Plasma Physics R&D for Some non-Fusion Physics & Industrial Applications

Ady Hershcovitch
Brookhaven National Laboratory

Fusion research has been dominant in the great strides of plasma physics advancement for over fifty years. But interest in light bulbs and vacuum tubes, which eventually led to industrial applications, and astrophysical phenomena started plasma physics development. Non-fusion plasma physics R&D has been continuing and expanding into different areas.

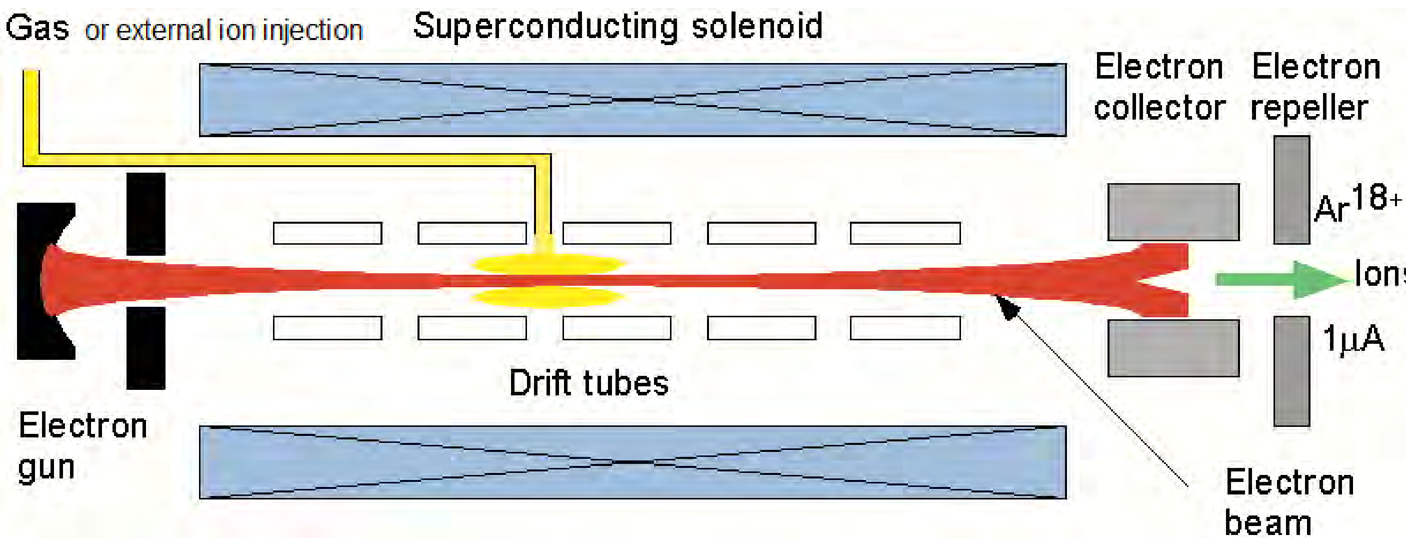
Talk Outline

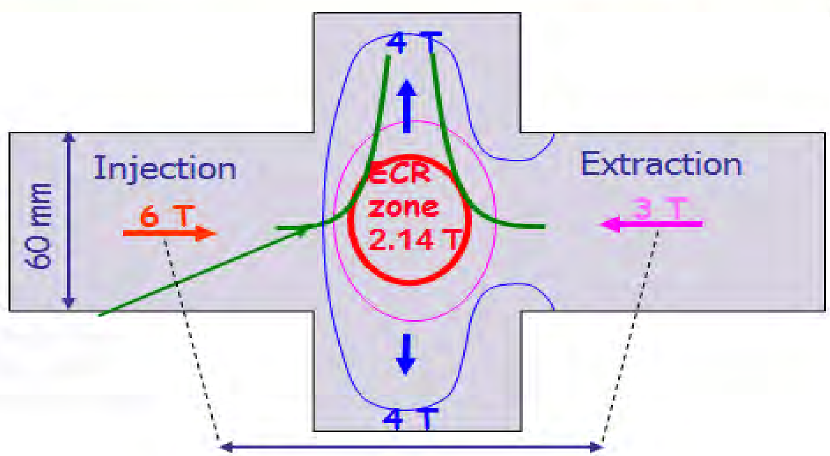
1. **Briefly covered ion sources for accelerator and industrial applications.**
2. **Plasma Sputtering Robotic Device for In-Situ Thick Coatings of Long, Small Diameter Vacuum Tubes, which is basically a magnetron mole designed to in-situ coat with copper the BNL Relativistic Ion Collider 7.1 cm ID cold bore sections with access points that are 500 meter apart, a rather challenging endeavor.**
3. **Plasma Window is a novel apparatus that utilizes a stabilized plasma arc as interface between vacuum and atmosphere or pressurized targets without solid material for various applications.**

Accelerator Ion Sources: Negative Ions (H^-) EBIS ECR

Negative Ions for Energy Multiplication (involves cesium)

High charge ions stepwise ionization





Industrial ion source R&D
example: semiconductor manufacturing

Ion Sources for Energy Extremes of Ion Implantation

Various ions, but mostly B, P, Sb, and As, are implanted, over a wide range of energies for fabrication of semiconductors. Energies range from as low as approximately 100 eV for shallow surface implantations, to as high as multi-MeV for deep implantation into the substrate. State of the art ion sources meet industry needs for the energy range of about 10 keV to about 300 keV. Room for improvement exists at energy extremes (100's of eV and at multi-MeV**?**) due to space charge limitations at low energies inefficiency in acceleration at the higher energy range.

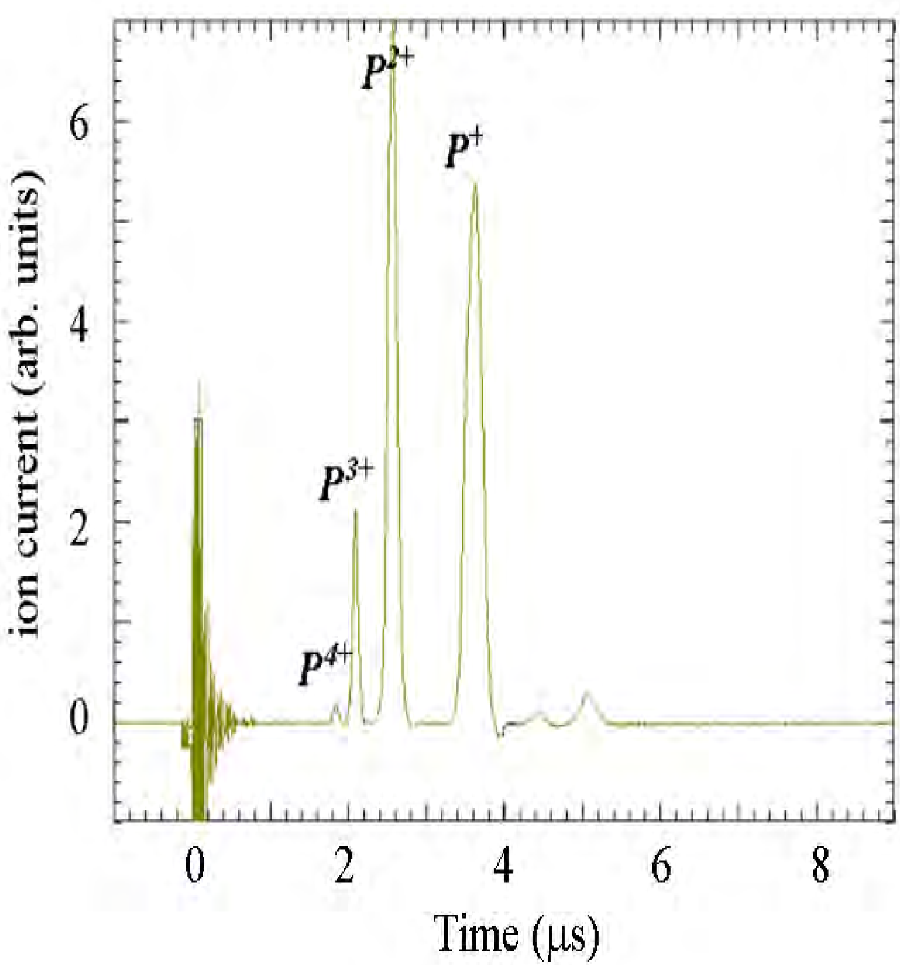
Higher currents of high-charge-state ions require sources with larger electron currents and current densities at lower operation pressures.

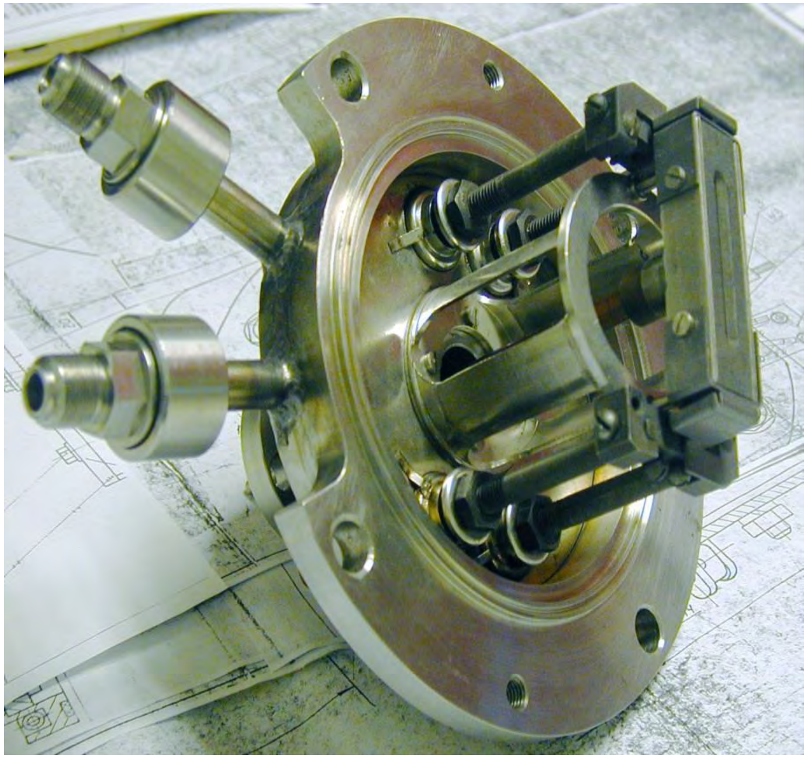
Endeavor based on above approach resulted in record steady state output currents of higher charge state Antimony and Phosphorous ions: P^{2+} (8.6 pmA), P^{3+} (1.9 pmA), and P^{4+} (0.12 pmA) and 16.2, 7.6, 3.3, and 2.2 pmA of Sb^{3+} Sb^{4+}, Sb^{5+}, and Sb^{6}+ respectively

However, the semiconductor industry really needs low energy (100's of eV) ions, where space charge problems limit implanter ion currents, thus leading to low production rates. To tackle the space charge problem, two approaches were followed: using molecular ions and ion beam deceleration with gasless/plasmaless space charge compensation. To date, 3 emA of positive decaborane ions were extracted at 14 keV and 0.2 mA of negative decaborane ions were also extracted. But, focus was on carborane.

Results that were obtained with phosphorous ions. With the higher charge states record results by an order of magnitude were obtained:

P^{2+} (8.6 pmA), P^{3+} (1.9 pmA), and P^{4+} (0.12 pmA)





Molecular ions reduce space charge difficulties: one charge carries numerous ions. Source operation requires stable ions, & is tricky: drive source hard results in fragmentation; gentle operation ⇒wall deposition

Most stable molecular boron ion is carborane ($C_2B_{10}H_{12}$).

Leaves carbon residue; solution: m-Carborane-1.7 dicarboxylic acid

Plasma Sputtering Robotic Device for *In-Situ* Thick Coatings of Long, Small Diameter Vacuum Tubes

A novel robotic plasma magnetron mole with a 50 cm long cathode was designed fabricated & operated. Reason for this endeavor is to alleviate the problems of unacceptable ohmic heating of stainless steel vacuum tubes and of electron clouds, due to high secondary electron yield (SEY), in the BNL Relativistic Heavy Ion Collider (RHIC). The magnetron mole was successfully operated to copper coat an assembly containing a full-size, stainless steel, cold bore, RHIC magnet tubing connected to two types of RHIC bellows, to which two additional pipes made of RHIC tubing were connected. To increase cathode lifetime, movable magnet package was developed, and thickest possible cathode was made, with a rather challenging target to substrate (de facto anode) distance of less than 1.5 cm. Achieving reliable steady state magnetron discharges at such a short cathode to anode gap was rather challenging, when compared to commercial coating equipment, where the target to substrate distance is 10’s cm; 6.3 cm is the lowest experimental target to substrate distance found in the literature. Additionally, the magnetron developed during this project provides unique omni-directional uniform coating. The magnetron is mounted on a carriage with spring loaded wheels that successfully crossed bellows and adjusted for variations in vacuum tube diameter, while keeping the magnetron centered. Electrical power and cooling water were fed through a cable bundle. The umbilical cabling system is driven by a motorized spool. Excellent coating adhesion was achieved. Measurements indicated that well-scrubbed copper coating reduced SEY to 1, i.e., the problem of electron clouds can be eliminated. Room temperature RF resistivity measurement indicated that 10 μm Cu coated stainless steel RHIC tube has conductivity close to that of pure copper tubing. **Excellent coating adhesion** was **achieved**.

Relativistic Heavy Ion Collider, RHIC needs luminosity enhancement; solution: Coat cold bore tube with copper (lower SEY & R)!

Complex Photo

Problems that must be solved in order to enhance RHIC luminosity

Lower vacuum chamber resistivity & control electron cloud formation, lower SEY!

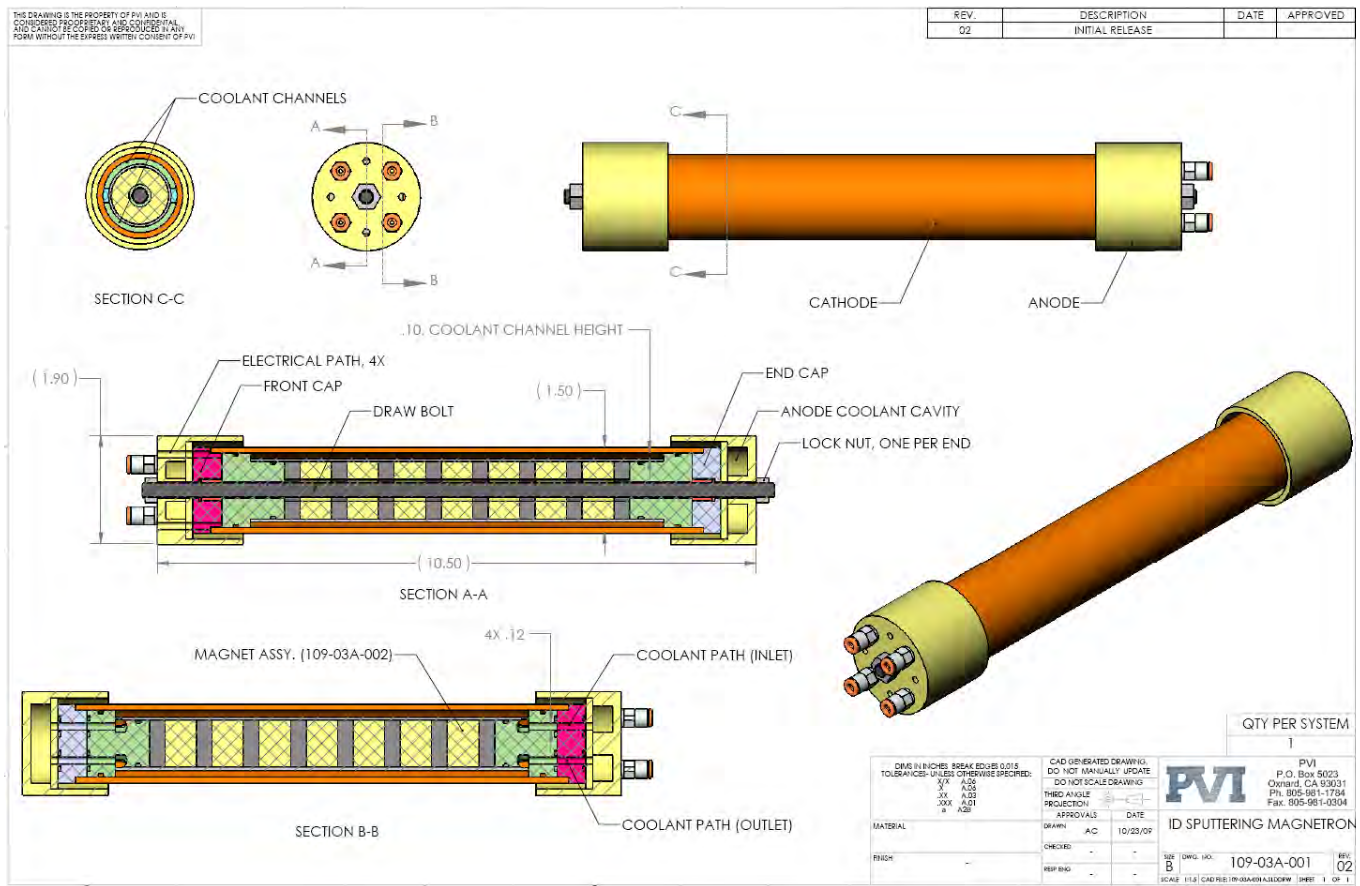
The RHIC vacuum chamber is made of 7.1 cm ID stainless steel tubing with 1.6 μm surface roughness in cold bore (2.1 μm in warm section).

Coat cold bore tubes with OFHC copper! Rather challenging: access points are 500 m apart.

10 μm of OFHC should more than suffice to reduce resistivity. Well-scrubbed copper can have SEY close to 1. To prevent electron clouds need SEY<1.3.

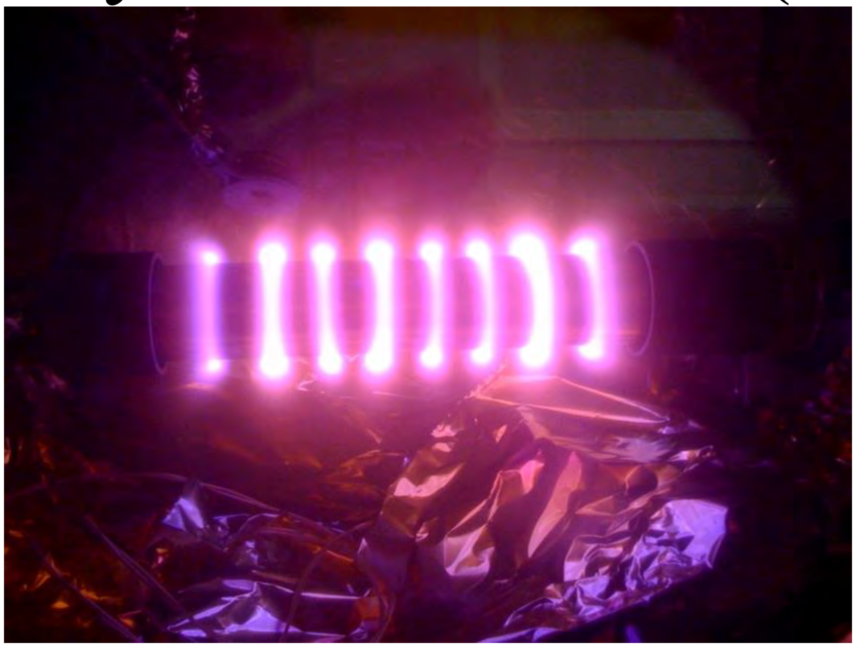
Magnetron Developed After Iterations

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

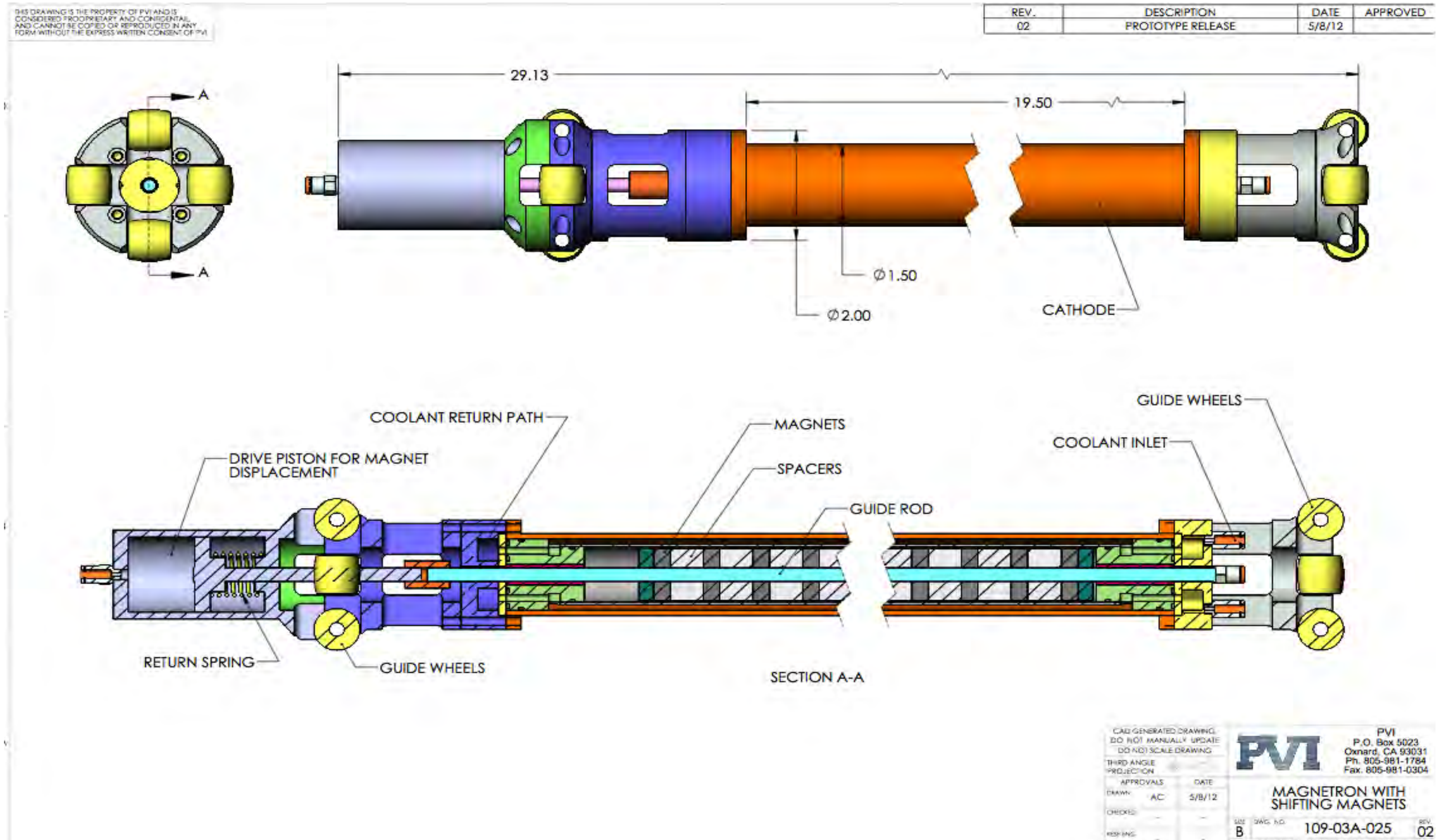
Inadequate copper utilization: thin cathode & very uneven erosion(magnetron integrity structural restrictions magnetics).

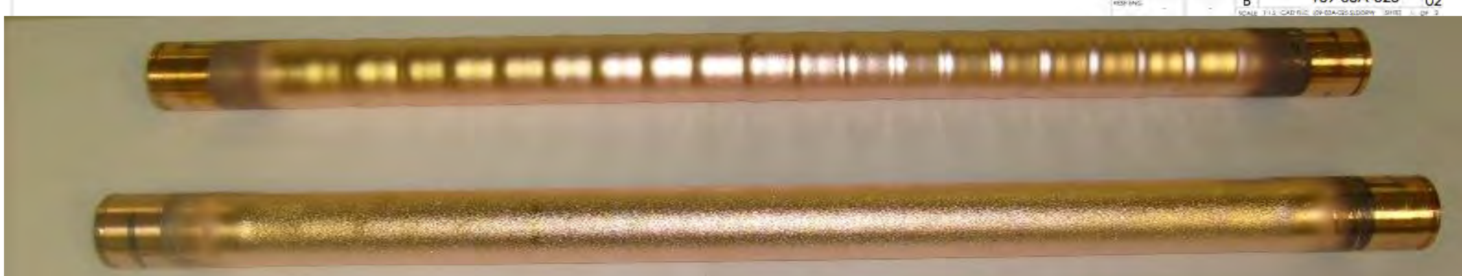


Inconsistent adhesion, which did not always meet rigorous industrial standard (tape; nail).

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.





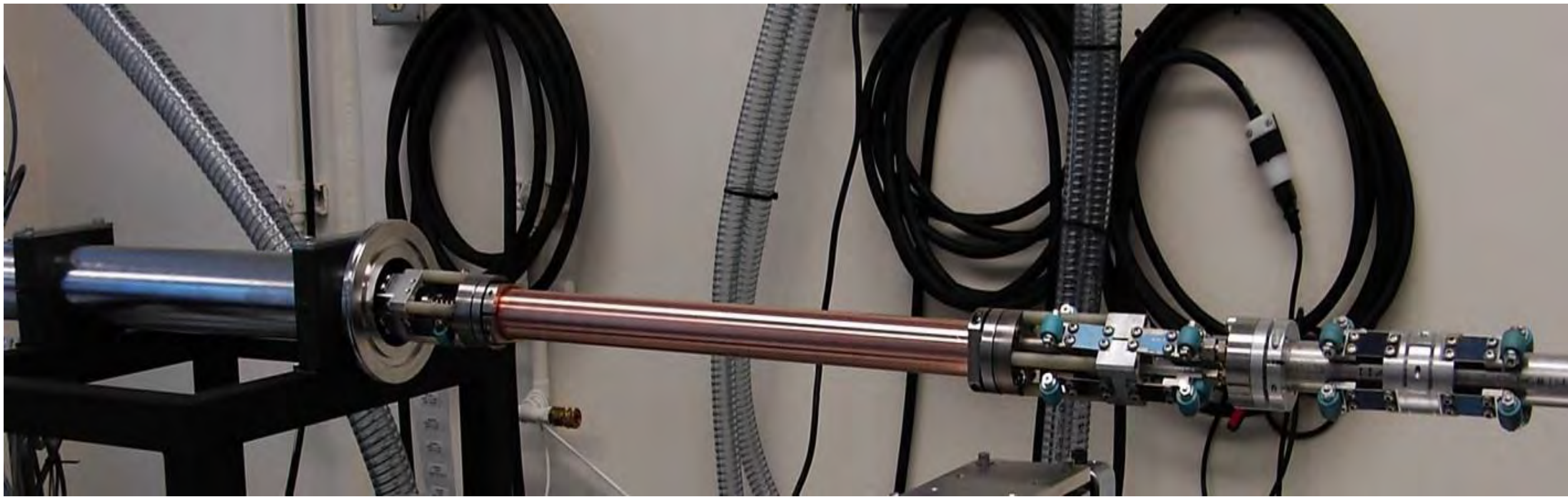
Coating Adhesion Strength

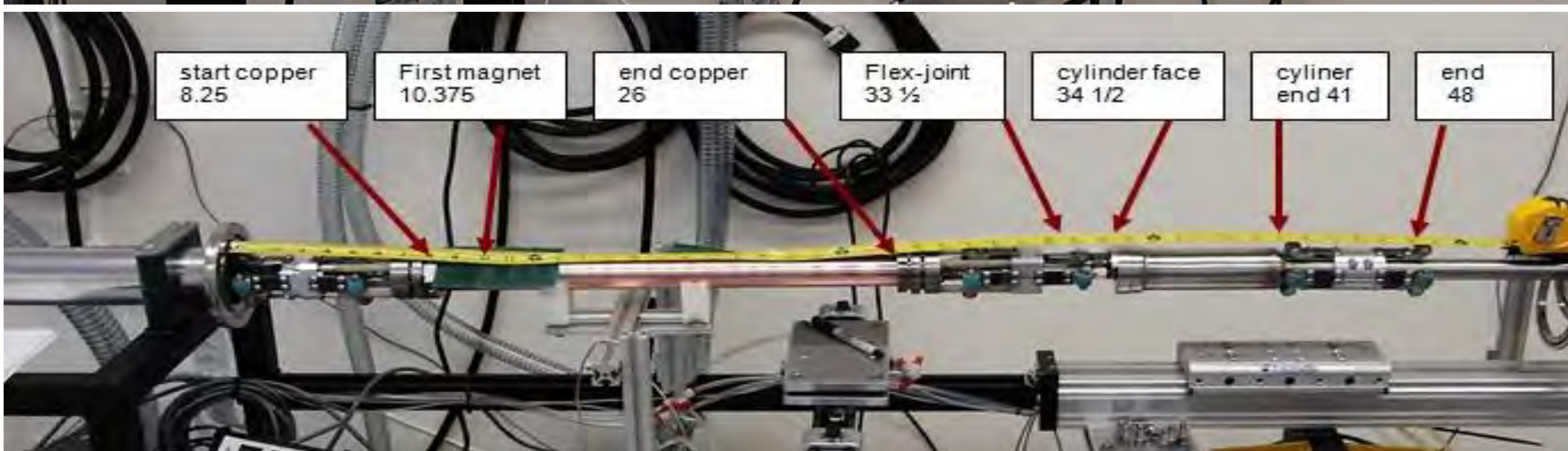
Consistent coatings with good adhesion are achieved routinely with first (proprietary) step that may not be needed in RHIC followed by optimized discharge cleaning: positive voltage (of about 1 kV) is applied to the magnetron at a pressure of over 2 Torr. The optimized results yielded **adhesion strength** of **over 12 kg** (maximum capability pull test fixture) or at least **2.5×10^{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

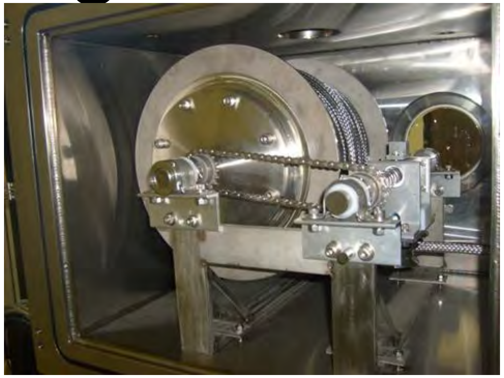




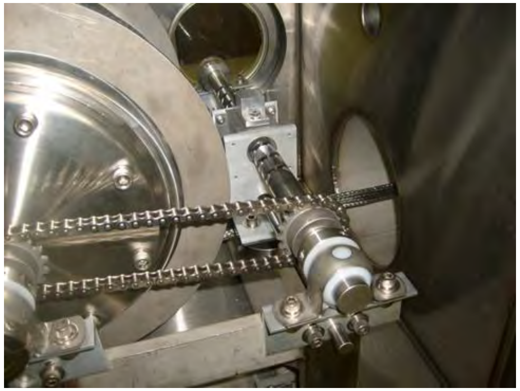
Deposition System Moving Mechanism

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.

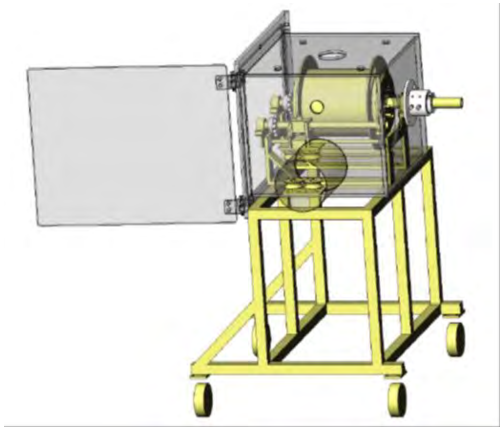
Spool



Drive

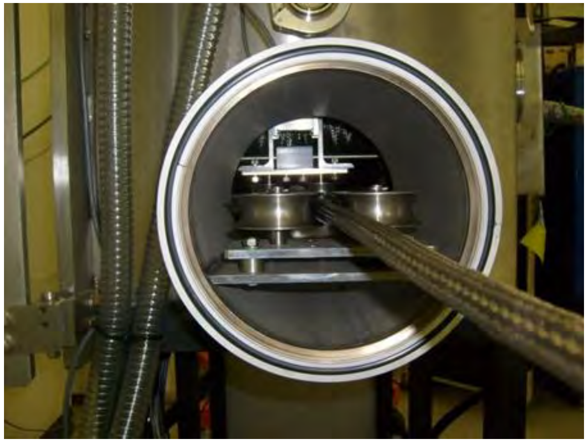


Umbilical
Drive drawing



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.

Photo of front part of the drive



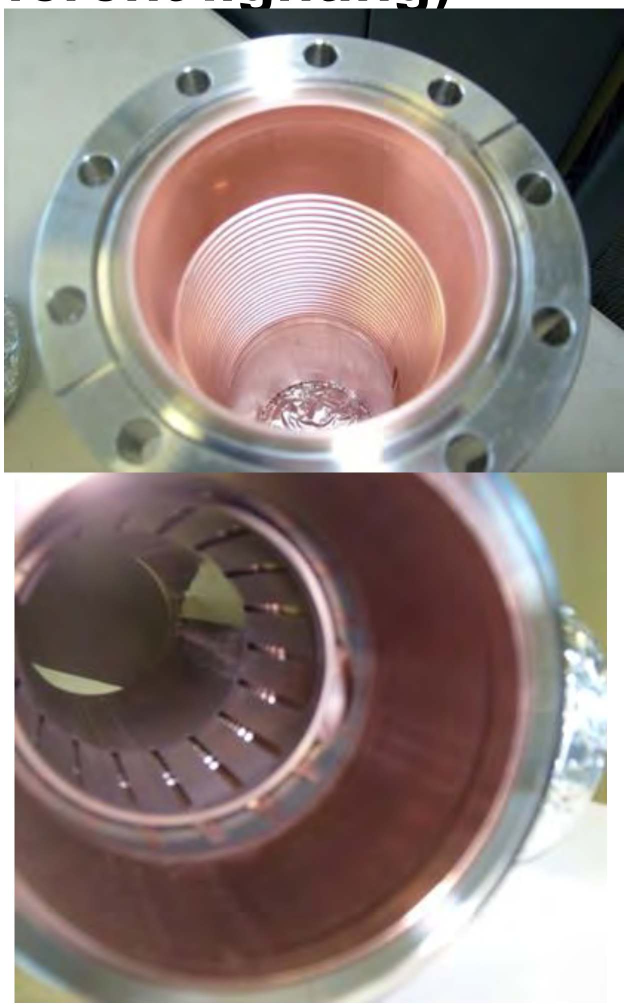
Coating an assembly of a RHIC magnet tube sandwiched between two types of RHIC bellows including a shielded bellow

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.

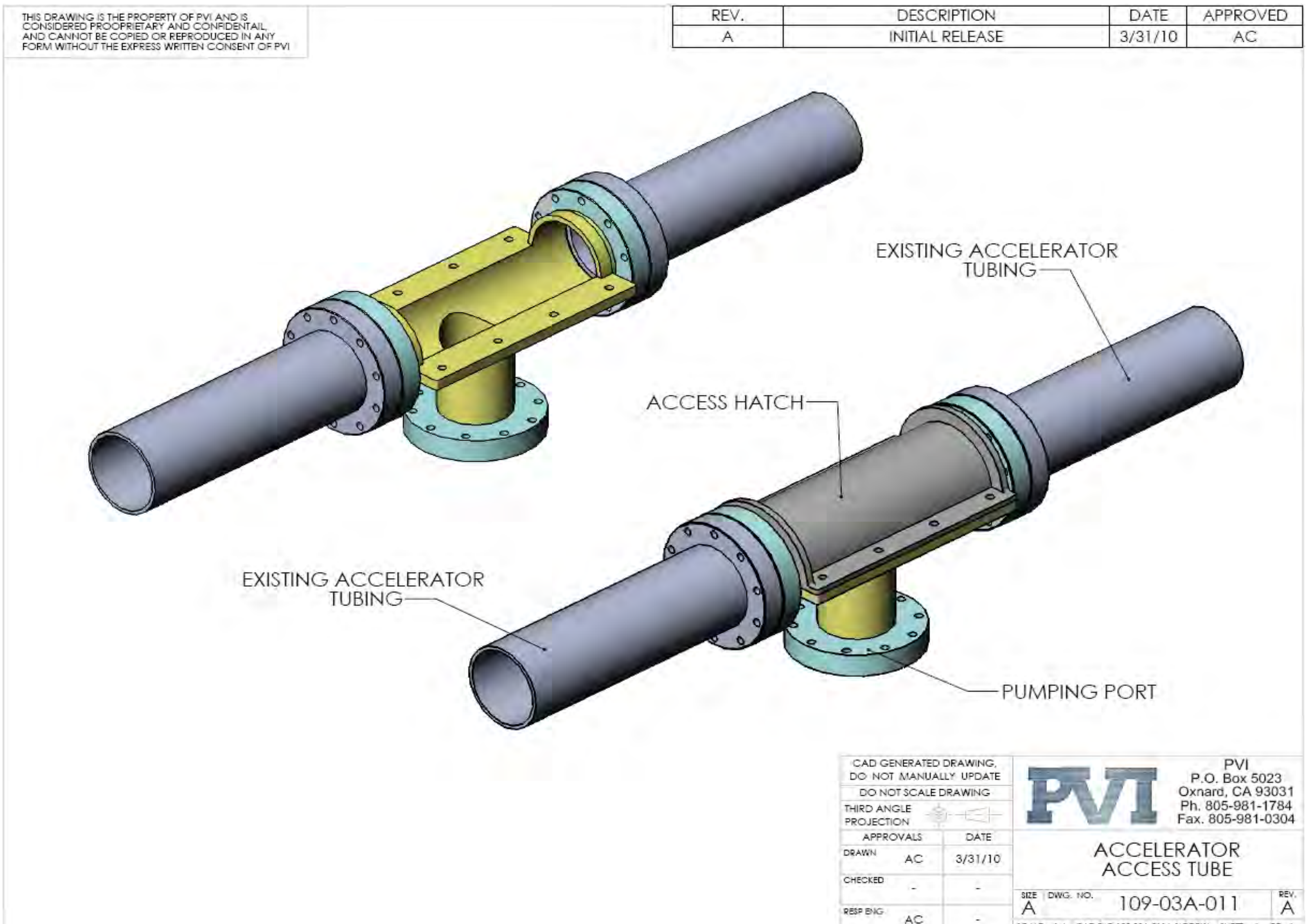
Photos of copper coated RHIC stainless steel tubes and bellows

Photos of coated bellows (at different lighting)



Photos of coated RHIC tubes

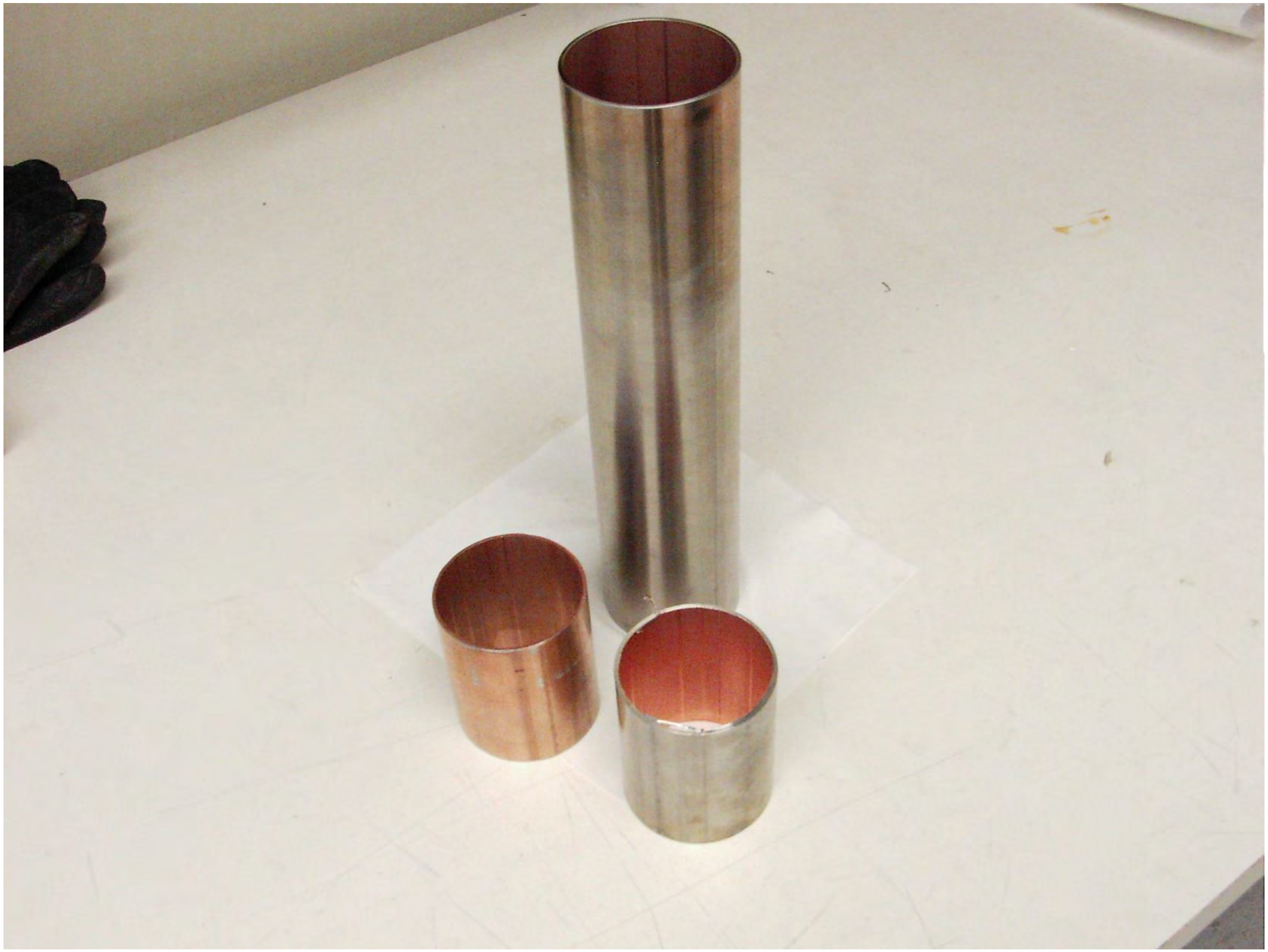
Originally coating 500 meter section in-situ was considered, requires RHIC bellows replacement with access bellows for copper cathode reloading



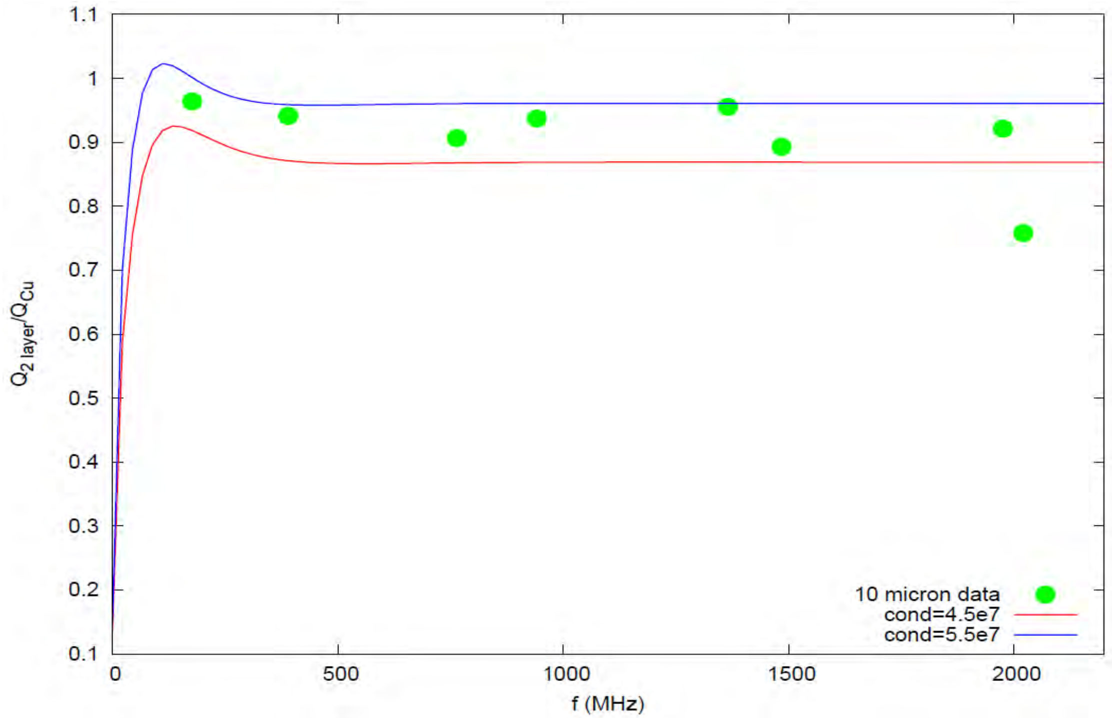
Other Options Being Considered

- 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

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



RF Resistivity Measurements

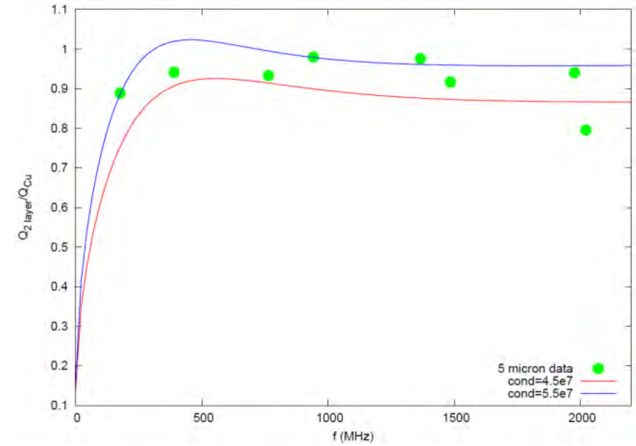


Ratio of SS tube coated with 10 μm of copper to pure copper tube versus frequency; experimental data is represented by green dots; red and blue lines are **theoretical** values based on σ of 4.5 and 5.5 x 10^7 mho/meter respectively (5 μm yielded similar results).

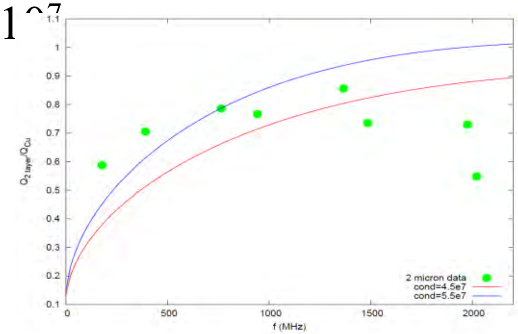
RF Resistivity Measurements continued

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 10^7



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

The Plasma Window

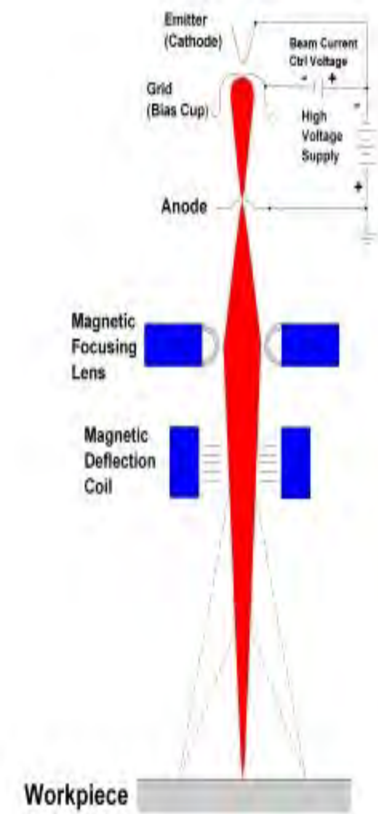
The Plasma Window utilizes ionized gas comprising of hot ions and electrons to interface between vacuum & atmosphere or pressurized targets without solid material. It's useful in non-vacuum electron beam welding, as well as in some physics experiments

Section Outline

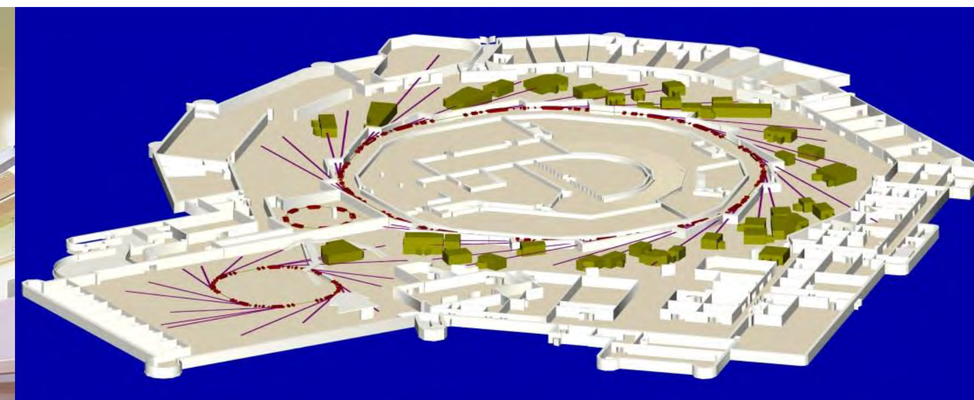
1. Why Plasma Windows
2. Operation Principles
3. Results/Application
4. The sky is not the limit
5. Sci-Fi (disclaimer! Sci-Fi statements are exaggerated)

Particle beams and electromagnetic radiation are usually generated in vacuum. For some applications it is desirable to bring beams in air or pass the beams through internal gas targets.

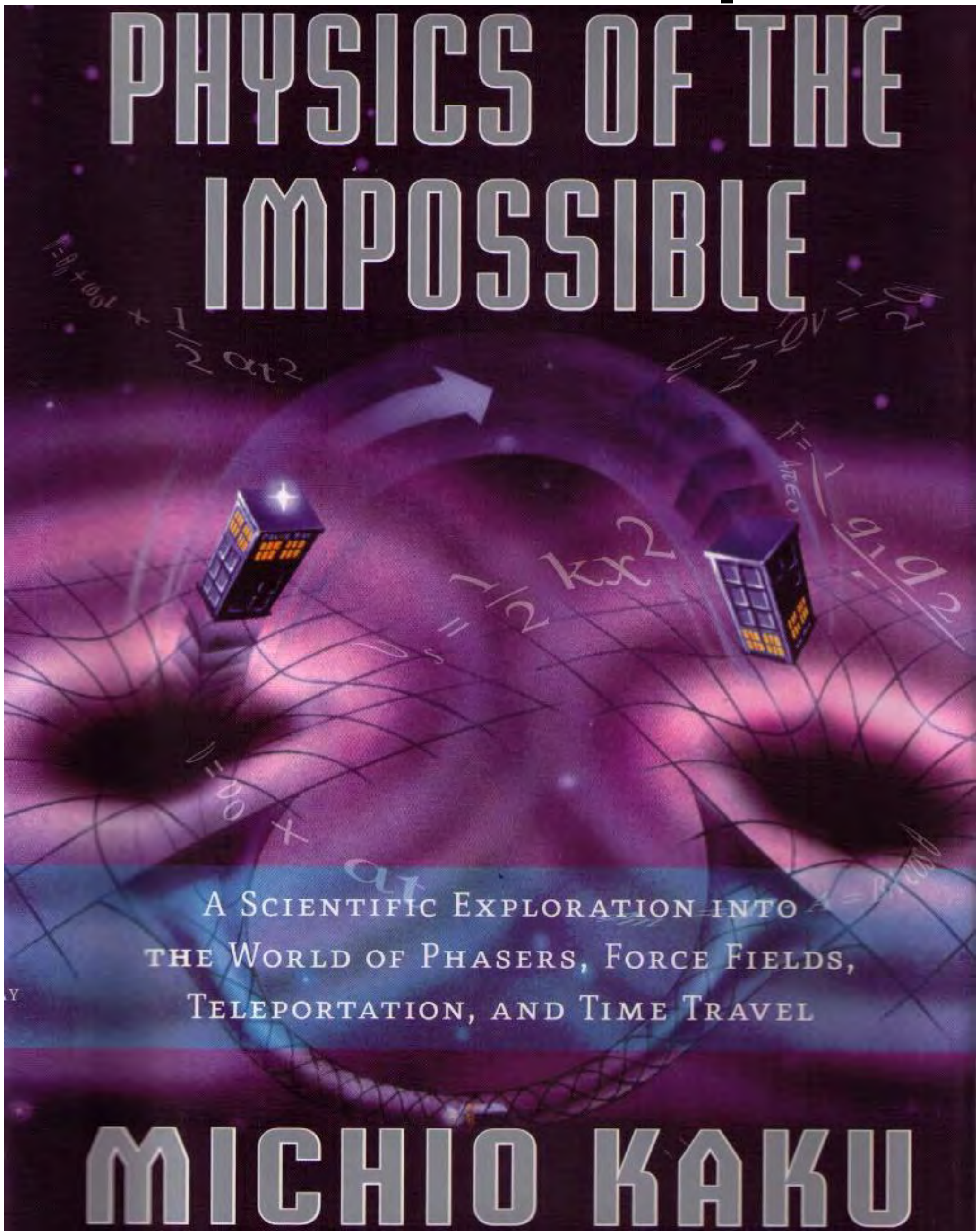
Electron beams for welding



X-ray, VUV, EUV for use in microscopy, lithography etc.



Predicted not to be Implementable

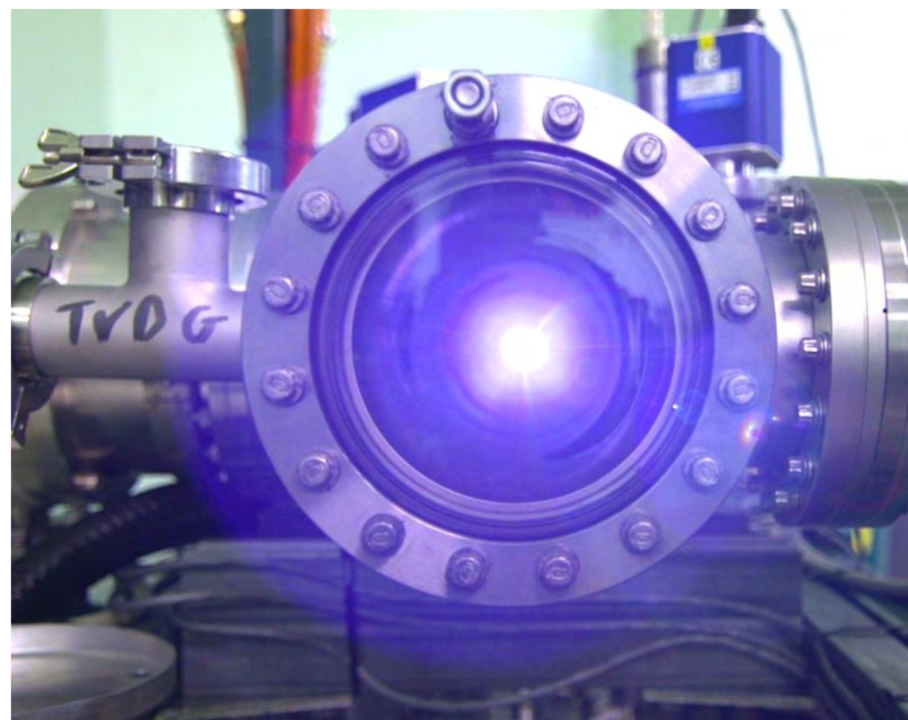


Plasma Window Has Captured People's Imagination: Sci-Fi Meets Reality

Featured in popular science magazines, newspapers, Michio Kaku's book **Physics of the Impossible**, and in an accompanying syndicated article **10 Impossibilities Conquered by Science** @ #8 **PW** is listed under **Creating force fields**

Star Trek Shuttle Bay Door

Plasma Window at BNL



Operation Principles

Pressure P is: $P \propto nT$

Where n is gas or plasma density and T is temperature of the gas or the plasma.

Gas flow Q $\boldsymbol{Q \propto \frac{d^2}{\eta l}(p_1 - p_2)}$

Equation for the gas flow rate Q , where d and ℓ are the tube radius and length, η is the gas or plasma viscosity, and p_a is the arithmetic mean of p_1 and p_2.

$$\eta_i \propto {T_i}^{5/2}$$

$$\eta_e \propto {T_e}^{5/2}$$

$$\eta_{gas} \propto T^x$$

Operation Principles (more rigorous)

Operation Principles

Ideal Gas

$$p = nkT \tag{1}$$

Where n is the gas or the plasma density, k is the Boltzmann constant, and T is the temperature of the gas or the plasma. Poiseuille equation for the gas flow rate Q applies.

Viscosity

$$Q = \frac{\pi d^2}{8\eta\ell} p_a (p_1 - p_2) \quad , \tag{2}$$

where d and ℓ are the tube radius and length, η is the gas viscosity, and p_a is the arithmetic mean of p_1 and p_2. A critical assumption, gas is incompressible. Compressibility can be neglected if the Mack number M satisfies $0.5\,M^2 << 1$. Some of the assumptions are no longer valid once a discharge is initiated, since the flow becomes compressible and nonisothermal. Therefore, a thorough analysis of such a gas and plasma flow requires solution of **Naviar-Stokes** equation for the gas. For electrons and ions, the relevant transport equations are the continuity and momentum transfer equations

$$\frac{D}{Dt} n_{e,i} + n_{e,i} \nabla \cdot \underline{V}_{e,i} = 0 \quad , \tag{3}$$

$$m_{e,i} n_{e,i} \frac{D}{Dt} \underline{V} = -\nabla p_{e,i} - \nabla \cdot \underline{P}_{e,i} + q_{e,i} n_{e,i} [\underline{E} + \underline{V}_{e,i} x \underline{B}] + \underline{R}_{e,i} \tag{4}$$

where m is the particle mass and q its charge. R is the species total momentum transfer, p its partial pressure and P is the stress tensor; and $\frac{D}{Dt} = \frac{\partial}{\partial t} + \underline{V} \cdot \nabla$.

The Naviar-Stokes equation is basically the momentum equation (Eq. 4) without the electric and magnetic field terms. It is usually written in a notation where nm = ρ, R = f, and with a partially expanded stress tensor. For ions & electrons,

$$\eta_i = 2 \times 10^5 \mu^{1/2} \frac{k}{\lambda_i} T_i^{5/2} \quad , \quad \eta_e = 2.5 \times 10^7 \frac{k}{\lambda_e} T_e^{5/2} \tag{5}$$

For gases,

$$\eta = aT^x \quad , \tag{6}$$

where a and x are constant characteristics of each gas. For air, e.g., at about 1000°F, x is somewhat larger than 1, and it seems to increase with temperature in this range.

Ionization

$$\tau_{ionization} = (n_e \sigma v)^{-1} \sim 0.1\ \mu s \quad << \quad \tau_{transit} \sim 10\text{'s}\ \mu s$$

Important in the case of **vacua separation**. Results in plug formation. Prevents back streaming of vapor and metal chips resulting from various industrial processes.

WHAT HAS BEEN ACHIEVED

- **Vacuum Separation**: Atmospheric pressure (even 9 bar gas cell) separated from vacuum
- **Transmission of charged particle beams and radiation** from vacuum through the plasma window to atmospheric

1). Electron beam transmission

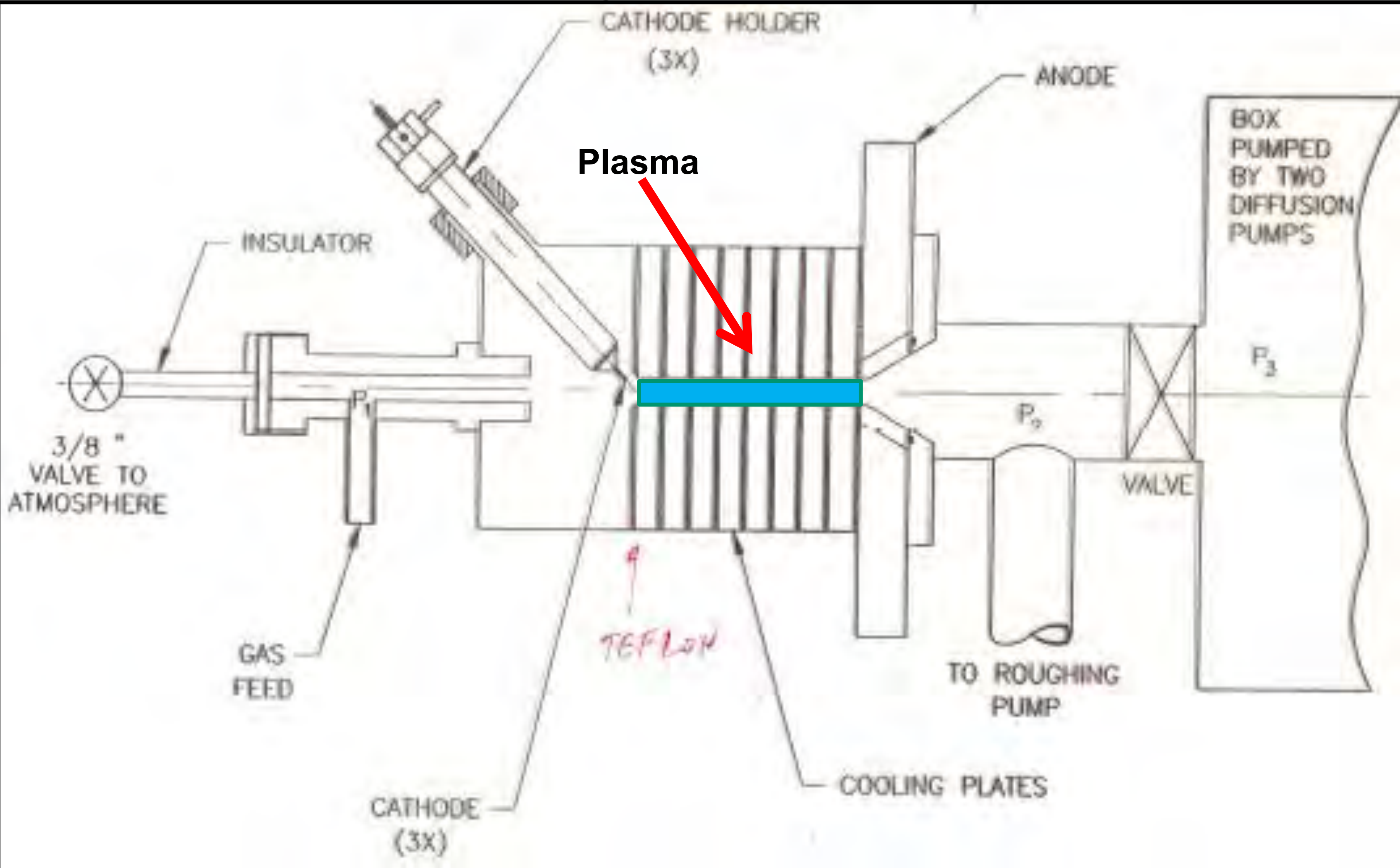
2). Radiation X-ray & VUV beam transmission

3). Ion beam transmission

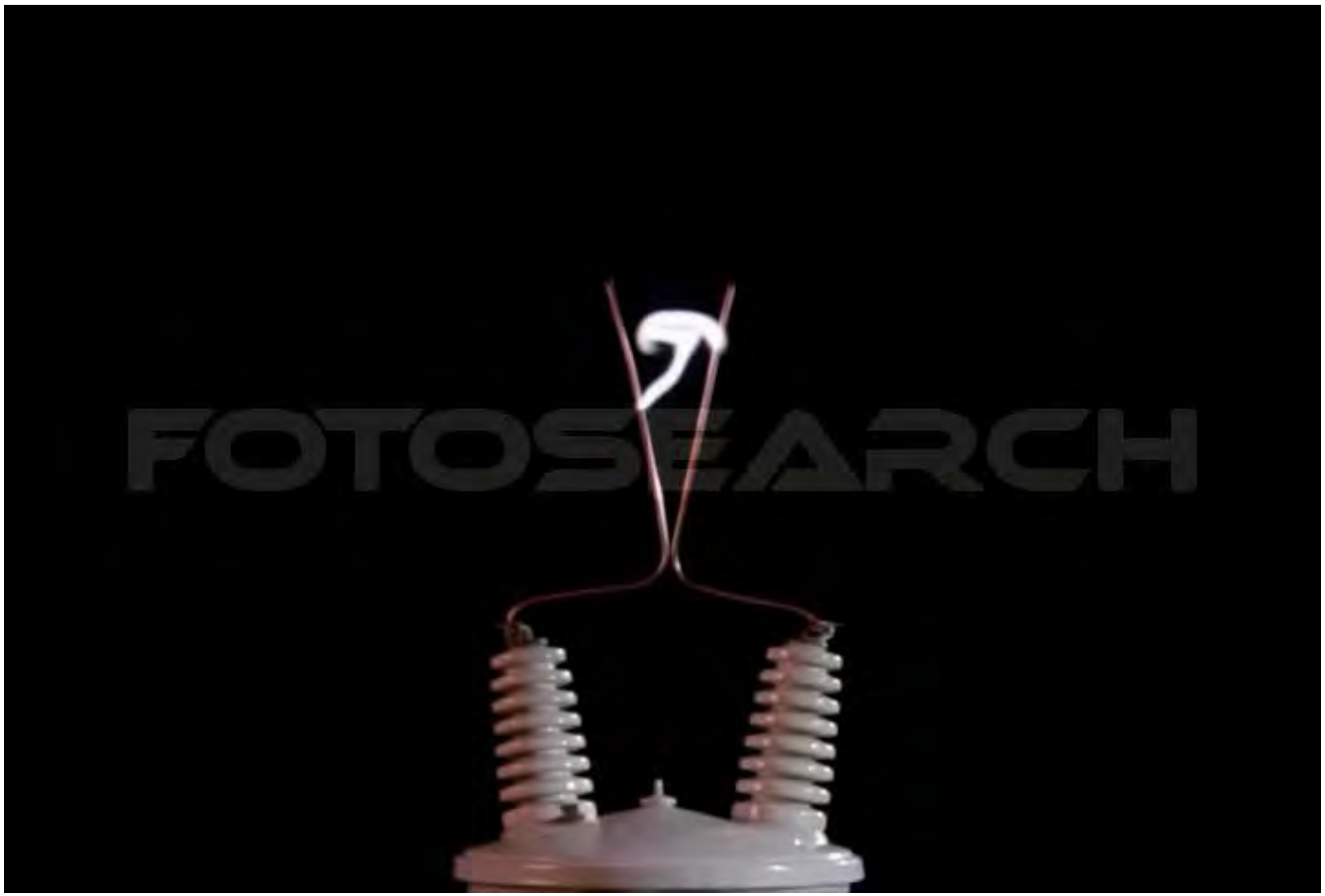
- Self-pinched E-beam propagation (6-25 mA, 90–150 KeV) compared to kA multi-MeV previously achieved.
- **High quality EBW-NV**; wire feed. Focus on EBW-NV most complete study performed
- Plasma shielding & plasma valve

1st Plasma Window Wall Stabilized Arc

cooling of plates paramount importance: plasma conductivity increases with temperature, as well as with increasing cross section



Jacob's Ladder demonstrates that plasma conductivity increases with temperature



Pressure Reduction Factor Gain Over Differential Pumping (plasma on vs plasma off)

Between Atmosphere and Vacuum (Tricky, since pumps choke with plasma off)

1st results: arc discharge 230; + venturi 600; + 3.1 Gauss* magnetic field 700 (unexpected: 20 Tesla needed for full effect)

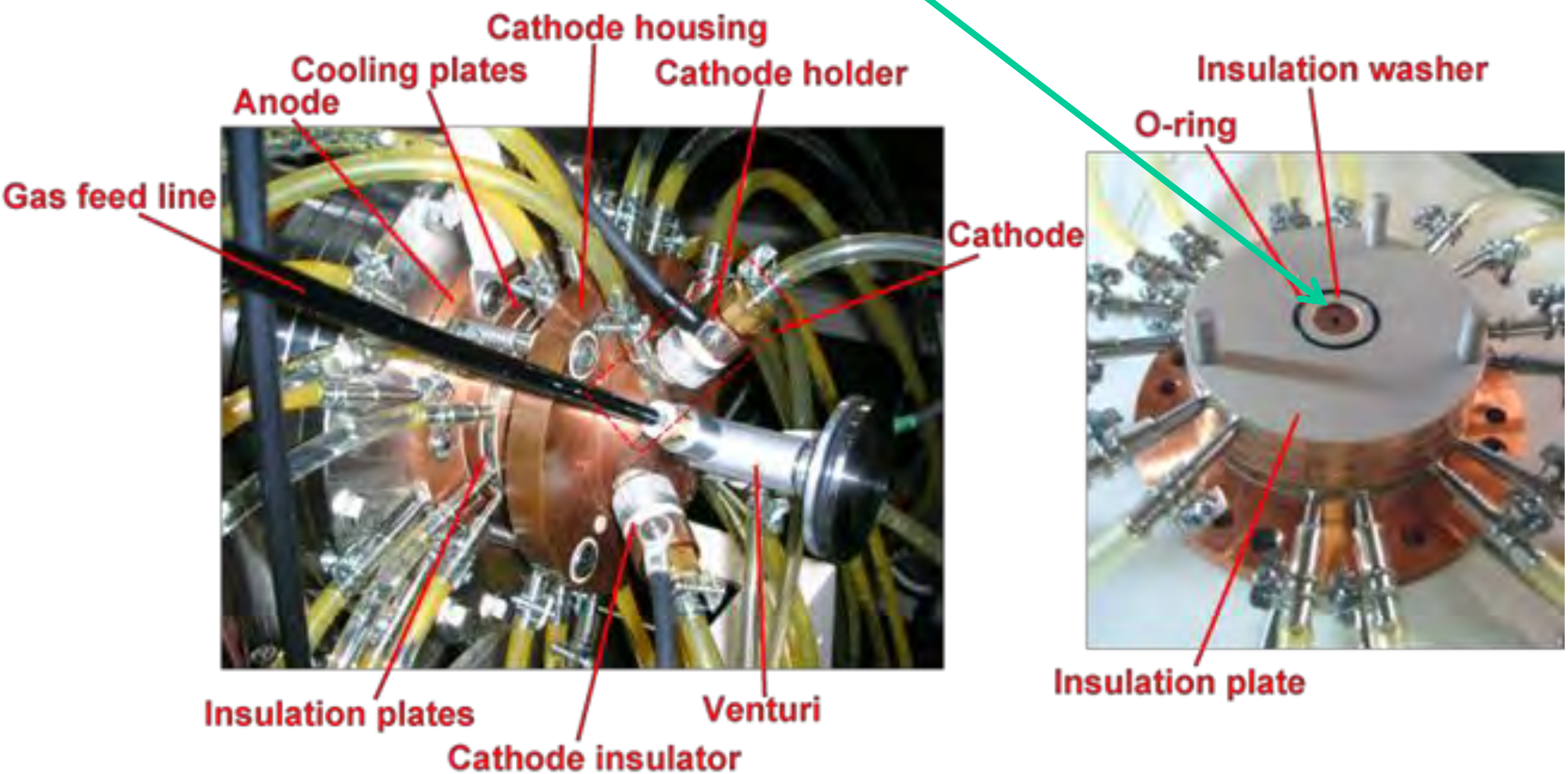
2nd set of record results: shortening the plasma window 1000 (Litton); going to high pressure 10,000 (MIT; PW reaching choked flow condition)

3rd set of record results: 24500 (RIKEN; overwhelmed the pump 1 atmosphere helium).

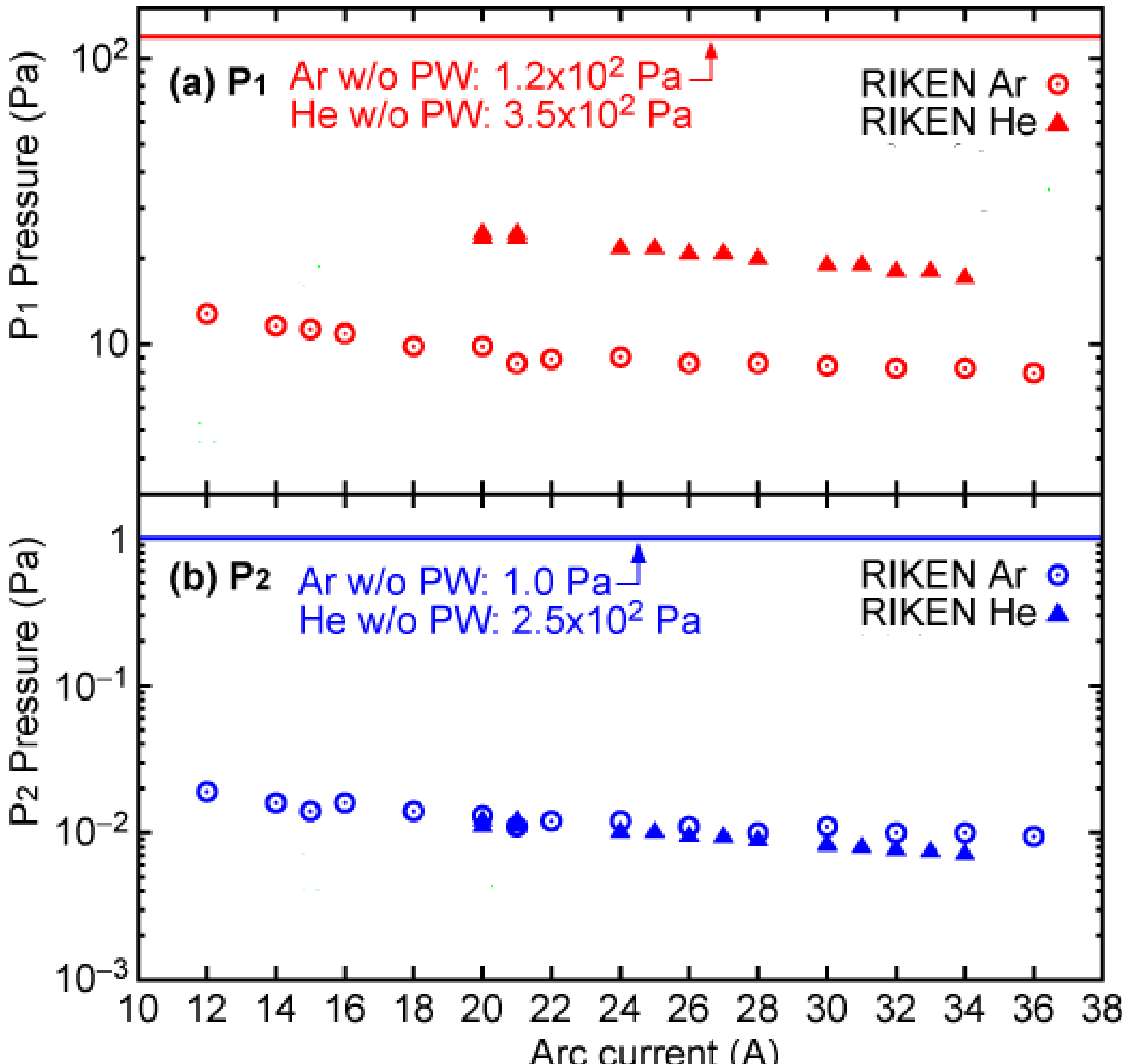
Trying to re-evaluate plasma window benefit by comparing gas flow into plasma window (measured) versus pumped out gas flow (estimated from pressure and pumping speed) obtained for ½ atmosphere helium gas cell conductance restriction factor of 20 (at a power of 8.5 kW; factor increases with power). But, this estimation skews the plasma window effect, by over estimating gas flow after the plasma window, i.e. not accounting for likely reduction in pumping speed.

REKIN (RIBF) Plasma Window

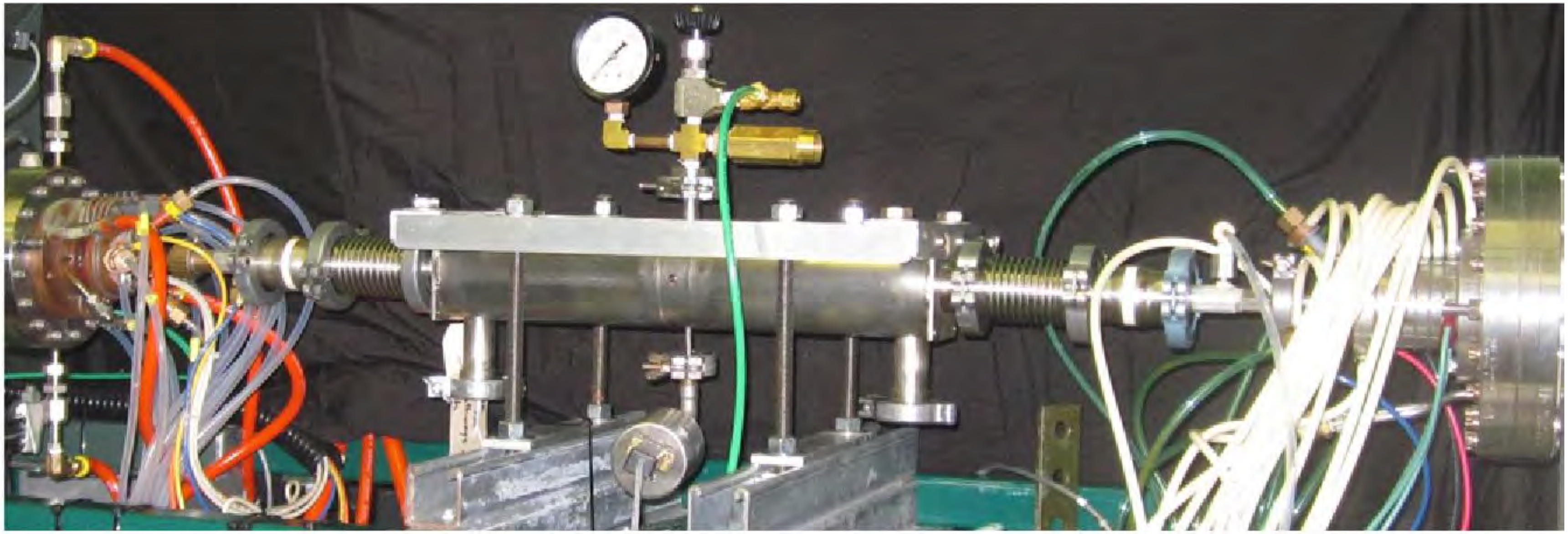
(empty hole becomes window when filled with plasma)

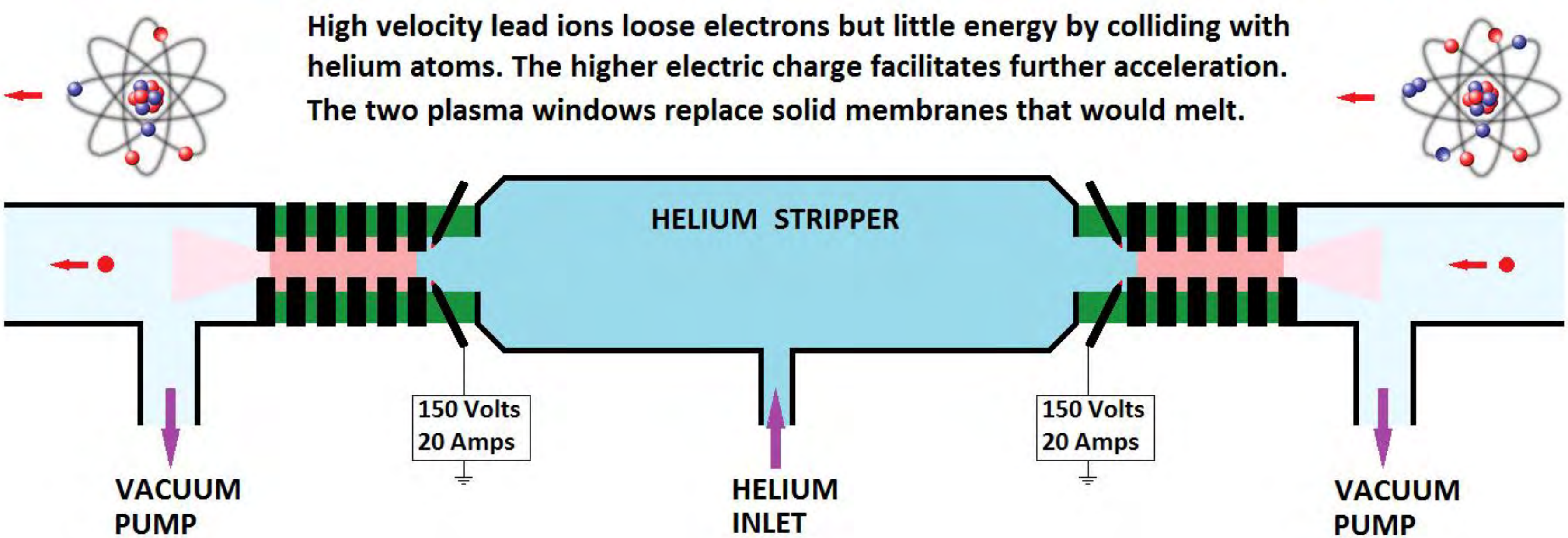


Pressure Versus Arc Current Latest Plasma Window (PW)

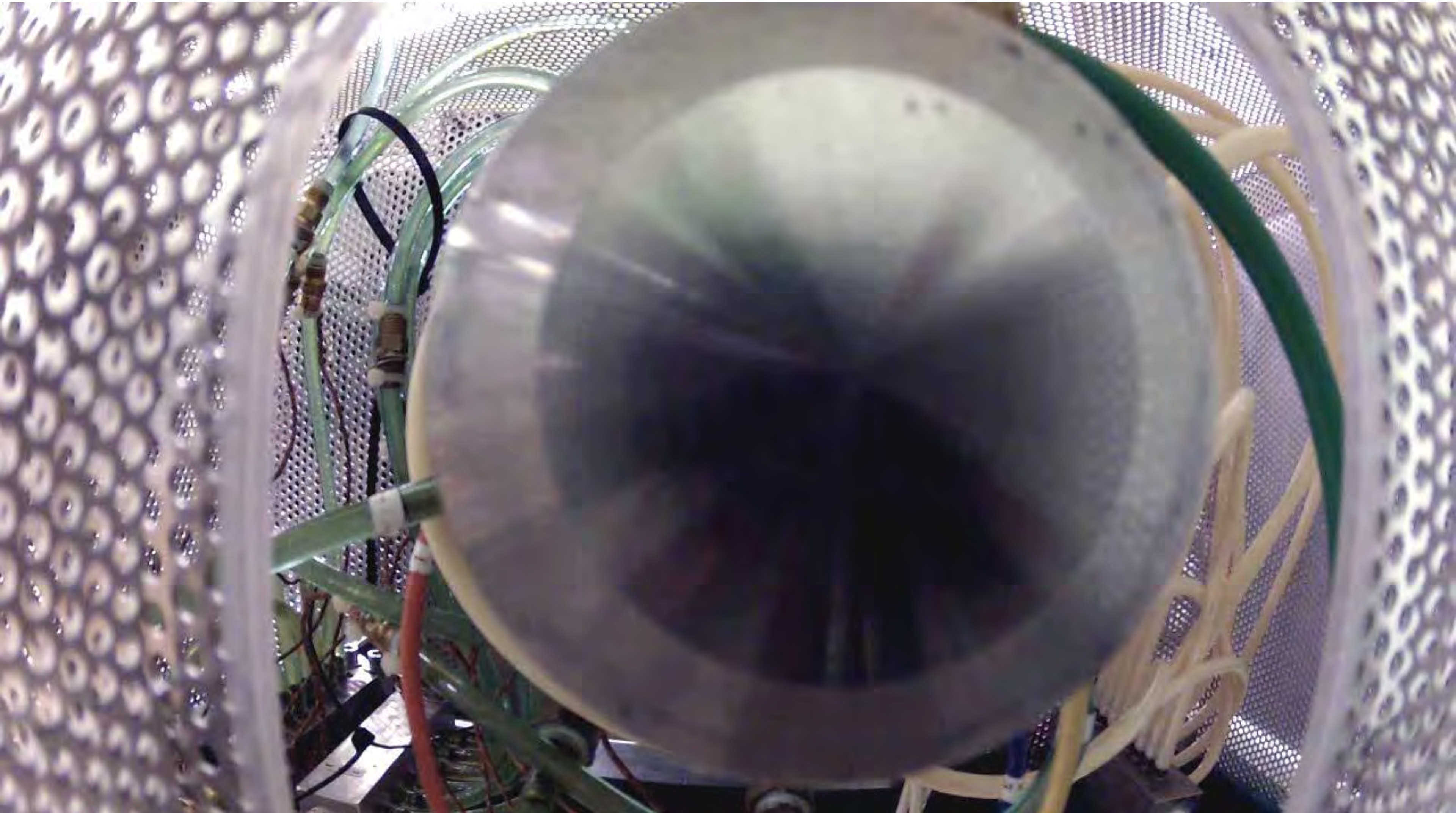


Gas stripper development for the Michigan State University's FRIB Facility



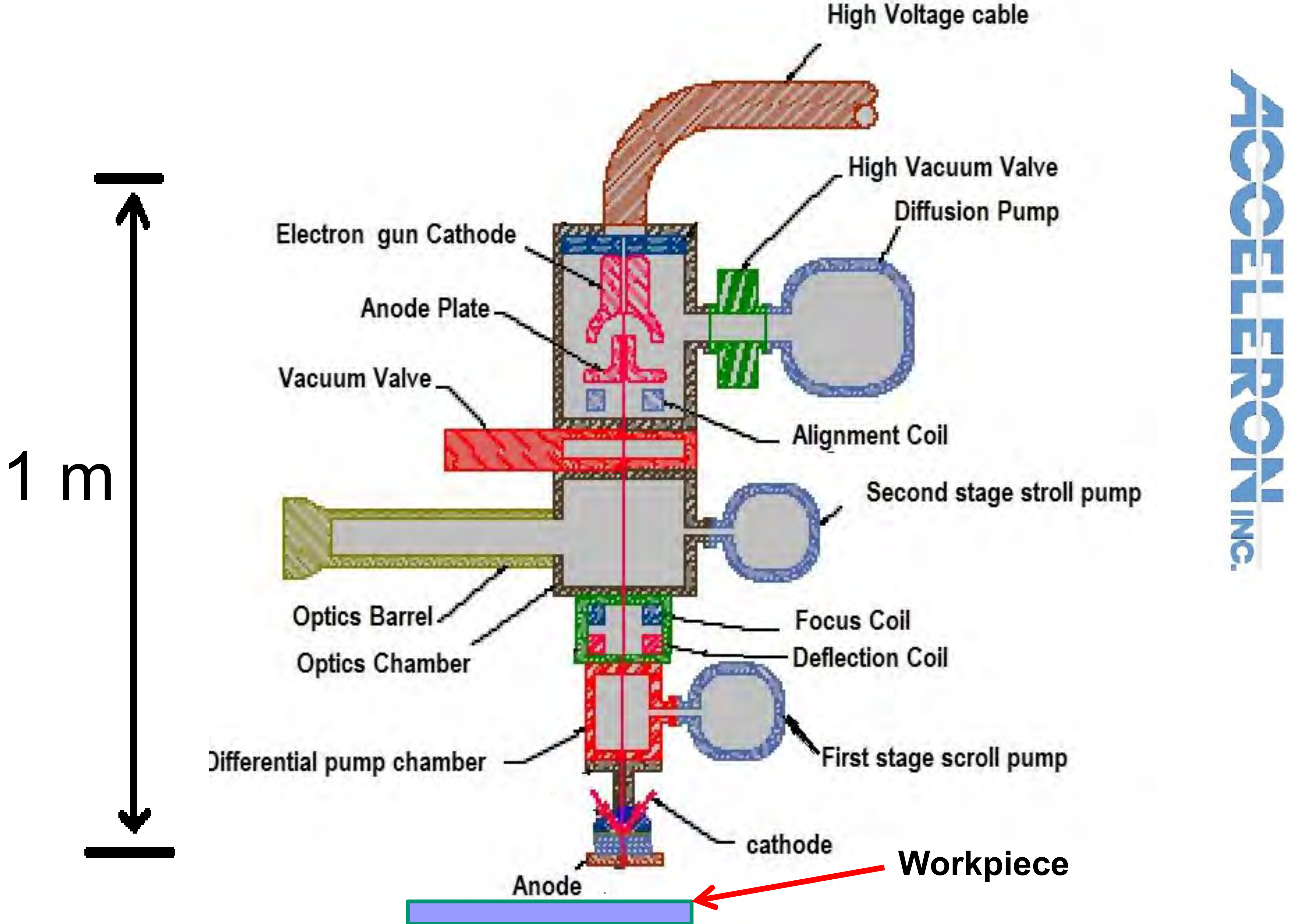


Setup in target room 2 in building 901A



Electron beam welding is the highest quality welding that can be performed. But, it’s done in vacuum, resulting in low production rates and limits on object size. Double hull ship can’t fit in a vacuum system. Past in-air EBW: lower quality. **A challenge!**

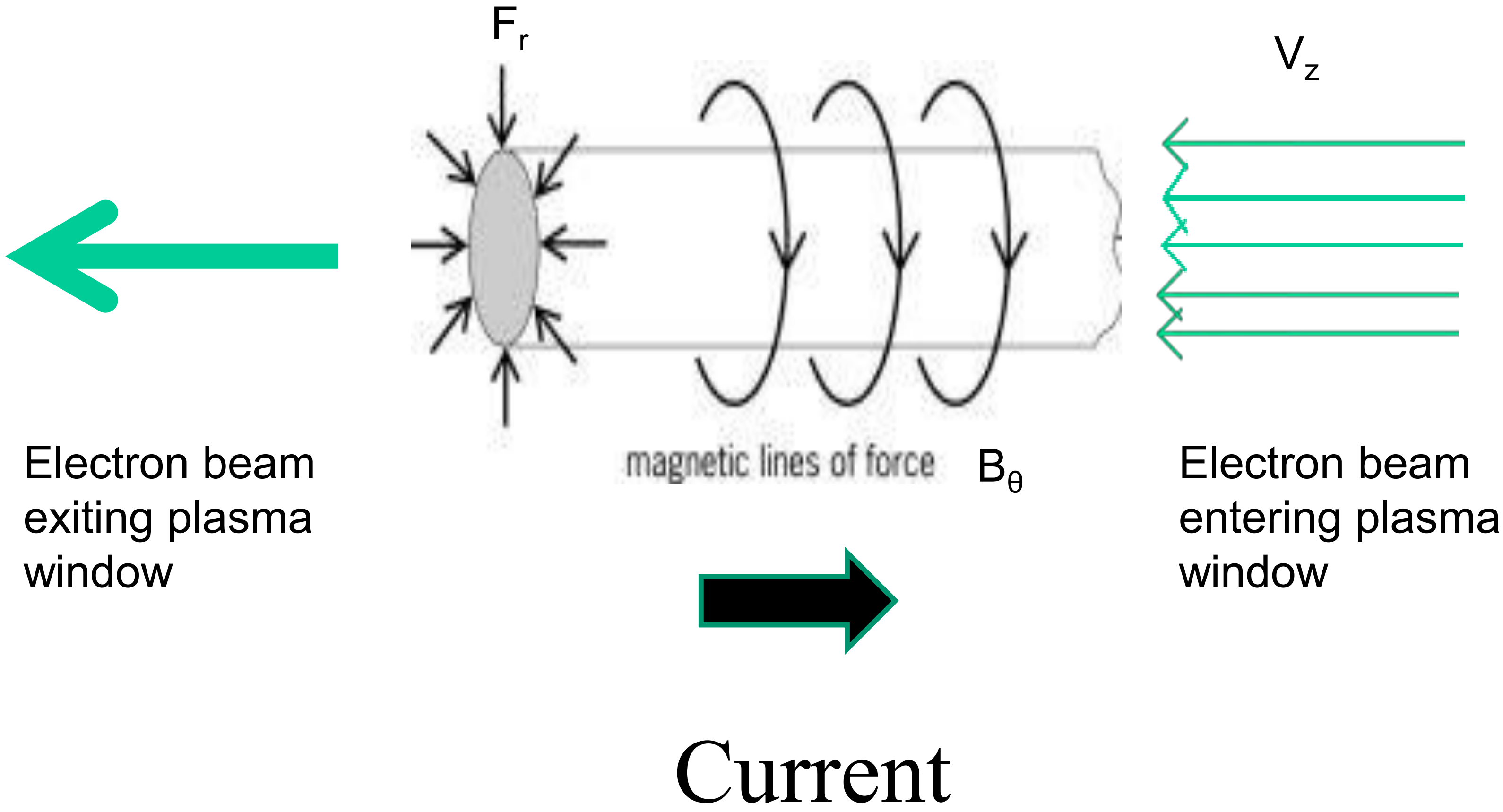
Electron Beam Through Plasma Window



Electron Beam Through the Plasma Window Reduces Pressure & Arc Power

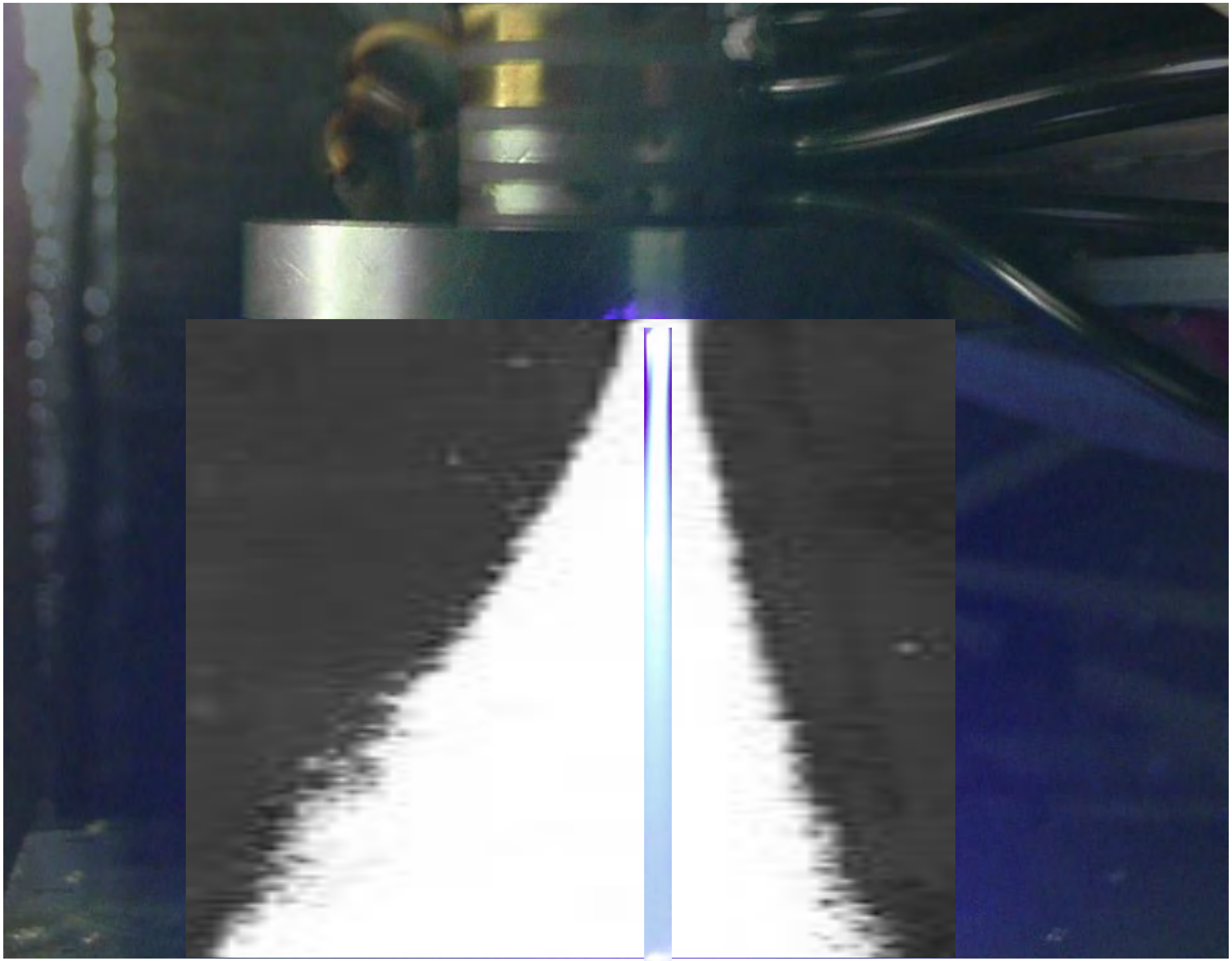
Electron beam current	Gauge reading (Ar-He ?)	PS Voltage (arc current 45 A; R = 1Ω)
No Current	2000 mTorr	148 V
15 mA	750 mTorr	135 V
20 mA	500 mTorr	129 V
25 mA	400 mTorr	123 V

Plasma Lens (focuses charged particles similar to light focusing by an optical lens)



$$\underline{F_r} = q\underline{V_z} \times \underline{B_\theta}$$

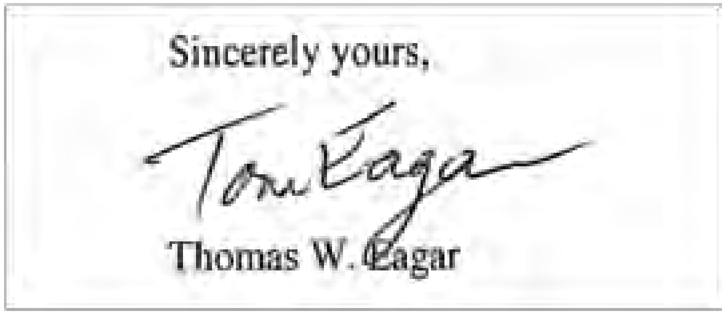
175 KeV 90 mA E_Beam Dispersing in Air from **EBW machine with Differential Pumping** Superimposed on (25 mA PW)



Welding in Air

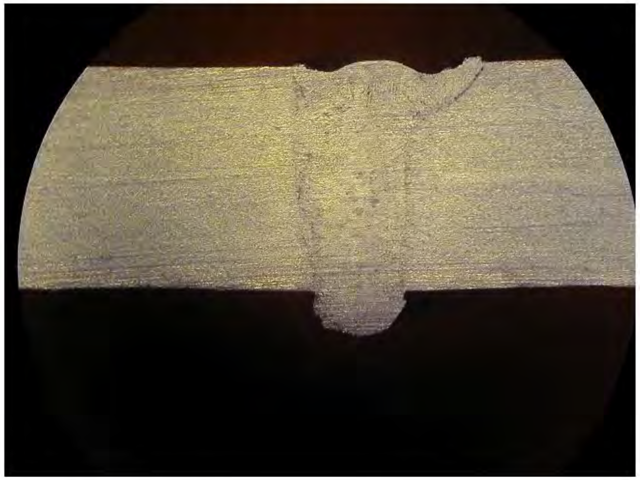
THOMAS W. EAGAR, Sc.D., P.E.
MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MA

"the bead shape represented by weld 3 is a significant improvement over the welds which were achievable in the past ……..this new plasma arc window represents a significant advance in out of vacuum electron beam welding technology."

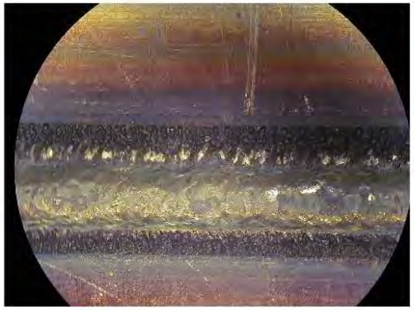


ACCELERON INC.

After rebuild and slight reconfiguration of Plasma Arc Window
Sample #:4-28-04
100% penetration .125 thick



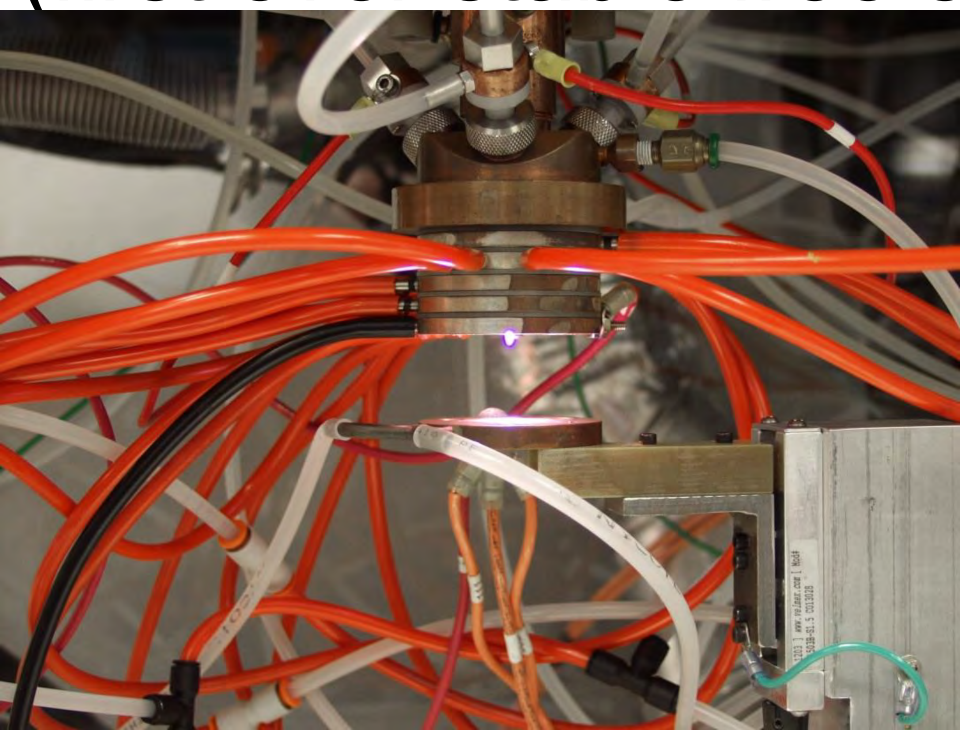
Top Weld Bead

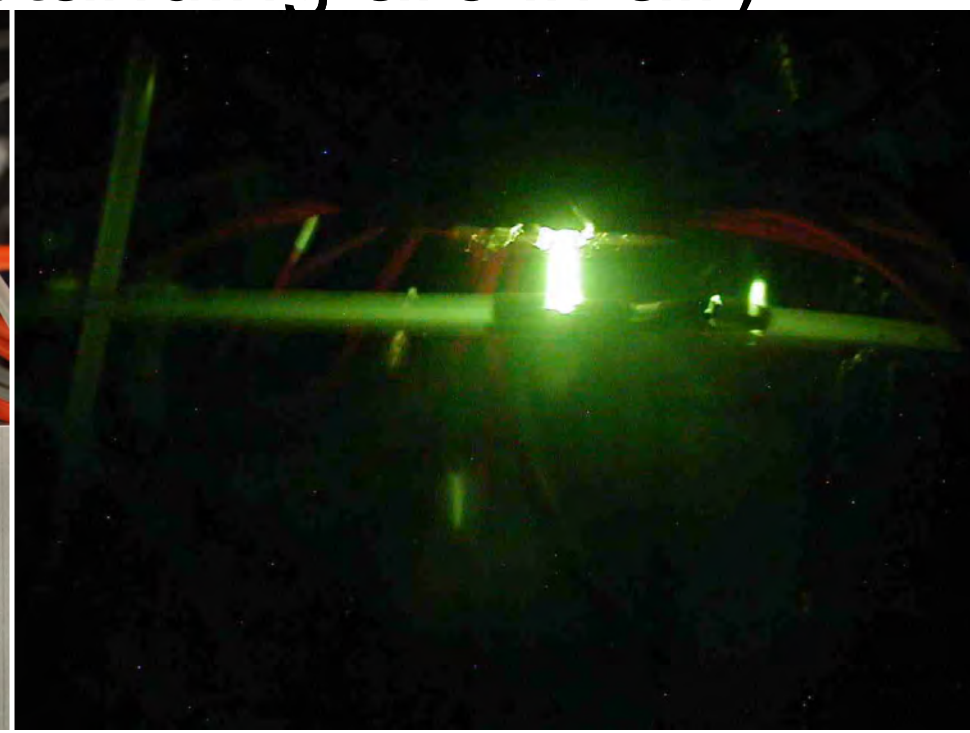


Bottom Weld Bead

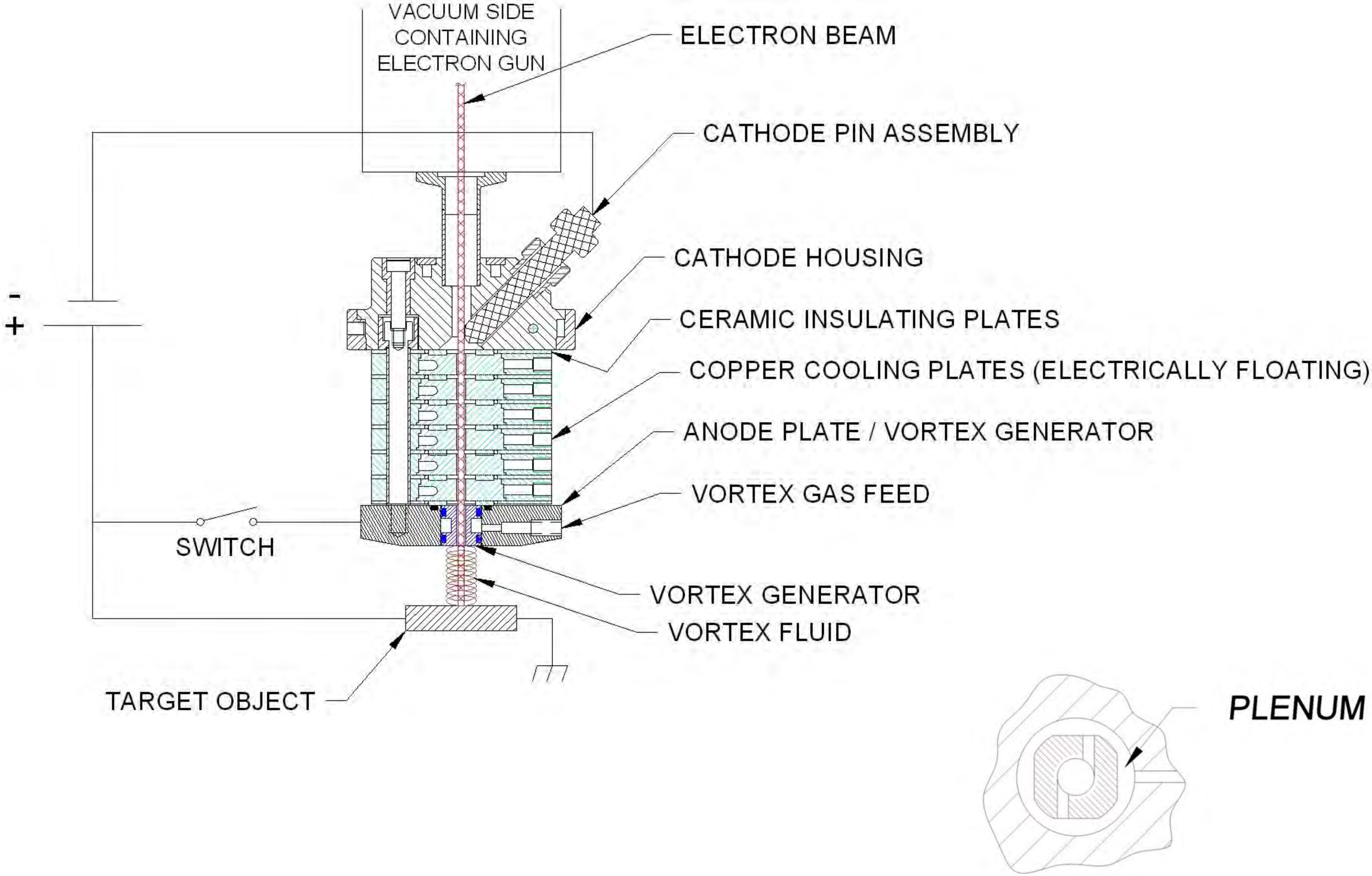
Plasma Shield to Prevent Oxidation (& thermal shielding) **Vortex Stabilized Plasma**

Fast swirling gas or liquid can generate a vortex (like a tornado) with low pressure in the center. Vortex can act like cooling plates and stabilized a plasma are. Early vortices to stabilize plasmas were made of water (first ever stable free standing arc in air)



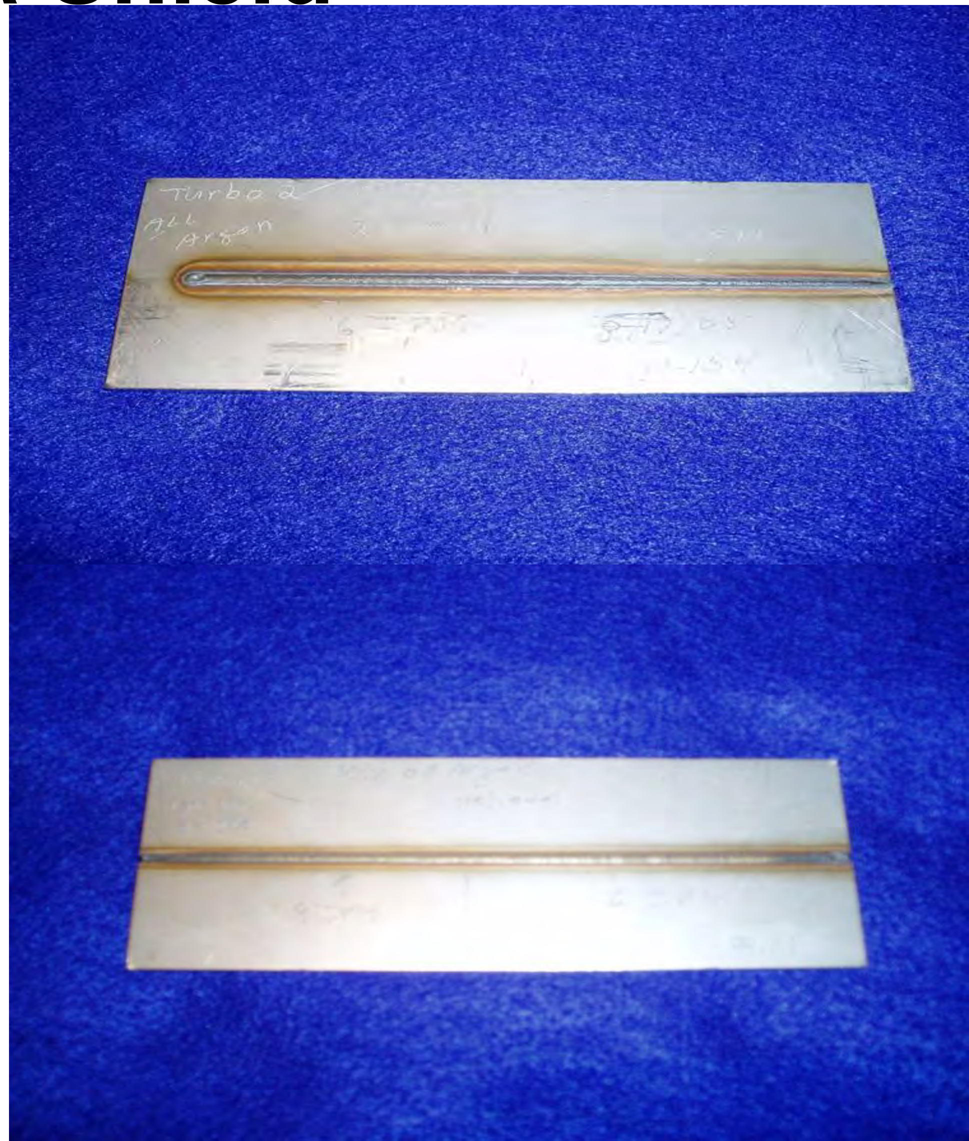


Plasma Window & Plasma Shield



Major Improvements in Welding and Electron Beam Propagation with a Partial Plasma Shield

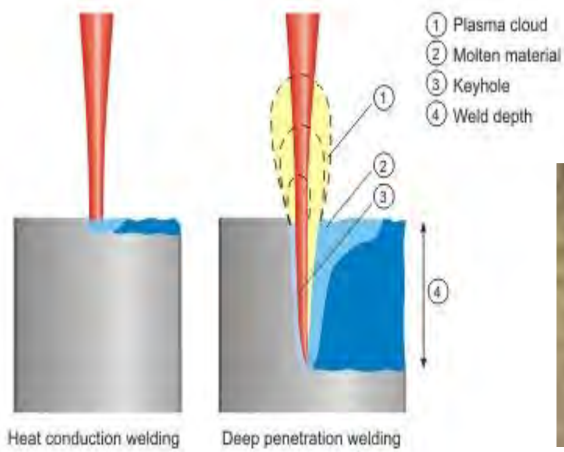
- Vacuum separation greatly improved (factor 4) over plasma window alone (can operate in pure argon).
- Electron beam propagation is a large factor better (about an order of magnitude)
- As expected, weld cleanliness improved
- Welds analyzed: of excellent quality; oxide thickness less than 1 micron
- **My dream: underwater electron beam welding**



Self-pinched Electron Beam propagation was most likely achieved with beam power level as low as 6 mA, 150 keV, compared to kA, MV NRL electron beams, no rejection by NRL; APS DPP press release

Keyhole Welding: 10^5 - 10^6 W/cm^2

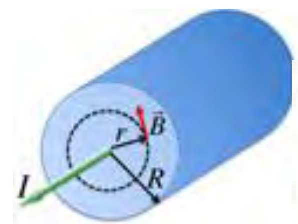
Determines range of "hot core" radius from as high as **0.2 mm to as low as 0.01 mm** hence needed self-pinched current density.



150 KeV electron beam penetration in steel is only 52 μm or 0.052 mm

Ampere's Law: B α J (not I)

Minute diameter electron beam



$$\oint_{loop} \mathbf{B} \cdot d\mathbf{l} = \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi R}$$

For even small current I, B (&F) can be enormous (compensate for in-air scattering)

$$\underline{F_r} = q\underline{V_z} \times \underline{B_\theta}$$

Commercialization: lasers are much cheaper **Niche**: double hull oil tankers

(double hull battleships) **Presently done manual with torches; EBW-NV will be a major breakthrough. Need $$$**

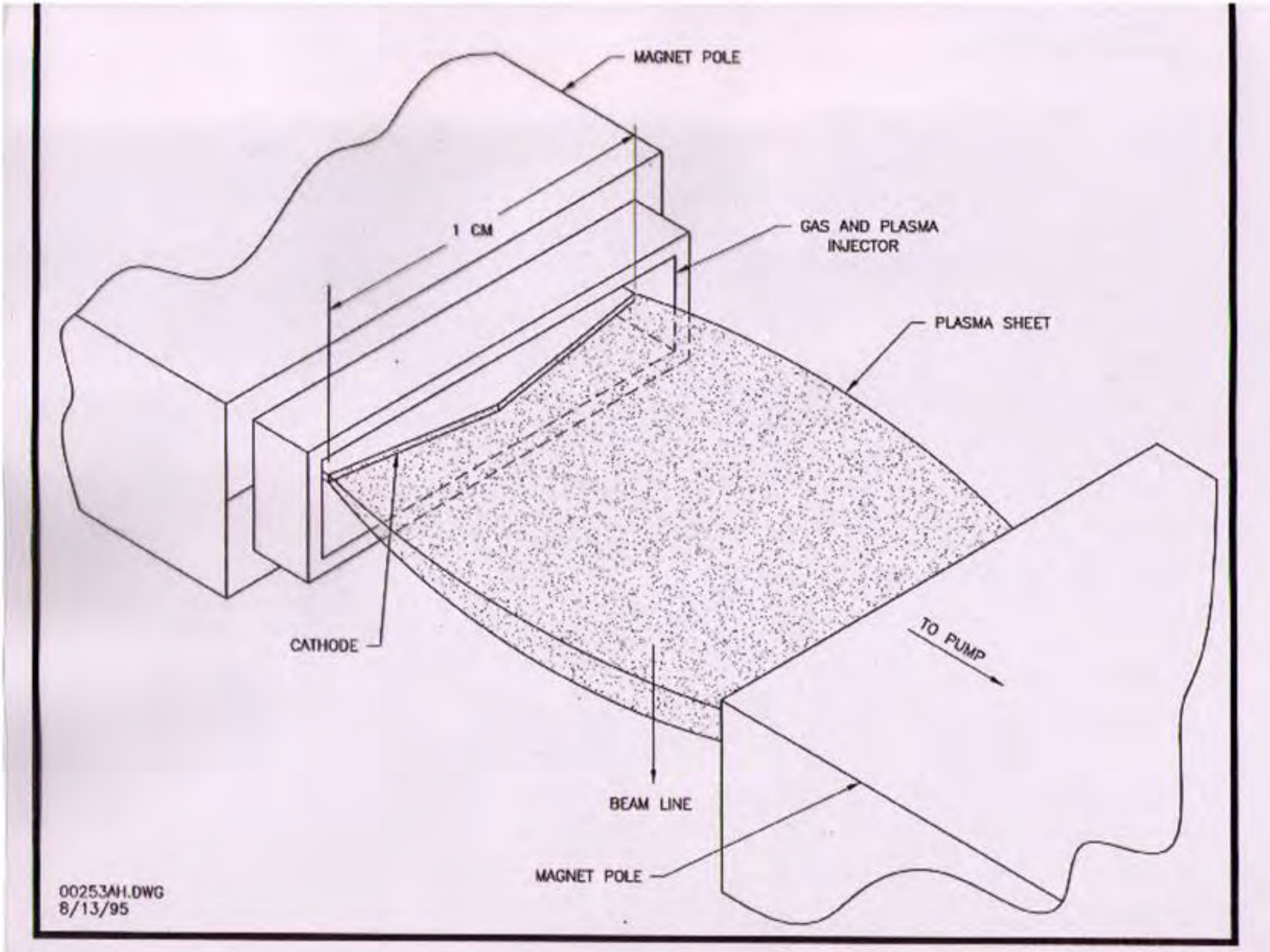
Electron Beam +Plasma Window & Plasma Shield Welder

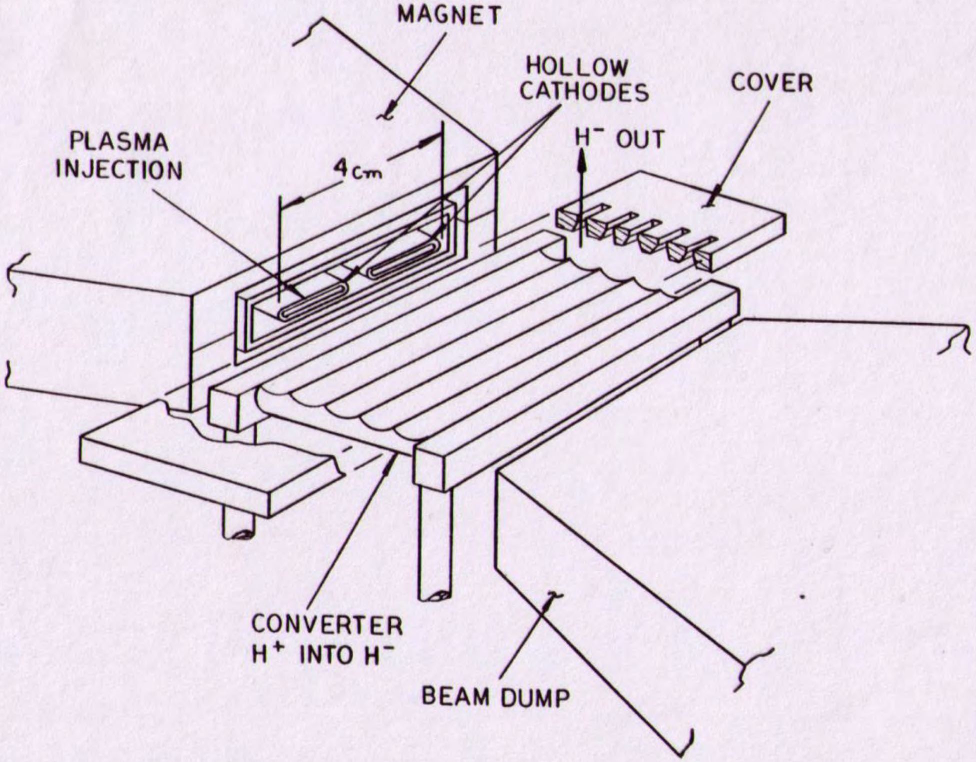
- Much better weld quality (depth to width ratio)
- Energy Efficient
- Much better gas (argon use) efficiency
- Generates X-ray requires shielding; and cameras to observe welding process
- Cost $1,000,000
- EBW double-hull oil tankers major environmental benefit

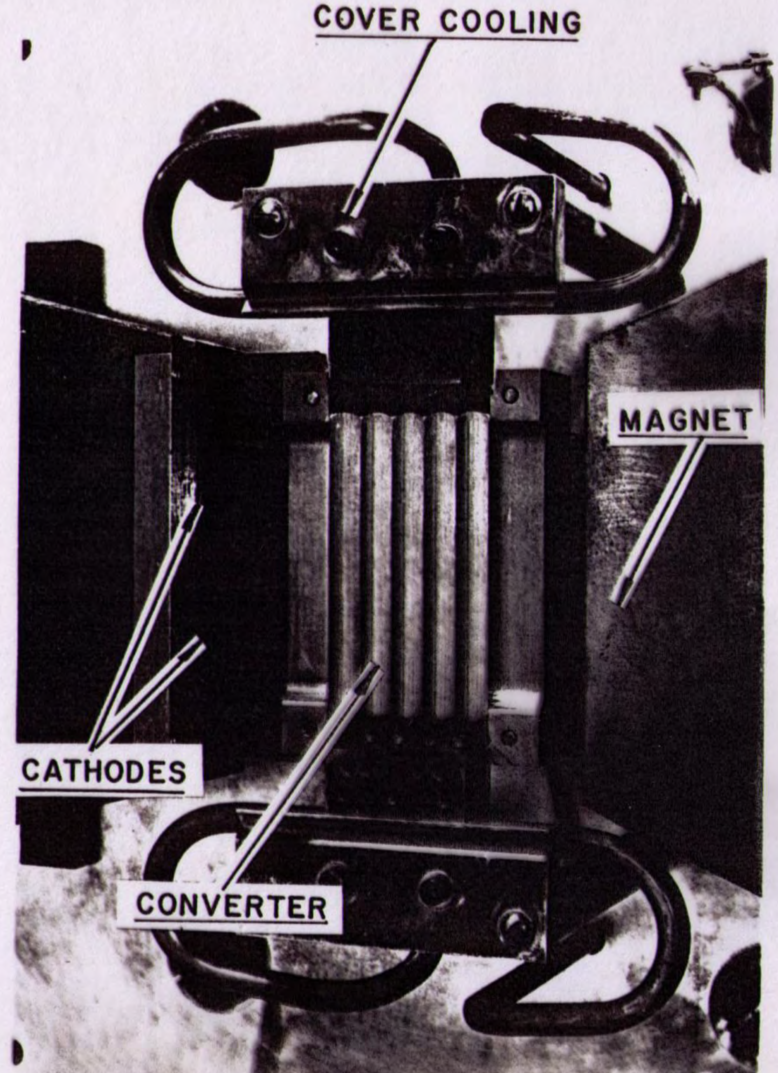
Laser Welder

- Lower weld quality
- Very poor energy efficiency in both electricity to laser and laser light to weld
- Need to flood large areas with argon
- No X-ray generation; no need for cameras
- **Cost $350,000**

Flat Plasma Arc Design



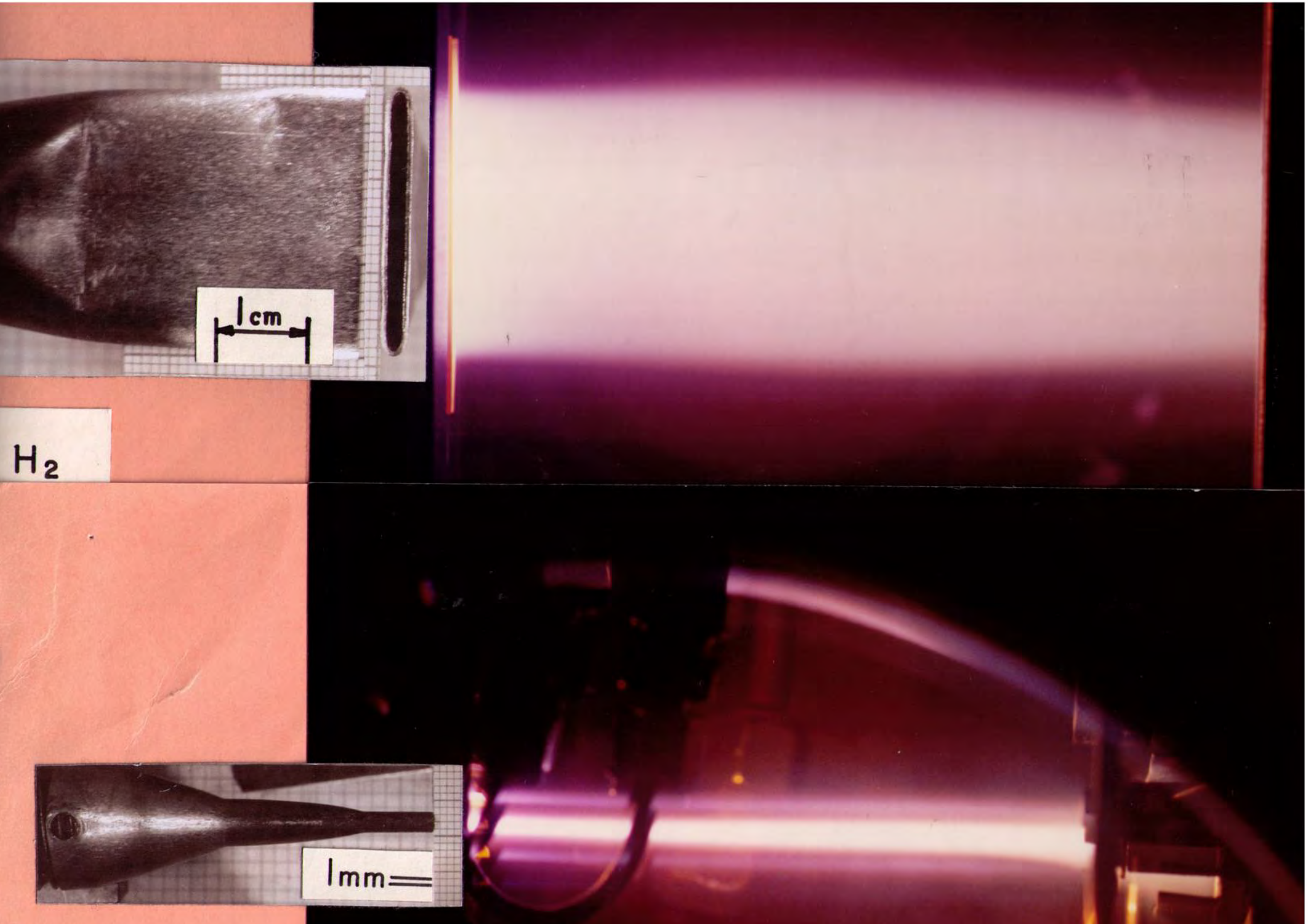




PERFORMANCE BNL HOLLOW CATHODE DISCHARGE SOURCE

H^- YIELD	0.5 A
EXTRACTED CURRENT DENSITY	100 mA / cm^2
EXTRACTOR VOLTAGE	7.5 KV
MODE OF OPERATION	STEADY STATE
HOLLOW CATHODE CURRENT	50 A
MAGNETIC FIELD	200-400 G
CONVERTER CURRENT	8 A in H_2 MODE

Experimentally Achieved

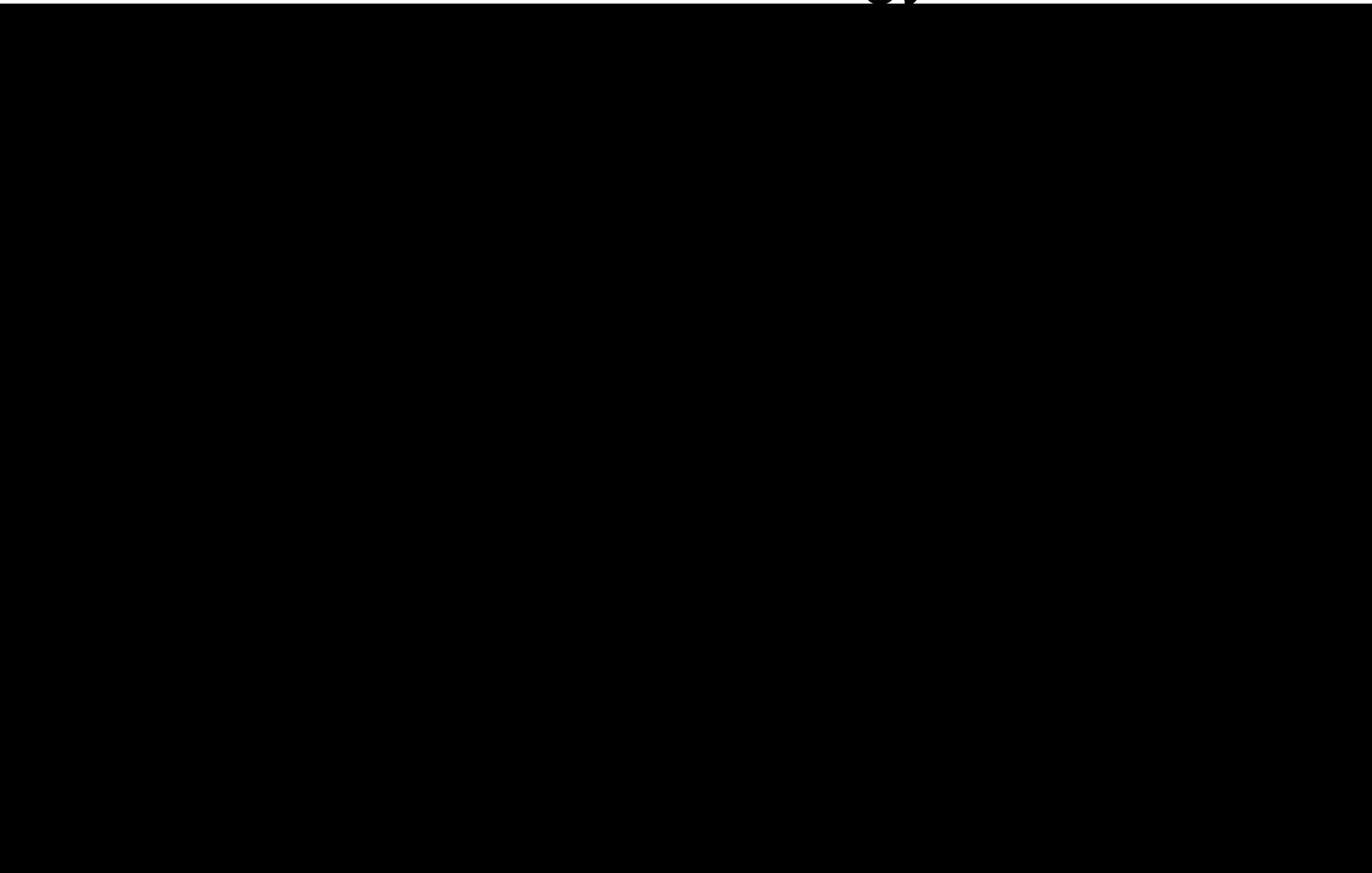


Windows & Shuttle Bay Doors

Star Wars Tech (Lucas') History Channel

Windows and Shuttle Bay Doors

Star Trek Technology PBS



List of people I must acknowledge requires too many slides
Sorry

Thank You for your Attention