Techniques for energetic ion assisted in-situ coating of long, small diameter, beam pipes with compacted thick crystalline Copper film.

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Phase II, Second Year Presentation

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About PVI:

- PVI is a system engineering and manufacturing company specializing in high vacuum and thermal process technologies.

- Current and previous products include tools used for thin film deposition, thermal diffusion systems, rotating grade titanium processing systems, and a variety of high temperature vacuum processing equipment.

Thermal Diffusion and Research Furnaces

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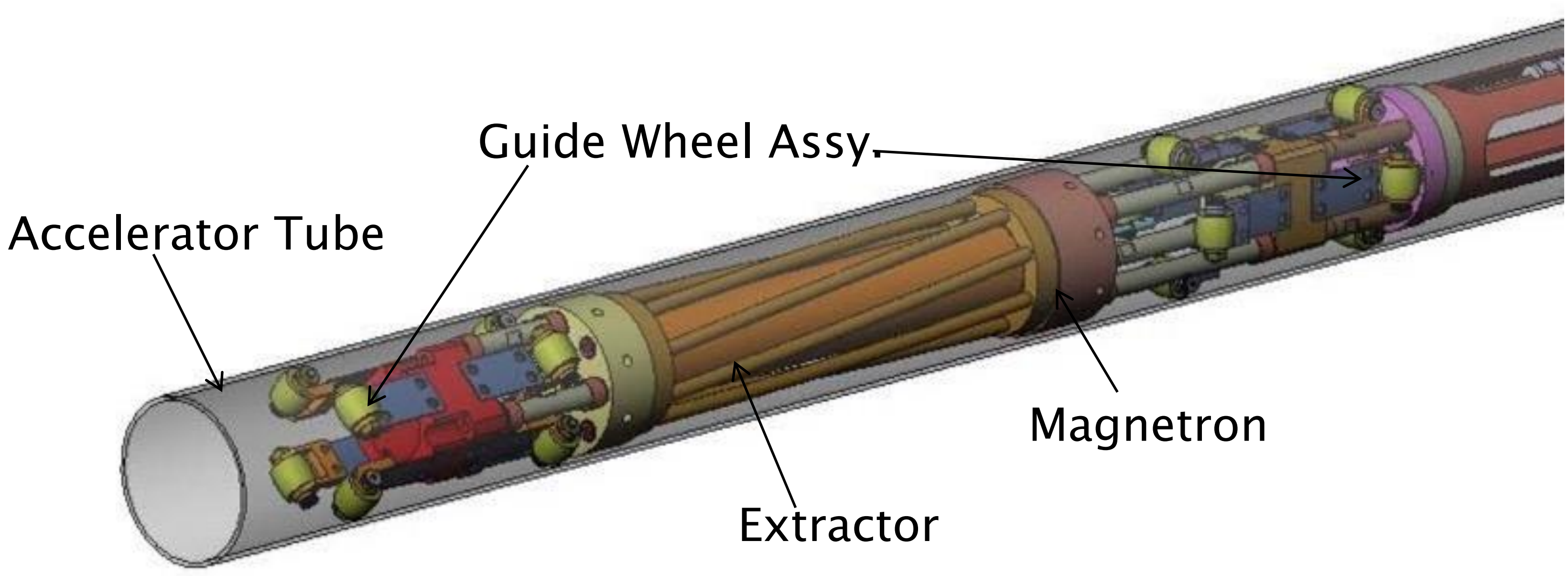
Phase II Primary Objective & Methodology:

- Design, build, and optimize operation of a robotic IAD (Ion Assisted Deposition) device for **in-situ** coating of long small diameter tubes with defect free Copper films.
- Approach chosen is fitting a cylindrical magnetron with an extractor.
- Utilize previous developed cylindrical magnetron technology.
- Integrate grid style extractor to cylindrical magnetron.



Integrated IAD Cathode Sputtering Magnetron in accelerator tube

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Relevance:

- RHIC accelerator vacuum tubes are made from relatively high resistivity 304L stainless steel.
- This results in unacceptable vacuum tube ohmic heating, especially when trying to increase ion beam luminosity resulting in superconducting magnets quenching and beam instabilities.
- A Copper film applied to the accelerator vacuum tubes will mitigate these issues and facilitated enhance luminosity.
- Utilizing IAD sputtering will provide a compacted crystalline structure with improved conductivity at cryogenic temperatures.

Original Phase II Goals:

- Design and fabricate a small scale (15cm cathode) robotic cylindrical IAD magnetron for deposition of defect free Copper films.
- Modify existing tube coating system (TCS) and optimize IAD operation.
- Process samples for cryogenic testing at BNL.
- Scale 15cm cathode IAD magnetron to 50cm cathode. Optimize operation.
- Test with BNL dipole magnet assembly.
- Perform coating tests with thermal sensors and determine maximum deposition rate. (for thermal management).
- Design removable guides for cable bundle mechanism.

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Prior Accomplishments

- Developed Cylindrical Magnetron which successfully Sputters uniform coating at challenging target to substrate distance of 1.5 cm.
  - Film thickness up to 10 µm.
- Sputtered Coating on close to 20 meter sections of accelerator tubing with 50 cm Magnetron utilizing automated tube coating system (TCS).
- Successfully developed guide wheel assemblies to drive Magnetron thru accelerator sections with bellows.
- Fitted Magnetron with motor drive to cycle internal magnet position to optimize target material utilization.
  - Up to 85% target utilization has been achieved.
- Developed discharge cleaning process to improve adhesion characteristics
  - Test samples exceed capability of 12 kg test fixture.
- Designed and fabricated cryogenic resonator (most components) for testing samples at BNL at PVI expense.

Tube Coating System

- 20 m tube test system containing full RHIC magnet tube & its two type of bellows.
- Chamber with umbilical for water cooling, power supply & motion system.

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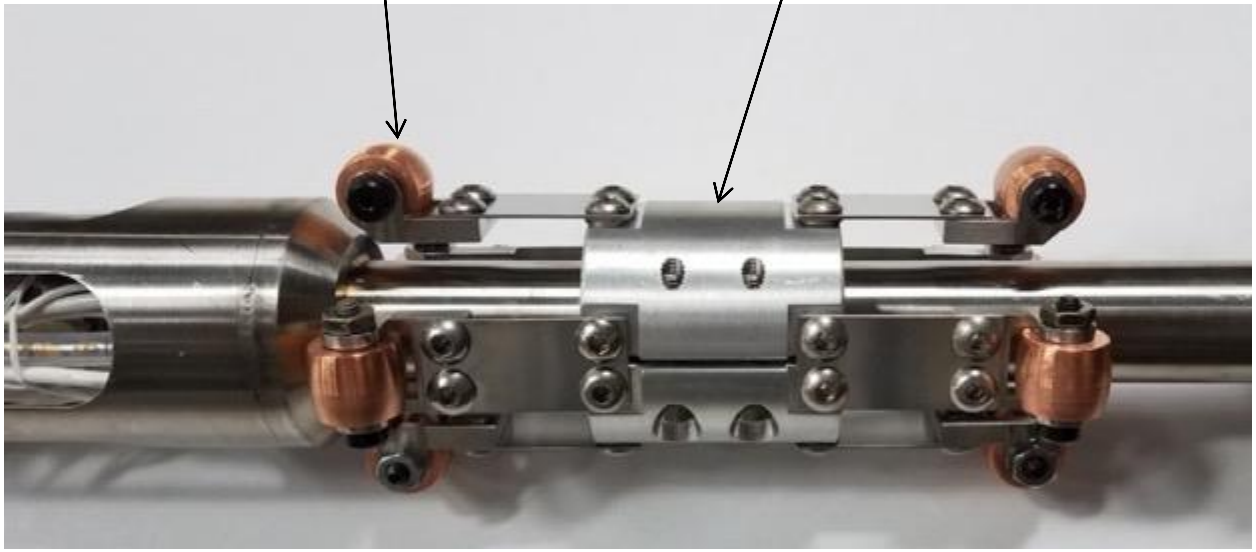
Guide Wheel Assembly

- Designed for long (500 m) narrow (6.88 cm) tubes.
- Able to travel thru bellows and other ports.

Copper wheels with Stainless Steel body



Cryogenic Test Tool/Testing

- Conductivity enhancement of RHIC tubing coated with 5 µm and 10 µm thick copper at 4K was a factor of 2.3 times higher than room temperature copper, i.e. conductivity of (2.3x5.7) x 10^7 Siemens/meter, which is within a factor of 2 of what is needed for EIC!
- Routine magnetron operation coating rate of 3.175×10^{-4} meter/sec at 500 W DC implies 1.57×10^6 seconds or 18.22 days to coat 500 meter long section of RHIC.
- Excellent adhesion was maintained under thermal cycling test conditions. Samples were immersed and warmed up 10 times over a period of 6 hours.

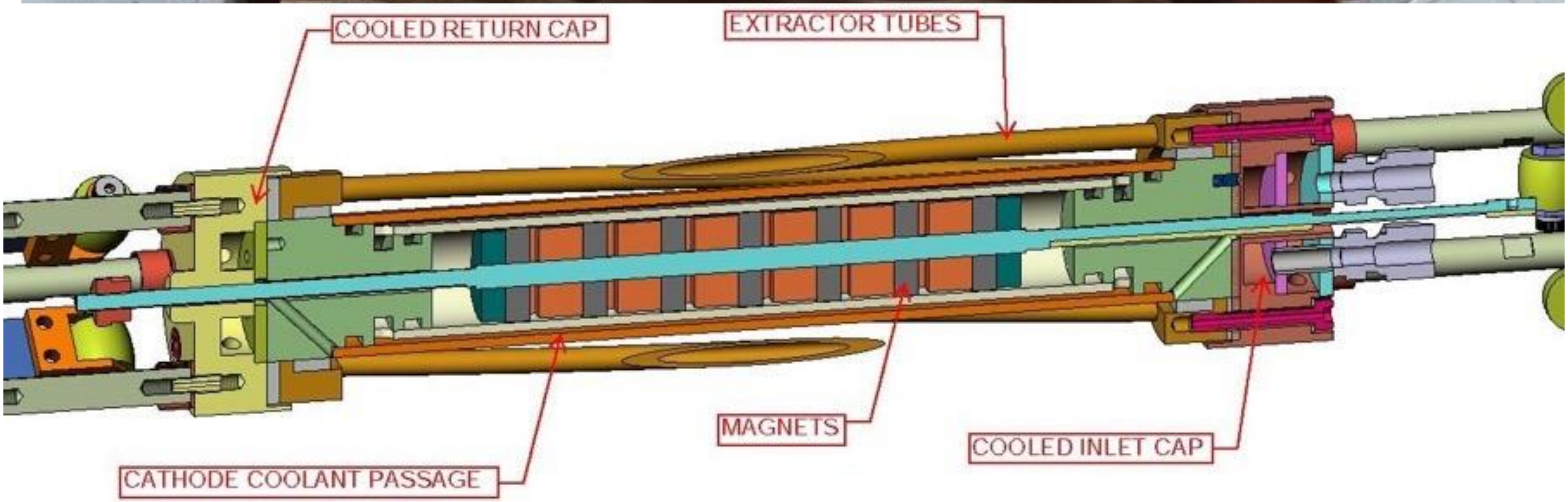
Cryogenic conductivity and thermal cycling tests were performed at BNL

Setup for thermal cycling test sample is at the end of the crane line about to be inserted into the cryogenic Dewar

Test sample pulled out of Dewar and being warmed up

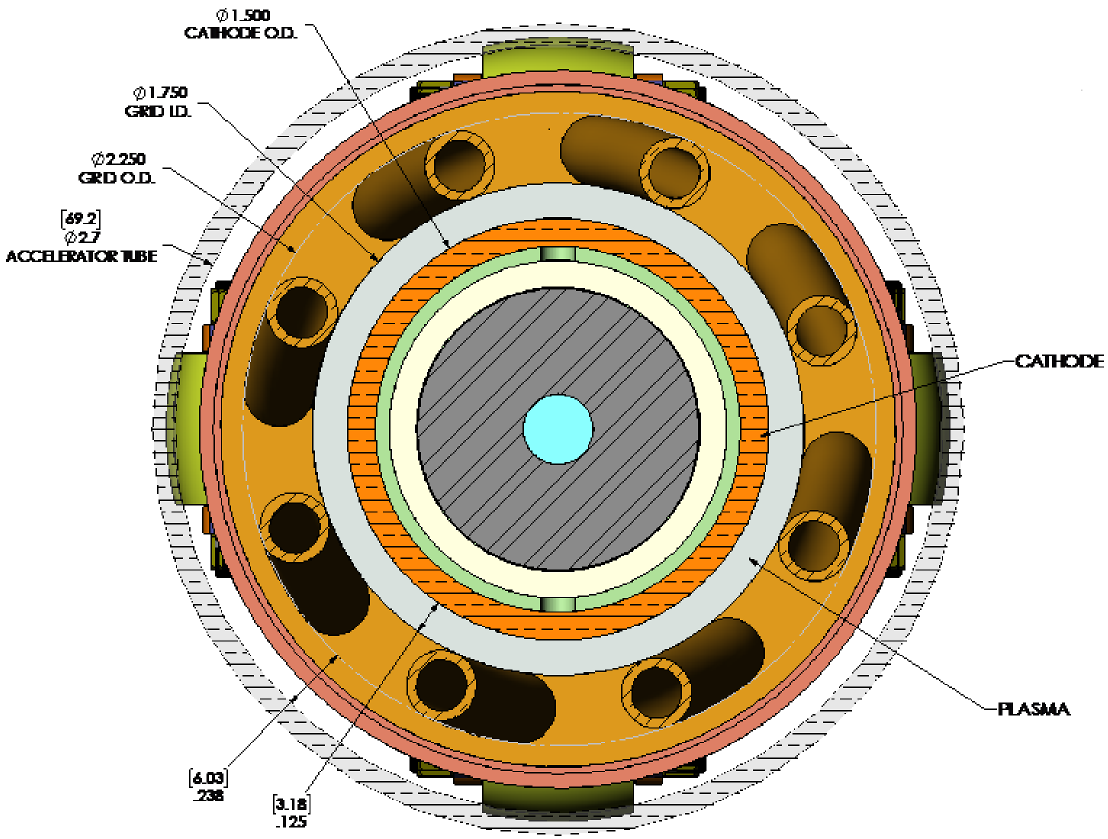
Assembled Magnetron with Extractor & IAD Magnetron Cross Section

First generation OFHC anode weldments

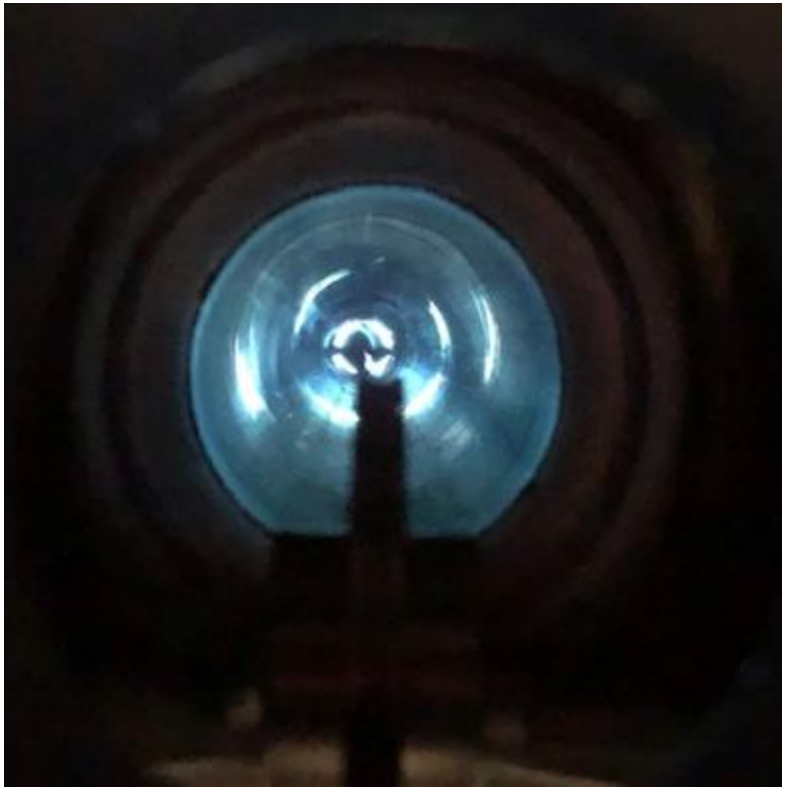


IAD Cylindrical Magnetron Prototype

"IAD" Magnetron End Section View



Magnetron
Cross-Section



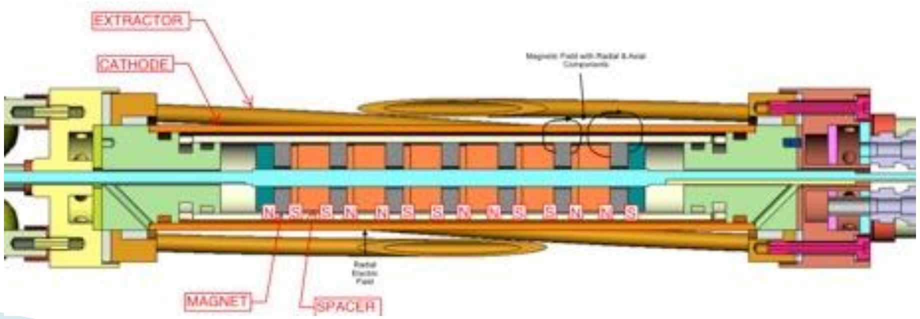
Magnetron During
Deposition

Initial "IAD" Magnetron Operation

- Ignition of plasma at previous operating parameters was not possible.
- Typical deposition parameters are pressure of 5mTorr and voltage of 275 V.
- IAD Magnetron required ignition pressure of 300 mTorr and operating voltage of 311V.
- Resulting samples were thinner then anticipated, target 5µm sample measured .276µm.
- The higher pressure likely resulted in most of the Copper vapor being diluted in the Argon gas and pumped away.
- Coated samples at higher pressure also appear to be amorphous black Copper that are not crystalline.
- Coated glass slide →

Magnetron with Extractor Sputtering Analysis

- Problem: extractor is too close to cathode (3 mm compared to 1.3 cm to substrate). Consequently, **radial magnetic field** components **guide electrons straight into** the **extractor** resulting in 300 mTorr magnetron operation versus the optimal 5 mTorr.
- Quick analysis: at a pressure of 300 mTorr ≈ 300 micron, mean free path (mfp) for a copper or argon gas atom is 5/(pressure in microns) = 0.0166 cm, which is much smaller than cathode to tube distance of ≈ 1.3 cm [*e.g. Scientific Foundations of Vacuum Technique Edited by Saul Dushman and James M. Lafferty, John Wiley & Sons, New York (1962)*]. Magnetron plasma operating at 300 mTorr, with only 1% ionization, has a Debye length of 9×10^{-6} cm, across which 300 eV argon ions are accelerated. And, cross section for 300 eV argon on argon is about $\sigma \approx 10^{-16}$ cm^2 (*A.V. Phelps et al J. Phys. B; At. Mol. Opt. Phys. 33 2965*). Argon density of 300 mTorr is $n = 3.6 \times 10^{16} \times .3 = 1.08 \times 10^{16}$/cc (probably less since the temperature is higher than room temperature), which means that their mean free path (at 300mT) = $1/n\sigma$ = 0.926 cm. Therefore, attenuation of argon ions across this sheath is minimal $e^{-(9\times\exp-6)/0.926} \approx 0.99999$, i.e., almost 100% of the argon ions reaching the sheath strike the cathode unattenuated.
- Good deposition requires mfp > cathode to substrate distance. **Cu mfp 0.0166 cm cathode to substrate distance is 1.3 cm!**
- Moving the extractor 9 mm away from the cathode, lower operating pressure was achieved (down to 9 mTorr); a step in the right direction; Biasing the extractor position resulting in arcing, limiting our run time.
- **Radical new approach is needed**



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Solution: Magnetron Mole with Permanent Magnet Solenoidal Magnetic Field

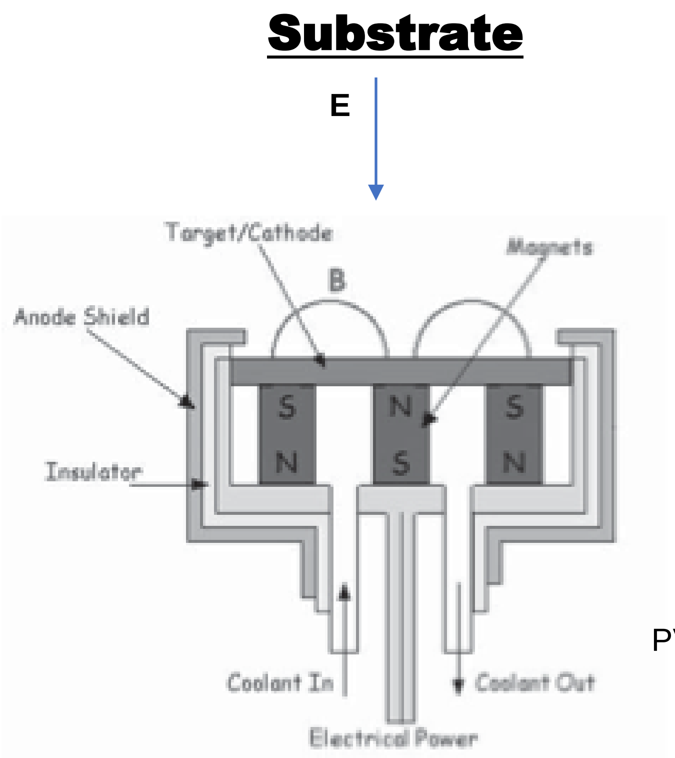
- Original magnetrons, subsequent RF generating magnetrons & ion source all have had solenoidal magnetic fields. At BNL and other labs worldwide ion sources, operate at pressures lower than 5 mTorr having anode to cathode gaps of 2-3 mm.

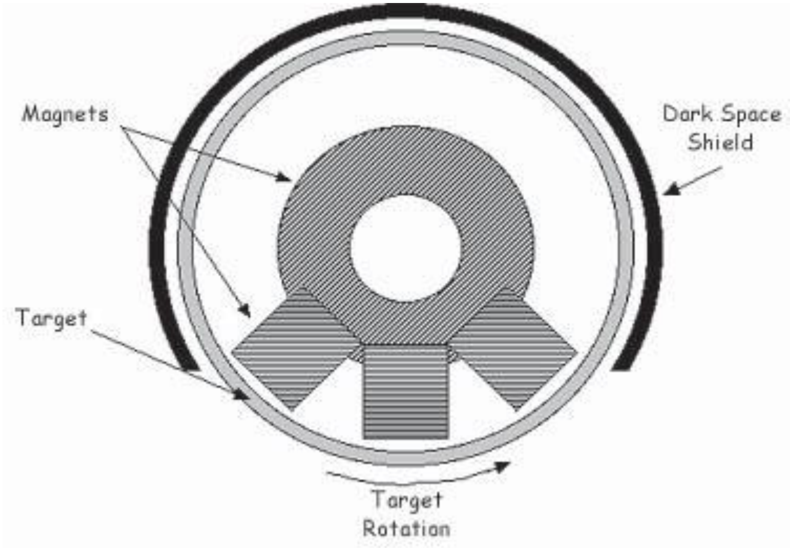
- These magnetrons are much more efficient than sputtering magnetrons, Sputtering magnetrons use permanent magnets in a bucking mode generating non-uniform fields with very non-uniform erosion requiring cathode and/or magnet packet movement.

- So why did industry adapt permanent magnet magnetrons? Answer: in very large various shape deposition chambers applying external magnetic fields is not a practical option.

Industrial PVD Magnetrons

Industrial PVD sputtering magnetrons are primarily planer magnetrons or a variation of, utilizing permanent magnets. Planer magnetrons can deposit on large areas and are versatile. Drawbacks are poor power, gas efficiencies and material utilization due to low or zero magnetic fields in some areas.



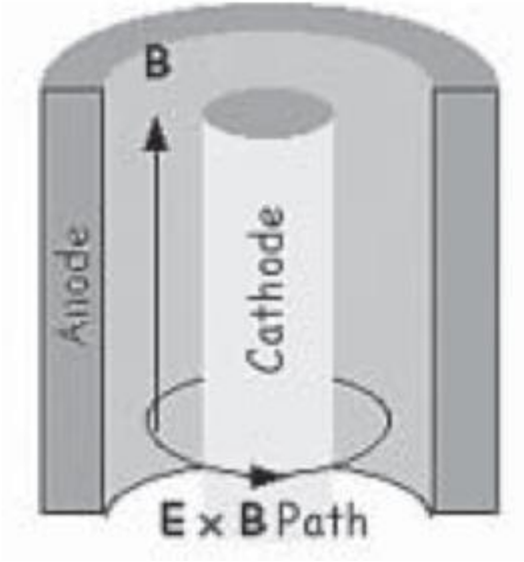


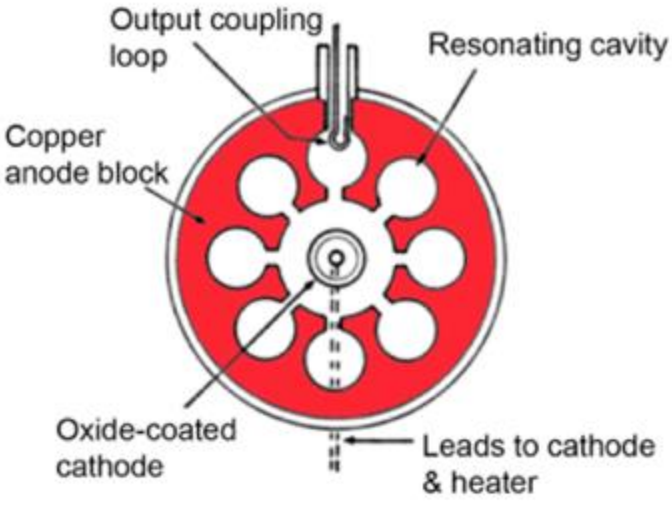
PVI magnetron mole

Original Magnetrons

Magnetrons are based on the Lorentz **ExB** force which guides discharge electrons in a closed-loop motion, which confine the electrons in orbits that maximize gas ionization, **covering the whole cathode**; they are power and gas efficient (most for RF generation are gasless!).

Original use of magnetrons was for RF/microwave generation and later ion sources (e.g. BNL H^- ion sources).

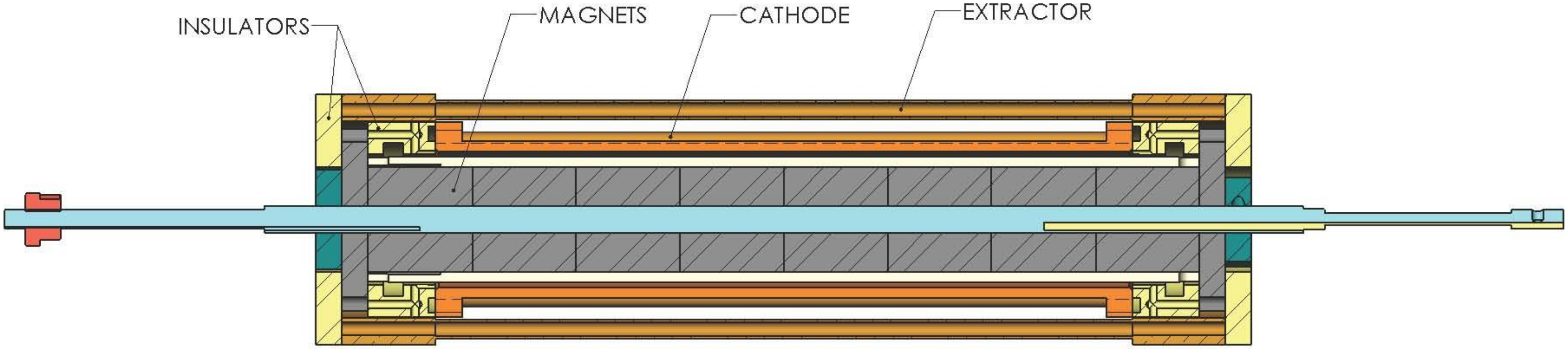




Resonant cavity magnetron high-power high-frequency oscillator

IAD Magnetron with Solenoidal Field

“Back to the Future”(Ady’s dream). IAD magnetron device with self contained solenoidal magnetic field is theoretically possible, since soft iron in the extractor can provide magnetic field return path to magnets enforcing each other.



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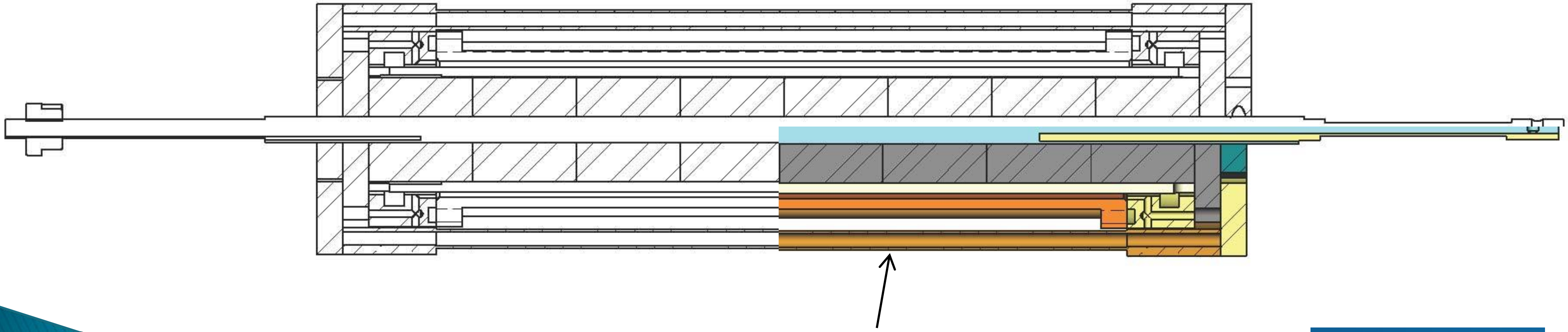
Magnetic Field Simulation

- The 15-cm long cathode IAD magnetron, (drawing shown in slide 19) is the simulations subject. Since the magnetron has azimuthal symmetry, as well as axially about the mid-point, magnetic field flux lines are shown for **one quadrant**. Simulations were performed by Steve Kahn from Muonsinc.

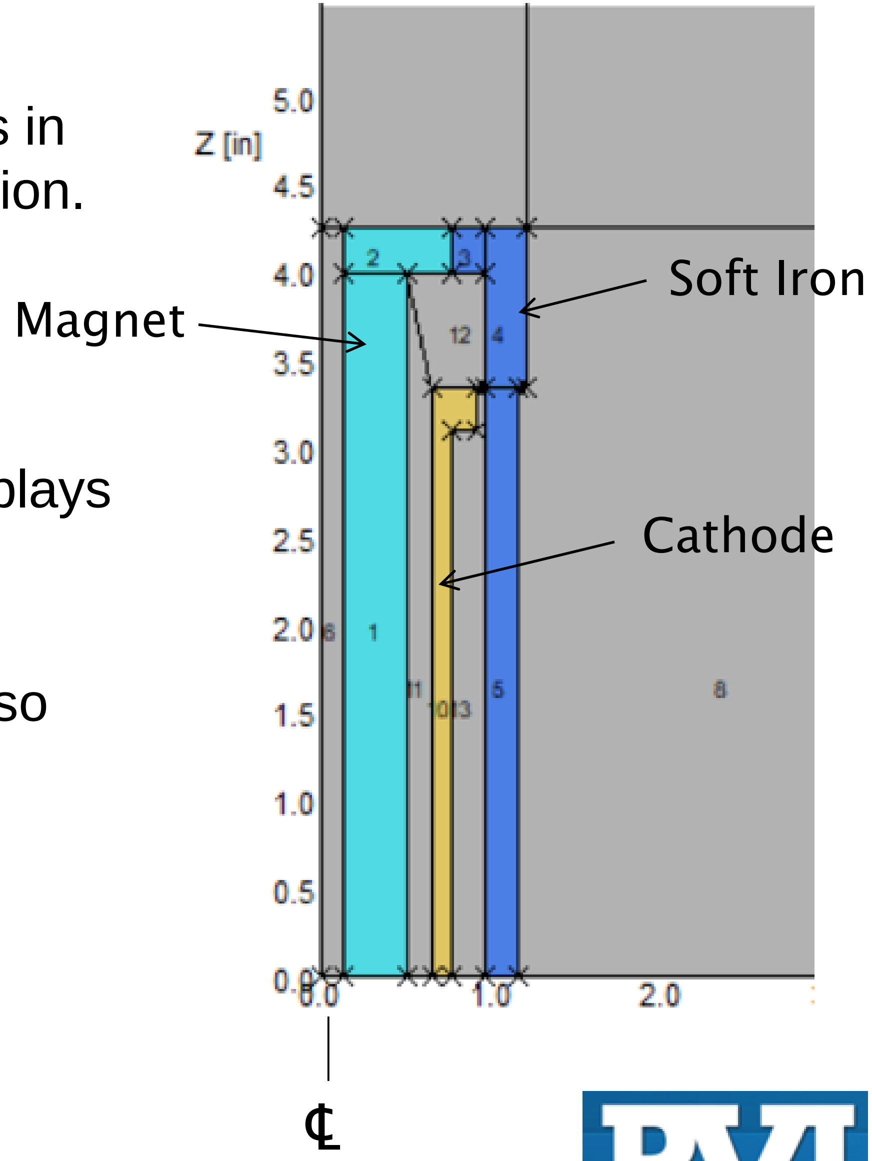
- Although the IAD magnetron was designed and fabricated in metric unit length, the simulation program utilized (Opera) has length dimensions in inches.



Section used for simulation

Magnetic Field Simulation Setup

- Cyan is neodymium. In region 1 field is in Z-direction Region 2 field is in R-direction.
- Blue is soft iron.
- Yellow represents the cathode, which plays no magnetic role.
- In this IAD magnetron, the extractor also serves as magnetron anode (due to substrate proximity).



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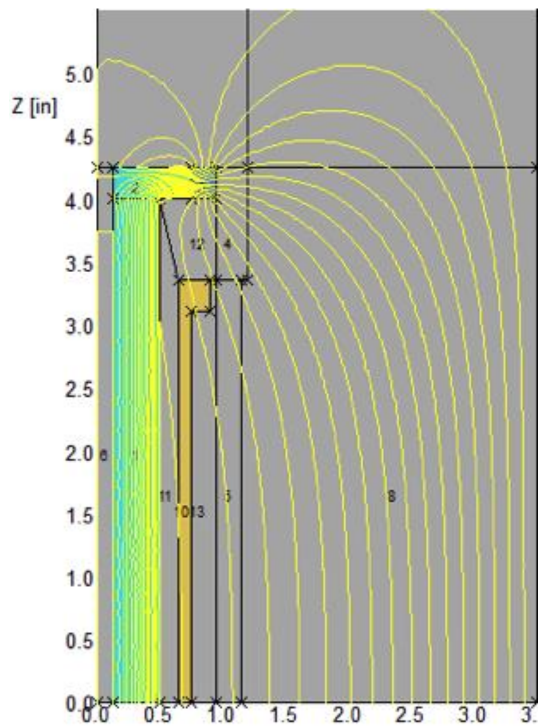
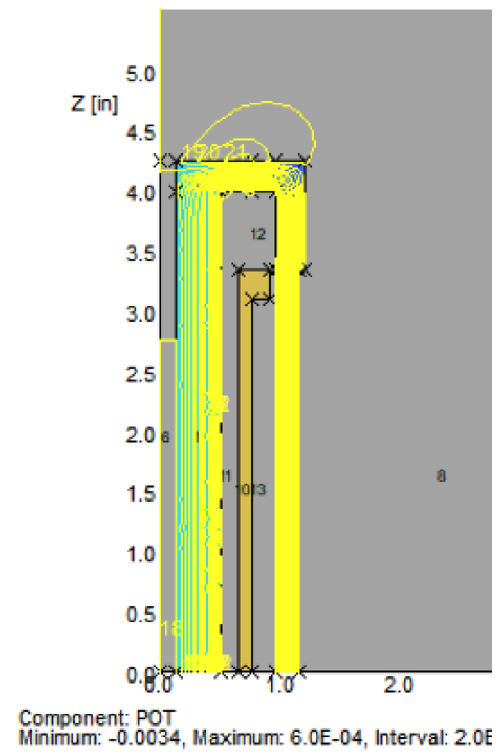
Magnetic Field Simulation Results

- Simulation is that of neodymium permanent magnets (IAD magnetron utilizes neodymium magnets).
- The exact magnetic field strength is not very important; it's exact field line shape is significant; Below figure shows magnetic flux lines without (a) and with (b) soft iron in the extractor/anode.



(a) Without Iron Extractor



(b) With Iron Extractor

Magnetic Field Simulation Results continued

- The 2 mil of soft iron in the 0.25” extractor (will allow for more than adequate cooling) yields an axial magnetic field at the cathode of 361 Gauss (too much iron confines too much flux).
- In this configuration, the electron gyroradius (Larmor) $2.38xT^{1/2}/B = 6.7x10^{-3}$ cm, $2x10^{-2}$ cm, for electron temperatures of 1 & 10 eV respectively.
- Basically, a 3 mm cathode to anode/extractor gap is more than an order of magnitude larger than an electron gyroradius.
- Furthermore, the radial magnetic field component is practically 0! **System can be optimized for industrial setting with no length limitation**!

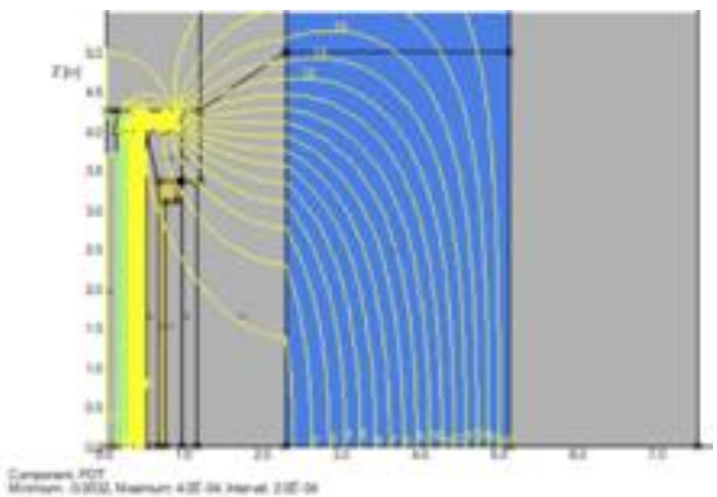
Magnetic Field Simulation for RHIC Cold Bore

- In the RHIC cold bore sections, there are large iron yokes, which greatly affects the magnetic field flux much more than any amount of soft iron that can be inserted in the extractor.
- The Presence of the external iron yoke alters the flux pattern when ring magnets enforce each other (minimal effect on the axial magnetic field components, which are important to magnetron operation, when permanent magnets are bucking each other; some effect on radial components).

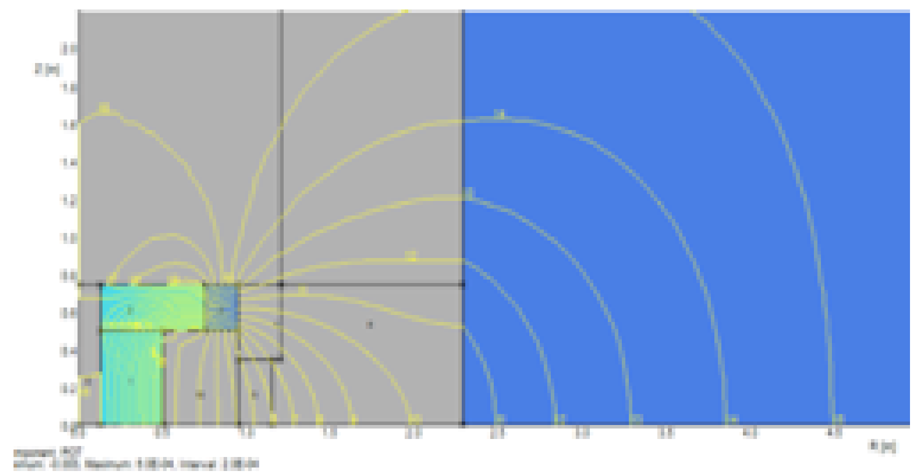
RHIC Cold Bore Magnetic Field Simulation

- **Preliminary** simulations for a RHIC cold bore dipole section show that for long magnetrons (left figure) most of the return magnetic field is through the iron yoke (blue). Basically, magnetic field flux line are confined to the end magnets and end plates. Such a configuration is not workable.

- A workable configuration made up of multiple magnetrons 1” in length (with 1” gaps) is shown in right figure (only one quadrant of one cell; field lines in yellow).



Long Magnetron



Short Magnetron

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RHIC Cold Bore Magnetic Field Simulation (continued)

- Quantitatively, simulation has shown that axial magnetic fields of 850 to 1900 Gauss on cathode can be reached.
- Gyroradii of 2.8×10^{-3} cm, 8.8×10^{-3} cm, for 850 Gauss and electron temperatures of 1 & 10 eV indicated that a well-working configuration of multiple short magnetrons is feasible for extractor gaps of 3 mm.
- Unlike the case without an iron yoke, which has roughly uniform magnetic fields on the cathode, short magnetrons reduce the issue of field non-uniformity seen with the iron yoke.

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Summary

- Project has been extended (currently in 4th month of 6-month extension); little progress since March due to Covid-19 closures; need extra extension & reduced restrictions.
- BNL EIC program has been changing: Cu deposition is backup to cage insertion. Developed technology could be applied to low SEY coating. Magnets will need to be taken apart.
- Going forward, plans are to fabricate a modified 15-cm long cathode magnetron with soft iron in extractor, re-orient magnets. Design and testing at PVI; parts fabrication at BNL [PVI budget low; still some money in the BNL portion of the funding].

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