Novel Device for *In-Situ* Thick Coatings of Long, Small Diameter Accelerator Vacuum Tubes

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Relativistic Heavy Ion Collider (RHIC) Complex

Problems that must be solved in order to enhance RHIC luminosity

Lower vacuum chamber resistivity and control electron cloud formation!

The RHIC vacuum chamber is made of 7.1 cm ID stainless steel tubing with 1.6 μm surface roughness in cold bore (2.1 μm in warm section).

Stainless steel has high resistivity. Coat tube with copper!

Electron clouds, which have been observed in many accelerators including RHIC can act to limit machine performance through dynamical instabilities and/or associated vacuum pressure increases. Formation of electron clouds is a result of electrons bouncing back and forth between surfaces, which cause emission of secondary electrons (electron multipacting effect). a-C coating!

Possible Solutions

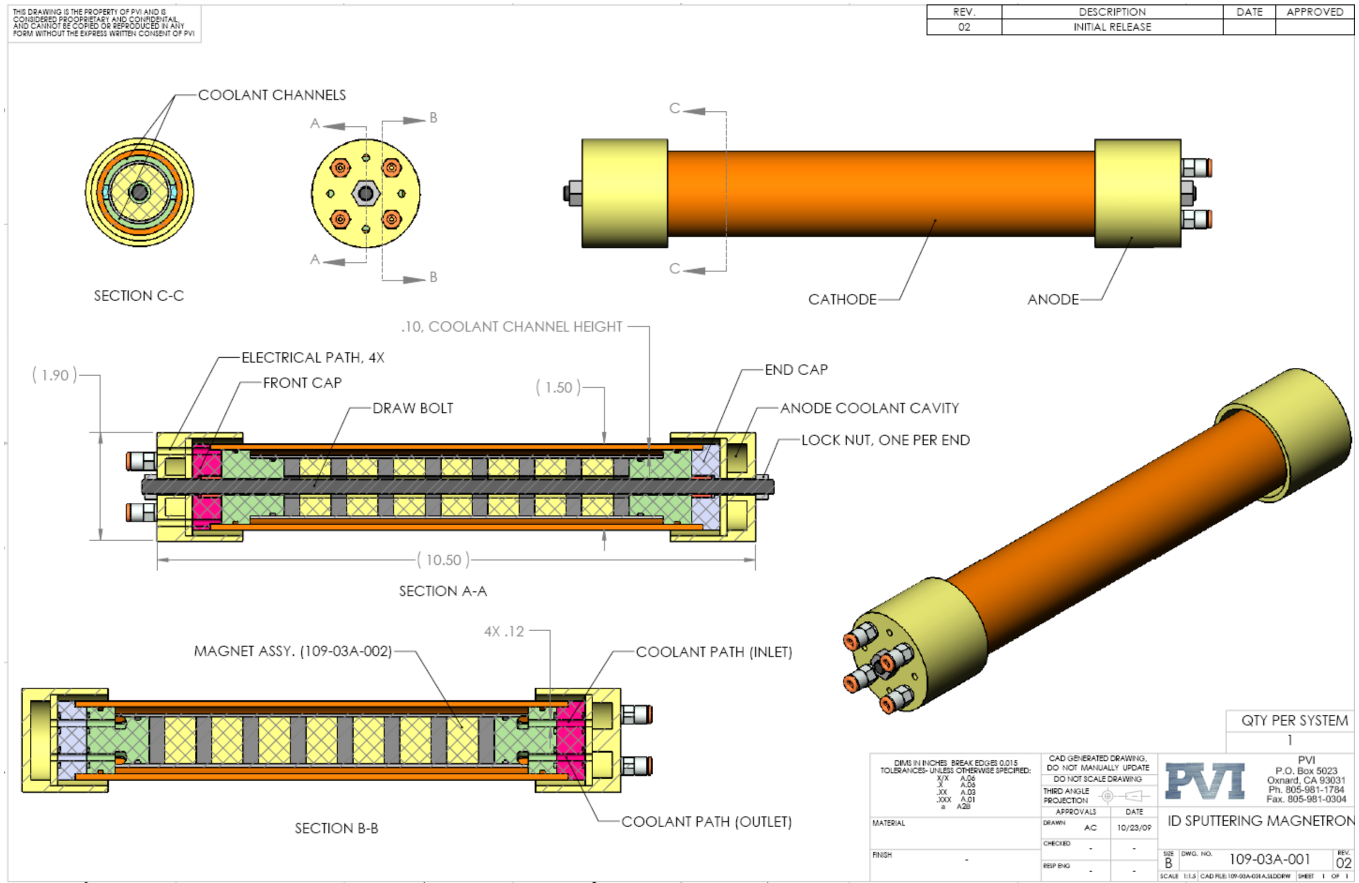
- Coating the stainless steel walls with about **10** micrometers of oxygen free high conductivity copper (OFHC) can prevent problems arising from high resistivity.
- Mike Blaskiewicz made rigorous computations, which are appropriate for our case. Mike combined effects of low temperature and large magnetic fields will yield a net reduction in room temperature resistivity of RRR=50 in the copper coating. The mean free path of conduction electrons is 2 microns, which is equal to the skin depth at 20 MHz. It is therefore prudent to include the anomalous skin effect when calculating the effect of the coating. When this is done it is found that **10 micrometers of copper should be acceptable for even the most extreme future scenarios**. Complete details can be found at BNL report: M. Blaskiewicz, “Copper Coating Specification for the RHIC Arcs”, C-A/AP/ note #413 Dec 2010 (unpublished).
- Covering the OFHC with a very thin layer of amorphous graphite to reduce SEY (secondary electron yield)
- **But, Cu coatings thicker than 2 μm have columnar and other grain structures that might have lower SEY like gold black.** SEY measurements of copper coated stainless steel discs and rectangular samples were sent to CERN for SEY measurements at both room and cryogenic temperatures. Encouraging results were obtained**. Nevertheless, new experimental SEY measurements indicated that there was no need to pursue a-C coating either, since well-scrubbed bare copper can have its SEY reduced to 1** (SEY < 1.3 is needed to eliminate electron cloud problems).

DEPOSITION PROCESSES & OPTIONS

- Coating methods can be divided into two major categories: chemical vapor deposition (CVD) and physical vapor deposition (PVD). Due to the nature of the RHIC configuration, only PVD is viable for in-situ coating of the RHIC vacuum pipes. First, the temperature under which coating can be made cannot be high (400 C is required for some conventional CVD), since the RHIC vacuum tubes are in contact with superconducting magnets, which would be damaged. A second very severe constraint is the long distance between access points. Introduction of vapor from access points that are 500 meters apart into tubes with 7.1 centimeters ID would likely not propagate far and result in extremely non-uniform coating. CVD out; but these constraints also severely restrict PVD options. Obviously evaporation techniques (ovens, e-beams) cannot be used in 7.1 centimeters ID, 500-meter long tubes. Therefore, evaporation must be accomplished locally. Of the plasma deposition devices like magnetrons, diodes, triodes, cathodic arcs, RF, etc., magnetrons are the most commonly used plasma deposition devices. In magnetrons, magnetic fields are utilized to confine electrons that generate high density plasma (usually argon or xenon) near the surface of the material that is being sputtered. Major advantages of magnetron sputtering sources are that they are versatile, long-lived, high-rate, large-area, low-temperature vaporization sources that operate at relatively low gas pressure and offer reasonably high sputtering rates as compared to most other sputtering sources. Chose to develop magnetron mole!

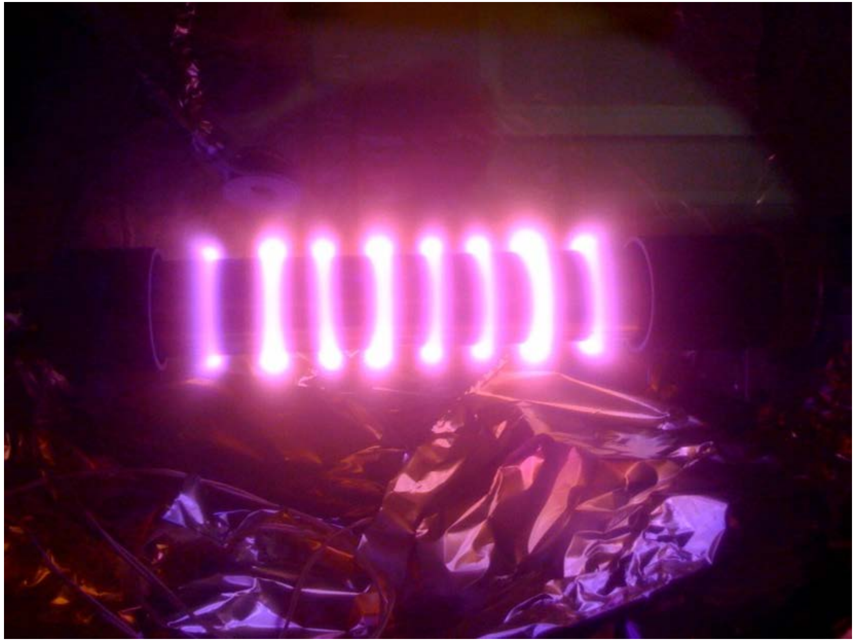
Magnetron Developed After Iterations

A mobile magnetron, shown below, with a 15 cm long cathode was designed, fabricated, and tested to coat samples of RHIC cold bore with OFHC at an average coating rate of **30 Å/sec** (factor 6 higher than absolutely needed). Copper deposition rates were measured with a 6 MHz crystal rate monitor: **500 m in 30 days**



Magnetron & Coating Challenges Solved

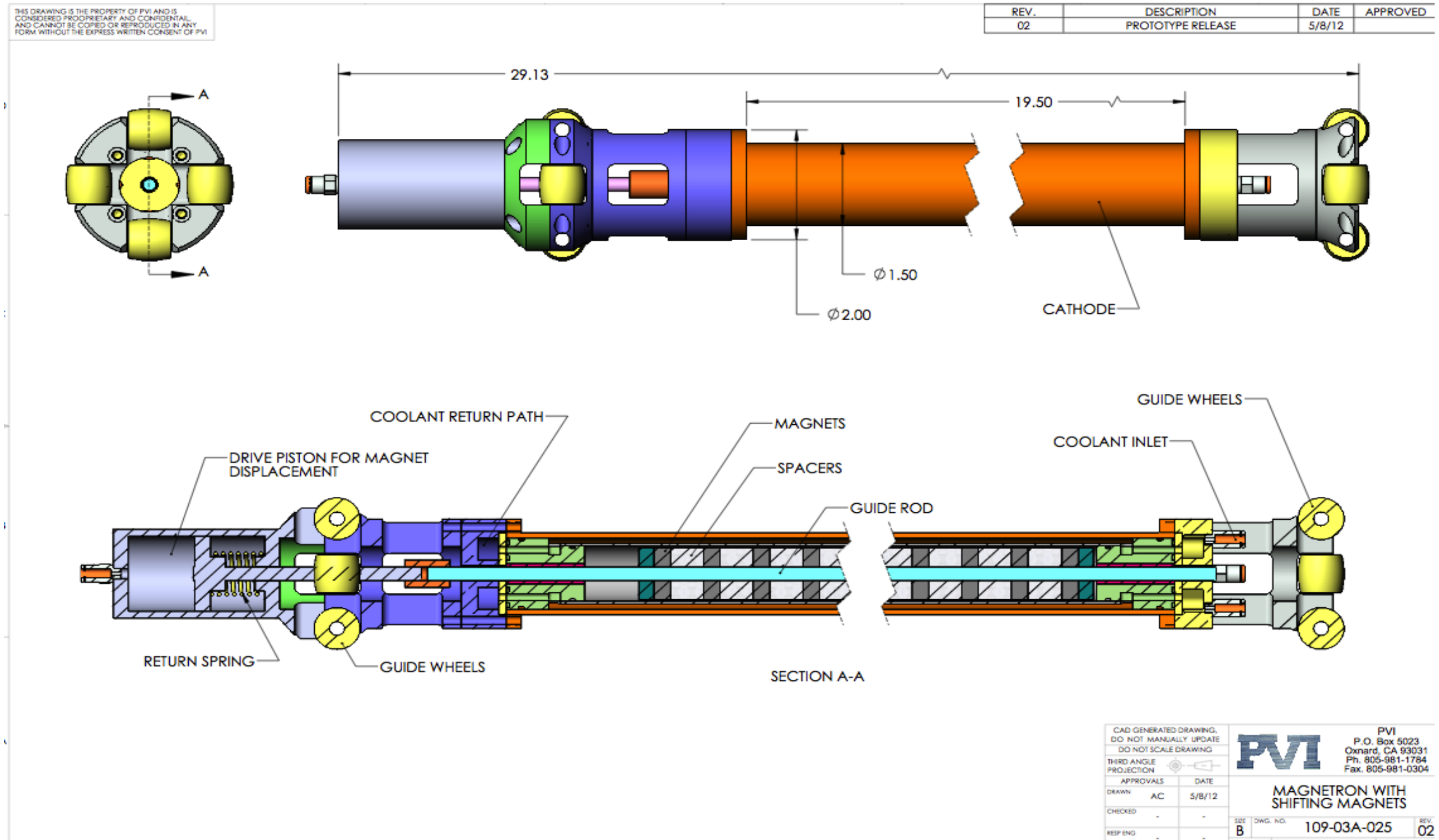
Inadequate copper utilization: thin cathode & very uneven erosion(magnetron integrity structural restrictions magnetics).

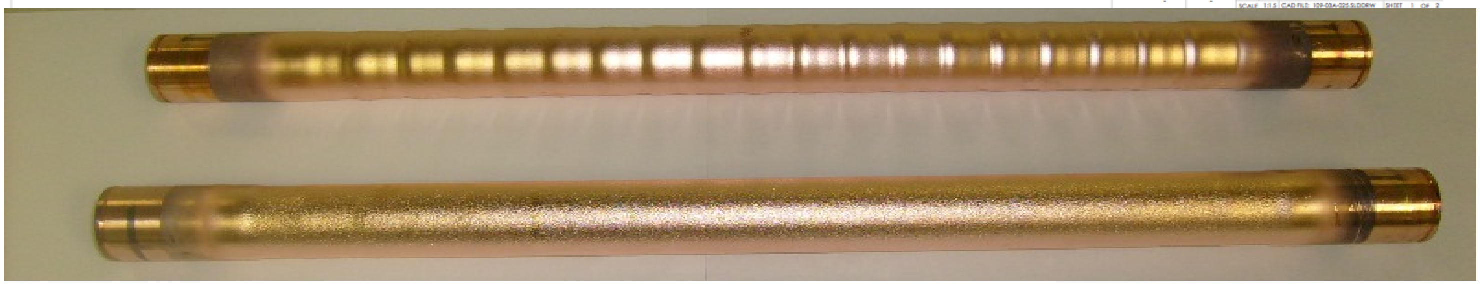


Inconsistent adhesion, which did not always meet rigorous industrial standard (tape; nail).

Magnetron with Moving Magnets & thickest possible cathode is used, which reduces the target to substrate distance to less than 1.5 cm (unprecedented)

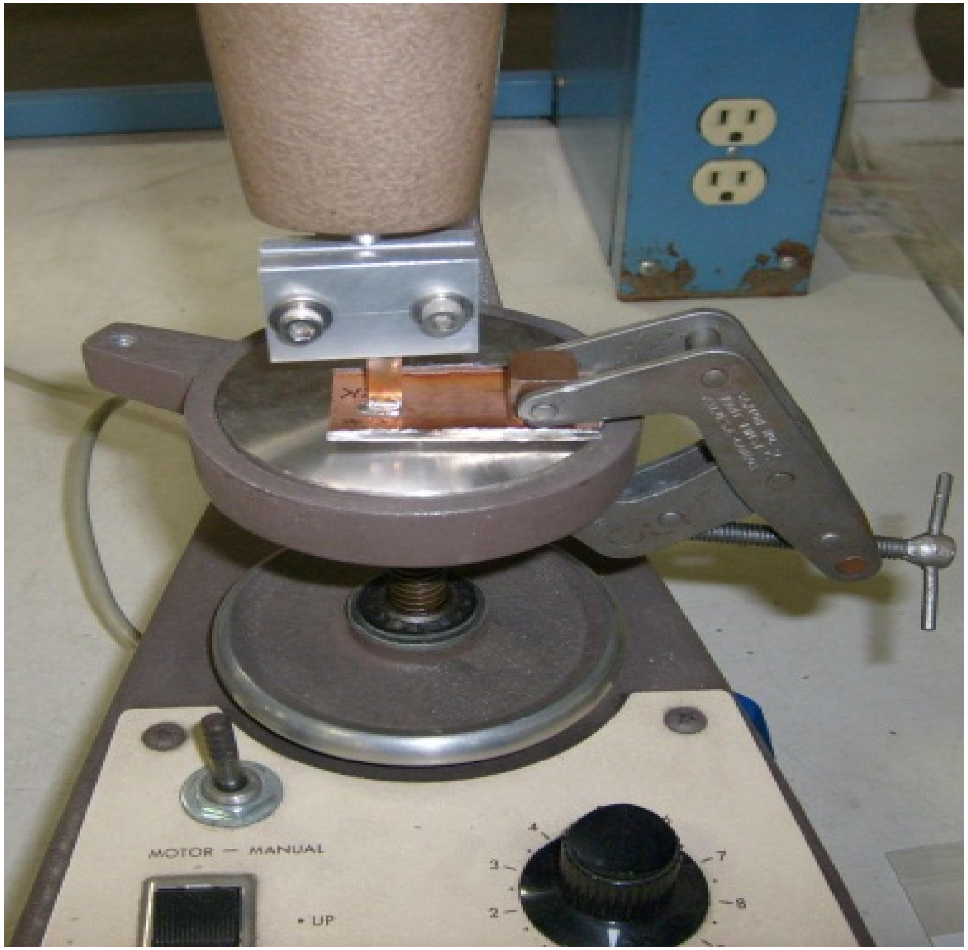
50-cm long cathode magnetron magnet package moving mechanisms: hydraulic (top) guide wheel motion (bottom); and, resultant erosion.





Coating Adhesion Strength

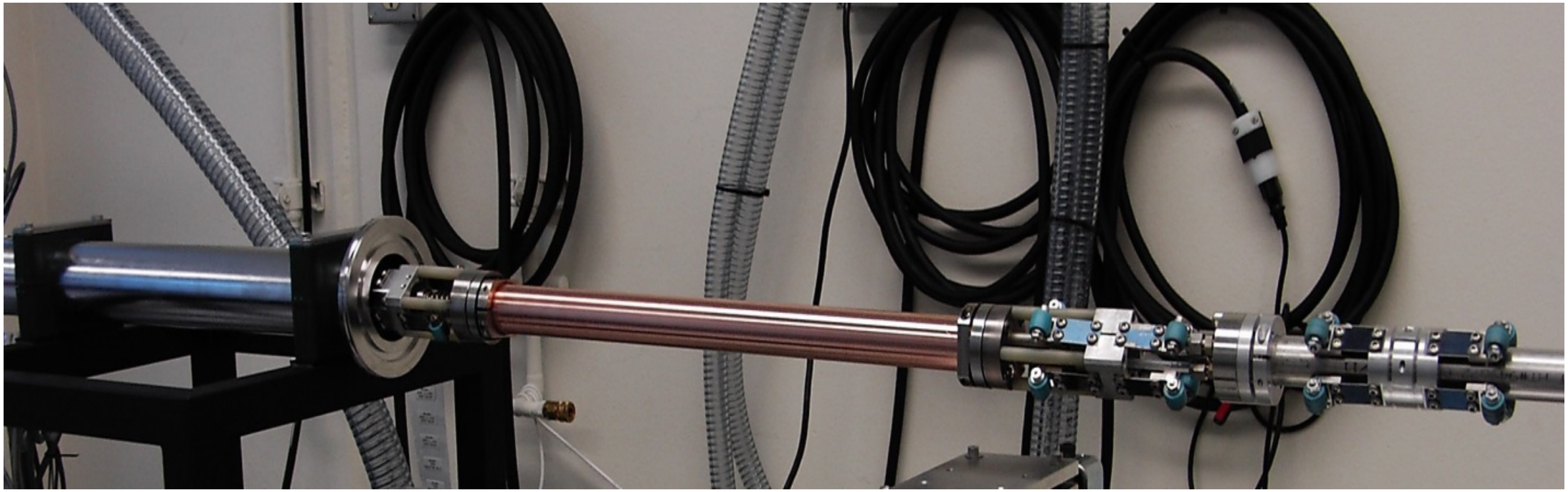
Consistent coatings with good adhesion are achieved routinely with first (proprietary) step that may not be needed in RHIC followed by optimized discharge cleaning: positive voltage (of about 1 kV) is applied to the magnetron at a pressure of over 2 Torr. The optimized results yielded **adhesion strength** of **over 12 kg** (maximum capability pull test fixture) or at least **2.5x10^{6} N/m**^{2}.

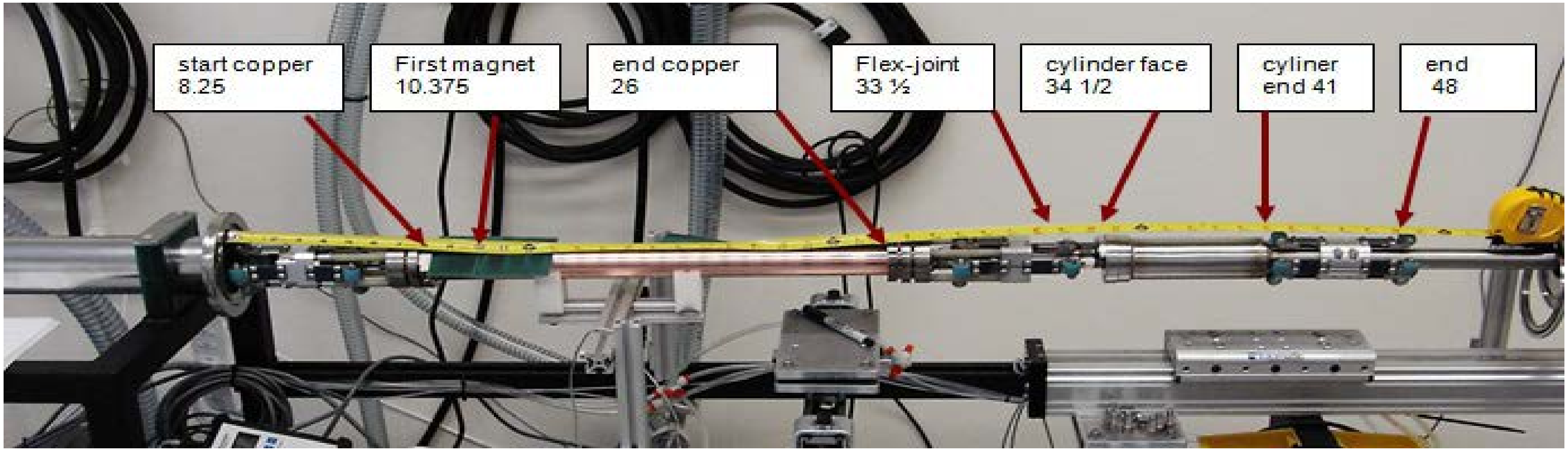


Magnetron Coating Mole

Top: photo showing the 50-cm long cathode magnetron spring loaded guide wheels. Leading edge guide wheels are inserted in a RHIC tube

Bottom: photo showing the 50-cm long cathode magnetron assembly

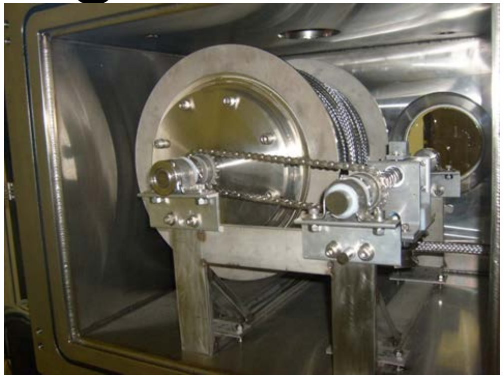




Deposition System Moving Mechanism

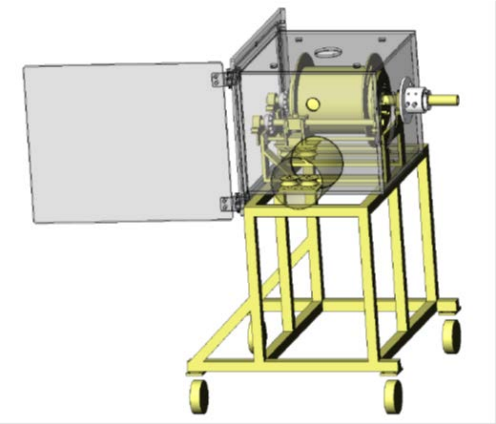
Cables moving the magnetron assembly with its electrical power and cooling water are fed through a cable bundle. An umbilical cabling system, which is enclosed in a flexible braided metal sleeve, is driven by a motorized spool. The whole magnetron and umbilical cabling systems are in vacuum.

Spool



Umbilical

Drive drawing



Drive

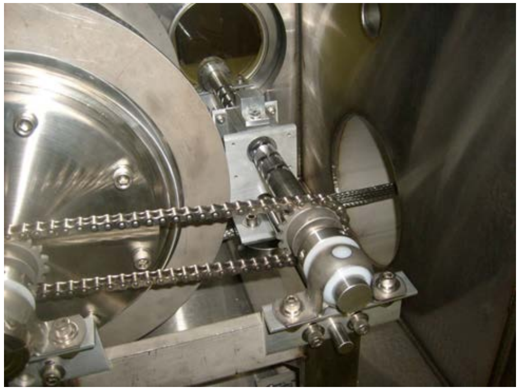
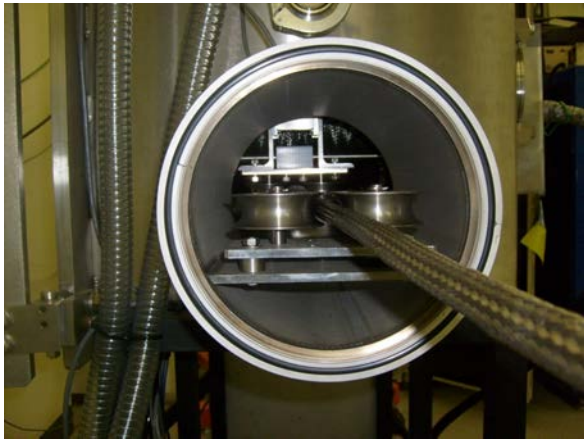


Photo of front part of the drive



Scaling the umbilical motorized spool drive system to a 500 m cable bundle yields a system that is 3 meters or less in any dimension (plenty room in the RHIC tunnel). Pull cable will be ¼” diameter stranded SS, is typically used in aircraft for flexible linkage with the various airfoil surfaces; very strong (20K tensile) with low elongation.

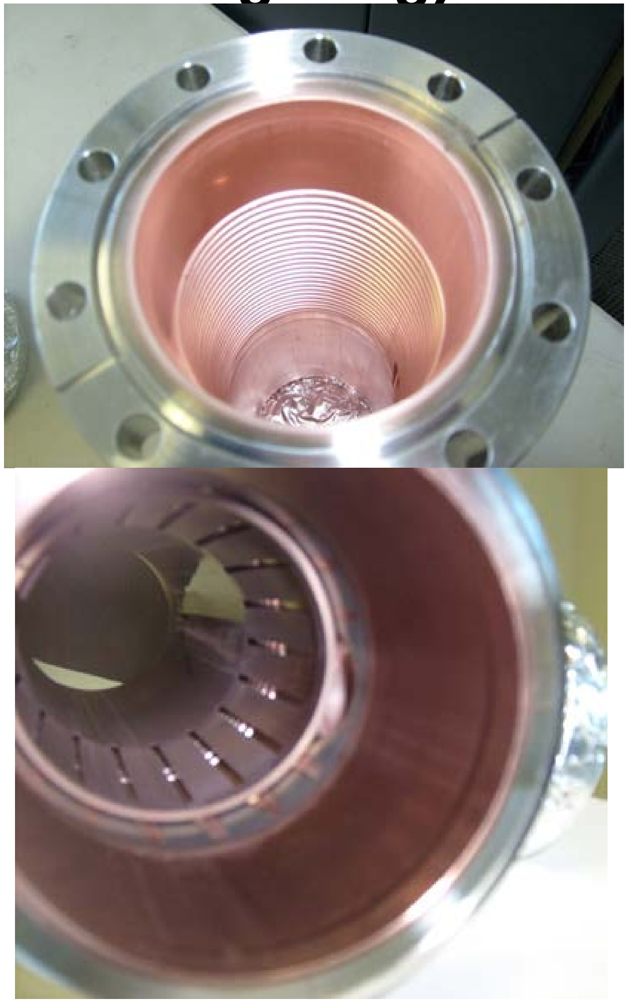
Coating an assembly of a RHIC magnet tube sandwiched between two types of RHIC bellows including a shielded bellow

Deposition experiments were performed with the magnetron whose carriage has a spring-loaded guide wheel assembly for bellow crossing that successfully crossed bellows and adjusted for variations in vacuum tube diameter, while keeping the magnetron centered.

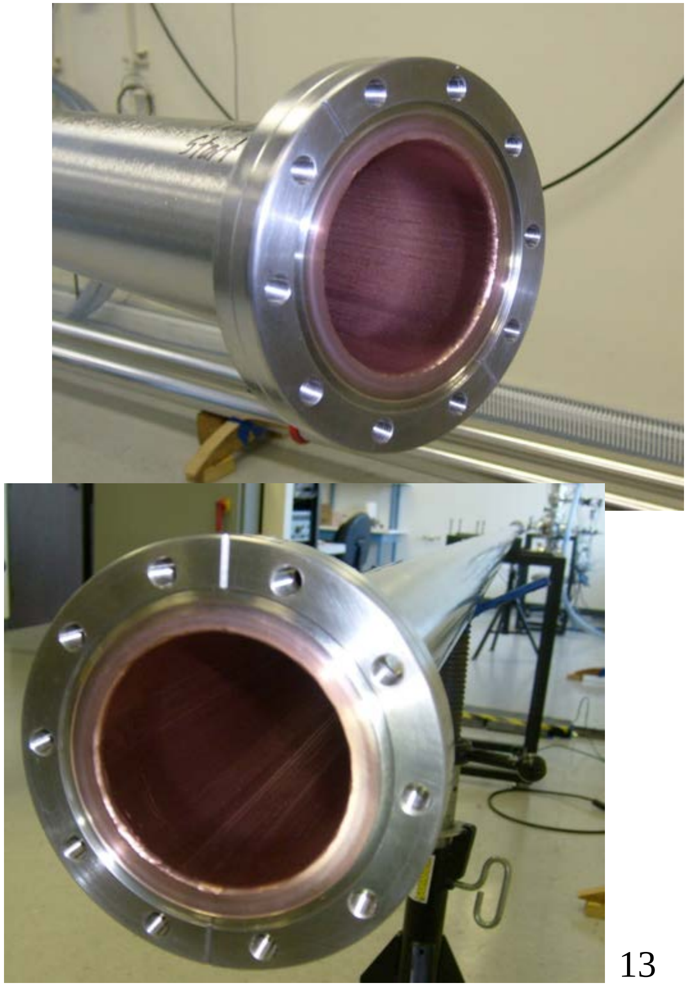
Some deposition experiments were performed with spring loaded wheels on both sides of the magnetron, such that a set of wheels rolls over coated areas. No indentation in or damage to coating was observed, i.e. the train like assembly option is viable.

Photos of copper coated RHIC stainless steel tubes and bellows

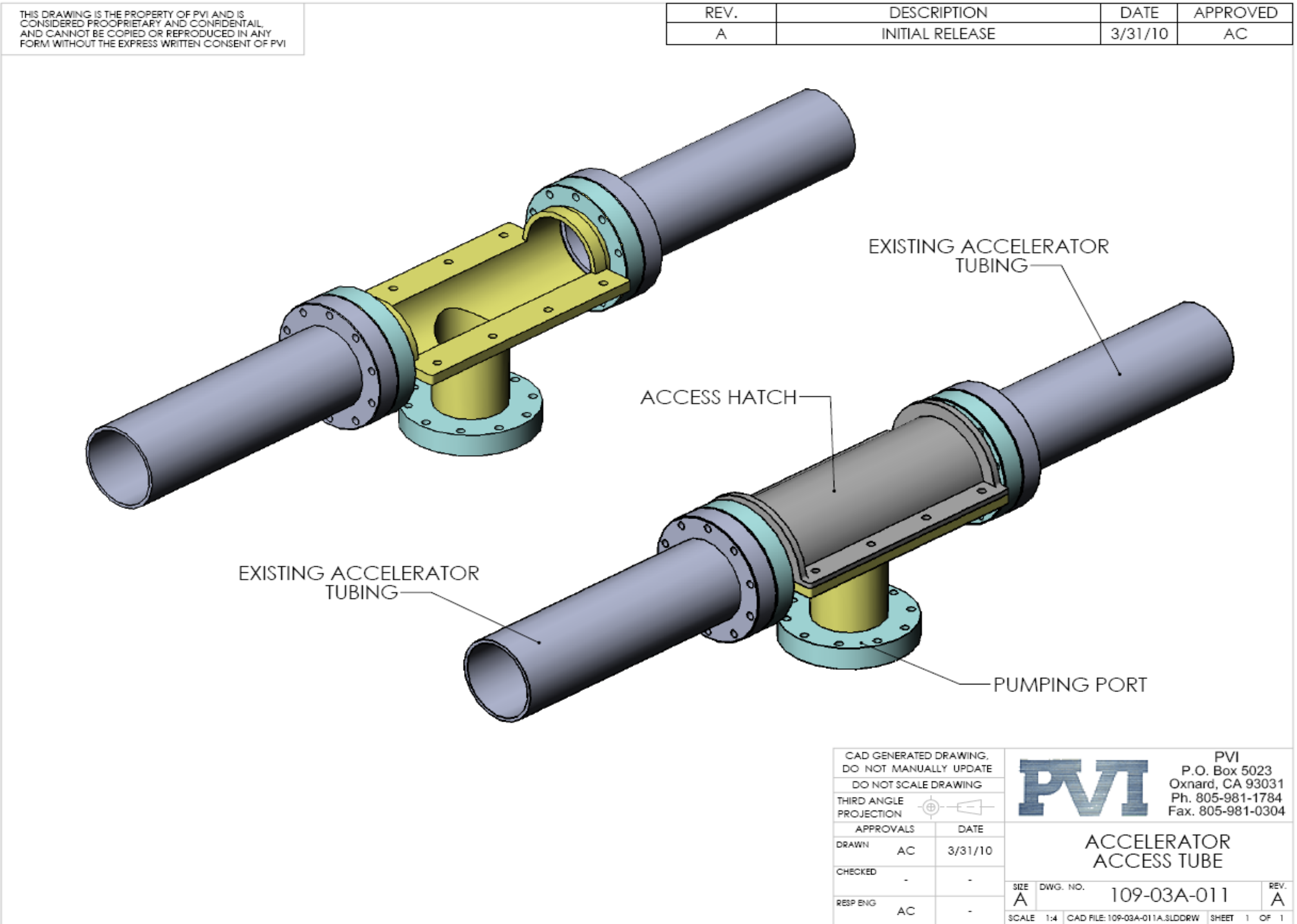
Photos of coated bellows (at different lighting)



Photos of coated RHIC tubes



Originally coating 500 meter section in-situ was considered, requires RHIC bellows replacement with access bellows for copper cathode reloading



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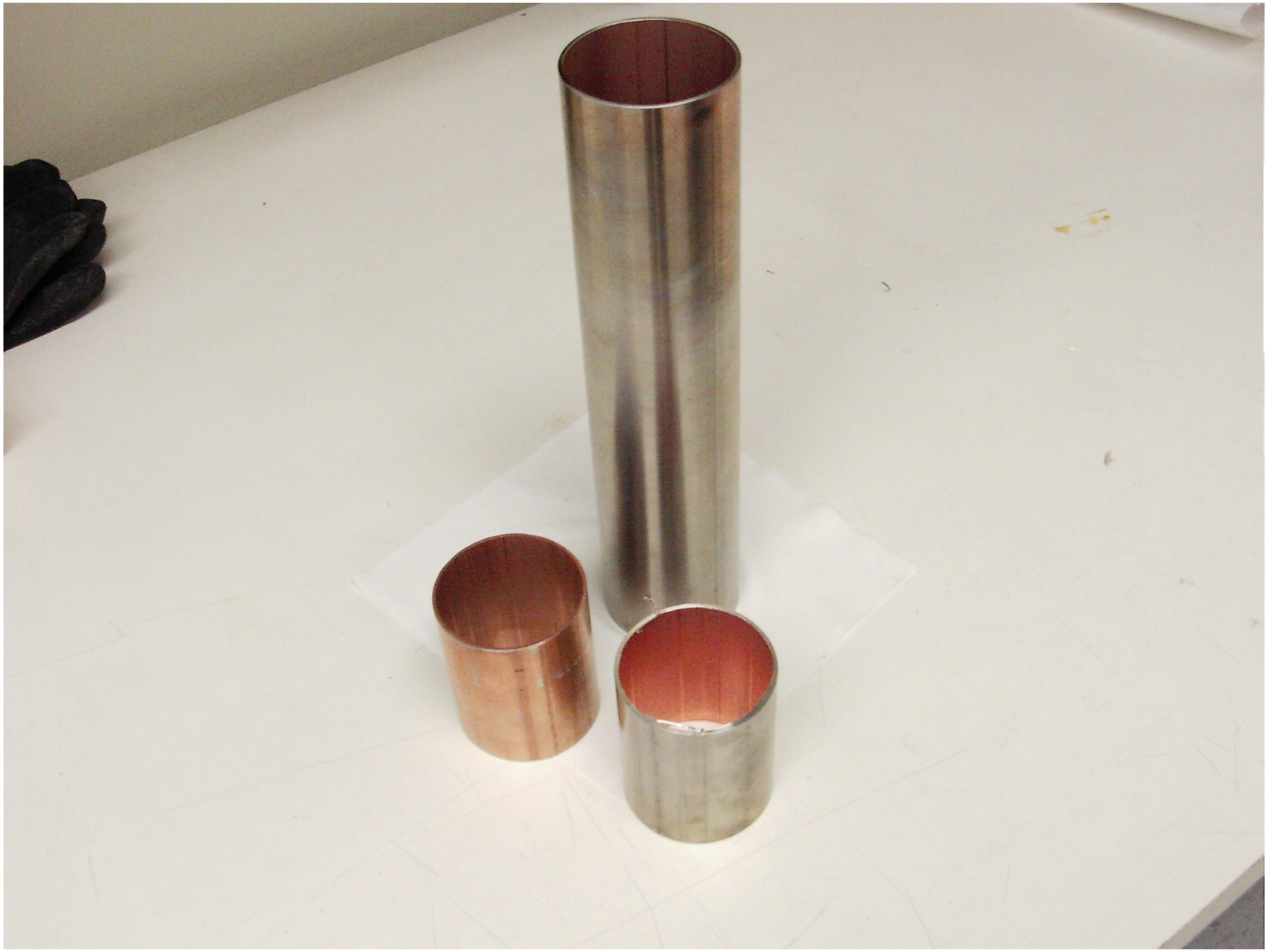
Other Options Being Considered

- Presently replacement cathodes utilizing access bellows is not the leading option.
- Some deposition experiments were performed with spring loaded wheels on both sides of the magnetron, such that a set of wheels rolls over coated areas. No indentation in or damage to coating was observed, i.e. the train like assembly option is viable.
- Taking few magnets out and coating a series of magnets at a time is being considered.
- No decision final has been made

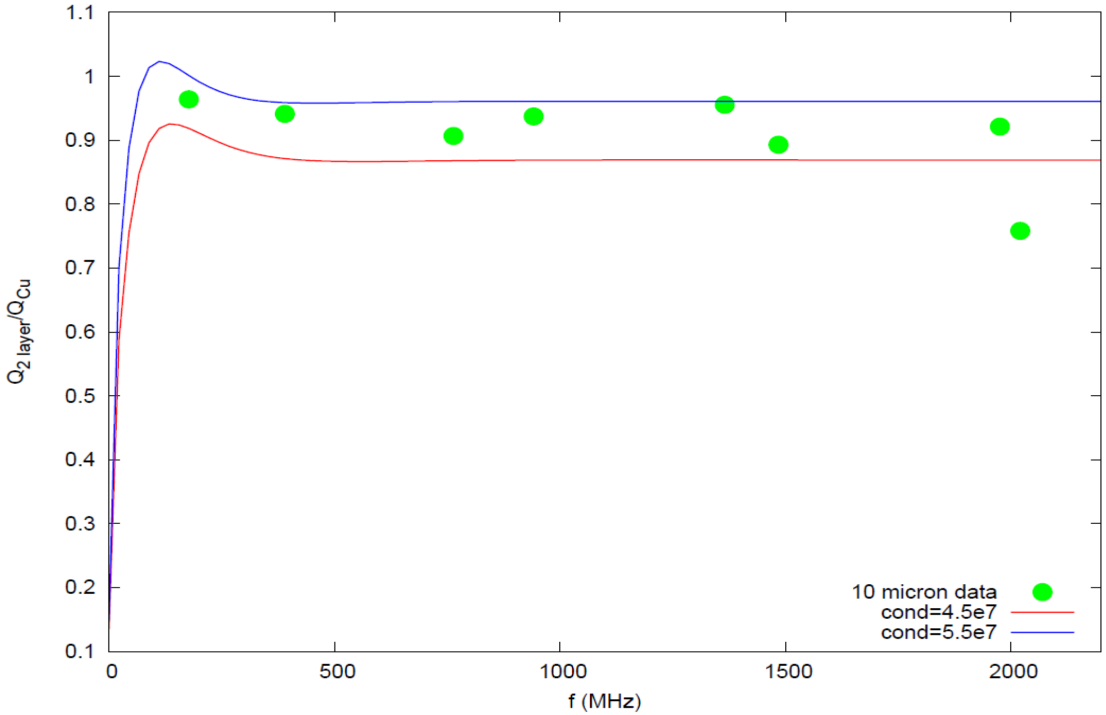
RF Resistivity

- First, without discharge cleaning, three 30 cm long RHIC SS tube samples were coated with 2.5 μm to 6.1 μm OFHC at 20 mTorr with AC power. Coating is axially non-uniform (thicker at edges; 6.1 μm had poor adhesion). Coating is matte in appearance (low SEY?).
- Room temperature resistivity of one of the coated samples 2.5 μm or about 4.5 to 5 μm, was indistinguishable from copper at 180 MHz with coating that’s far from ideal.

Coating 49cm long tubes (2 μm below); cut out the center 32cm for more RF testing



RF Resistivity Measurements

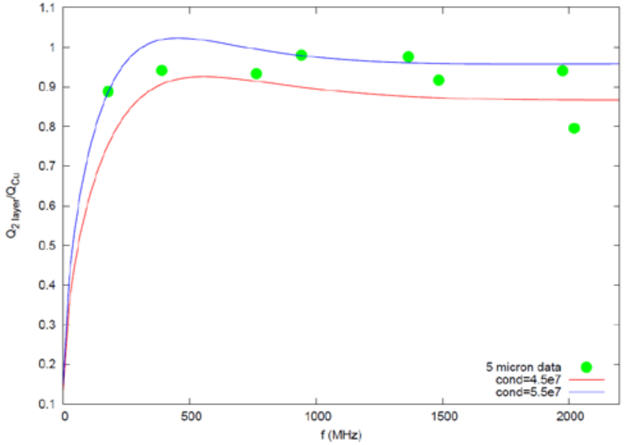


Ratio of SS tube coated with 10 μm of copper to pure copper tube versus frequency; experimental data is represented by green dots; red and blue lines are **theoretical** values based on σ of 4.5 and 5.5 x 10^7 mho/meter respectively (5 μm yielded similar results).

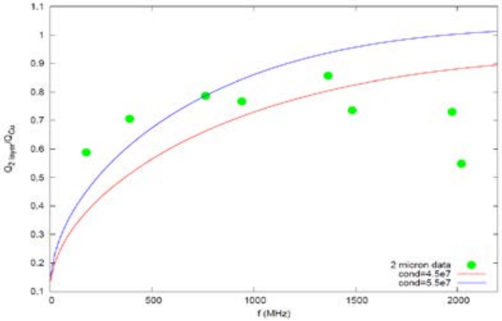
RF Resistivity Measurements continued

As it can be seen from the figures, the best value for the conductivity of the surface layer is between 4.5 and 5.5 x 10^{7} mho/meter. Pure copper has a value of 5.96 x 10^{7} mho/meter. Thus, based on these measurements the conductivity of the copper coating is between 75.5% and 92.3%, or about 84% of pure copper. Since **joints and connectors reduce experimentally measured Q, conductivity value of coatings may be even closer to pure solid copper.**

Although resistivity at cryogenic temperature might be different (it must be measure in a system that's being designed), Computations indicate that 10 µm of copper should be acceptable for even the most extreme future scenarios.



Ratio of SS tube coated with 5 µm of Cu to pure Cu tube vs frequency; experimental data (green dots); red and blue lines are theoretical values based on σ of 4.5 and 5.5 x 1^{7}



Ratio of SS tube coated with 2 µm of Cu to pure Cu tube vs frequency; experimental data (green dots); red and blue lines are theoretical values based on σ of 4.5 and 5.5 x 10^{7} mho/meter

Status

- **In-situ coating method w/excellent adhesion developed and proven.**
- **Resistivity of coated RHIC tube samples close to Cu @ room T; SEY lower than SS.**
- **Cabling system for mole & spool developed**

•Target to substrate distance 1.5 cm. Commercial coating equipment 10’s cm; 6.3 cm lowest experimental; unique omni-directional coating. Good copper utilization.

- **Lowering RHIC cold bore resistivity & SEY with in-situ Cu coating seems feasible!**
- **Need to determine & optimize RF conductivity at cryogenic temperatures & do magnet quench tests on copper coated RHIC cold bore tubing**

Acknowledgement

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