

Plasma Window for Various Applications

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The Plasma Window is a novel apparatus that utilizes a stabilized plasma arc as interface between vacuum and atmosphere or pressurized targets without solid material. Additionally, the plasma has a lensing effect on charged particles. Furthermore, plasma from a plasma window was extended over 4 cm into atmosphere to form a plasma shield (Plasma Shield is basically a Plasma Window extended to engulf a target object).

Scientific and industrial applications involving beam transmission from vacuum to atmosphere or to high pressure targets (like high quality electron beam welding that was performed in atmosphere) be enhanced by this technology. Specifically, the plasma window/shield can be beneficial to a number of scientific devices and machines like synchrotron light sources, high power lasers, internal targets, high current accelerators, and spallation neutron sources. A number of possible applications including windowless beamlines to atmosphere (or to high pressure targets) for neutron and/or x-ray generation will be discussed.

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The best results to date have been the following:

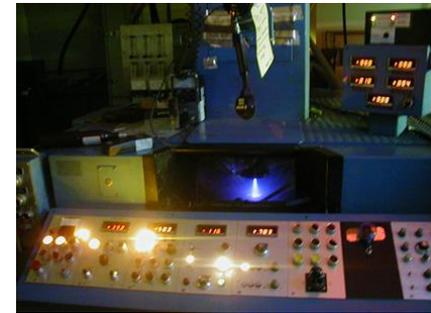
1. Vacuum (pressure of $\sim 10^{-6}$ Torr) was successfully separated from atmosphere or argon gas target pressurized up to 9 bar.
2. A 2 MeV proton beam was propagated from vacuum through the plasma window into atmospheric pressure.
3. Electron beams with energies of 90 - 175 KeV were transmitted from vacuum through the plasma window to atmosphere. And, Self-pinch beam propagation was achieved with 6 - 25 mA, 90 – 150 KeV electron beams. By comparison previously demonstrated self-pinch propagation used kA multi-MeV electron beams.
4. Successful transmission of X-rays from a light source to atmosphere.
5. Gas cell pressurized to 3 bar was successfully separated from atmosphere and HeNe laser light was transmitted through the gas cell and plasma window to atmosphere.
6. High quality electron beam welding in atmosphere performed.
7. Helium gas target (over 1 bar) sandwiched between two plasma windows was separated from vacuum on two opposite ends.

Plasma Window Aspects: Technology, Physics, and for More Entertaining Talk Sci-Fi

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

Talk Outline

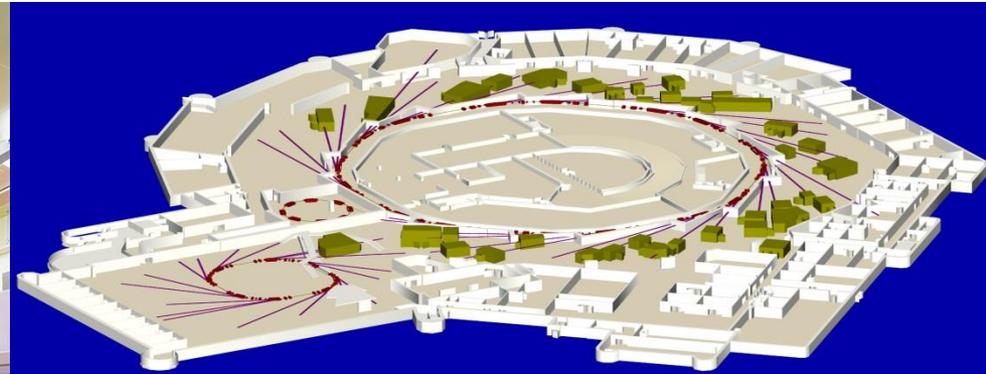
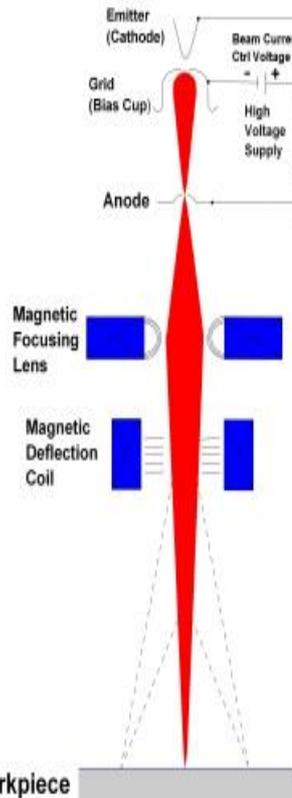
1. Why Plasma Windows
2. Operation Principles
3. Results/Application
4. The sky is not the limit
5. Sci-Fi (**disclaimer!** Sci-Fi statements are exaggerated)



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.

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

Electron beams for welding



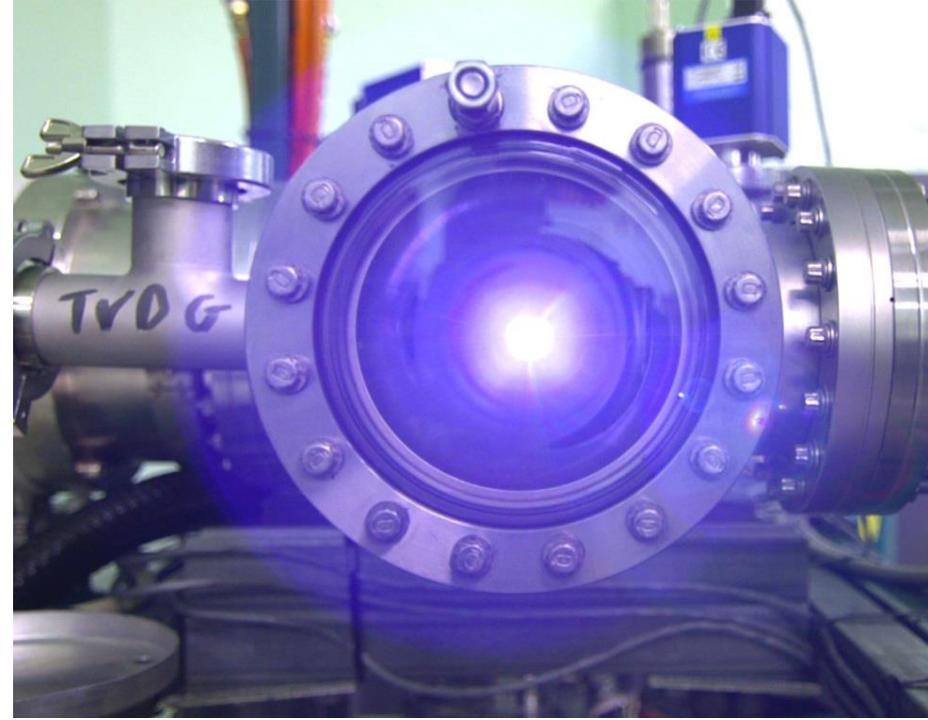
Plasma Window Has Captured People's Imagination: Sci-Fi Meets Reality

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

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

$$p = nkT \quad (1)$$

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

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

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 Mach number M satisfies $0.5 M^2 \ll 1$. 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 **Navier-Stokes** equation for the gas. For electrons and ions, the relevant transport equations are the continuity and momentum transfer equations

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

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

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

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

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

For gases,

$$\eta = aT^x \quad (6)$$

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.

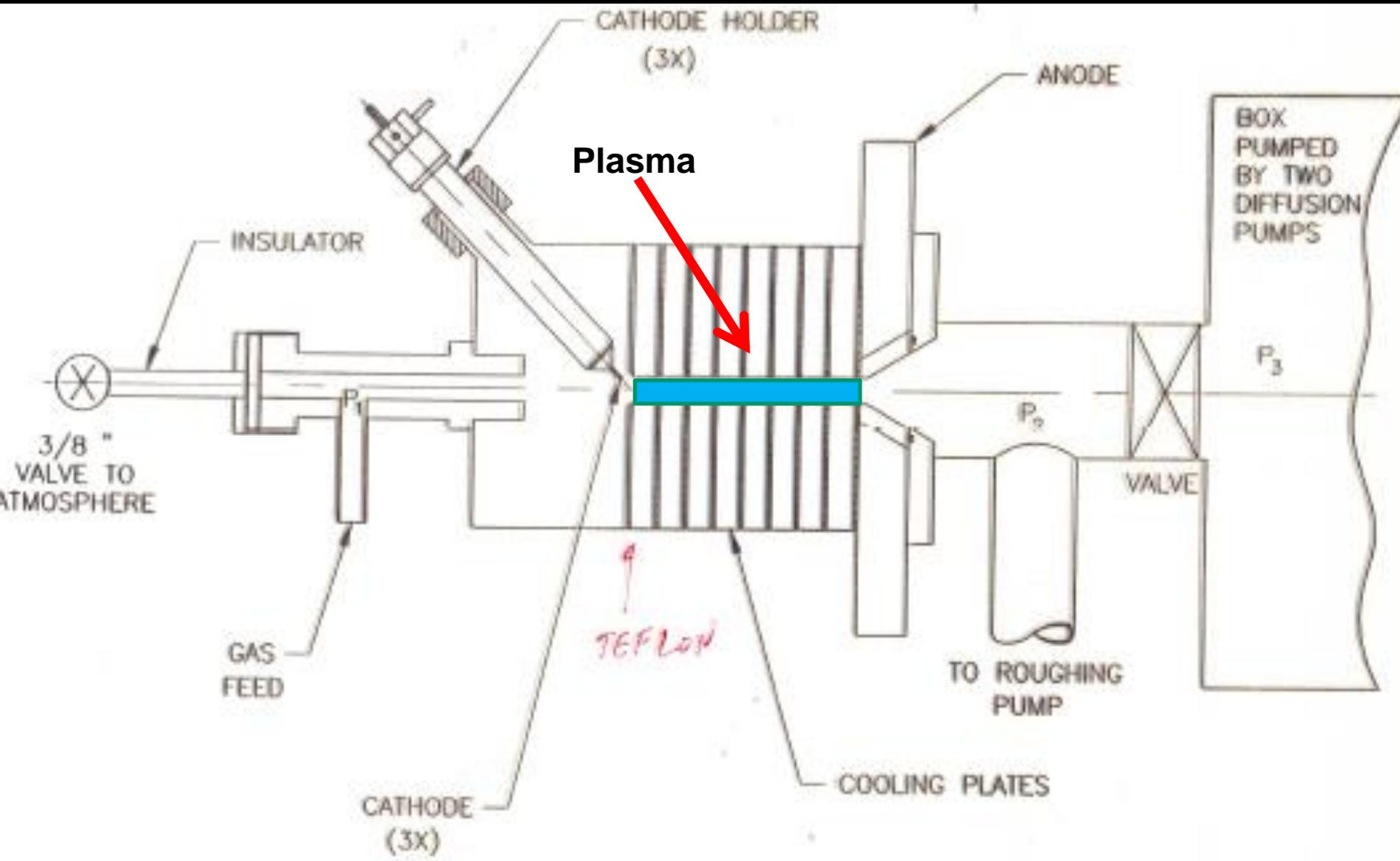
Ionization

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

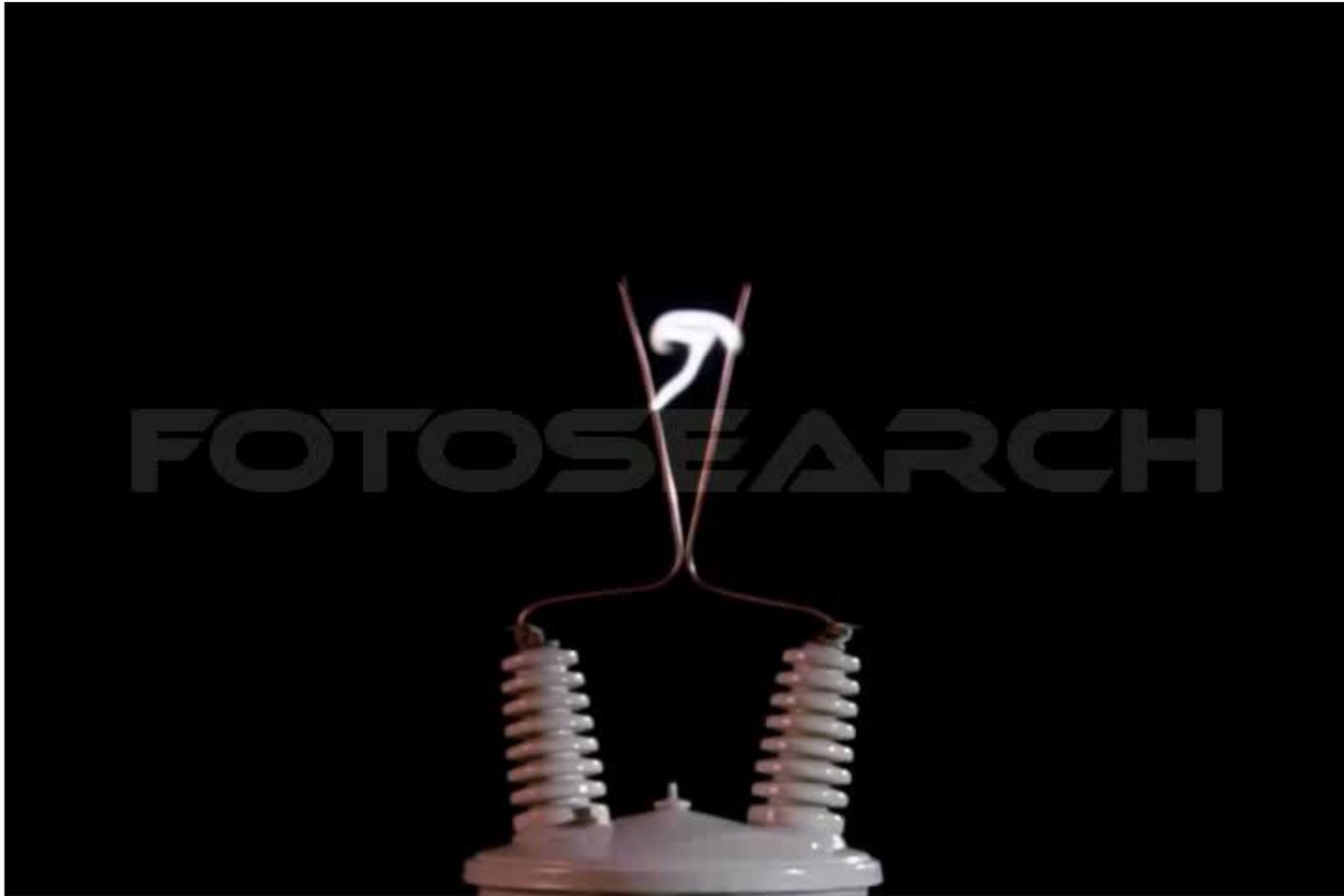
Important in the case of **vacua separation**. Results in plug formation. Prevents back streaming of vapor and metal chips resulting from various industrial processes.

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)

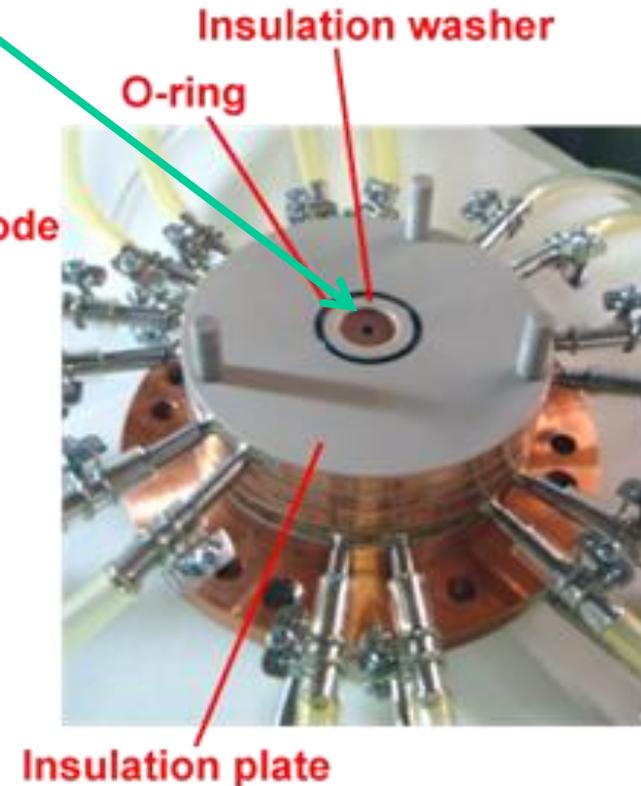
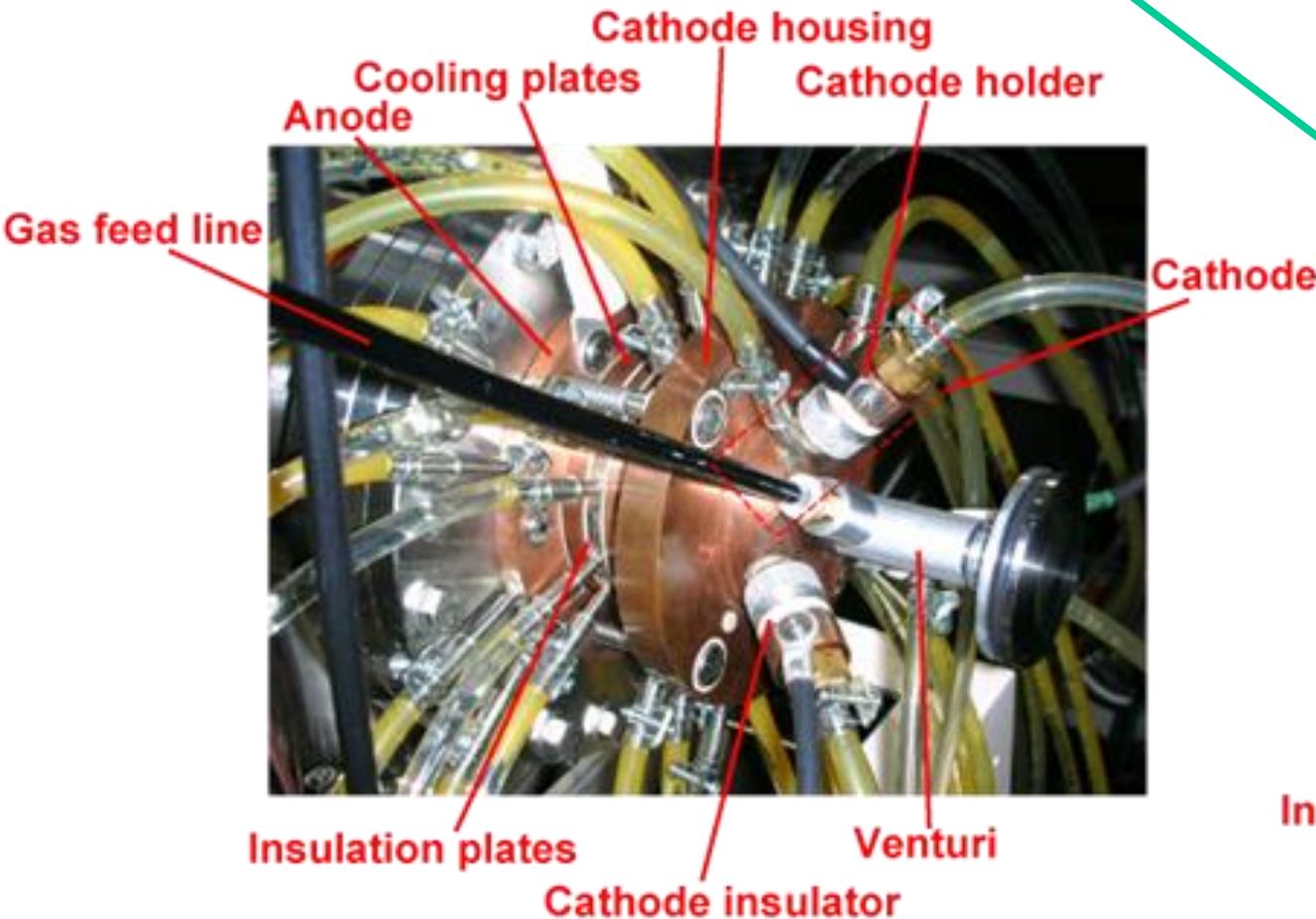
2nd set of record results: shortening the plasma window 1000 (Litton); going to high pressure 10,000 (MIT; PW reaching choked flow condition)

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

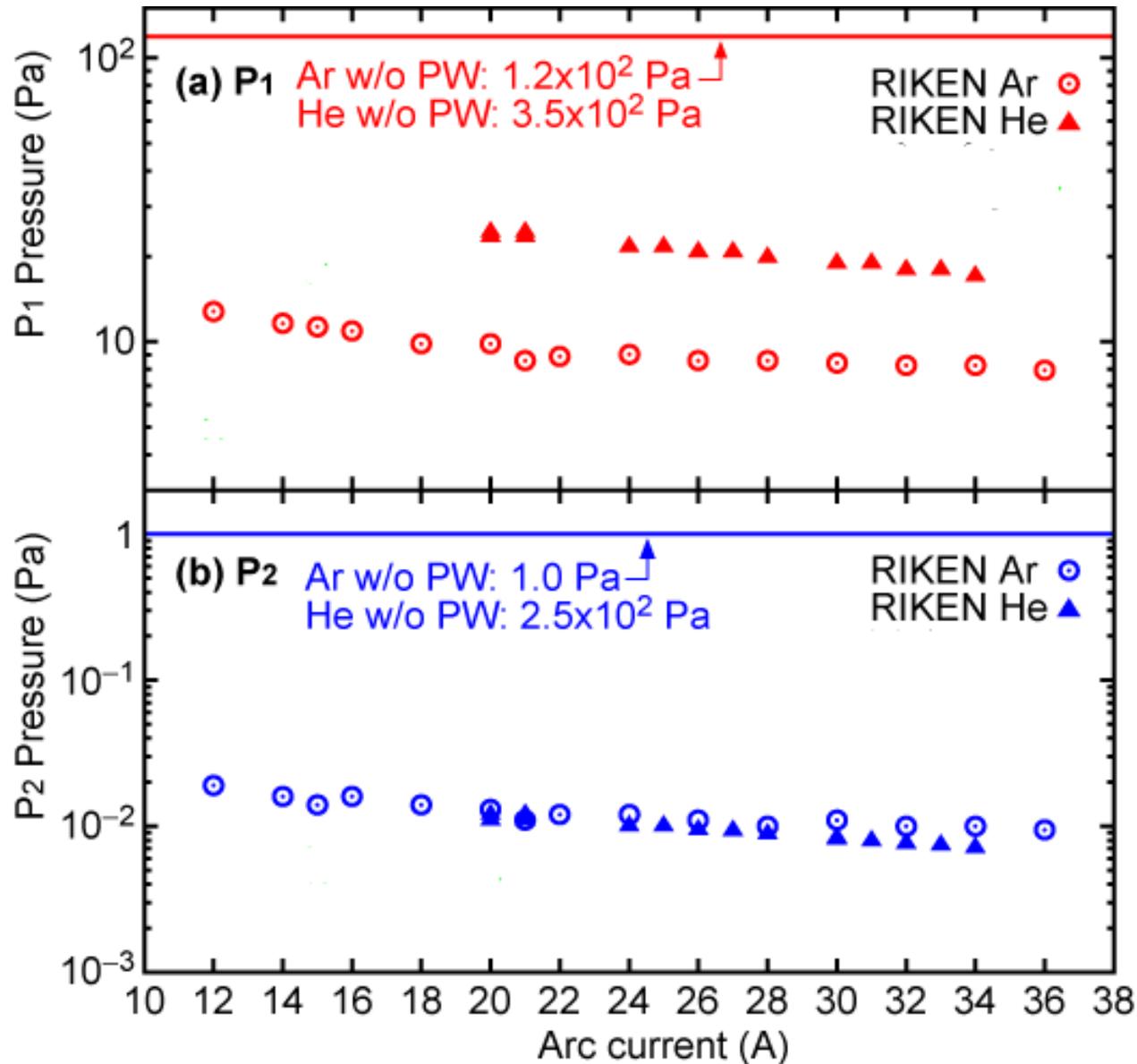
Trying to re-evaluate plasma window benefit by comparing gas flow into plasma window (measured) versus pumped out gas flow (estimated from pressure and pumping speed) obtained for 1/2 atmosphere helium gas cell conductance restriction factor of 20 (at a power of 8.5 kW; factor increases with power). But, this estimation skews the plasma window effect, by under estimating gas flow after the plasma window, with plasma window off, i.e. not accounting for likely reduction in pumping speed.

REKIN (RIBF) Plasma Window

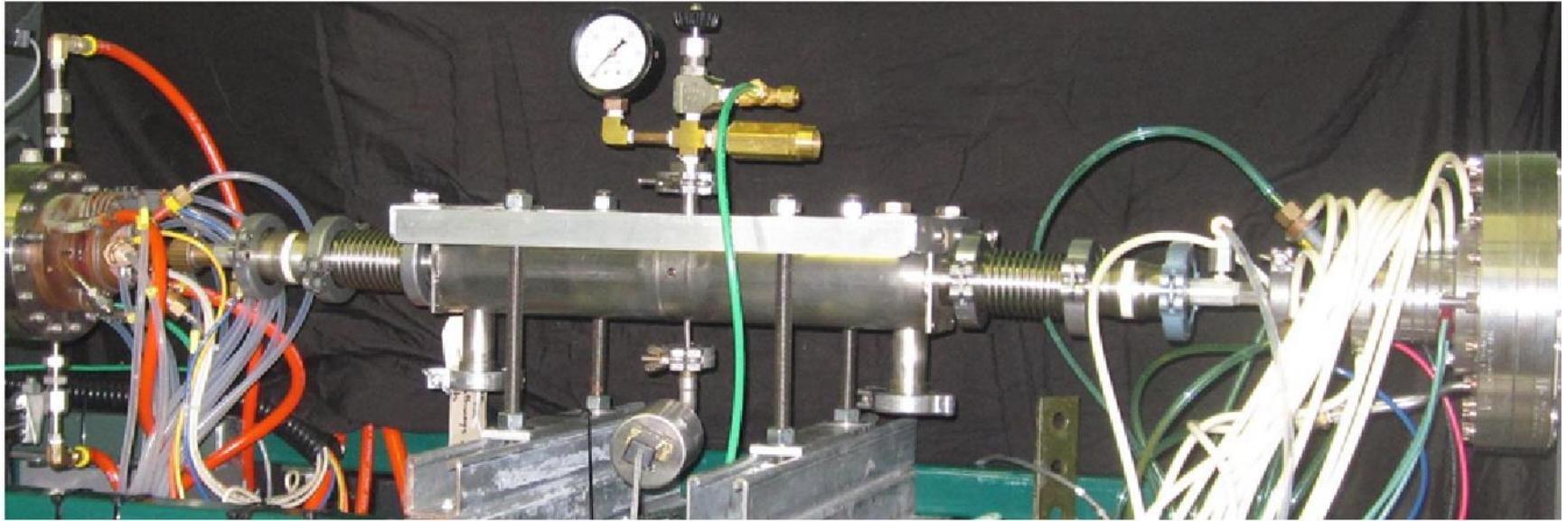
(empty hole becomes window when filled with plasma)



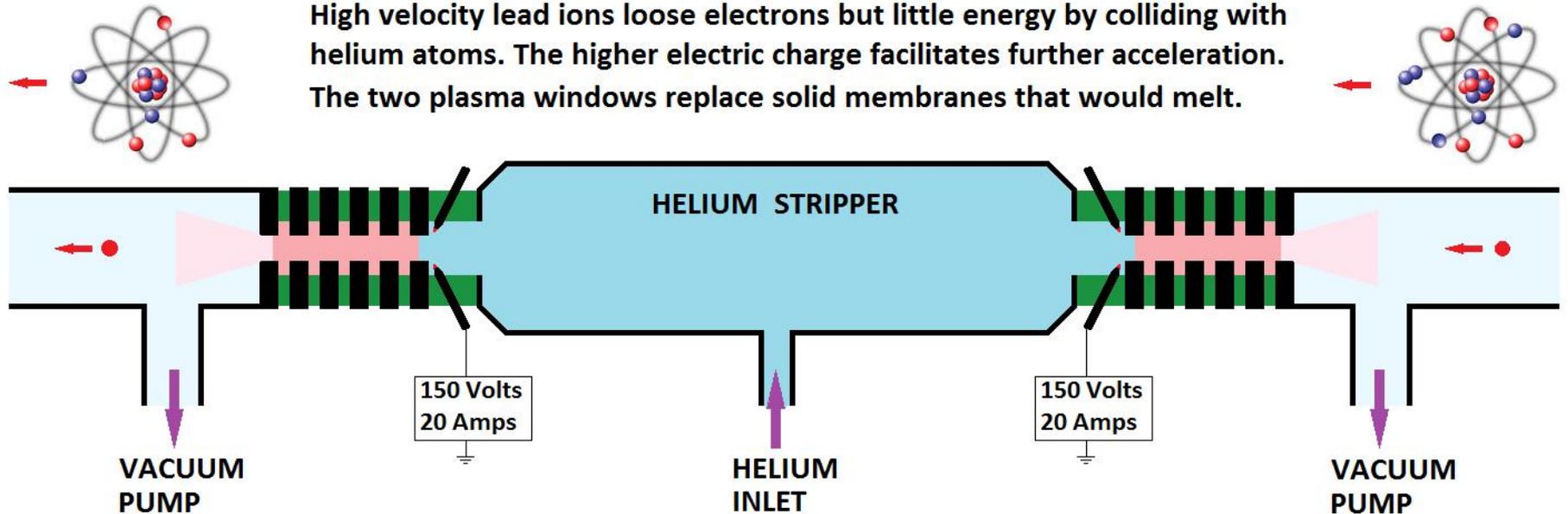
Pressure Versus Arc Current Latest Plasma Window (PW)



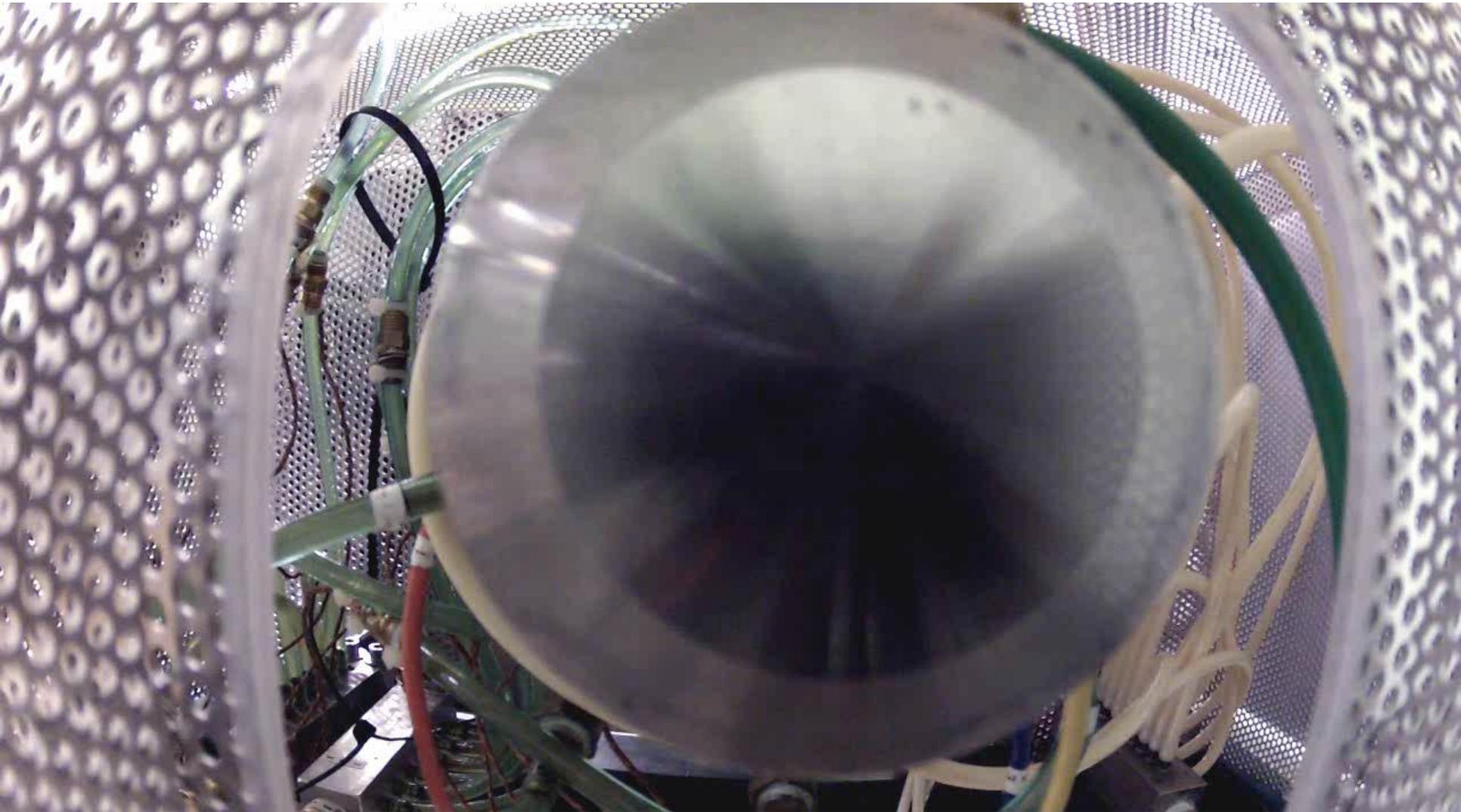
Gas stripper development for the Michigan State University's FRIB Facility



High velocity lead ions lose electrons but little energy by colliding with helium atoms. The higher electric charge facilitates further acceleration. The two plasma windows replace solid membranes that would melt.



Setup in target room 2 in building 901A

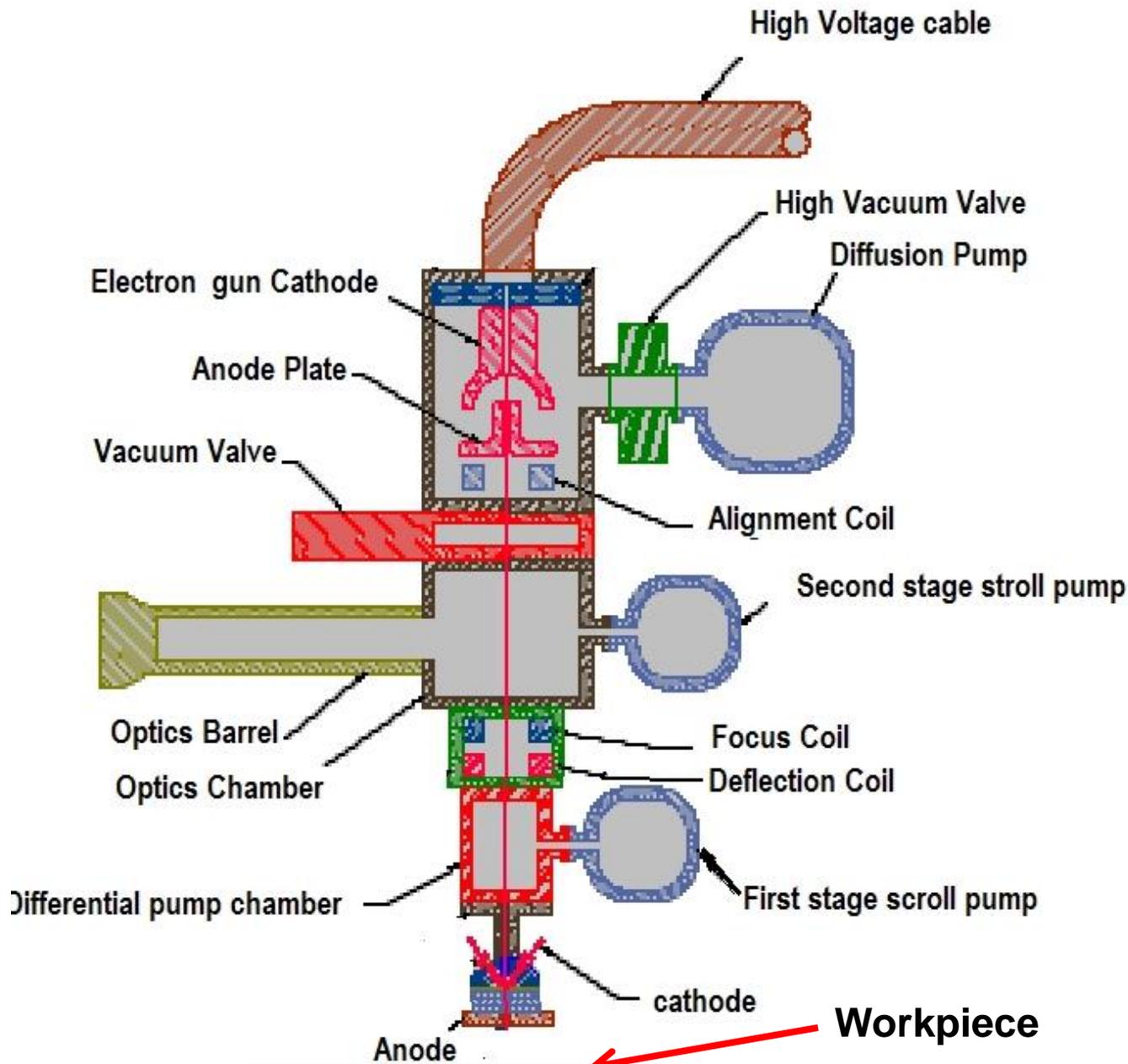


Electron beam welding is the highest quality welding that can be performed. But, it's done in vacuum, resulting in low production rates and limits on object size. Double hull ship can't fit in a vacuum system. Past in-air EBW: lower quality. A challenge!



Electron Beam Through Plasma Window

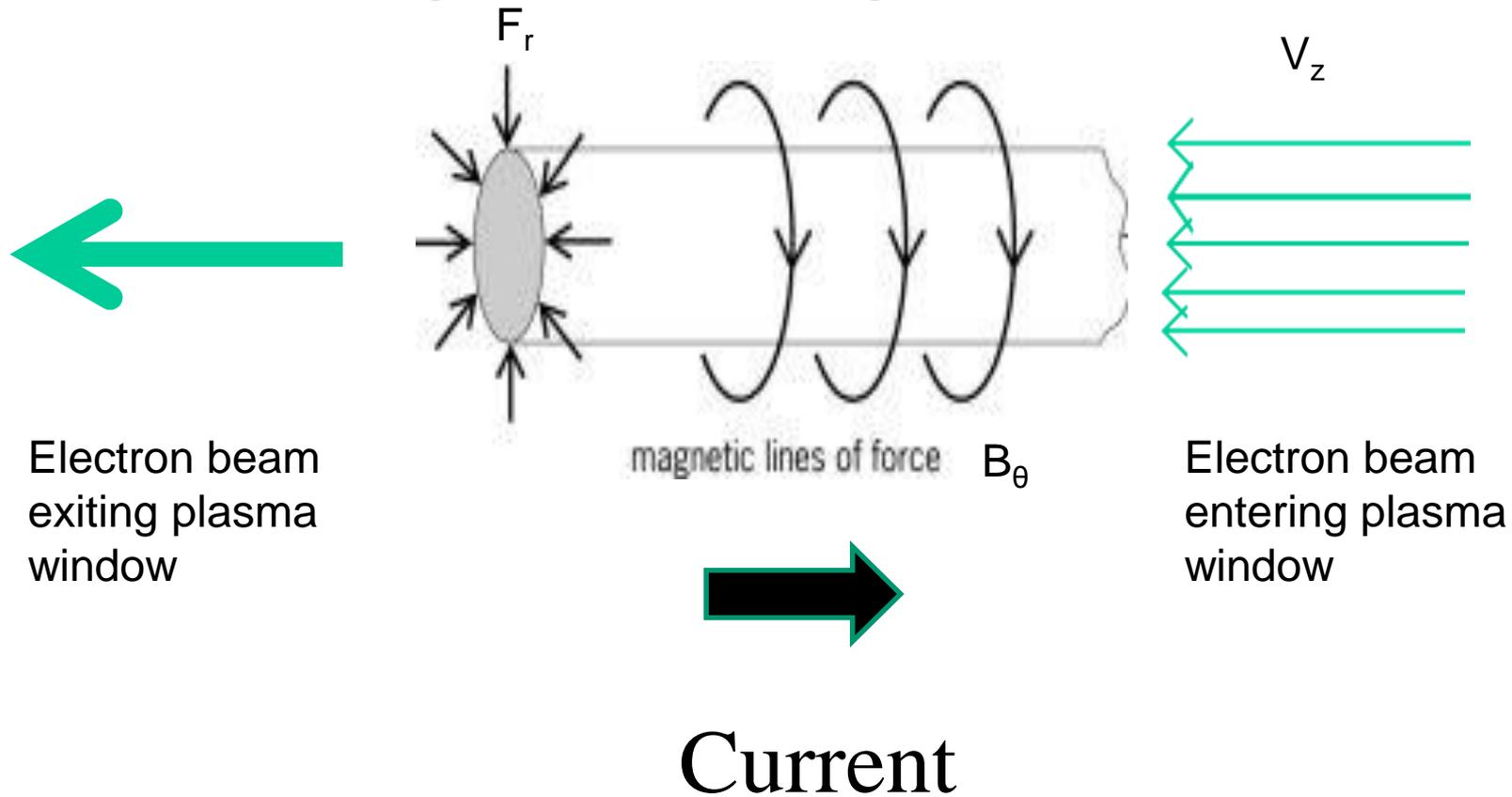
1 m



Electron Beam Through the Plasma Window Reduces Pressure & Arc Power

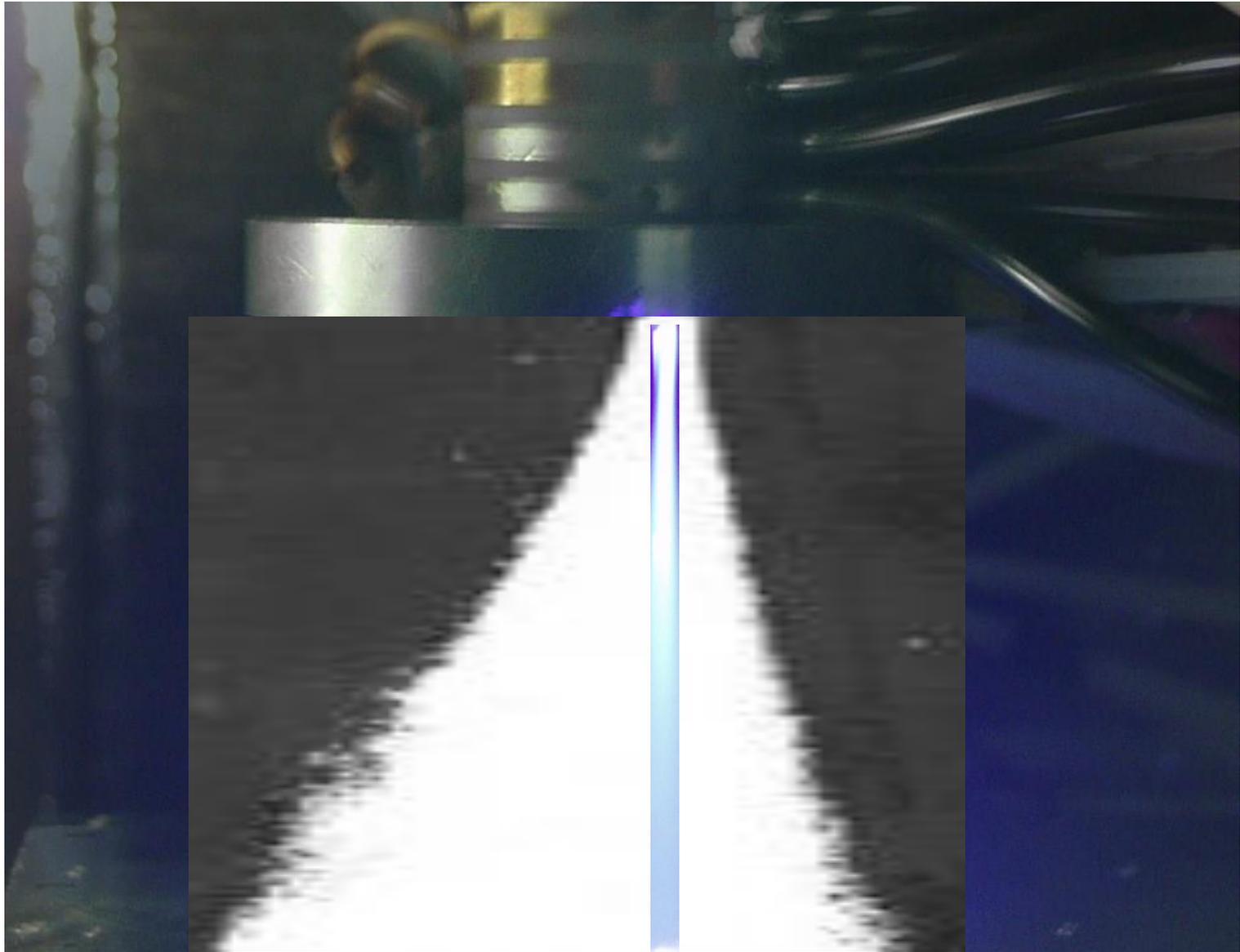
Electron beam current	Gauge reading (Ar-He ?)	PS Voltage (arc current 45 A; $R = 1\Omega$)
No Current	2000 mTorr	148 V
15 mA	750 mTorr	135 V
20 mA	500 mTorr	129 V
25 mA	400 mTorr	123 V

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 pastthis new **plasma arc window** represents a significant advance in out of vacuum electron beam welding technology.”

Sincerely yours,

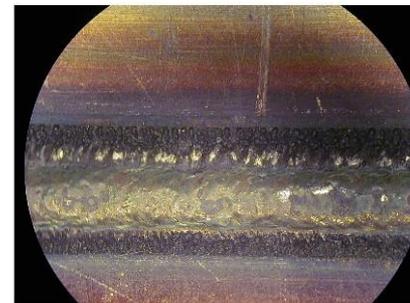

Thomas W. Eagar

ACCELERON INC.

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



Top Weld Bead

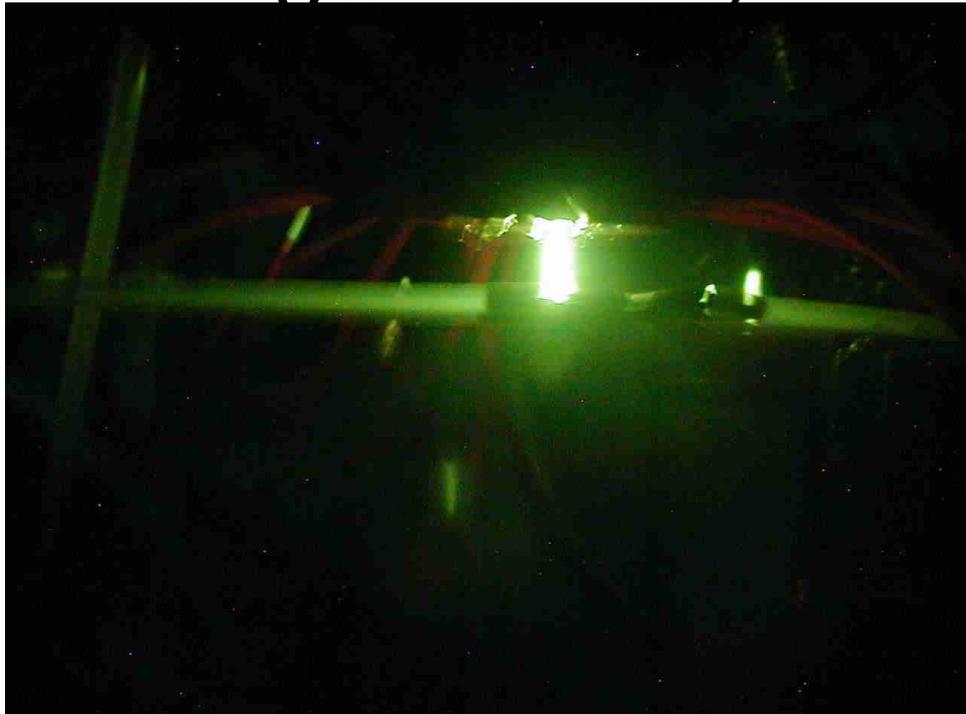
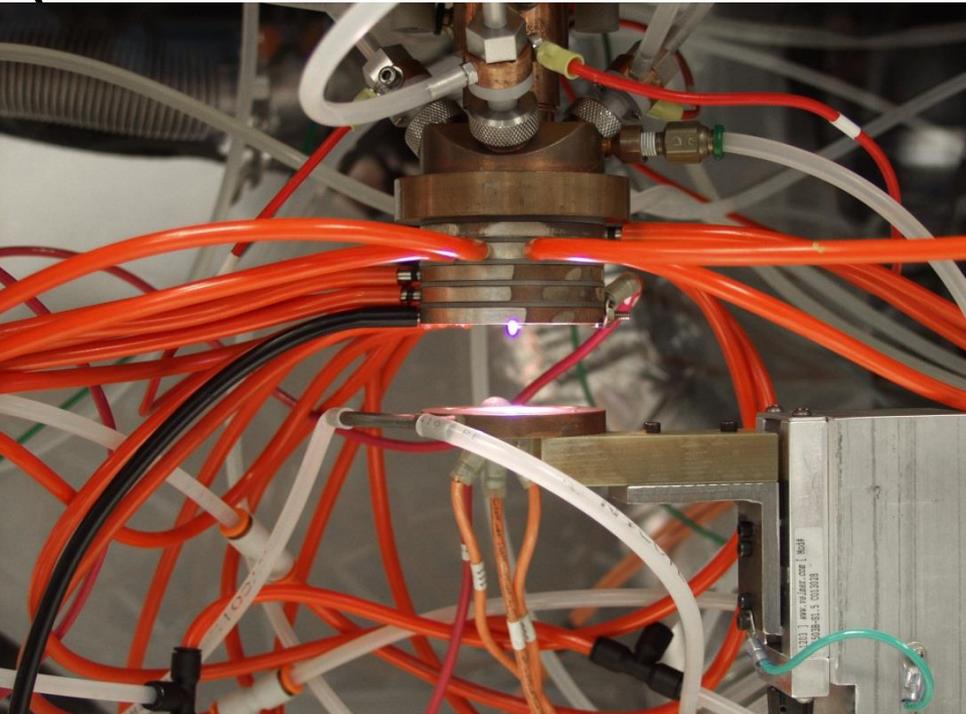


Bottom Weld Bead

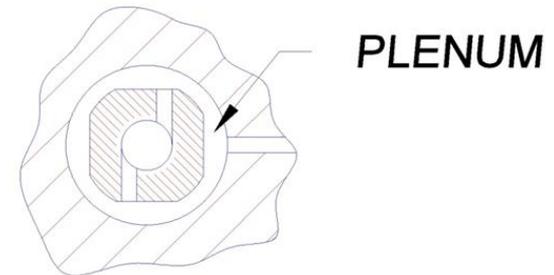
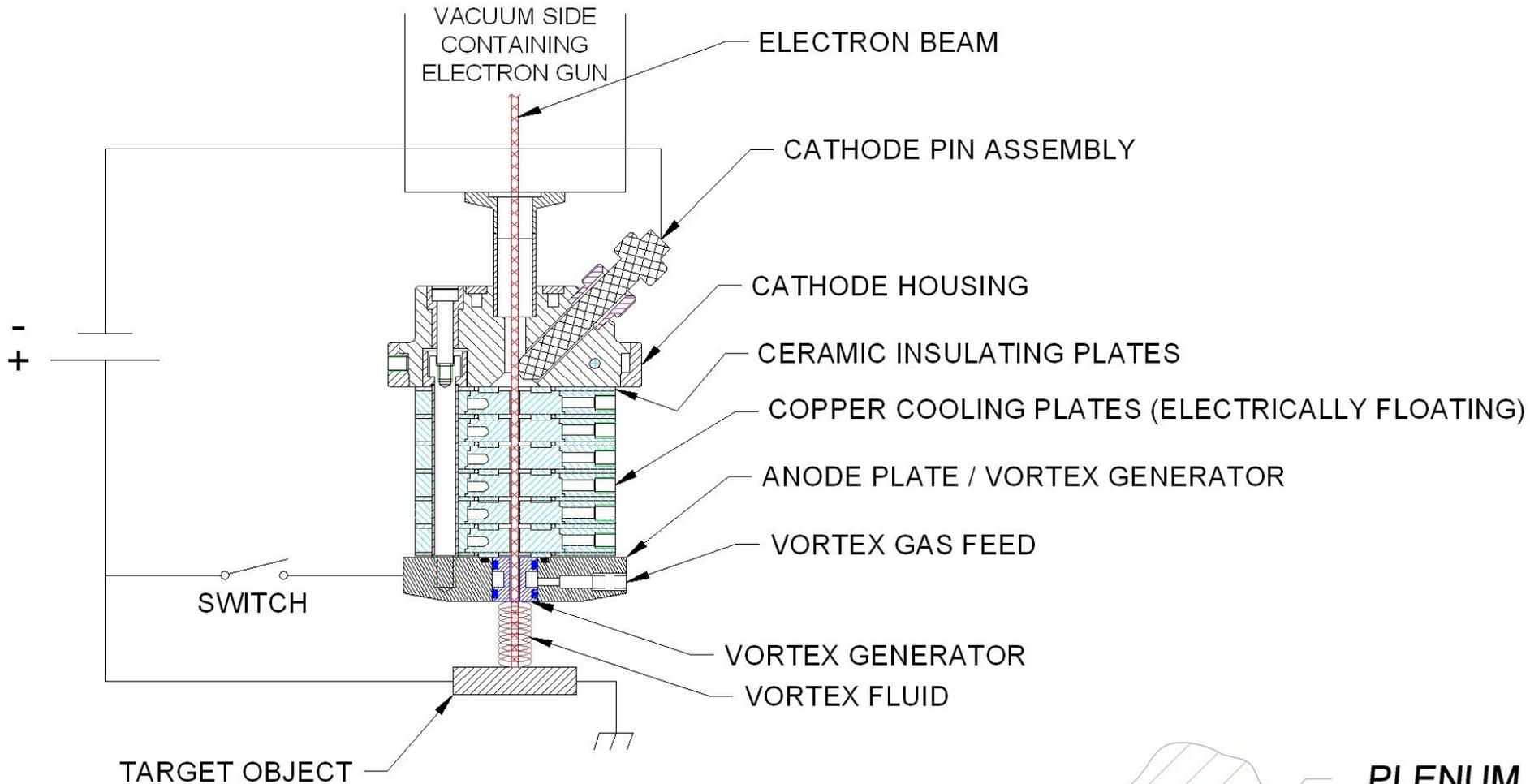


Plasma Shield to Prevent Oxidation (& thermal shielding) **Vortex Stabilized Plasma**

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 arc. Early vortices to stabilize plasmas were made of water (first ever stable free standing arc in air)

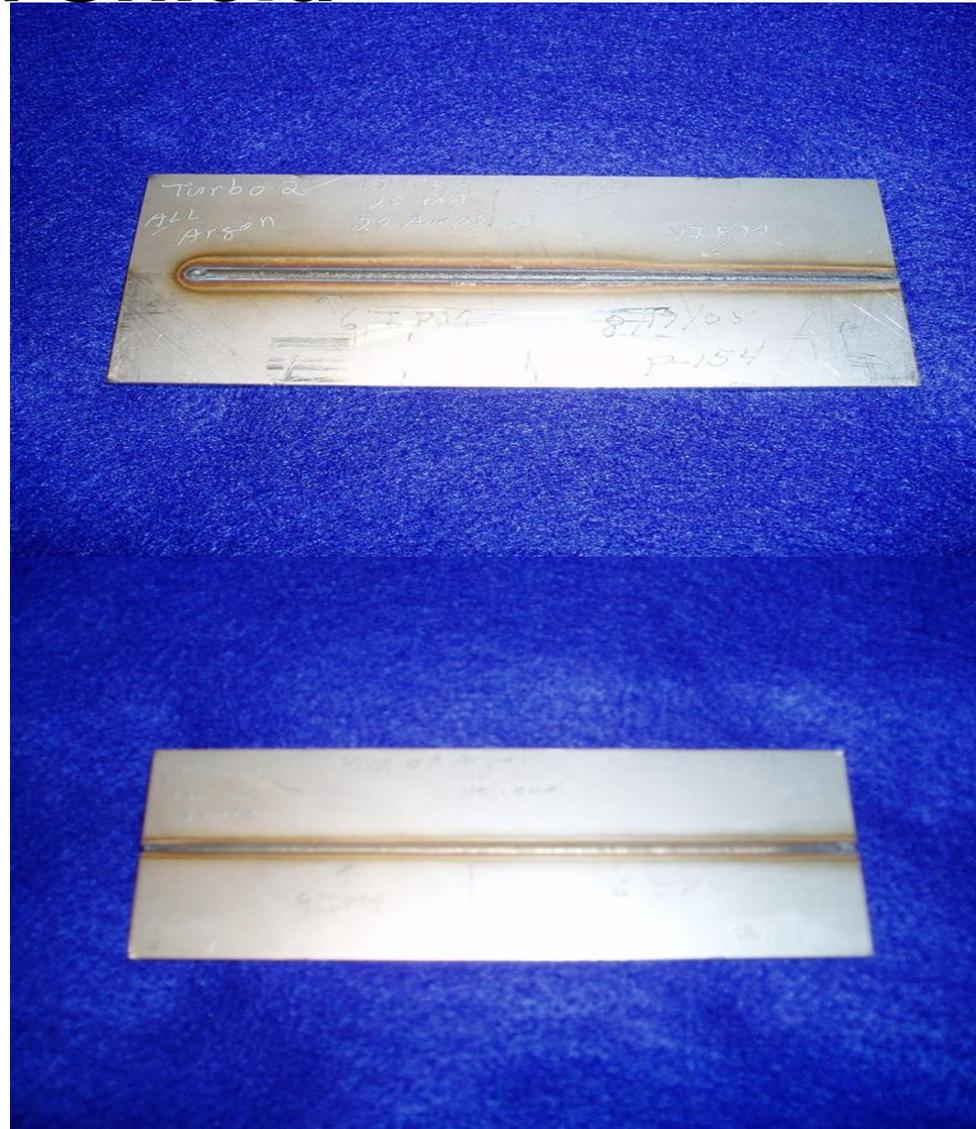


Plasma Window & Plasma Shield



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

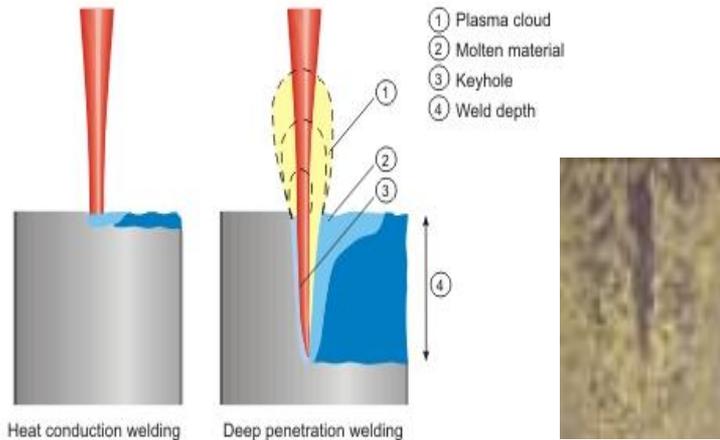
- Vacuum separation greatly improved (factor 4) over plasma window alone (can operate in pure argon).
- Electron beam propagation is a large factor better (about an order of magnitude)
- As expected, weld cleanliness improved
- Welds analyzed: of excellent quality; oxide thickness less than 1 micron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



Self-pinchd 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: $10^5 - 10^6 \text{ W/cm}^2$

Determines range of “hot core” radius from as high as 0.2 mm to as low as 0.01 mm hence needed self-pinchd current density.



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

Ampere’s Law: $B \propto J$ (not I)

Minute diameter electron beam



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

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

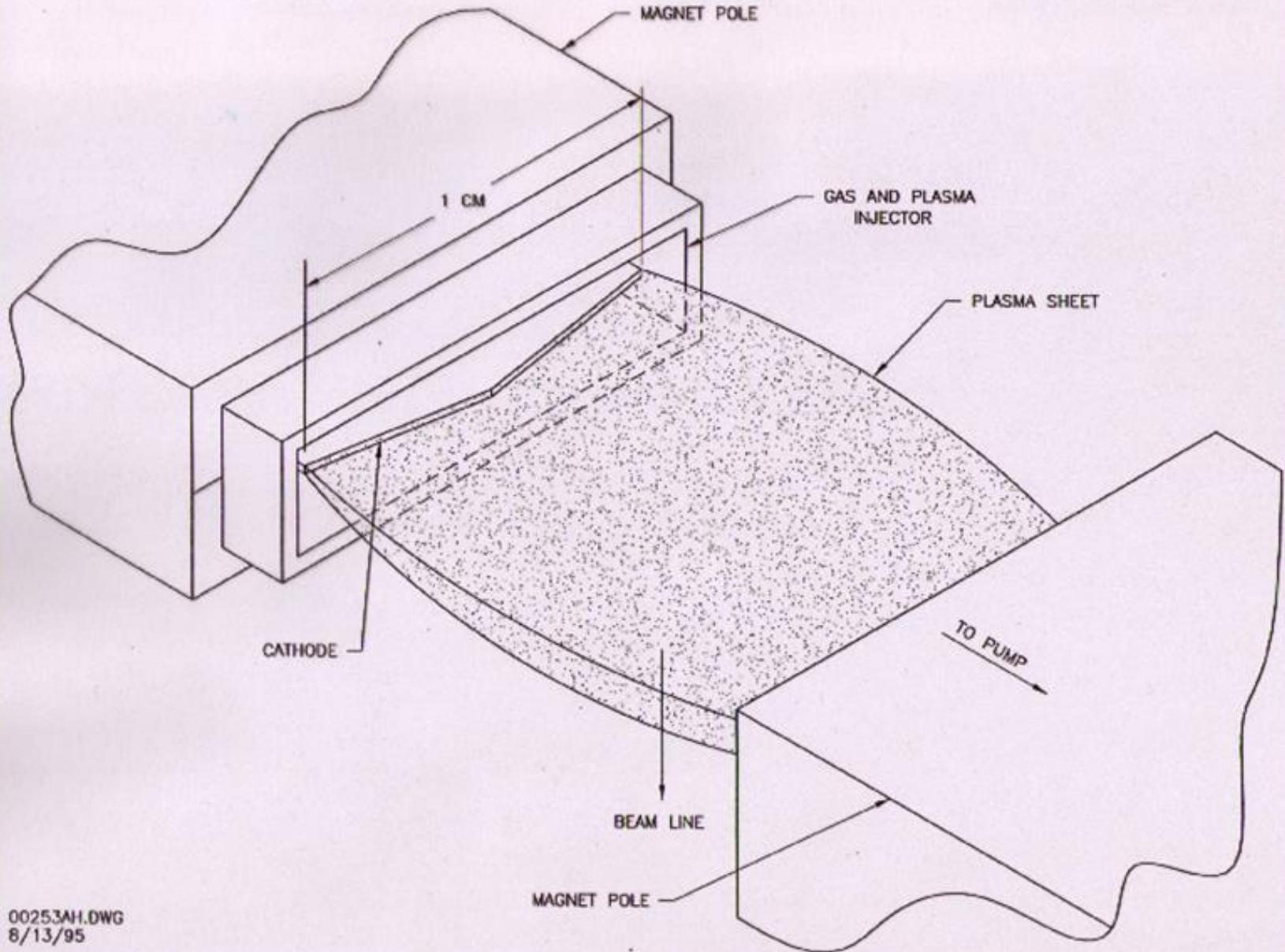
- Lower weld quality
- Very poor energy efficiency in both electricity to laser and laser light to weld
- Need to flood large areas with argon
- No X-ray generation; no need for cameras
- **Cost \$350,000**

Applications: Commercial & Scientific

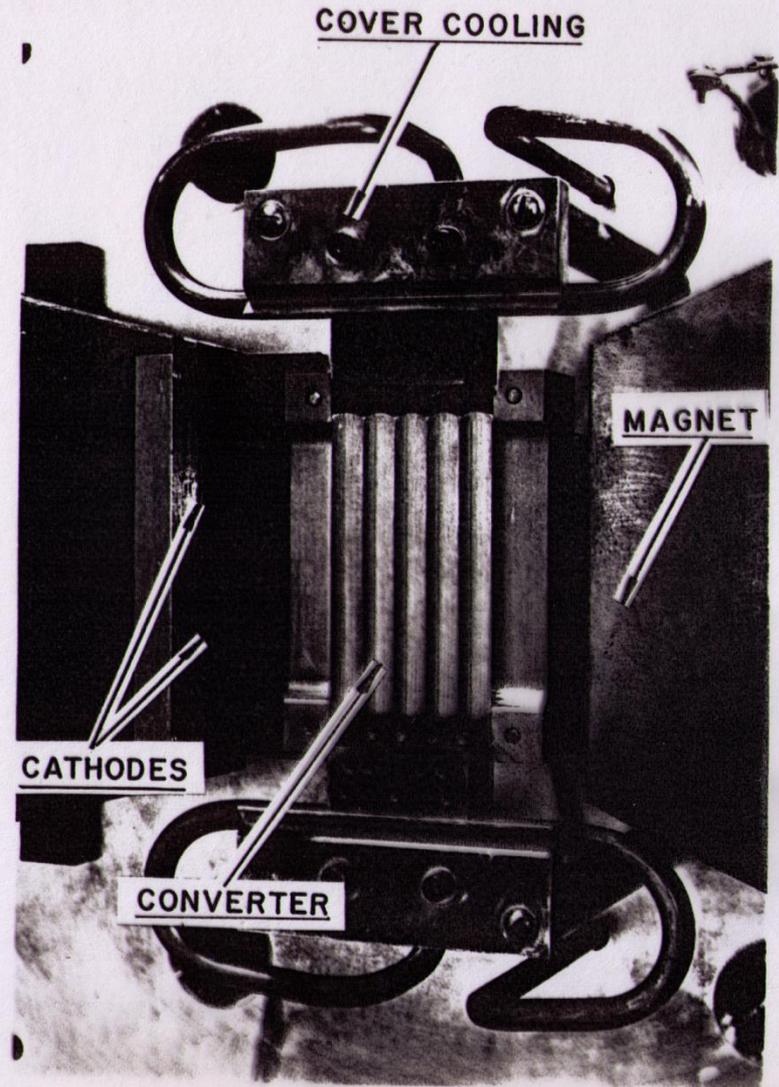
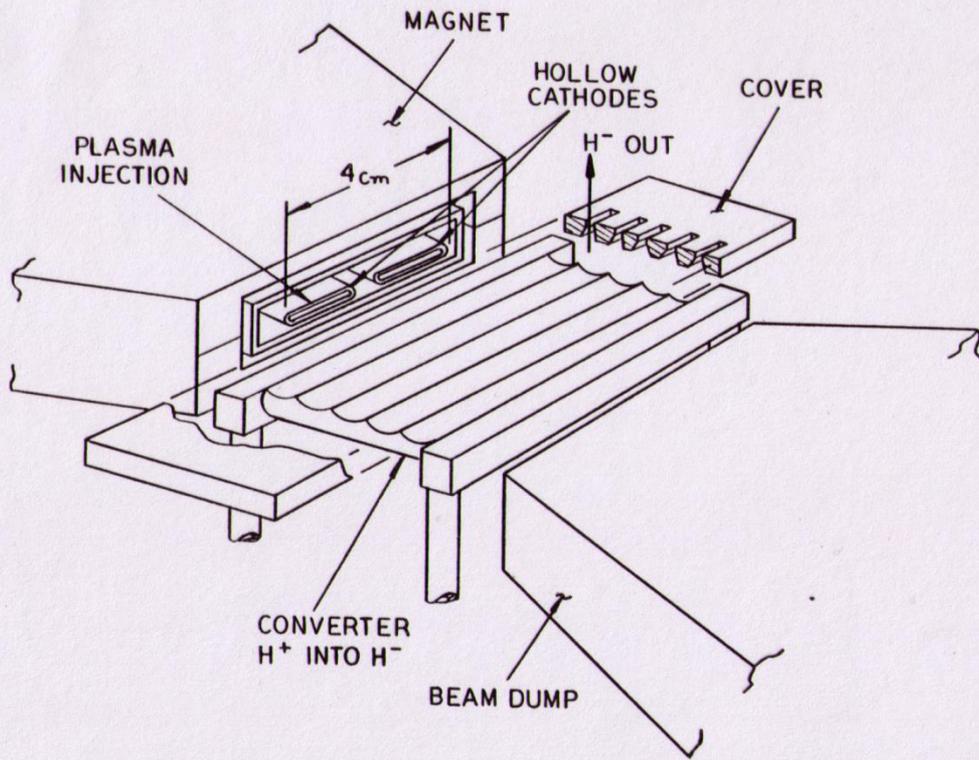
- **Hypersonic Scramjet: shoot e-beams to reduce stresses** or **Wind Tunnel to prevent air from liquefying**
- **Non-vacuum electron beam welding** With plasma windows, differentially pumped chambers and orifices, or thin walls, are replaced by a short high pressure arc, which also focuses the beams to overcome limitations, among which are low production rates due to required pumping time, limits on the size of target objects, and degradation of electron beams in foils or differentially pumped sections. **Technological breakthroughs potentials** (e.g., welding of double hull ships). Potential clients: ship builders, automotive.
- **Under water** (and other corrosive and hostile environments) **Electron Beam, Laser, & Ion Beam processes** with the plasma shield, in which plasma displaces fluids from (and engulfs) the work area, thus creating a "plasma shield" that isolates that area thermally and chemically (with noble gas plasma).
- **Electron Beam** material treatment.
- **Non-vacuum material modifications by ion implantation, and dry etching, or micro-fabrication** Presently performed only in vacuum, since ion beams at energies used in these applications are completely attenuated by foils and by long differentially pumped sections. Potentially very large yet unexplored market.
- **Electron beam melting** for manufacturing alloys is performed at a pressure of about 10^{-2} Torr. A major drawback of operating at this pressure range is the loss of elements with low vapor pressure. Consequently, it is desirable to raise the operating pressure to a higher level. Interested company.
- **Electron beam generation of photo-neutrons for the production of medical isotopes.** A 40 MeV electron beam strikes a W target. Resultant radiation can dislodge a neutron (via a giant resonance) to create a new element. One particular isotope is **Tc-99 (Technetium)**, which is presently used for 10 Million medical procedures in the US alone. Its half-life is only six hours, and it radiates enough energy to scintillate a scanner, but not enough to damage tissues. Presently, Tc-99 is made from Moly-100 in weapons-grade nuclear reactor, where a reactor neutron dislodges a Moly neutron to create a Moly-99, which subsequently decays to Tc-99. This process is expensive and it is monopolized. The presently pursued electron beam alternative is very limited, since the W target is in vacuum where poor cooling sets a lower limit on the electron beam spot. With a plasma window, the target can be in the air, sufficiently cooled to absorb an intense electron beam to generate photo-neutrons. A number of companies, which make medical accelerators, will be interested in plasma windows. Seems like a large commercial potential.
- **Windowless gas targets** (but with plasma windows) **for fast neutron radiography to detect nitrogen (weapons) and carbon (diamonds), as well as for other forms of neutron tomography and therapy (BNCT).** Some commercial potential.
- **Radioactive waste transmutation.** Project at Los Alamos: proton are accelerated to 2 GeV onto a heavy metal target in air. Resultant 2-8 MeV spallation neutrons reduce radioactive waste. Presently, windows limit proton output. **SNS** to be built.
- **Hardening of airplane wings and spacecraft parts with neutrons (or by implanting other ions)?**
- **Windows for high power lasers (especially high-pressure gas lasers).**

Flat Plasma Window at LCLS to separate samples studied area at a pressure of 10^{-4} Torr from the X-ray optics region at 1×10^{-10} Torr, since it's durable window that doesn't disturb the wavefront of the coherent X-ray beam from LCLS

Flat Plasma Arc Design



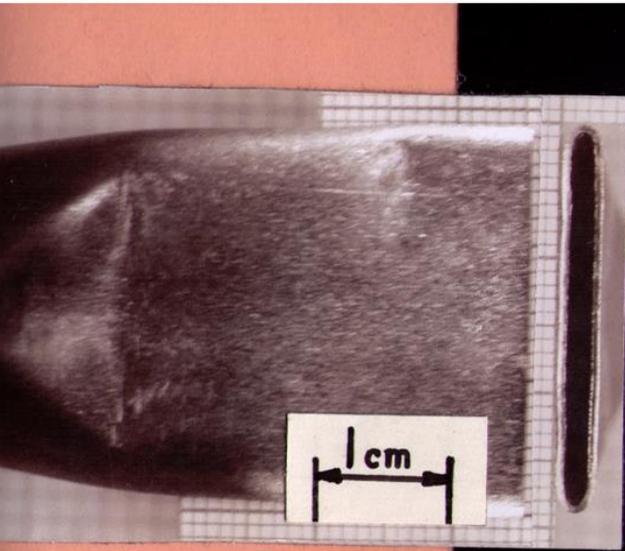
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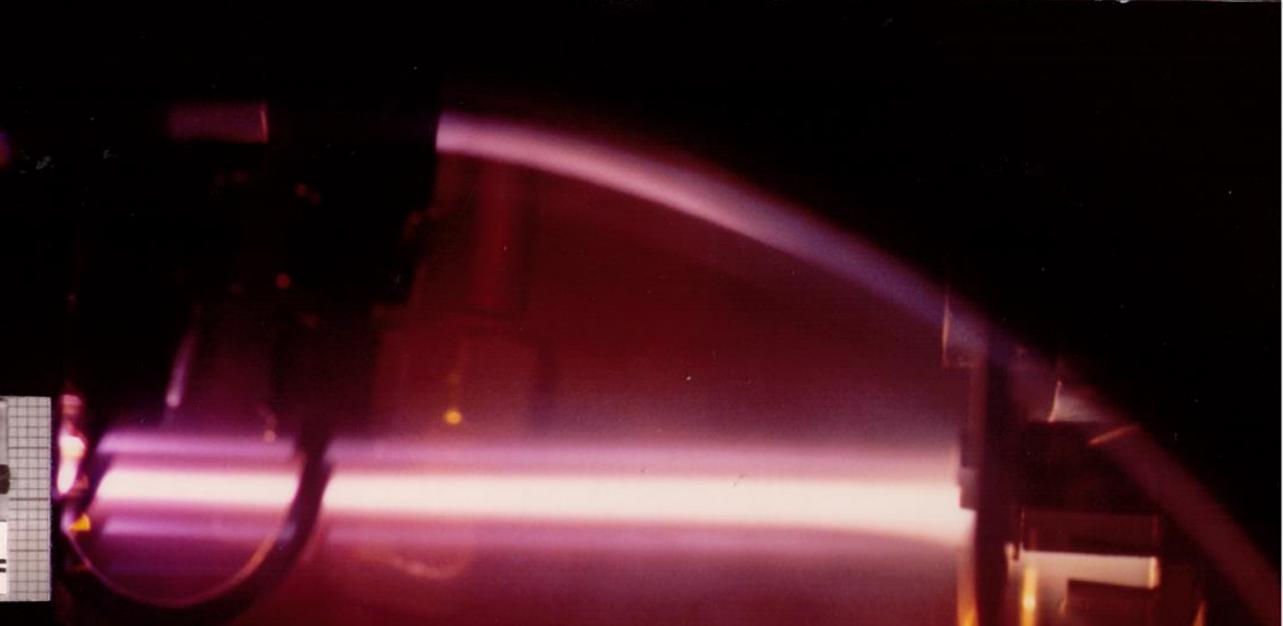
PERFORMANCE BNL HOLLOW CATHODE DISCHARGE SOURCE

H⁻ YIELD	0.5 A
EXTRACTED CURRENT DENSITY	100mA/cm²
EXTRACTOR VOLTAGE	7.5 KV
MODE OF OPERATION	STEADY STATE
HOLLOW CATHODE CURRENT	50 A
MAGNETIC FIELD	200-400G
CONVERTER CURRENT	8 A in H₂ MODE

Experimentally Achieved

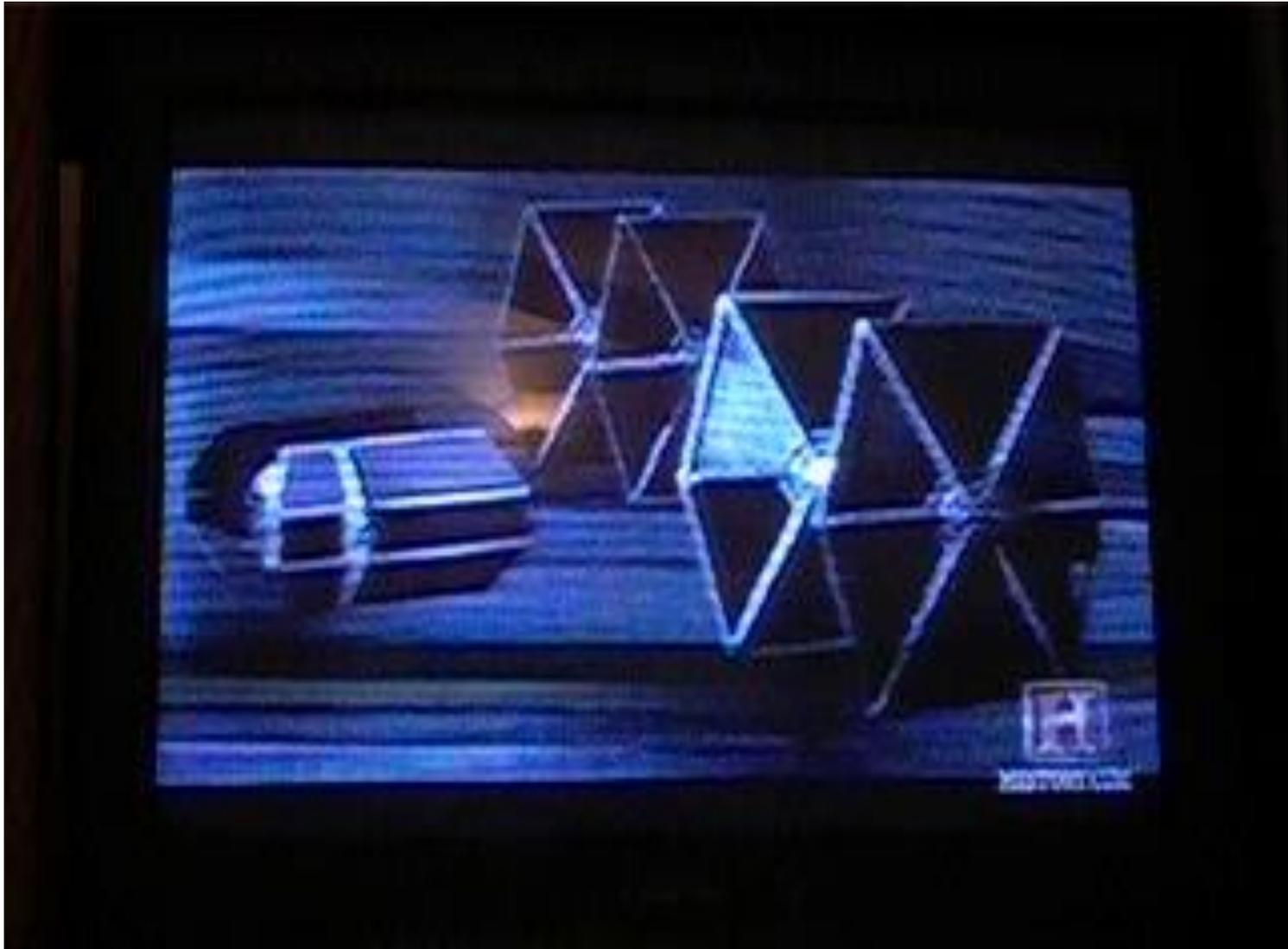


H₂



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