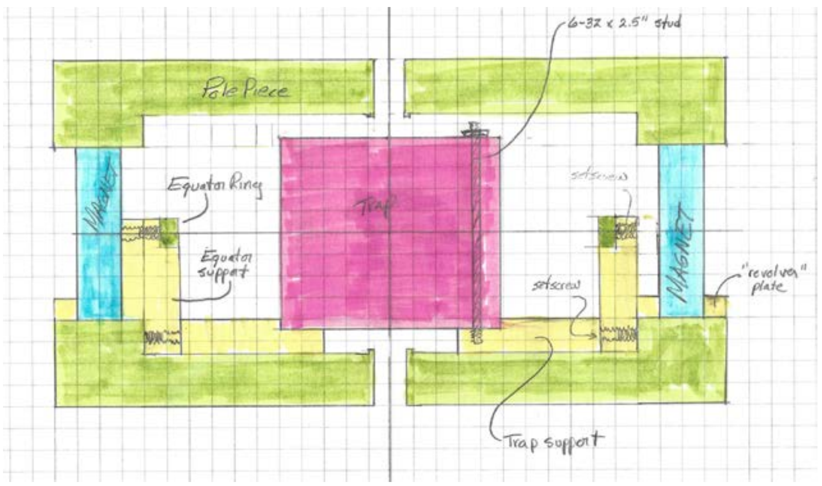
Neodymium-iron-boron (NIB) magnets
(numbers and sizes can vary).

Cross section of magnet assembly.

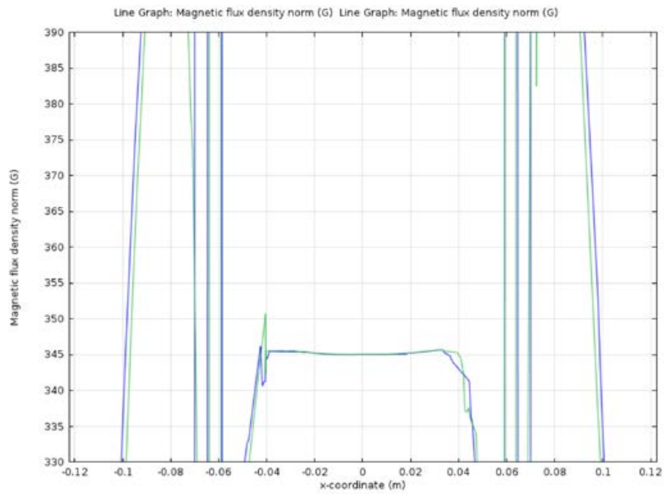


3D view of magnet assembly with
16 NIB magnets, 0.5 in. x 2.0 in.

Magnets and poles are assembled using a milling machine mechanism to avoid operator injury or magnet damage.

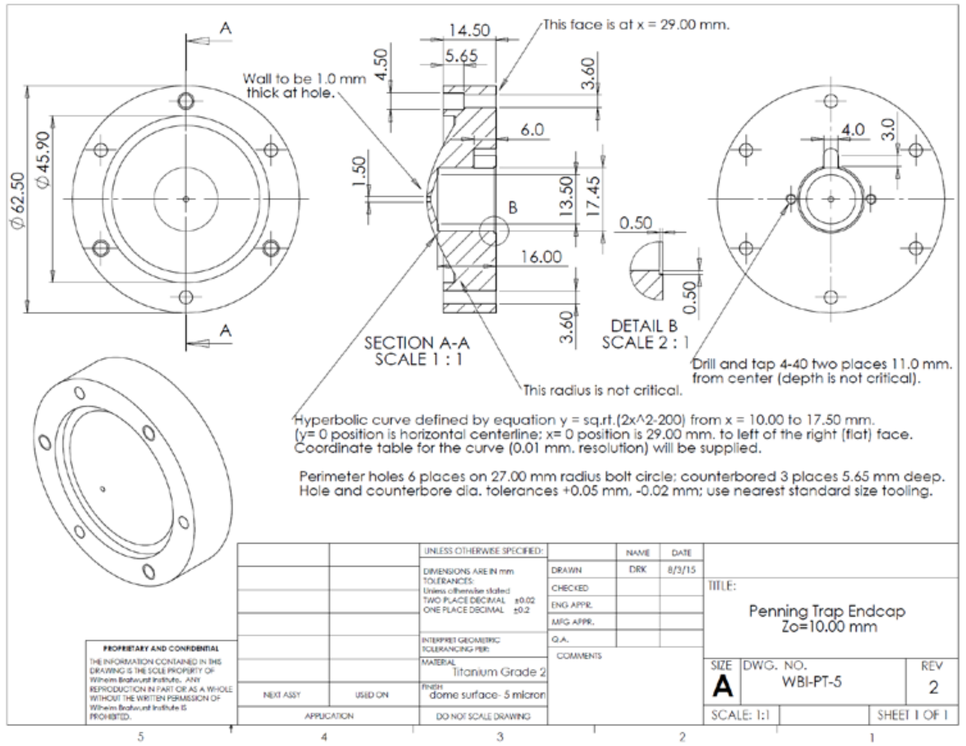


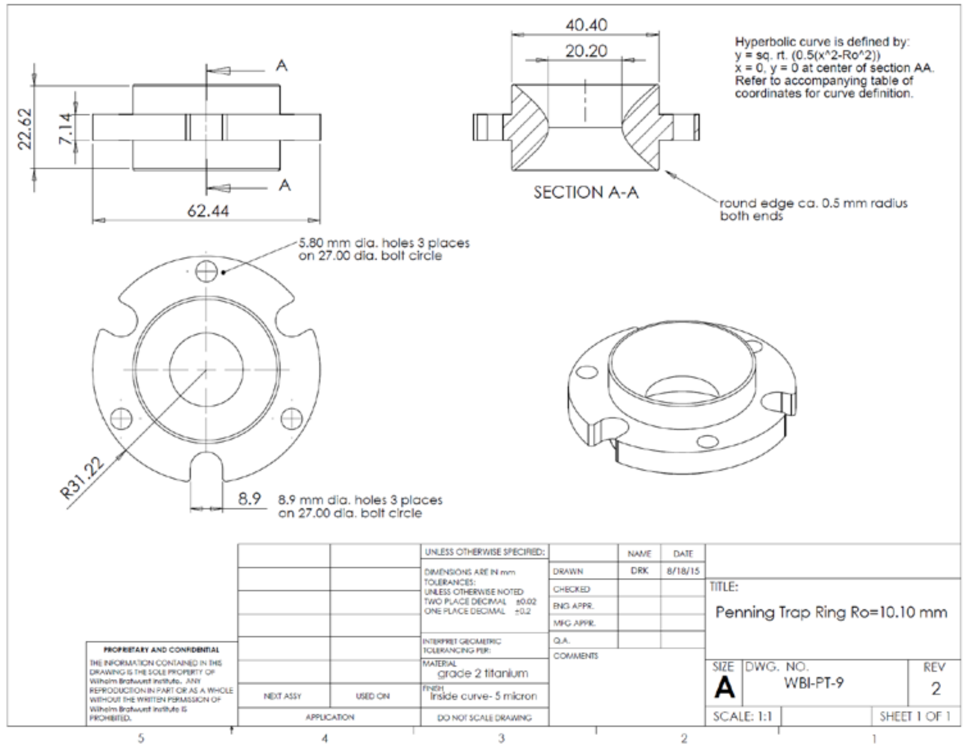
Sketch of magnet assembly showing trap
and aluminum support elements.

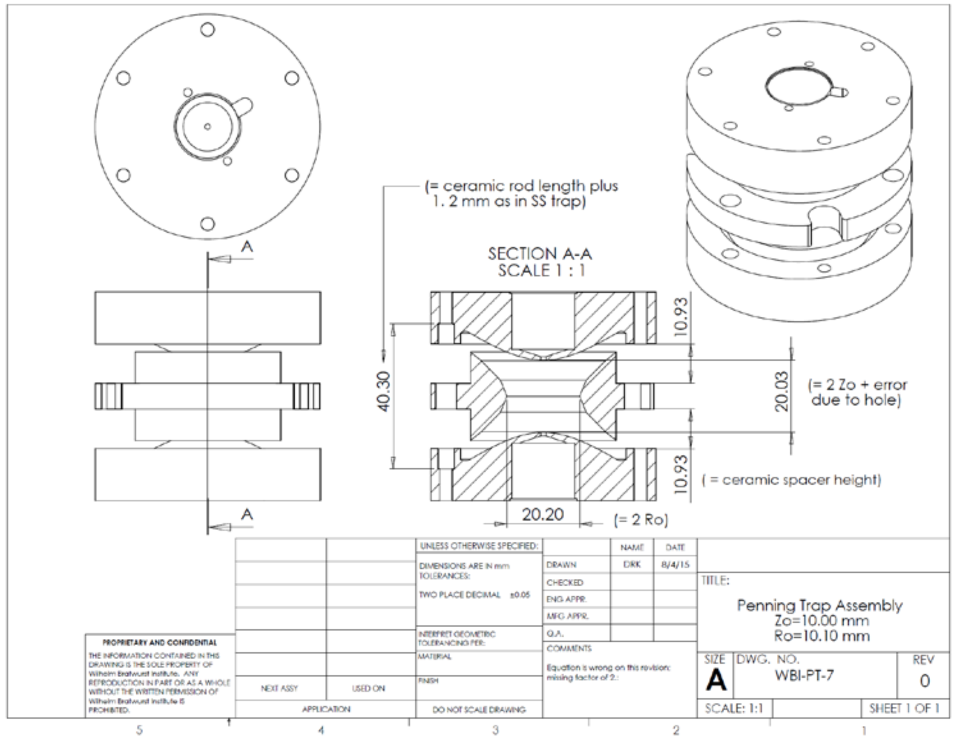


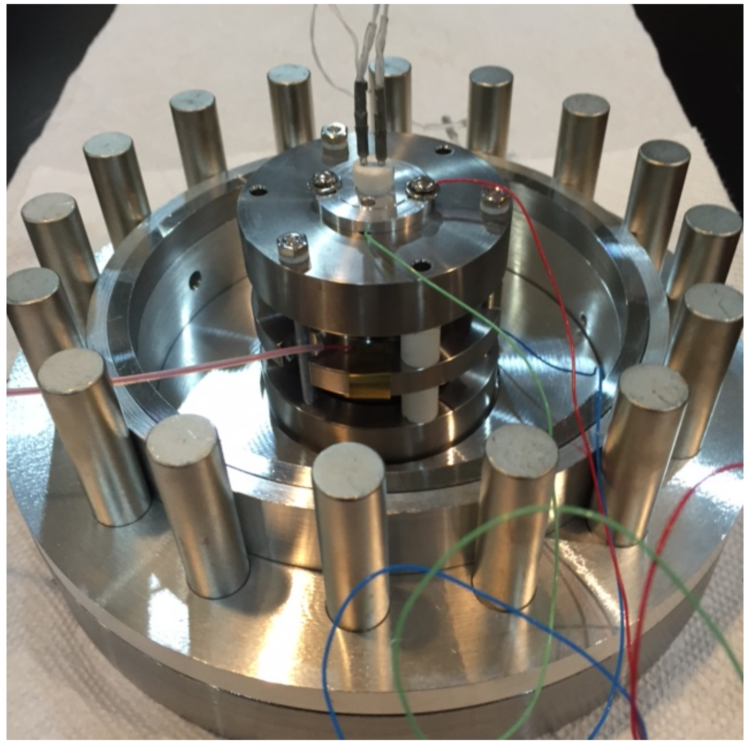
COMSOL finite element model plot
showing uniform central field.

Hyperbolic Trap and Electron Source





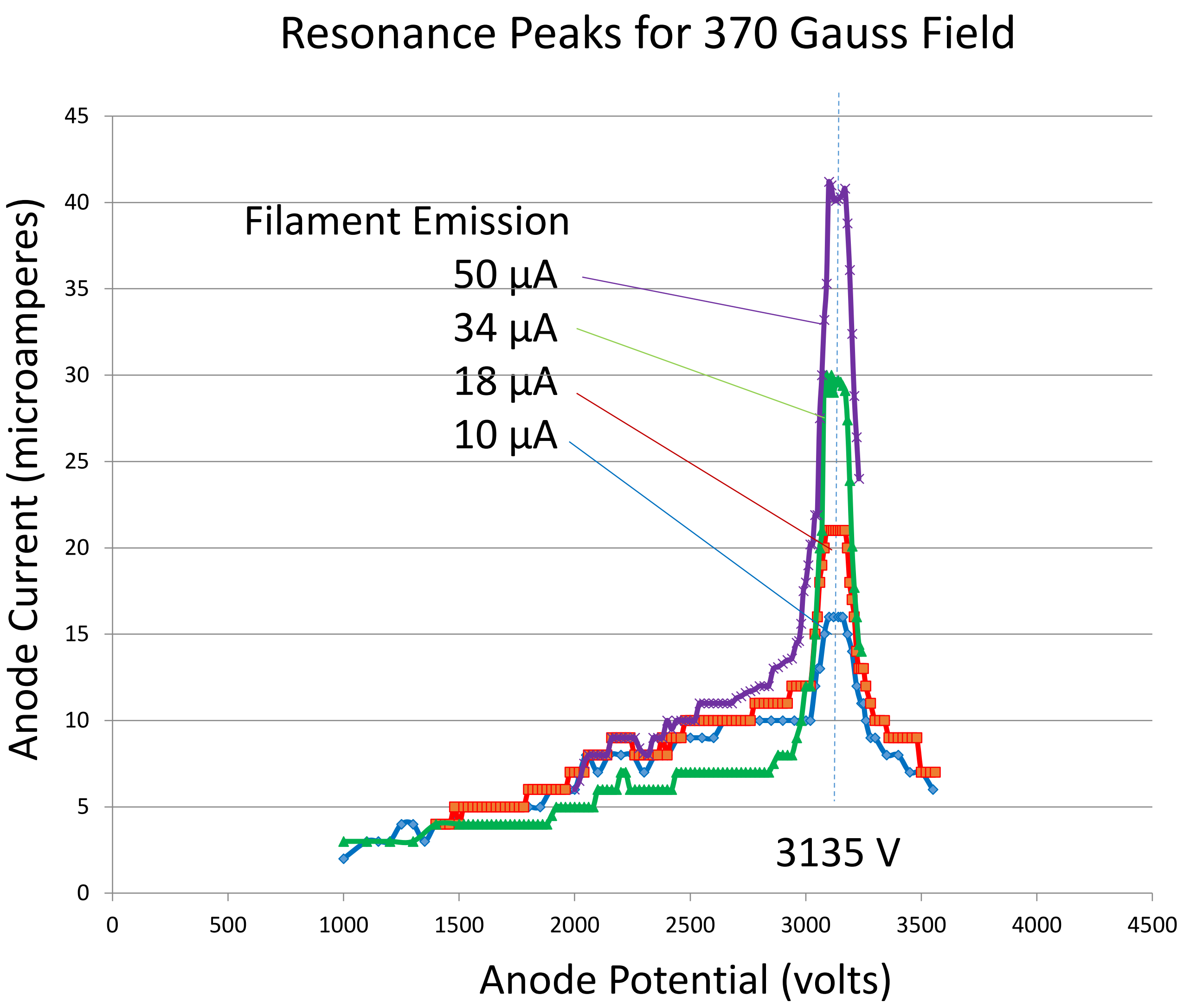




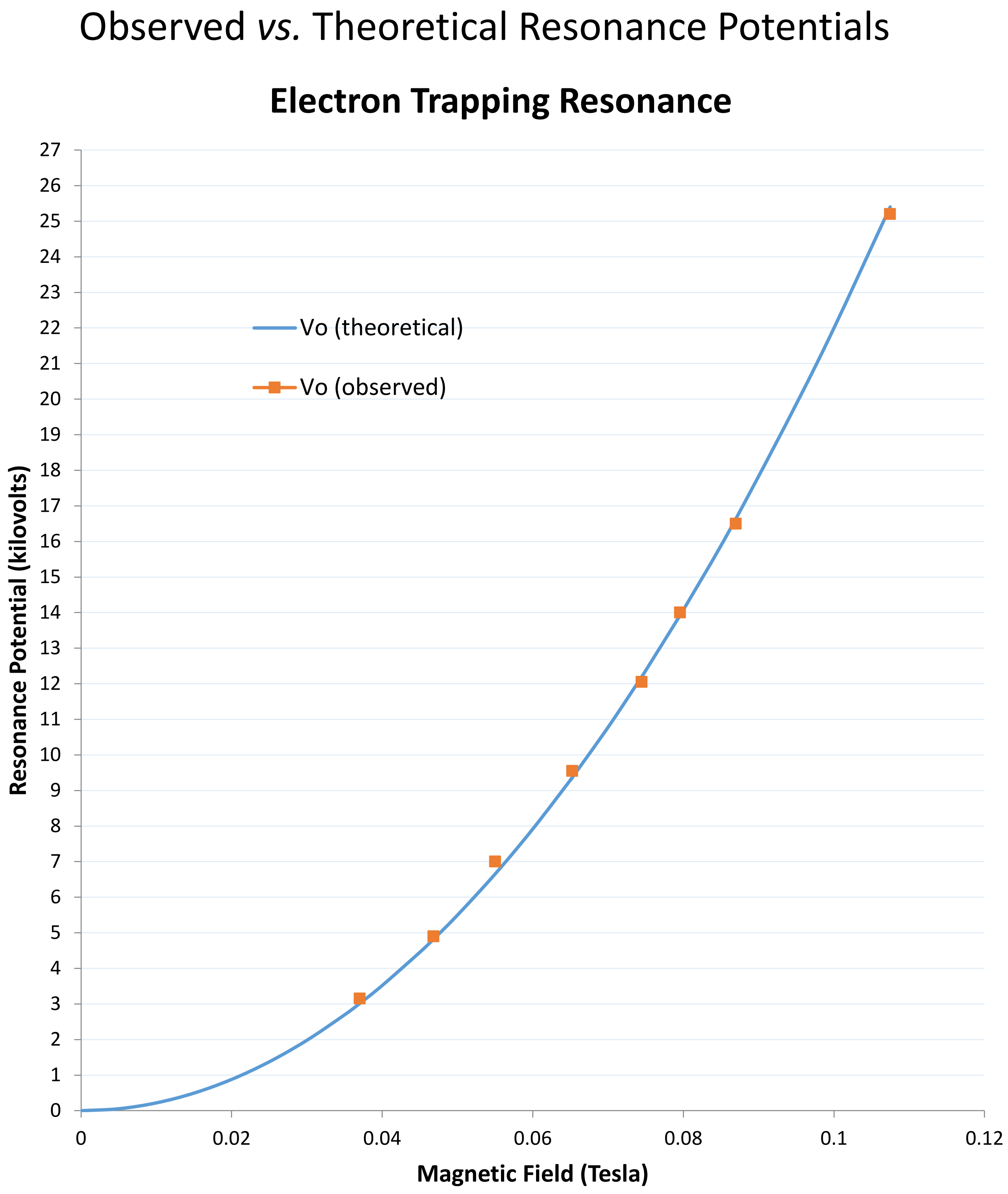
A new symmetrical titanium Penning trap was constructed for the next experiments. It also utilizes a titanium Wehnelt and a nonmagnetic electron source constructed from Macor, 316 SS pins, and a hairpin tungsten filament.

WILHELM BRATWURST
INSTITUTE
FOR
APPLIED PHYSICS
RESEARCH

Electron Trapping in Titanium Trap with Nonmagnetic Electron Source

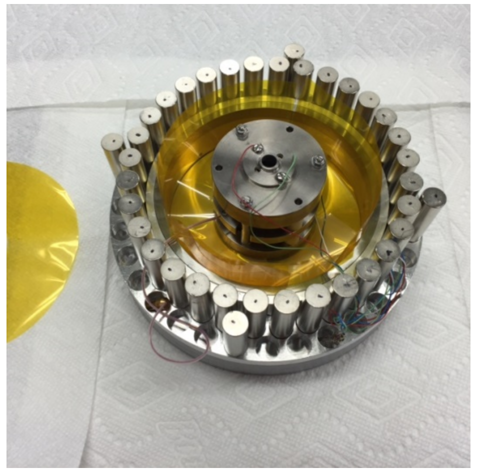


The electron trapping resonance peaks were observed at anode potential within 2% of the theoretical value.

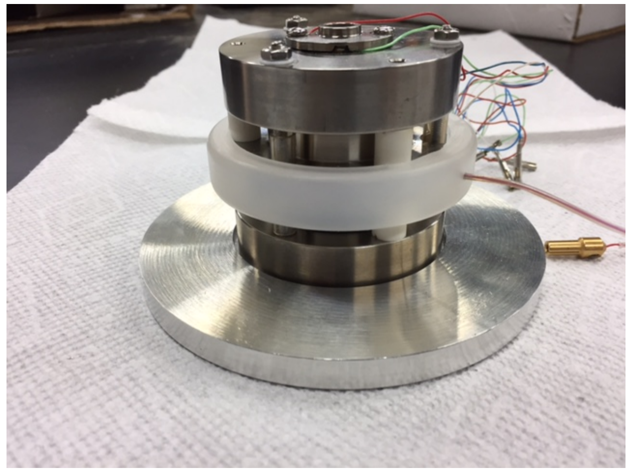


The 25 kV resonance peak was only observed once. Observation of peaks above 16 kV was obscured by runaway discharge.

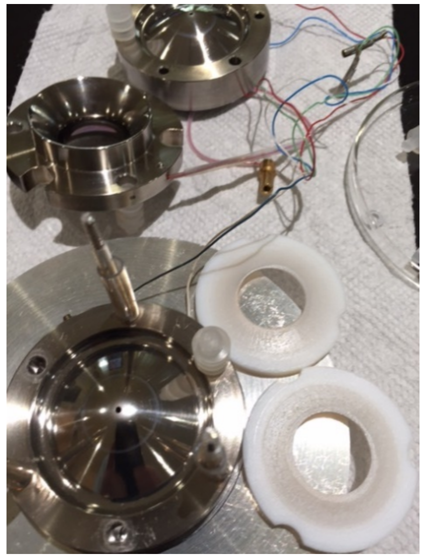
Attempts to Suppress Discharge Using Insulators and Cathode Surface Modifications to Suppress Secondary Electron Emission from Ion Impact.



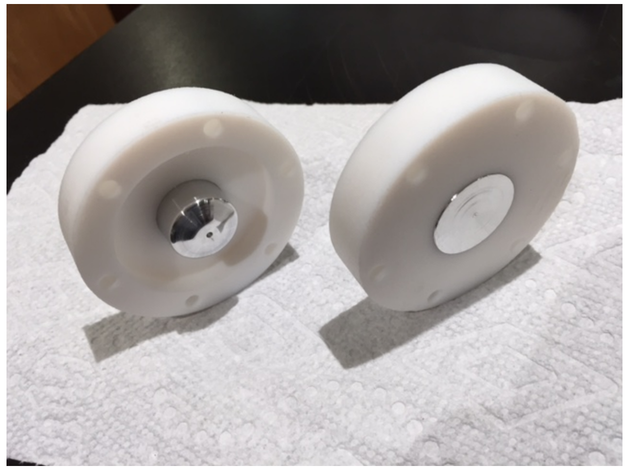
Various shapes of polyimide film insulation were examined to block discharge outside the trap .



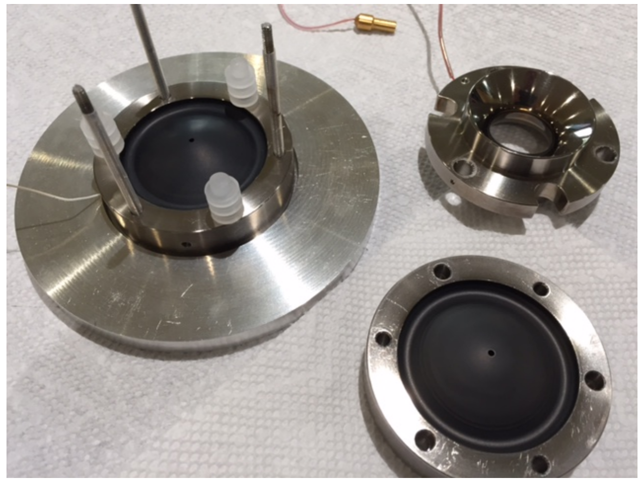
A Kel-F insulator ring around the anode outer ring had no effect on the discharge.



Teflon insulators between the electrodes had no effect.

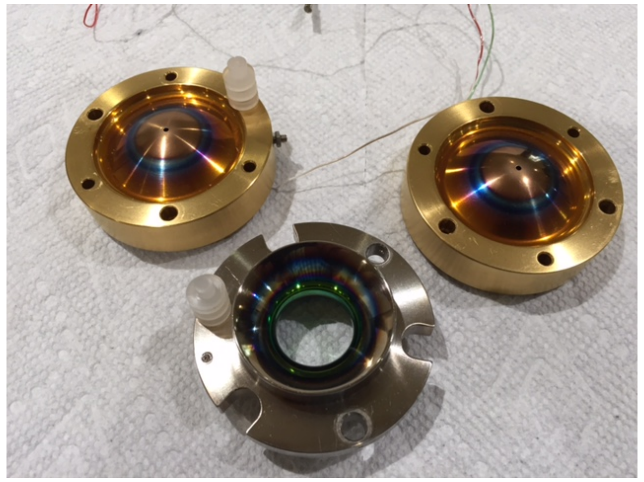


Cathodes with OD same as anode ID did not suppress discharge.



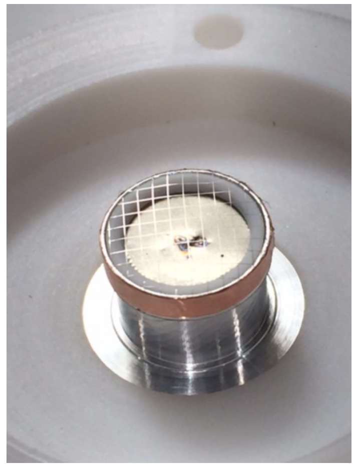
Coating the cathode surfaces with colloidal graphite failed to suppress the discharge.

Coating the cathode surfaces with titanium nitride also failed to suppress the discharge.



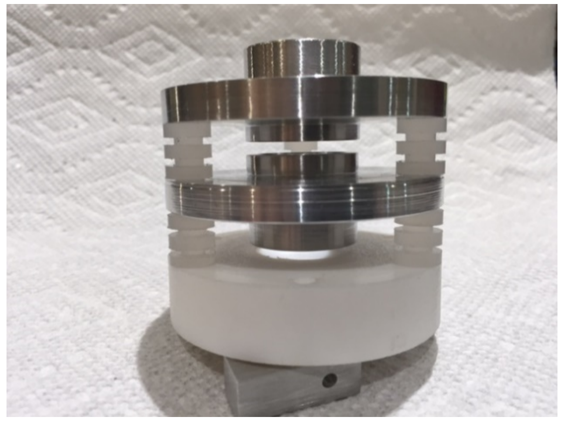
“Ion burn” on the electrode surfaces from the high voltage discharge. Note clean area corresponding to anode ID.

A Gridded Cathode was Designed and Tested as Another Approach to Suppression of Secondary Electron Emission.



An electron suppressor plate behind the grid biased several volts positive relative to the grounded grid was intended to capture secondary electrons produced from ion bombardment. This cathode showed the same high voltage discharge as the solid cathode.

Test Cylinder Electrodes Were Able to Sustain 28 kV Potential Difference at 4 mm Spacing.



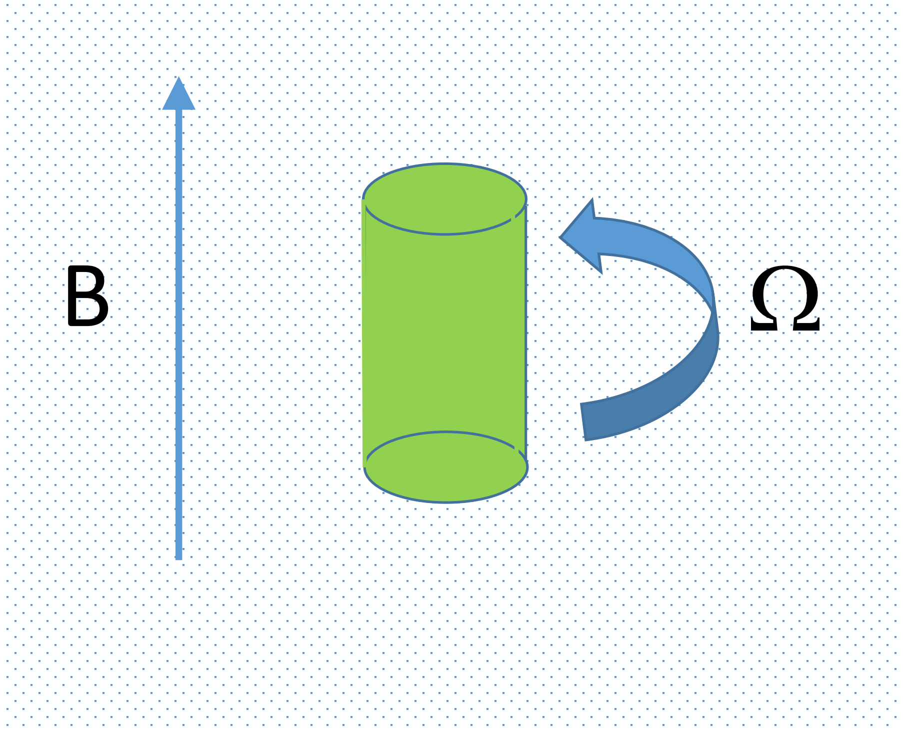
This result suggests that a Malmberg-Penning trap consisting of cylindrical electrodes might be less susceptible to high voltage discharge. The challenge will be to design such a trap with sufficiently accurate approximation of the ideal spherical potential well.

Current efforts are being directed toward better understanding the nature of the discharge in the trap (via direct observation inside the trap with a miniature video camera) and toward developing an alternative trap geometry that can sustain higher voltages.

Wilhelm Bratwurst
Institute
for
Applied Physics
Research

We have been investigating pulsing of the anode HV as a means to suppress unwanted discharge*

Without magnetic field, breakdown occurs very rapidly (ns time scale) but with field, quite slowly (100 μs time scale)



$$F_\theta = m v_\theta \sigma n_N v_\theta$$

$$v_r = \frac{cF}{eB}, \Omega = \frac{\Omega_e}{2} \Rightarrow$$

$$r = \frac{1}{C\left(t_0 - t\right)}, C = \frac{\Omega_e \sigma n_N}{4} = 2\times 10^{-5} / cm - s$$

$$r_0 = 0.04 cm \Rightarrow t_0 = 10^{-4} s$$

---

* Thanks to our colleagues at Apollo Fusion, Inc.

Previous study of Penning discharge initiation

Formative processes of cold-cathode Penning discharges at low pressures

Katsuhiro Kageyama

Citation: Journal of Applied Physics **55**, 723 (1984); doi: 10.1063/1.333130
View online: https://doi.org/10.1063/1.333130
View Table of Contents: http://aip.scitation.org/toc/jap/55/3
Published by the American Institute of Physics

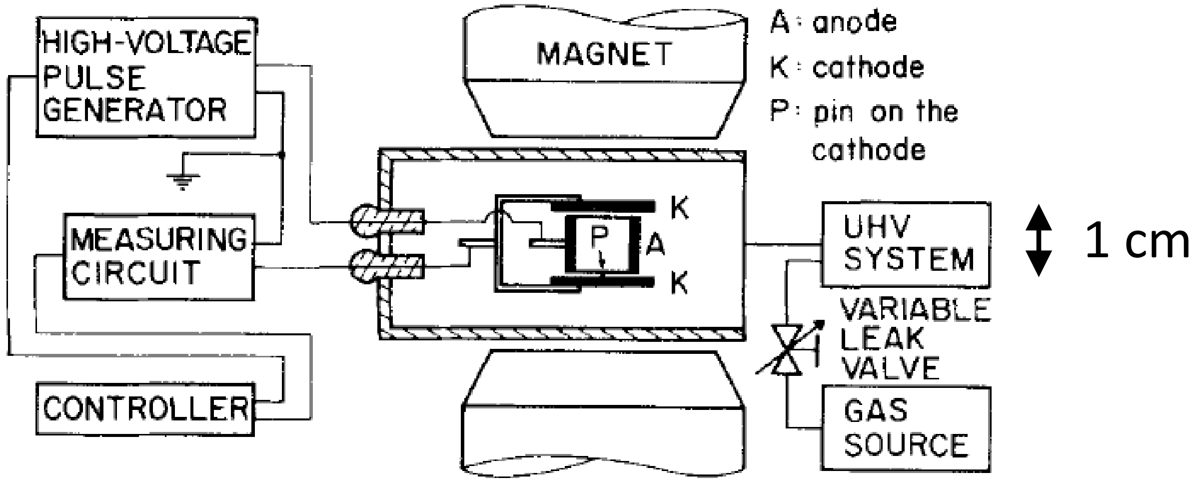


FIG. 1. Experimental setup. The Penning cell with a tungsten pin, 0.2 mm in diameter and 1 mm long, shown in the center, was used for all the experiments, except for that described in Sec. II F. Anode inner diameter and length are both 10 mm. The cathode is made of stainless-steel plates.

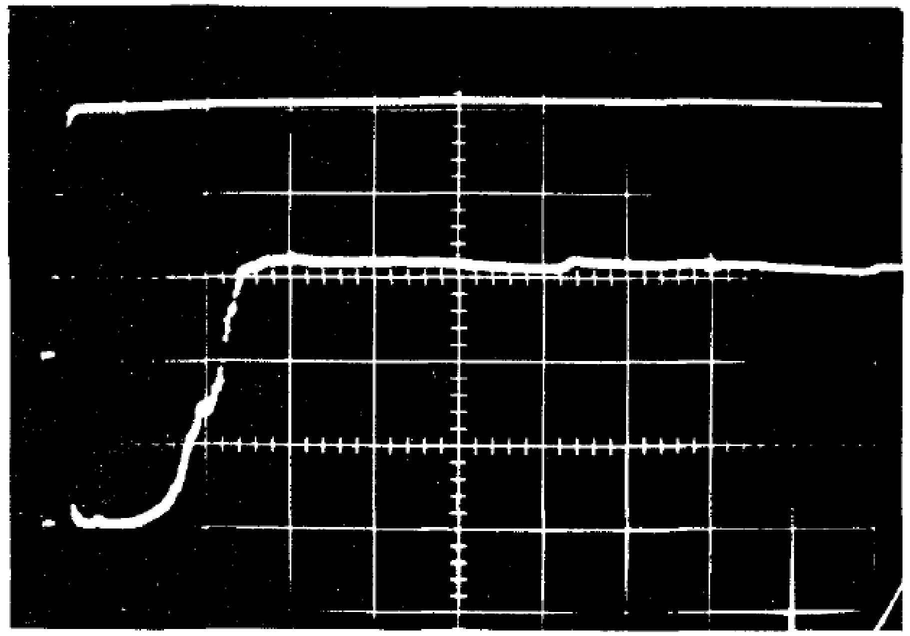
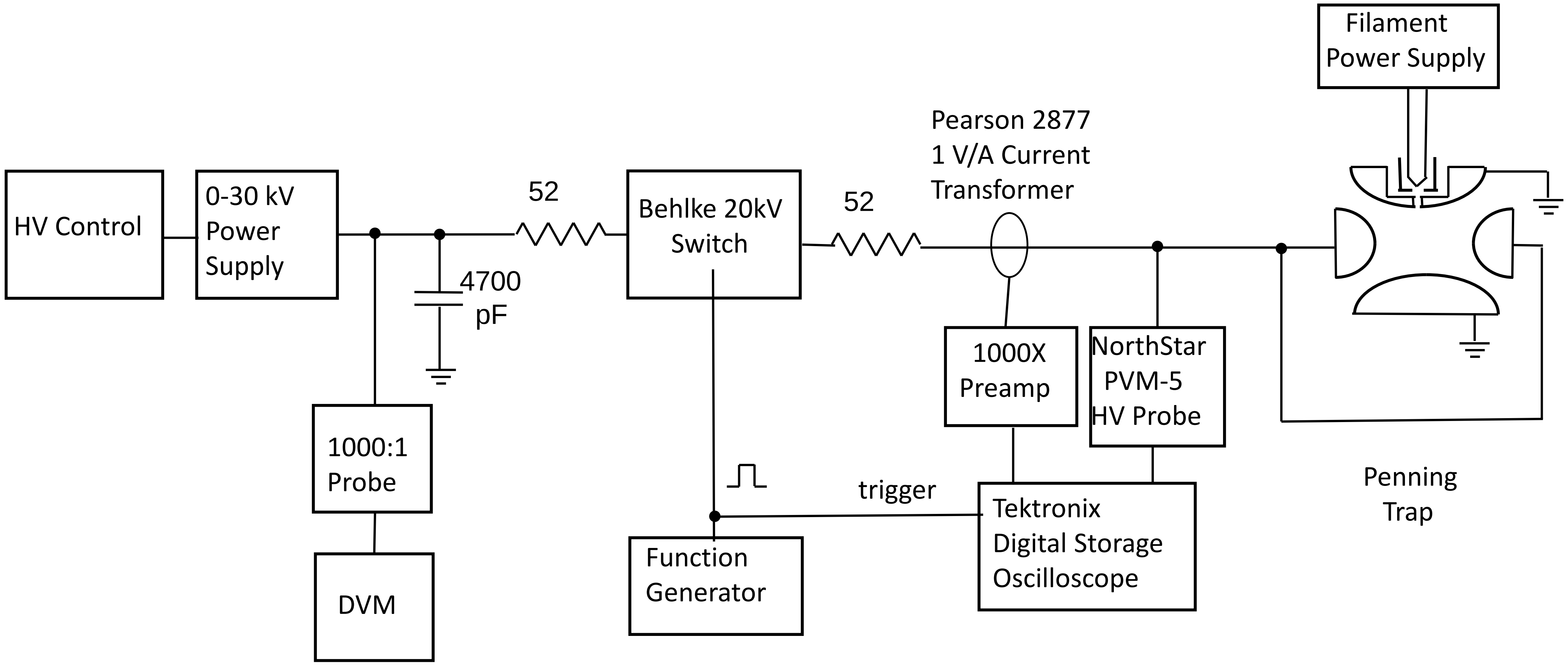


FIG. 3. Discharge-current I_d waveform for a stepped high anode voltage V_a. $B = 158$ mT, $P = 1.2\times10^{-4}$ Pa. Horizontal: 1 ms/div, vertical: 2.5 μA/div for I_d (lower trace) and 2 kV/div for V_a (upper trace). The spike superimposed onto I_d, while V_a is increasing rapidly, is a current flowing through a floating capacitance between the anode and the cathode.

1 ms/div

Wilhelm Bratwurst Institute for Applied Physics Research

Experimental study of discharge and resonant peaks with pulsed anode HV



HV Control

0-30 kV Power Supply

52

4700 pF

1000:1 Probe

DVM

Behlke 20kV Switch

52

Pearson 2877
1 V/A Current
Transformer

Filament Power Supply

1000X Preamp

NorthStar PVM-5 HV Probe

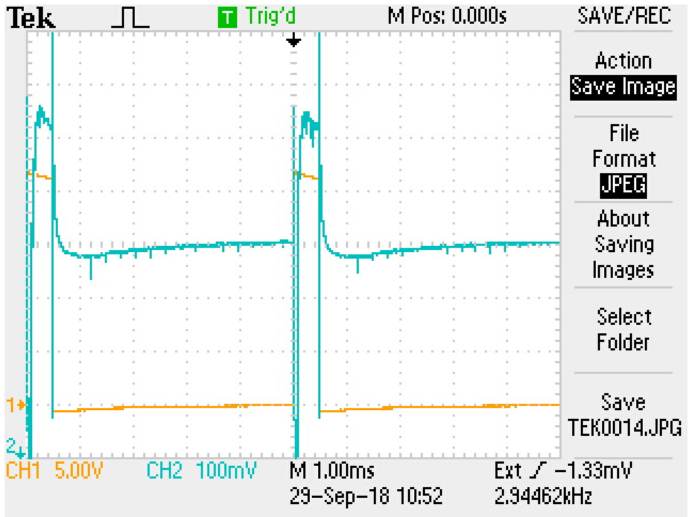
trigger

Function Generator

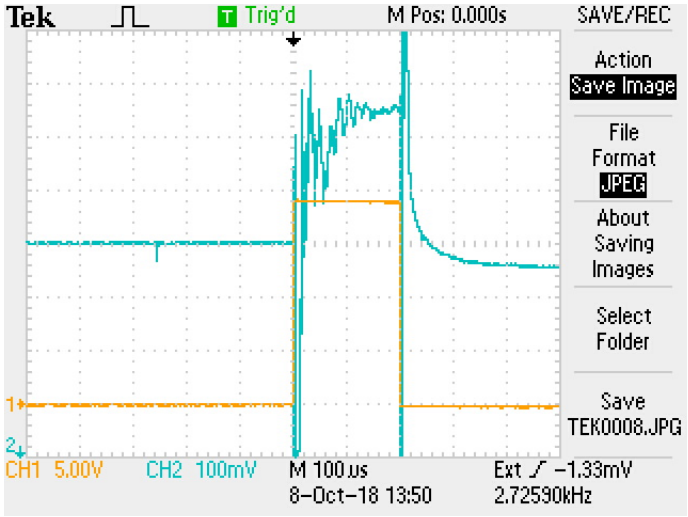
Tektronix Digital Storage Oscilloscope

Penning Trap

092618



CH1 5.00V CH2 100mV M 1.00ms Ext ⁄ -1.33mV
29-Sep-18 10:52 2.94462kHz

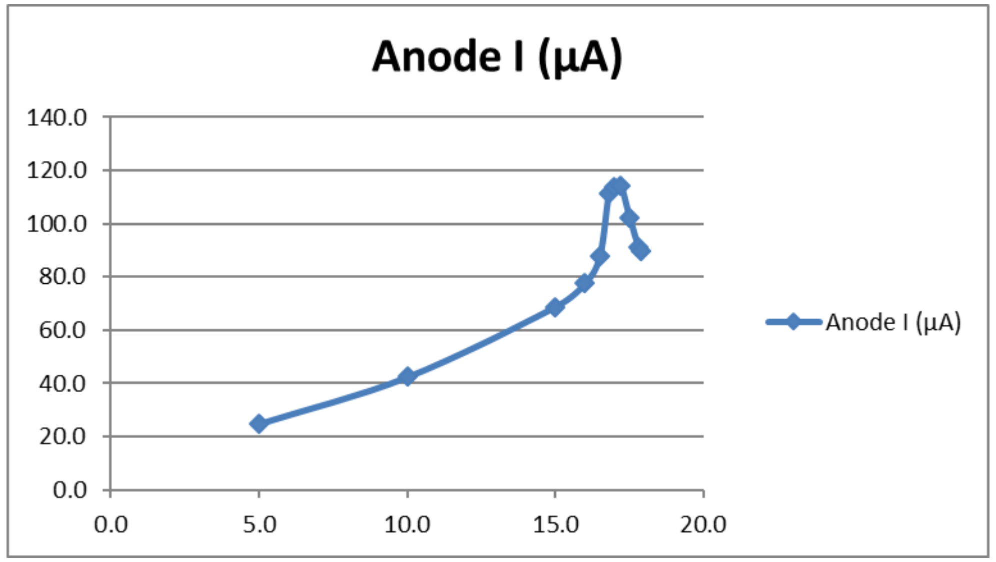


CH1 5.00V CH2 100mV M 100µs Ext ⁄ -1.33mV
8-Oct-18 13:50 2.72590kHz

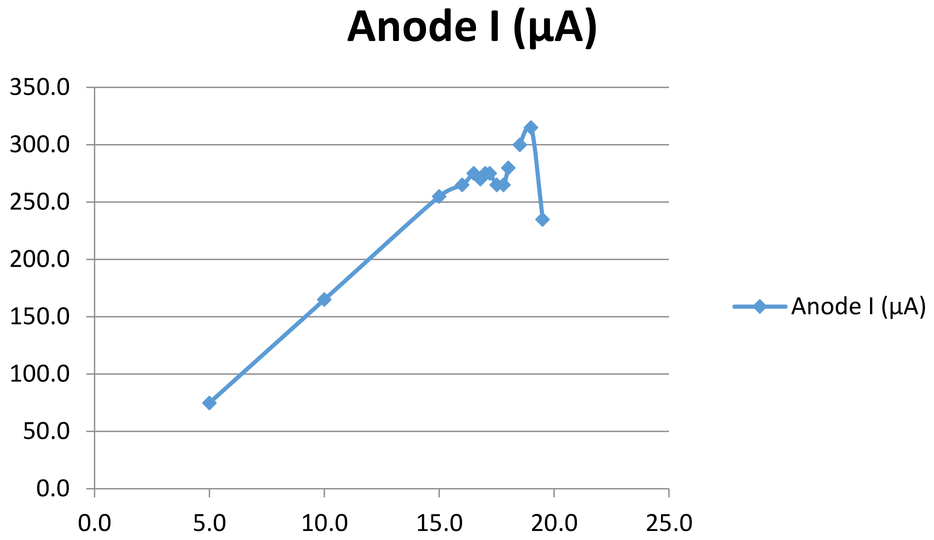
WILHELM BRATWURST INSTITUTE FOR APPLIED PHYSICS RESEARCH

Pulsed operation shows many new phenomena

- Pulses < 500 μs can eliminate discharge in conditions where DC discharge occurs
- Some indication of resonant peak in pulsed mode
  - Short pulses < 250 μs show no or reduced peak
  - Long pulses show discharge
- Some indication of suppression of resonance with pulsing



DC

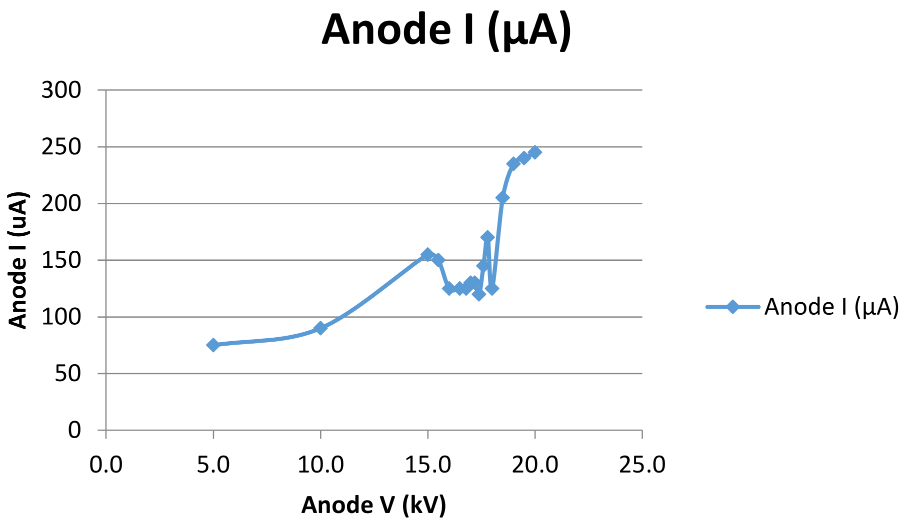


Pulsed (200 μs)

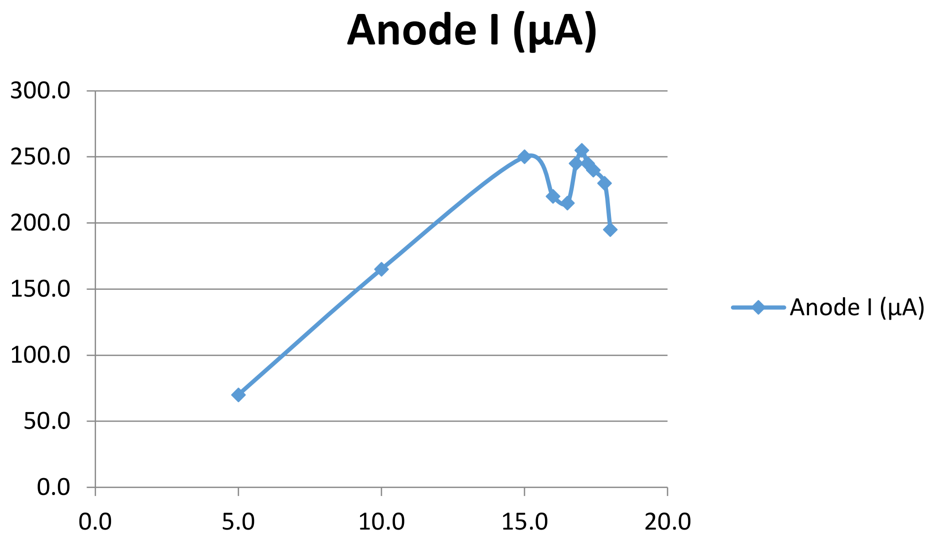
Wilhelm Bratwurst
Institute
for
Applied Physics
Research

Some recent data

- Two scans show
  - Precursor peak?
  - Resonance or not
  - Discharge or not



500 μs



200 μs

Upgrade to higher voltage

* Thanks to our colleagues at Apollo Fusion, Inc.

Summary and Planned Further Work

- We have designed and constructed a permanent magnet Penning trap which exhibits theoretically predicted electron trapping, but efforts to reach fusion relevant potentials have been blocked by problems with high voltage discharge in the trap.
- We have observed that puled operation can avoid discharge under favorable conditions
- We are studying if pulsed operation can avoid discharge and simultaneously allow resonant operation to provide virtual cathode for ion trapping in future work.
- We are re-designing the ^{3}He electronics to avoid electrical noise issues

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. 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).

7. D. C. Barnes, “Penning Traps as Neutron Sources,” Presented at the 16th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Applications, Madison, WI, October 1, 2014.

8. D. C. Barnes and D. R. Knapp, “Spherical Penning Trap as a Small Fusion Source,” Presented at the 2015 Meeting of the American Physical Socieity Division of Plasma Physics, Savannah, GA, November, 2015.