USPAS Course on Photocathode Physics

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Lecture 5
Ultra High Vacuum

Austin, TX January 16-20, 2011

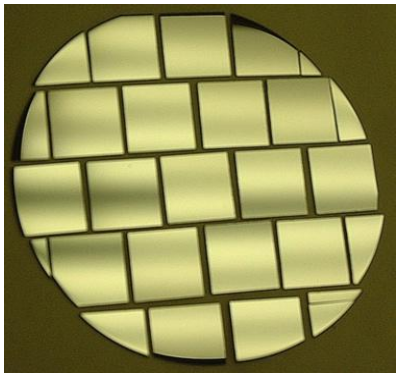
Lecture 5:

- Ultra High Vacuum: static and dynamic
- Ion Bombardment
- High Voltage: avoiding breakdown and field emission
- A clean photocathode
- An accelerator-friendly drive laser

Polarized Electron Source “Musts”

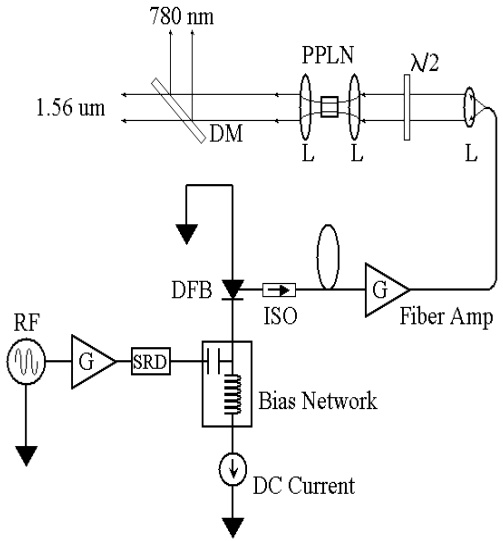
Good Photocathode

- High Polarization
- Many electrons/photon
- Fast response time
- Long lifetime



Good Laser

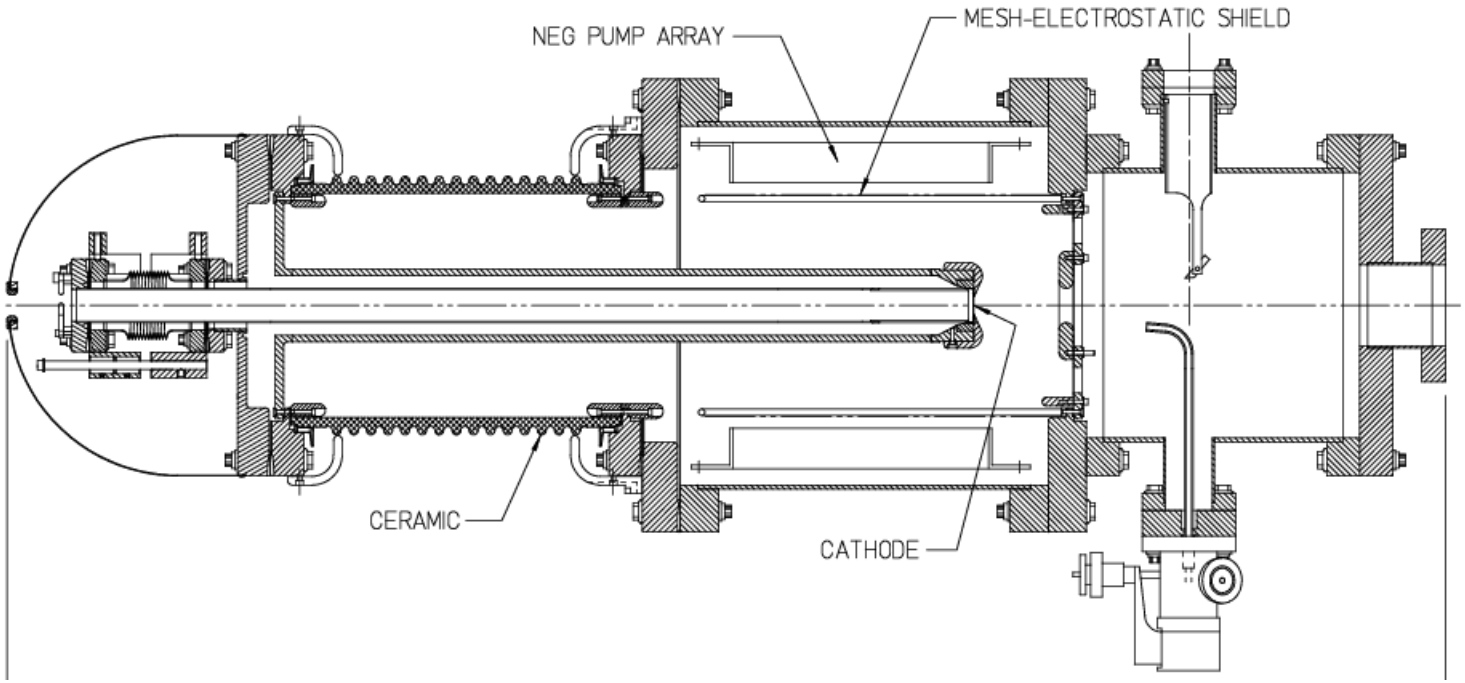
- “Headroom”
- Suitable pulse structure
- Low jitter



Good Electron Gun

- Ultrahigh vacuum
- No field emission
- Maintenance-free

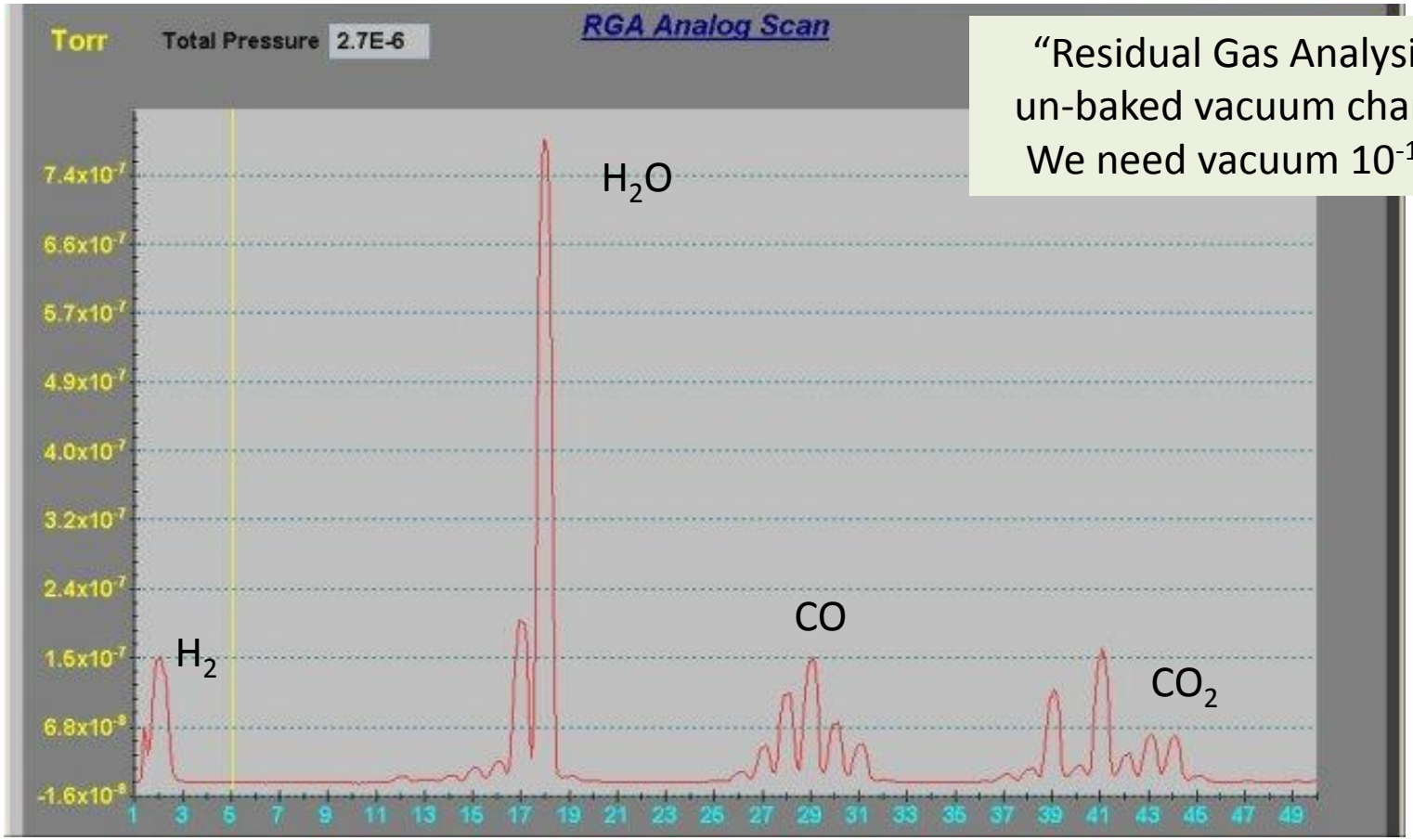
CEBAF Vent/Bake Polarized Electron Gun



- Simple photogun with good pumping near photocathode
- Polarized beam at average current ~ 100 uA with 1/e ***charge lifetime*** about 100 C (amount of charge that can be extracted before QE falls to 1/e of initial value)
- Want lifetime infinite, but limited by ***ion bombardment***

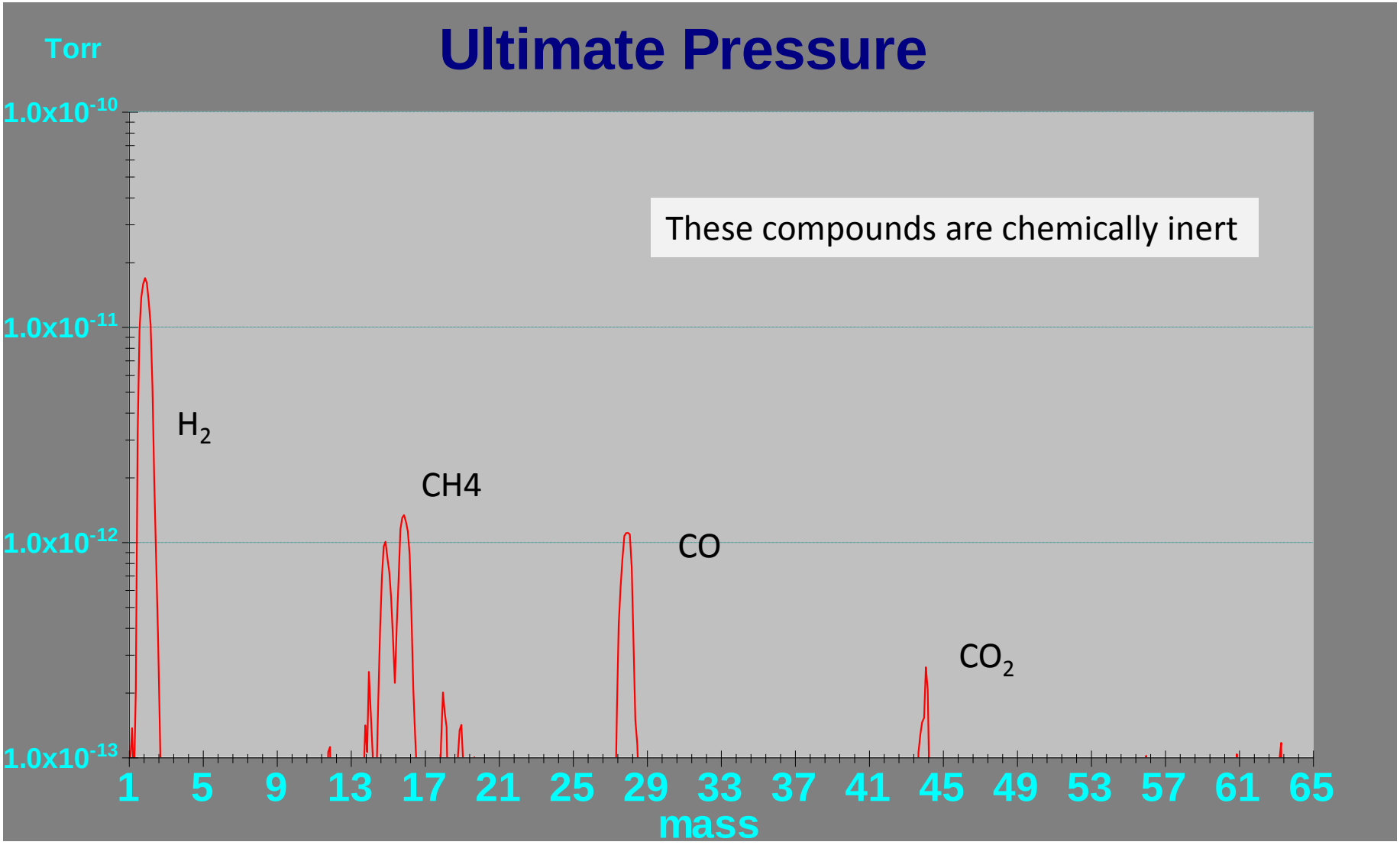
What Does “Bake” Mean?

It means get rid of water and other chemically reactive substances from inside the photogun…
Heat the vacuum chamber at 250C for 30 hours



“Residual Gas Analysis” of un-baked vacuum chamber:
We need vacuum 10^{-11}Torr

Post-Bakeout



Imperfect Vacuum = Finite Lifetime

Want good QE? Need to keep contaminants off the photocathode surface

Gas and Surface Parameters at XHV

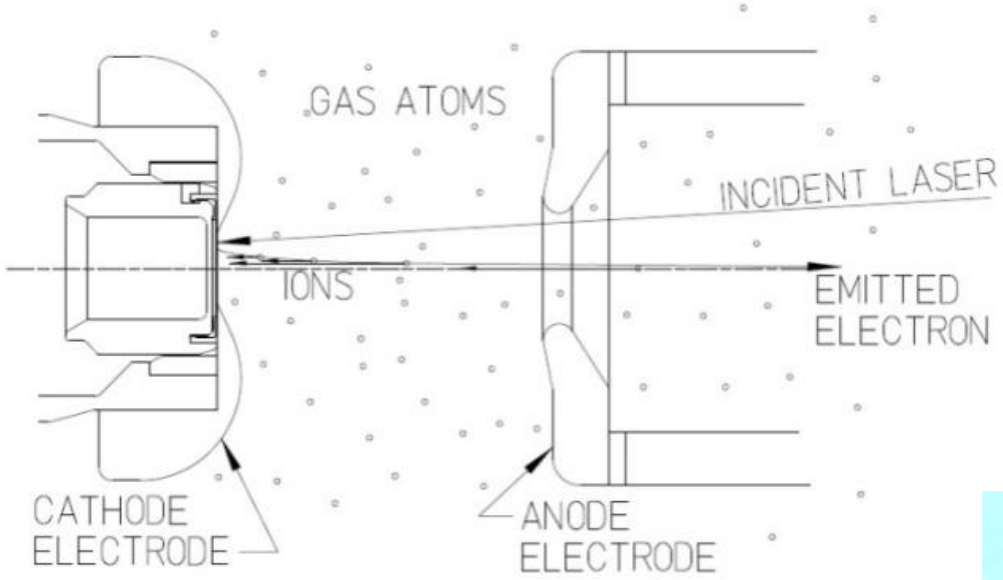
Pressure (Pa)	Molecular Density (@298K)	Molecular Flux at 298K (molec.cm^{-2}s^{-1}	Molecular Mean Free Path λ* (N_2 at 295K)	Monolayer Time**
10^{-10}	2.5 x10^4 cm^{-3}	2.9x 10^8	3.4 x 10^4 km	44 days
10^{-13}	25 cm^{-3}	2.9 10^5	3.4 x 10^7 km	120 yrs
10^{-17} Interstellar space	0.25 m^{-3}	29	2.3 x 10^3 a.u.	1.2 x 10^6 yrs

About where we are at today

* Mean free path for electrons, $\lambda e = 4\sqrt{2}\lambda$ and for ions $\lambda i = \sqrt{\lambda}$.

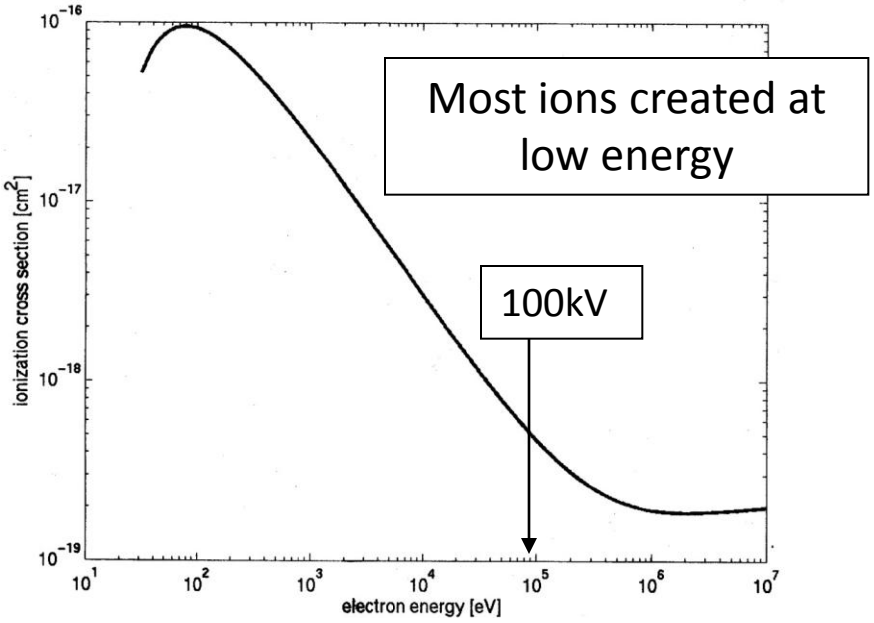
** Assuming 10^{15} sites per cm^2 and a sticking probability of 0.5

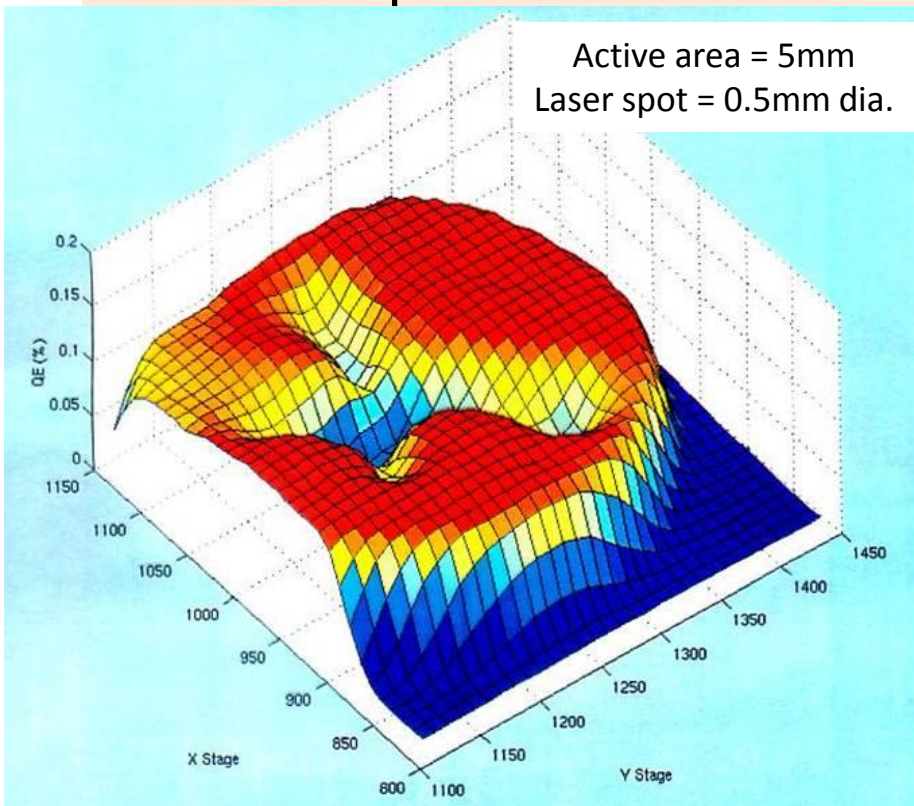
Imperfect Vacuum = Finite Lifetime



- What about while you run beam?
- Ion bombardment – notice characteristic “trench” from laser spot to electrostatic center of photocathode

Ionization cross section for H_2





Improve Vacuum and Improve Lifetime

$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{Q}{S} = \frac{q\ A}{S}$$

Q= gas load, q= outgassing rate, A = surface area, S = pump speed

Make Gas Load small and Pump Speed large

Gas Load inside a polarized photogun comes from:

- leaks (real and virtual)
- outgassing from the vacuum chamber walls and things you put inside the gun
- from the accelerator beamline

Limited selection of pumps for UHV and XHV

The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum

Vacuums are nothings. We only mention them to let them know we know they're there.

Middle school student's answer on a science test

Vacuum Definition

- There are 2.5×10^{19} molecules of air in 1 cm^3 at sea level and 0°C
  - $PV=nRT$, $N_A=6.02 \times 10^{23}$, $n=(N_A/R)(P/T)$
- Any reduction of this density of gas is referred to as vacuum
- Nature doesn't abhor a vacuum
  - Intergalactic space vacuum: ~1e-16 Torr

Scales to measure vacuum

Atmospheric pressure at sea level and 0°C

- 760 Torr
- 1013 mBar
- 101,330 Pa
- 14.7 PSI
- 29.92 inches of mercury
- 33.79 feet of water

Torr (USA)

mBar (Europe)

Pa (SI - Asia)

Vacuum regimes

- Low, Medium Vacuum (>10^{-3} Torr)
  - Viscous flow
    - interactions between particles are significant
  - Mean free path less than 1 mm
- High, Very High Vacuum (10^{-3} to 10^{-9} Torr)
  - Transition region
- Ultra High Vacuum (10^{-9} - 10^{-12} Torr)
  - Molecular flow
    - interactions between particles are negligible
    - interactions primarily with chamber walls
  - Mean free path 100-10,000 km
- Extreme High (<10^{-12} Torr)
  - Molecular flow
  - Mean free path >100,000km

Vacuum Life is complicated: there are different pumps and gauges for each of these regimes

We want to go here

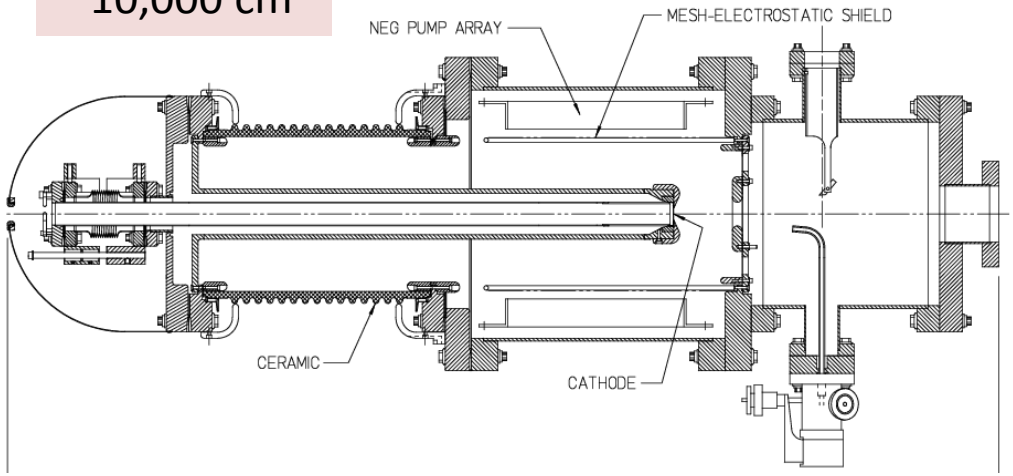
Reducing the Gas Load

$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{Q}{S} = \frac{q\,A}{S}$$

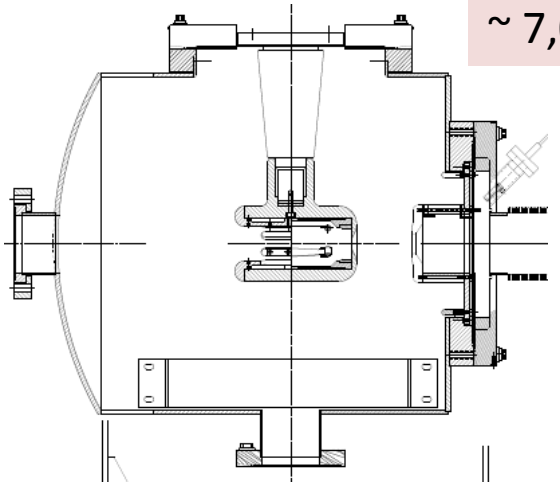
$$Torr = \frac{\frac{Torr \times L}{s \times cm^2}\ cm^2}{\frac{L}{s}}$$

Q= gas load, q= outgassing rate, A = surface area, S = pump speed

~ 10,000 cm^2



~ 7,000 cm^2



Which gun will have best pressure?

Reduce the size of the vacuum chamber, and move as many components to “preparation” chamber

Reducing the Gas Load

$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{Q}{S} = \frac{q\,A}{S}$$

$$Torr = \frac{\frac{Torr \times L}{s \times cm^2}\ cm^2}{\frac{L}{s}}$$

Q= gas load, q= outgassing rate, A = surface area, S = pump speed

Outgassing Rate:

- A large reservoir of hydrogen within the vacuum chamber walls and internal components
- First, limited by diffusion
- Then, by recombination

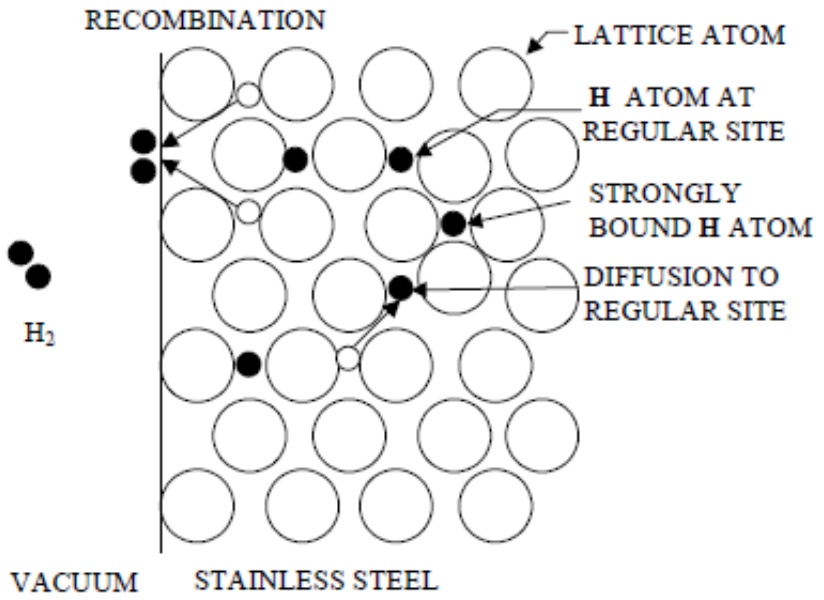


Fig. 3. Schematic diagram of a recombination process at the SS surface.

Yuichi Ishikawa, Vincenc Nemanic, Vacuum 69 (2003) 501–512

Talk about leaks on Friday

Outgassing Rate

- Reduce Surface Area
- Choice of materials (304SS, 316LN, Al, BeCu, etc.)
- Choice of heat treatment
- Coatings

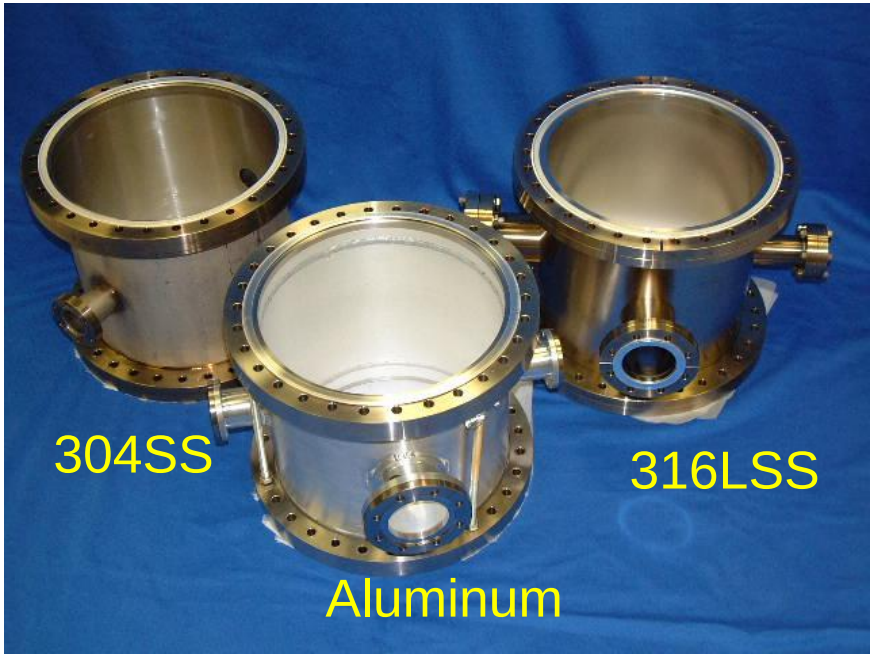
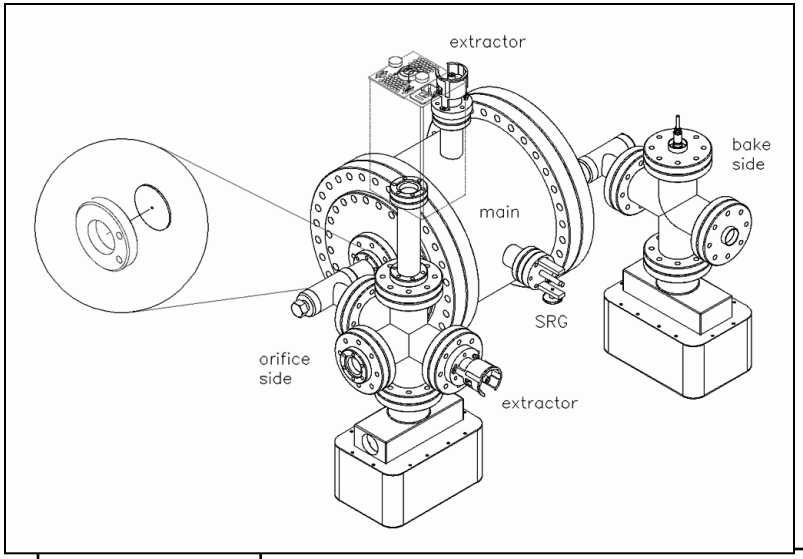


Table 1
Some published data of outgassing rates q_{out} of stainless steel chamber walls after different outgassing procedures

Preprocessing			Processing in situ					
T (°C)	t_0 (h)	F_0	T (°C)	t_0 (h)	F_0	ΣF_0	q_{out} (mbar l s^{-1} cm^{-2})	Refs.
950	2	39.6	150	168	0.12	39.7	2.5×10^{-14}	
400	38 (air)	9	150	168	0.12	9.1	1.1×10^{-14}	[15]
			150	24[a]	0.03	0.03	3×10^{-12}	
390	100 (air)	3.3	150	24[a]	0.03	3.33	5×10^{-15}	[14]
			200	48	0.1	0.1	4×10^{-12}	
950	2	43	200	48	0.1	43.1	4×10^{-13}	[53]
			250	72	0.46	0.46	3.8×10^{-12}	
400	72	7.7	250	72	0.46	8.16	4×10^{-15}	
550	72	46	250	72	0.46	46.5	1×10^{-15}	[20]
			404	1.4	70	70	3×10^{-16}	[22]
			200	72	3	3	1×10^{-13}	[23]

Yuichi Ishikawa, Vincenc Nemanic, Vacuum 69 (2003) 501–512



Outgassing Rate

- Orifice and Rate of Rise Methods
- Studied 304, 316L and 6061 Al
- Degreasing and solvent cleaning vs EP and vacuum firing

	Preprocessing				In situ bake parameters		Outgassing Rate (Torr·L/s·cm^2)	
Chamber	t(h)	T(°C)	EP	Surface roughness	t(h)	T(°C)	Orifice Method	Rate of Rise Method
Old 304			no	3.7 μm	400	250	9.7×10^{-13}	1×10^{-12}
New 304			no	3.7 μm	180	250	1.9×10^{-12}	2.5×10^{-12}
EP 304	4	900	yes	2.1 μm	30 then 90	150 250		8.9×10^{-13}

Extremely low values (e.g., 10^{-14} to 10^{-15}) reported in literature elude us….

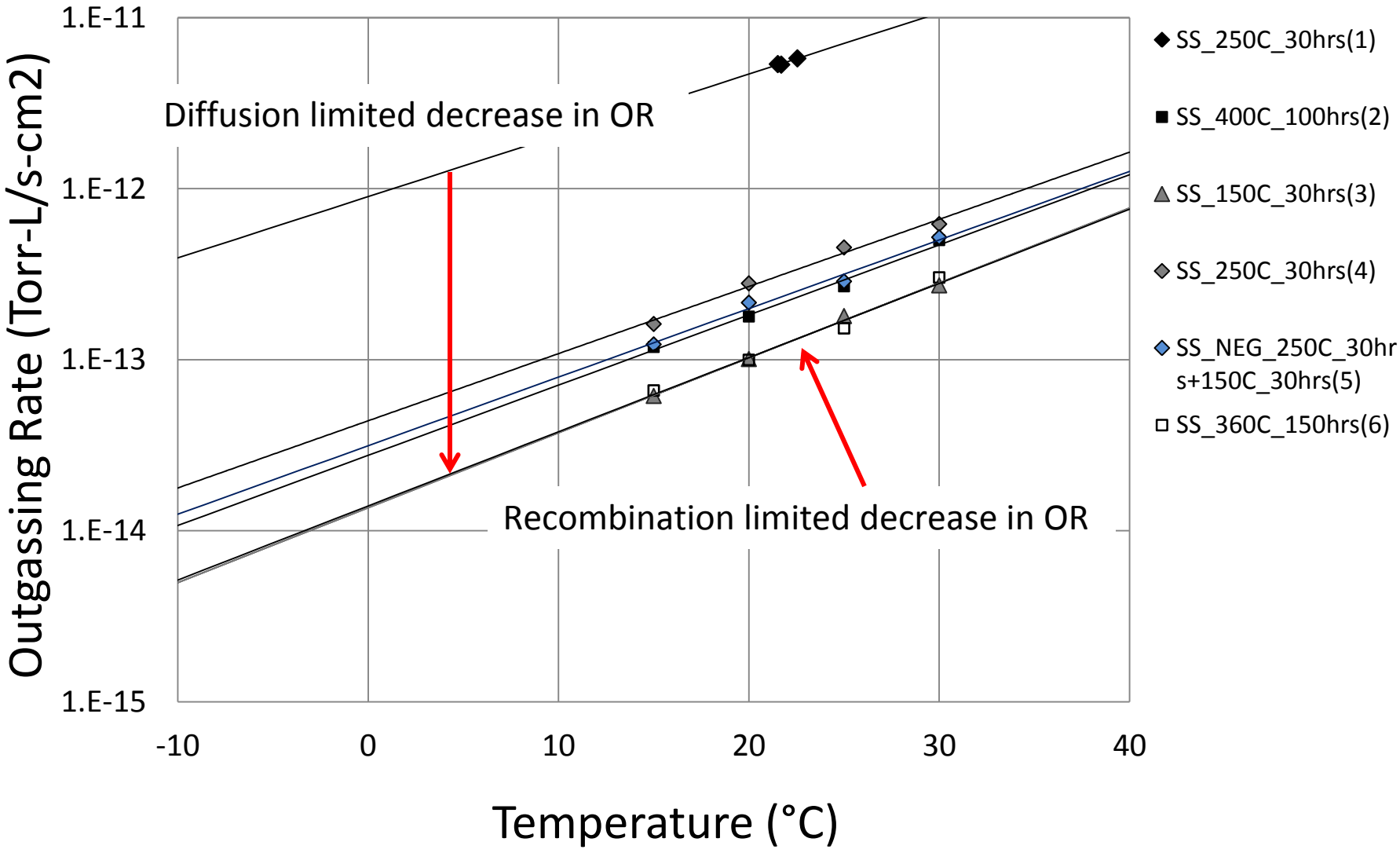
"Characterization of the CEBAF 100 kV DC GaAs Photoelectron Gun Vacuum System," M.L. Stutzman, et al., Nucl. Instrum. Meth. A, 574 (2007) p. 213-220

Then we started Baking at 400C…LIGO technique….

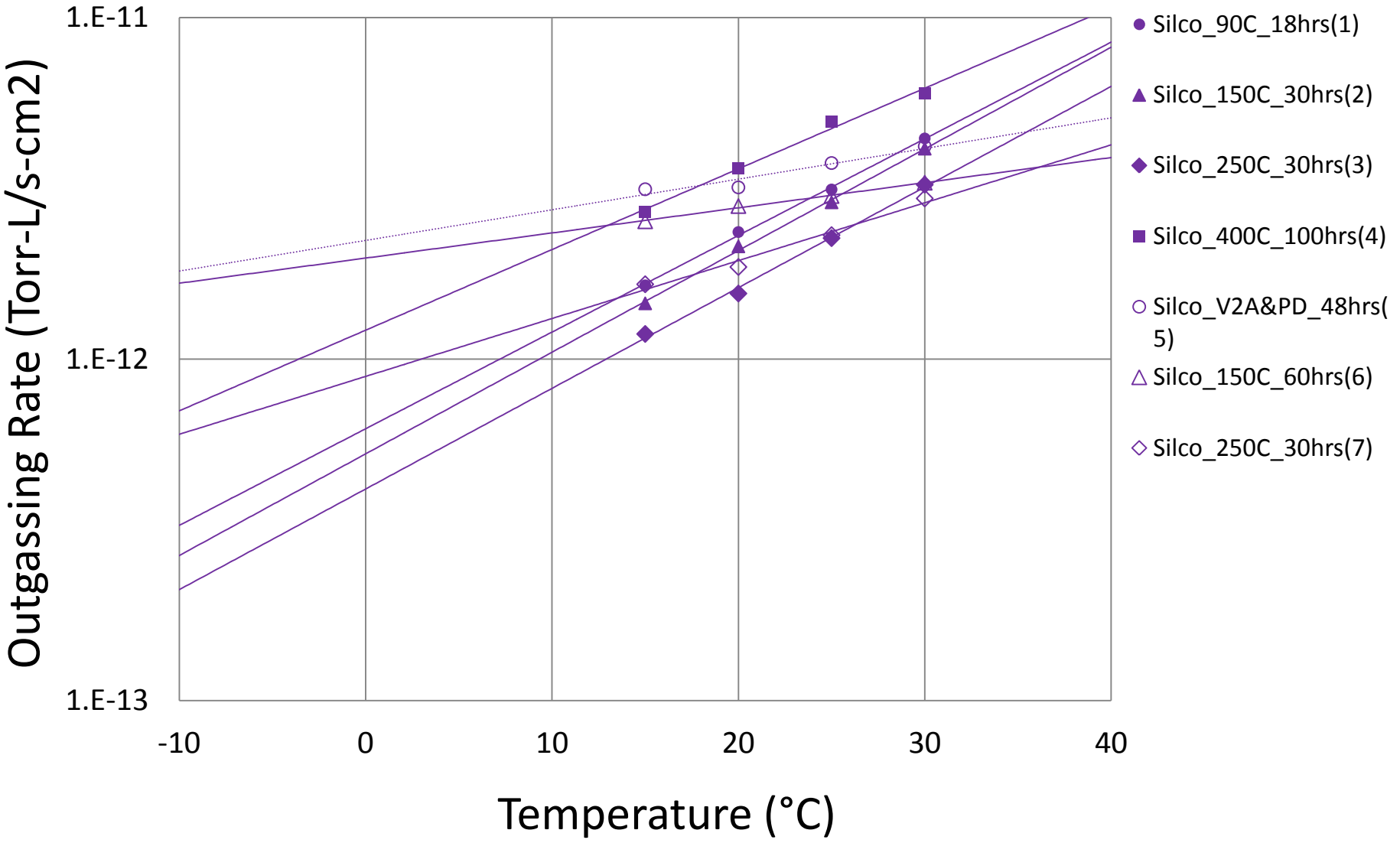
Spinning rotor gauge

- As much “thin-wall” material as possible
- 316LN (hard knife edges)
- Manufactured and electropolished by NorCal (EP was not necessary)
- 400C bakeout for 9 days, under vacuum
- Pumped by oil-free turbo, then added ion pump, while monitoring “effluent” with RGA
- At 9th day, vacuum still improving by ~15% per 24 hours
- RGA shows H2, methane, CO and HCl from electropolishing
- Outgassing rate = 1x10^{-13} Torr·L/s·cm^2
- Another chamber, not EP-ed, provided outgassing rate 1x10^{-14} Torr·L/s·cm^2
- When filled with NEGs and small ion pump, extractor gauge 2x10^{-12} Torr (raw value), our lowest value….

Bare SS 304 chamber

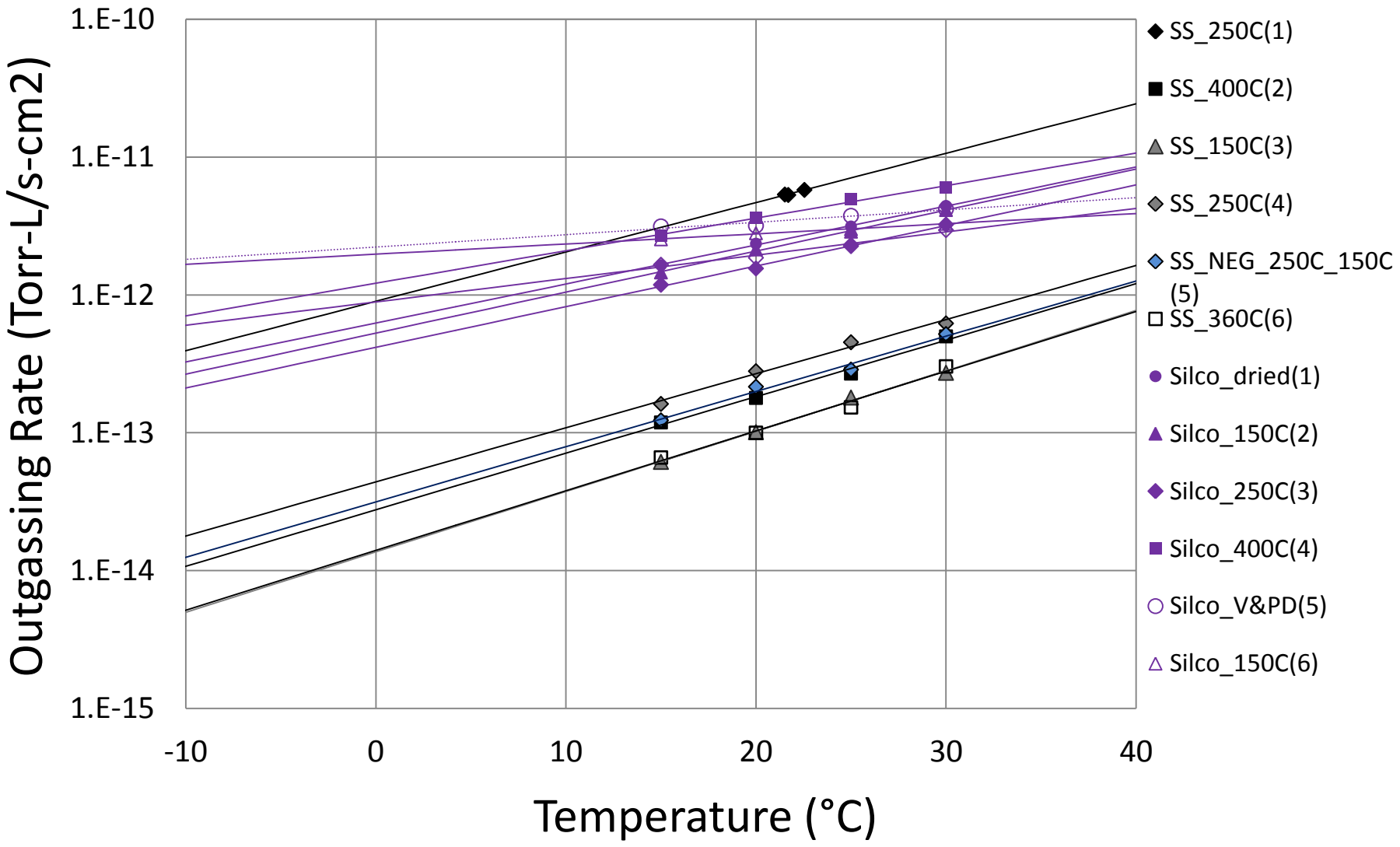


Silco Coated Chamber: OR vs. Temp



Amorphous silicon coating: hydrophobic and likely a good H2 barrier

Bare 304 SS and Silco 304 SS



Now, coat bare chamber with Silco following 400C bakeout

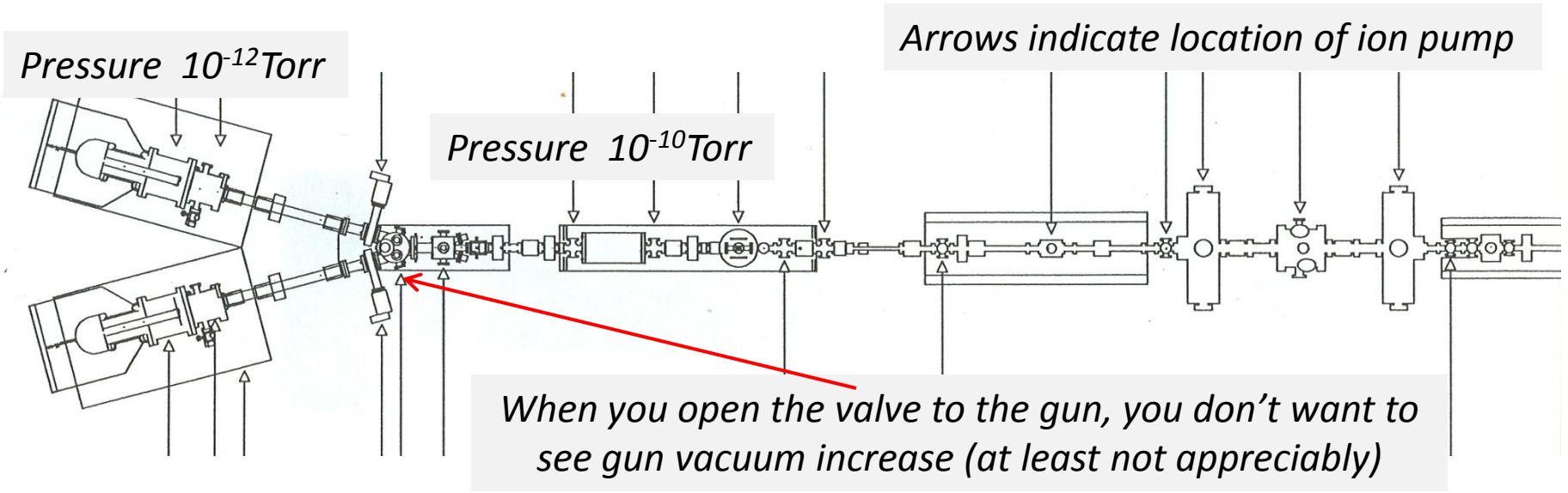
Then only low temp bakeout required

Minimize the Impact of the Beamline

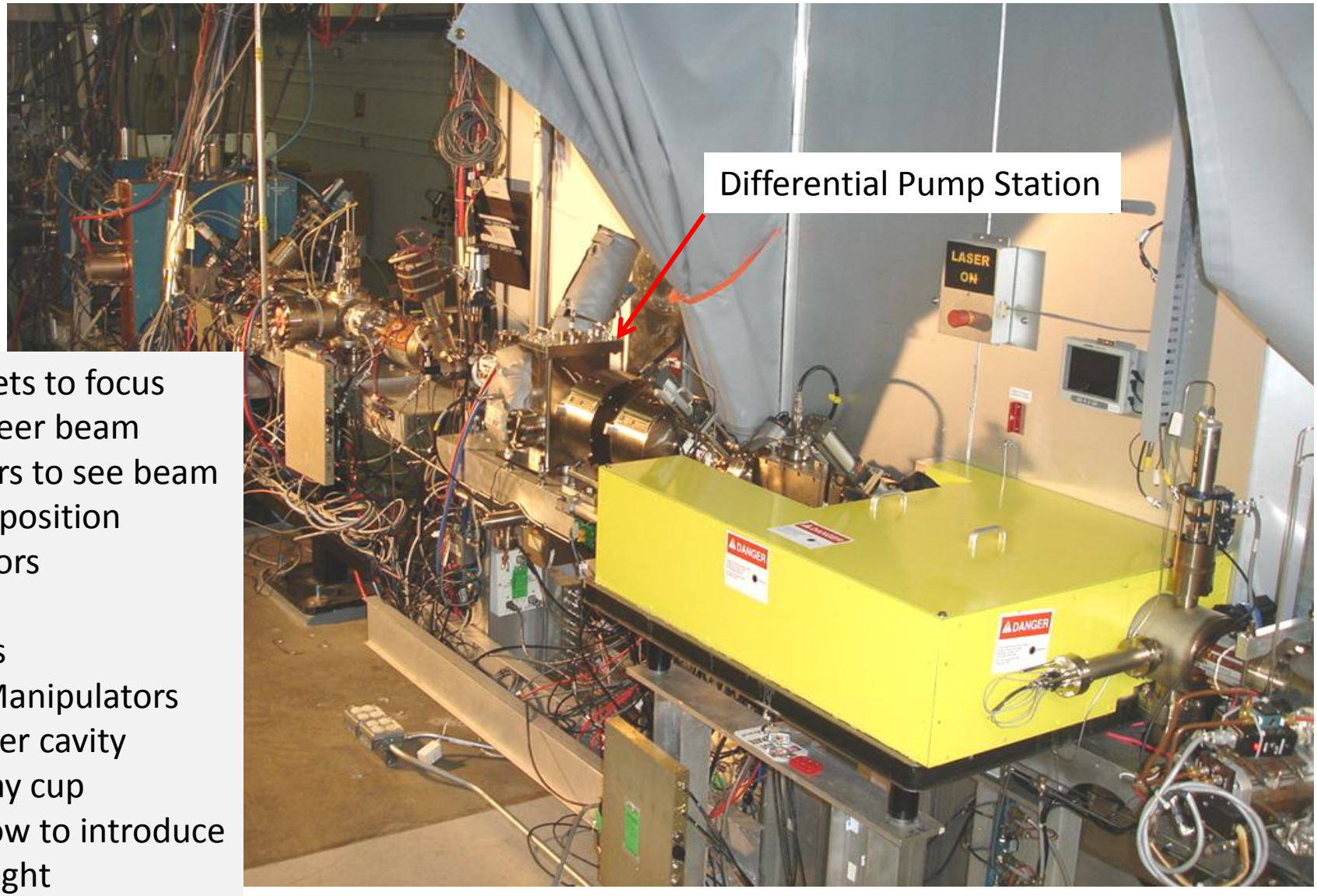
$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{q\ A + Q_{bl}}{S}$$

Beamline vacuum not nearly as good as the gun vacuum

- Bake the beamline
- Add as much distributed pumping as you can
- Employ conductance limitations



Complicated Beamline



- Magnets to focus and steer beam
- Viewers to see beam
- Beam position monitors
- Valves
- Pumps
- Spin Manipulators
- Buncher cavity
- Faraday cup
- Window to introduce laser light
- Emittance filter

Conductance

Definitions

- Resistance

$$P_1 - P_2 = Z \cdot Q$$

- Conductance

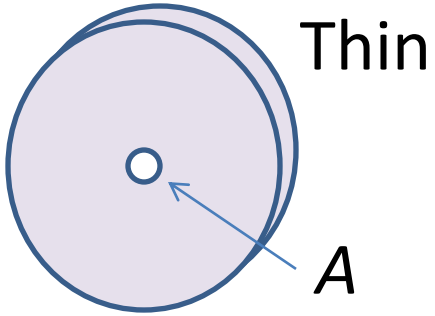
$$C = \frac{Q}{P_1 - P_2}$$

- C, S, same units, but
  not the same quantity

Conductance

$$C = \frac{1}{4}\, v \cdot A$$

$$C\left({}^{L}/_{s}\right) = 11.6 \cdot A(cm^2)$$



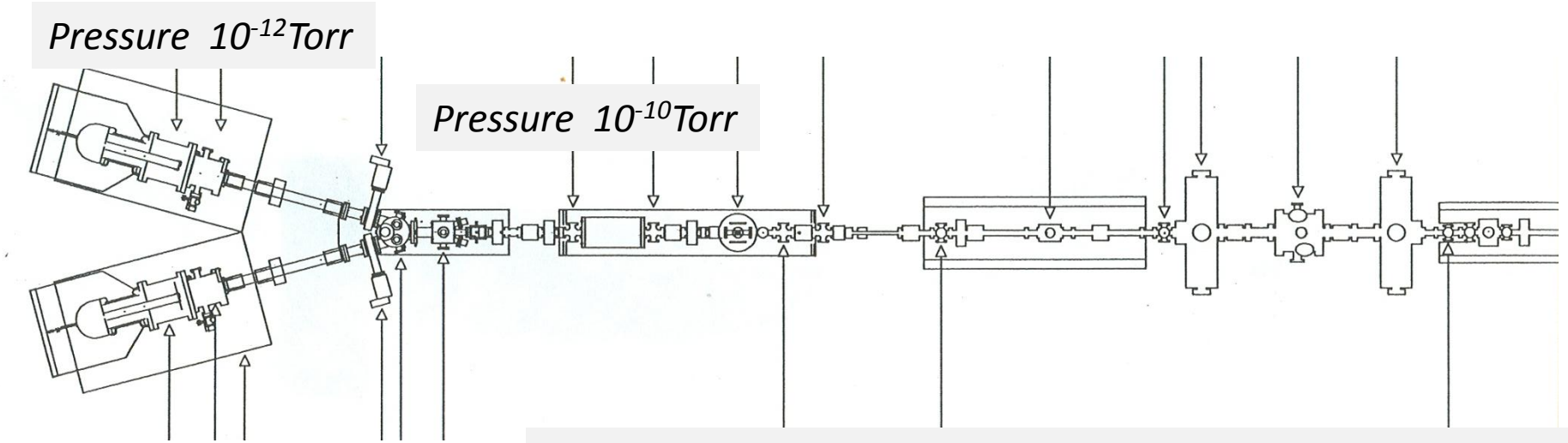
$$C = \frac{\pi}{12} v \frac{d^3}{L}$$

$$C\left({}^{L}/_{s}\right) = 12.1 \frac{d^3}{L} \quad (d \text{ and } L \text{ in } cm)$$

What about the Beamline Vacuum?

$$C = \frac{Q}{P_1 - P_2} \qquad P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{q\ A + Q_{bl}}{S}$$

$$C\ \left(^{L}/_{s}\right) = 12.1\frac{d^3}{L}\ \ (d\ and\ L\ in\ cm)$$



HW: Estimate the pressure rise inside gun when valve opened

Increasing Pump Speed

$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{Q}{S} = \frac{q\ A}{S} \qquad Torr = \frac{\frac{Torr \times L}{s \times cm^2}\ cm^2}{\frac{L}{s}}$$

Vacuum dominated by hydrogen and small amounts of methane, CO, CO2 and inert gasses like He and Ar

Your Pump Choices

- Ion Pump for methane and inert gas
- Non-evaporable getter pump (NEG) for the hydrogen, CO, CO2
- Cryopump? Needs to be evaluated

These are all Capture Pumps: We turn gas into a solid

Ion Pumps

Ion pumps are electro-physical vacuum pumps and remove gases from their environment by turning them into solid materials.

Step 1:
Create a high magnetic field

Step 2:
Generate a cloud of electrons (plasma)

Step 3:
Ionize gas molocules

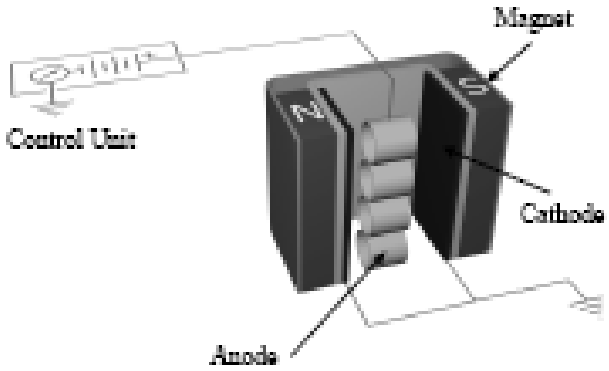
Step 4:
Capture gas ions

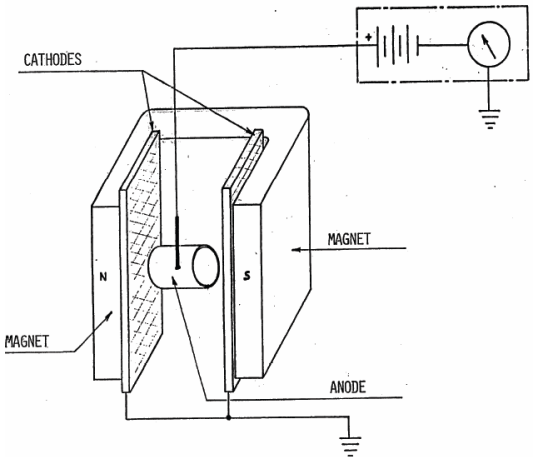
Step 2: Generate a plasma
High voltage is applied to the element assembly after rough pumping. Electrons are pulled into the anode tube assembly and generate a cloud of spinning electrons, commonly referred to as a plasma, and are trapped by the high magnetic field.

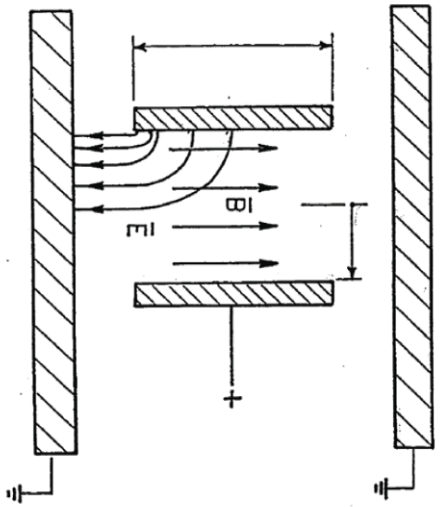
Previous Step Next Step

Gamma Vacuum http://www.gammavacuum.com/operation.asp

Ion Pumps







Ion Pump Fun Facts

- Electrons leave anode and get trapped inside cylinder (i.e., Penning cell) by B field and form plasma. For ion pump operating properly, electron production is not field emission. What is it?
- Size of the ion pump depends on how many Penning cells are used
- Diode ion pump, Differential ion pump, Triode ion pump….all this refers to the cathode/anode material and geometry

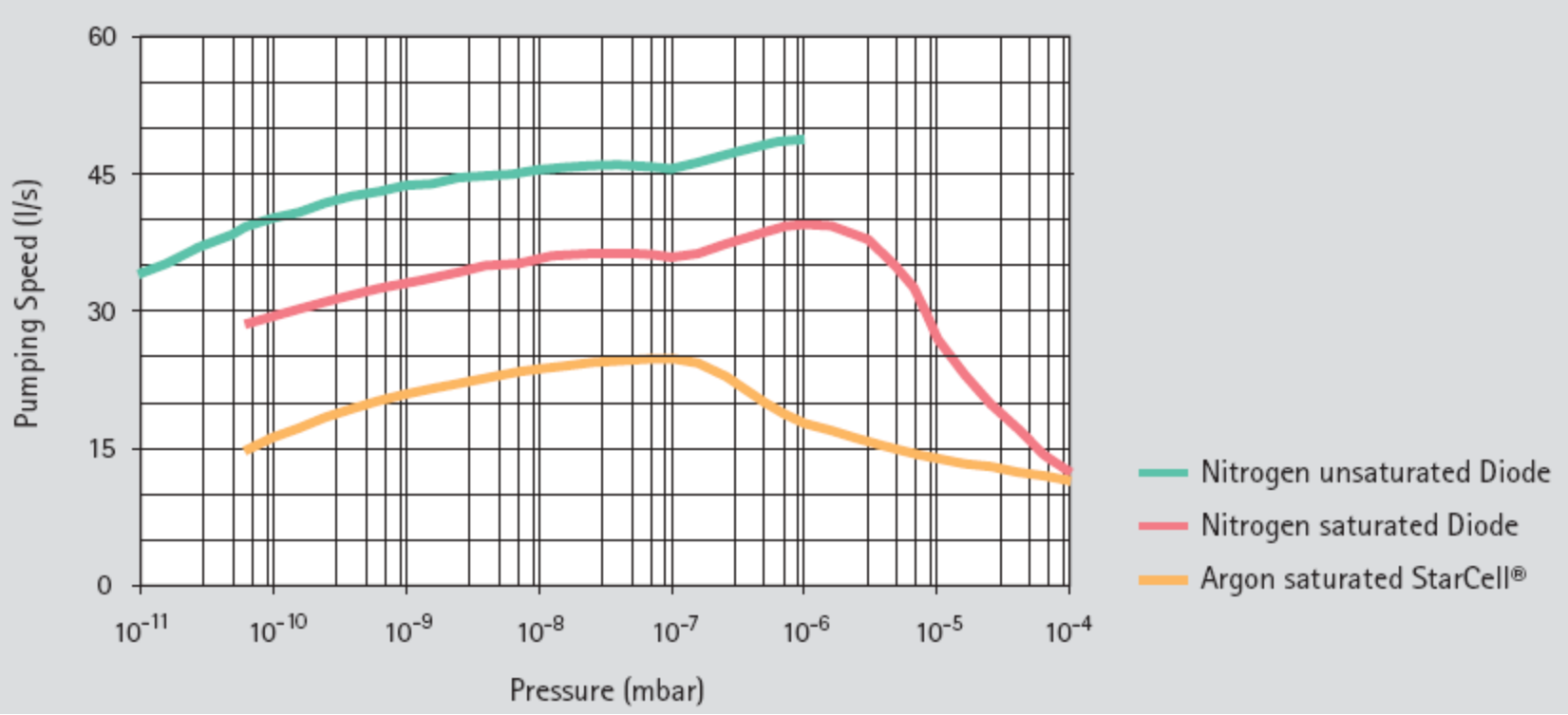
Types of sputter ion pumps

- Diode – both cathode plates made of titanium, highest hydrogen pumping speed
- Differential (Noble Diode) – one titanium plate, one tantalum plate: a compromise for hydrogen pumping speed with limited argon stability
- Triode/Starcell - good hydrogen pumping speed, also pumps argon well. Good choice for pumping down from higher pressures often.

Sputter ion pump characteristics

- Pumping speed - is sensitive to gas species, inlet size, pressure, and history of pump
- Starting pressure - ion pumps must be roughed to 20 milliTorr or less before starting (should be more like 10^{-6} Torr)
- Capacity - sputter ion pumps are gas capture type pumps and do have a limited capacity
- Advantages
  - Ultra clean, quiet, high pumping speed for water and hydrogen
  - Essential to maintain 10^{-10} Torr vacuum in accelerator beam lines
- Disadvantages
  - Gas species sensitive, limited capacity

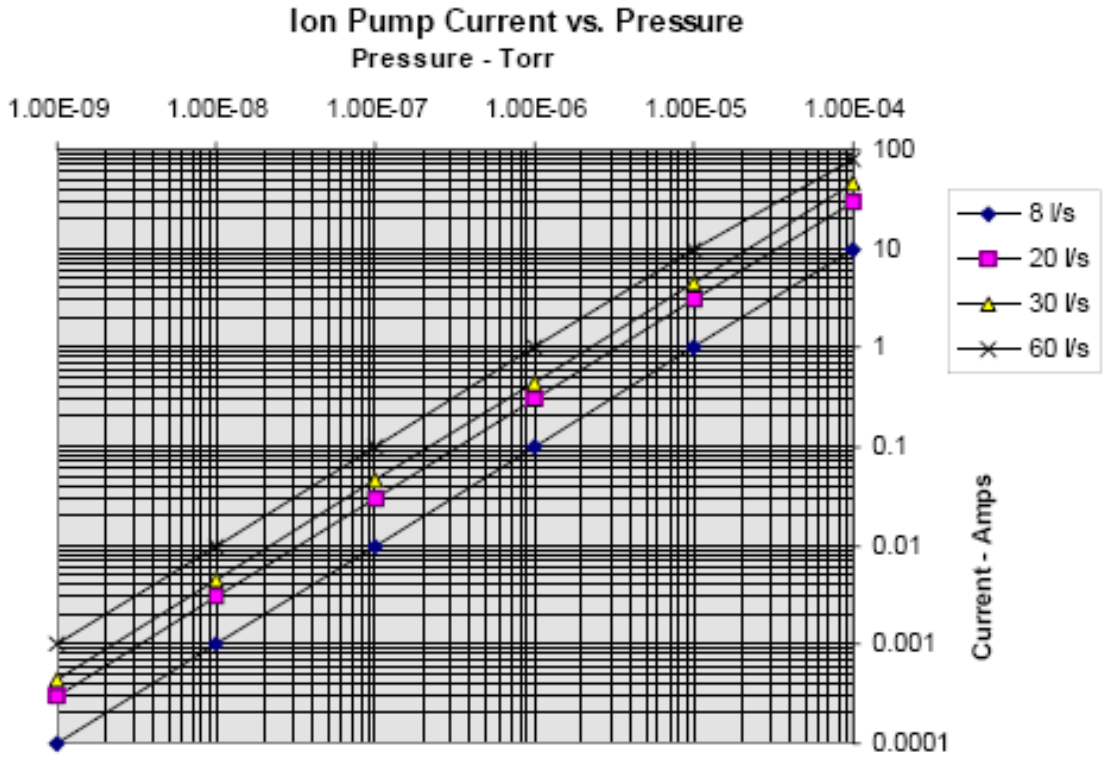
Ion Pump Speed falls at lower pressure.... but by how much? do they Turn OFF at low pressure?



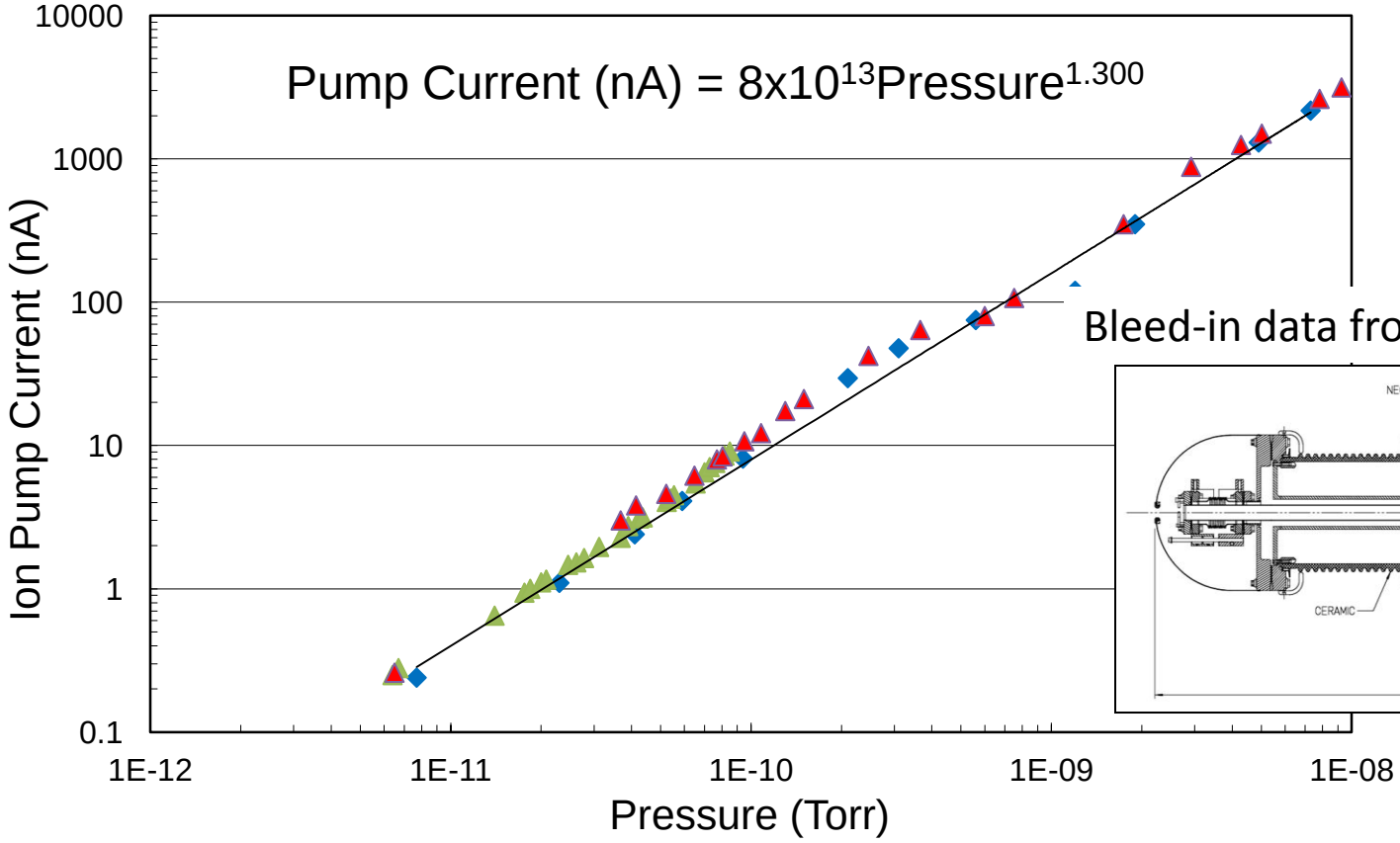
Typical plot from a vendor….mostly, they don't provide much info re: UHV, XHV

Ion Pump as Pressure Gauge

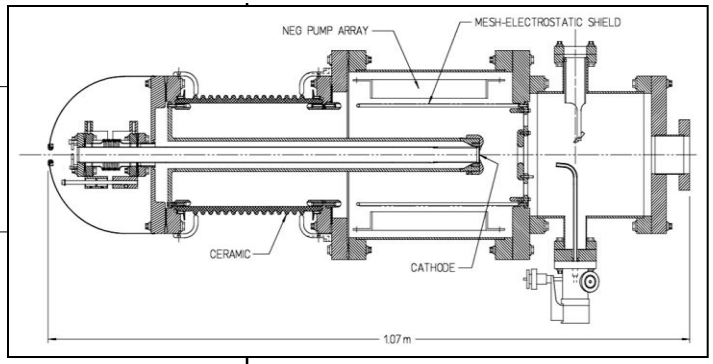
$$P = kI^n \; where \; n \; varies \; from \sim 1.05 \; to \; 1.3$$



Do Ion Pumps Limit Ultimate Pressure?



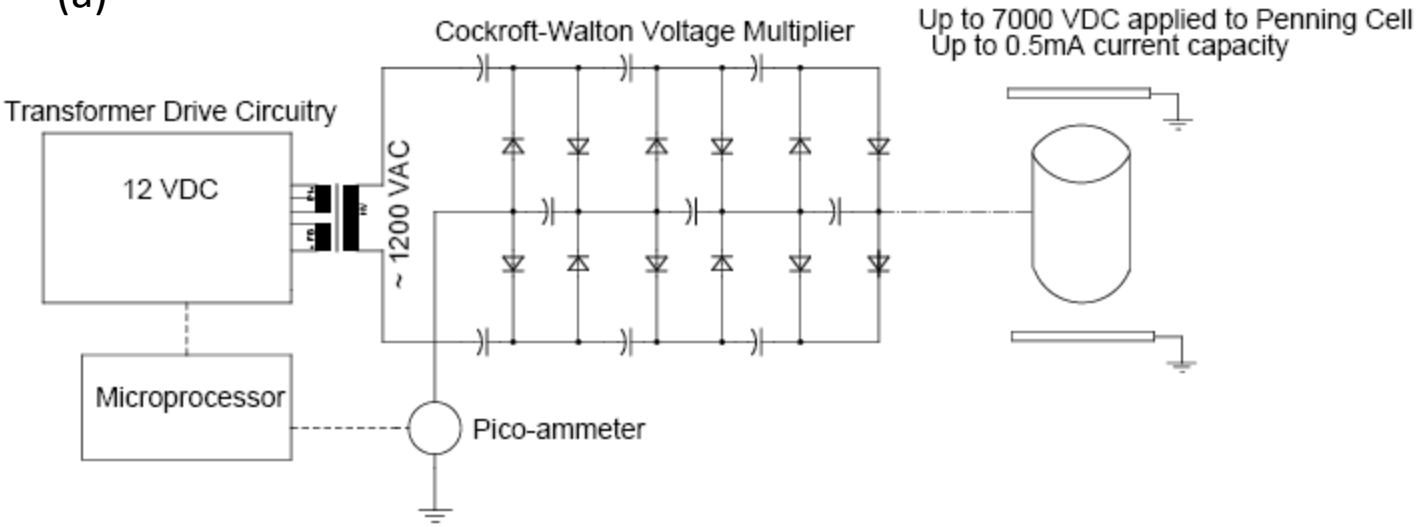
Bleed-in data from vent-bake guns



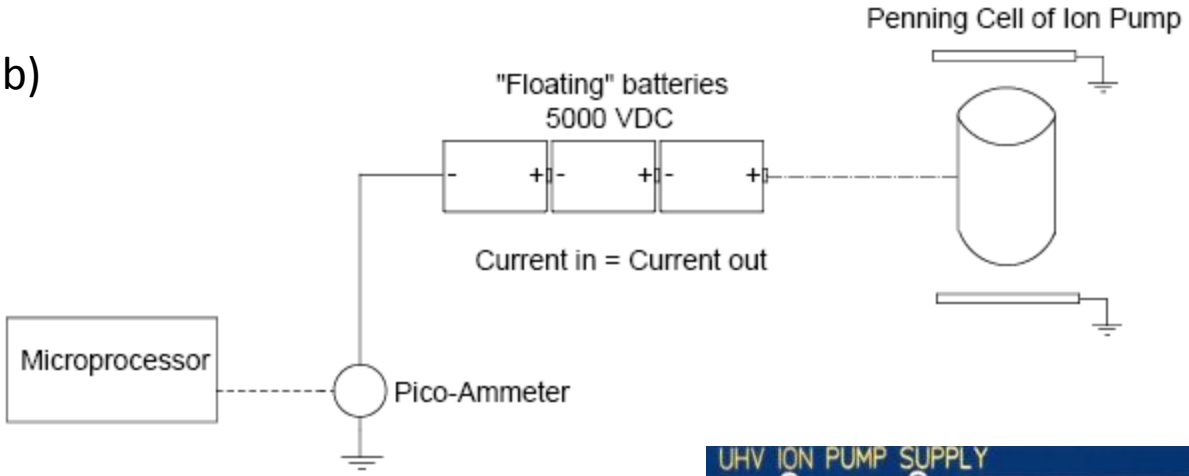
- Measure ion pump current using sensitive ammeter…
- Ion pump current <1nA at gun HV chamber...
- Does this mean ion pumps operate at -12Torr range, or are they OFF?

Hansknecht UHV Ion Pump Power Supply

(a)



(b)



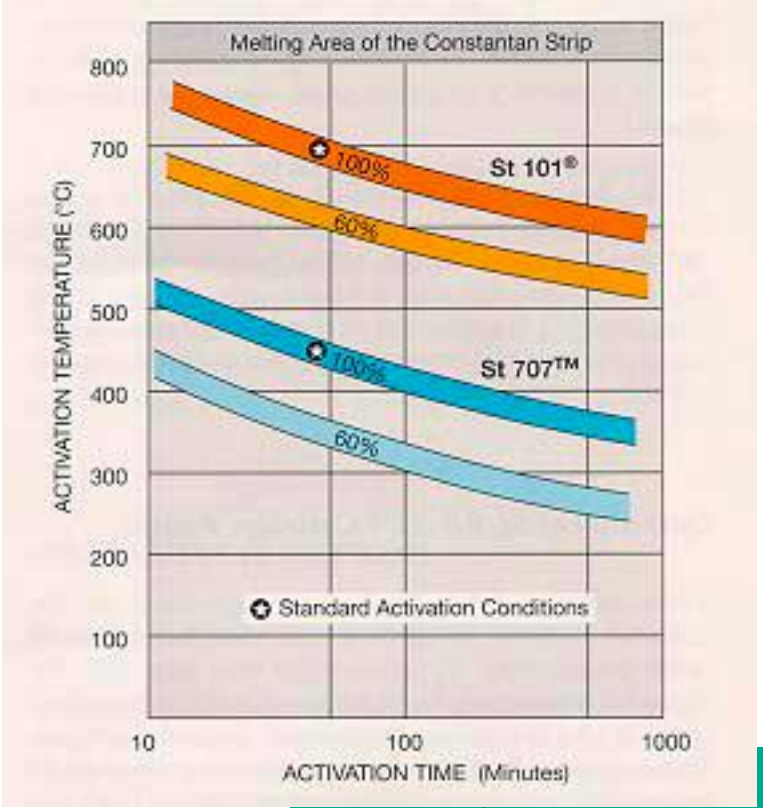
Commercial sputter ion pumps come in a wide variety of pumping speeds

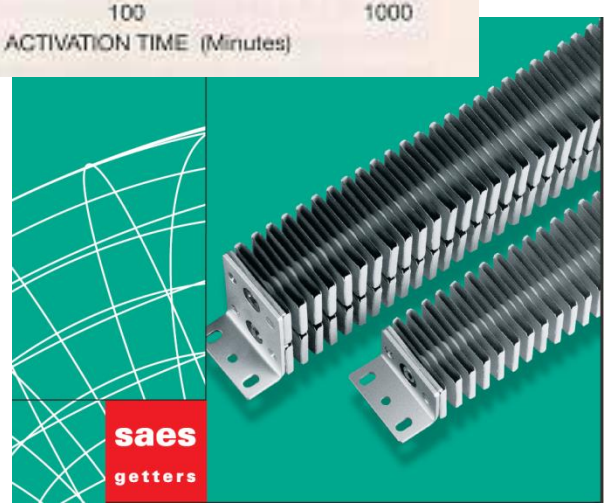
Non-evaporable getters (NEGs)
a revolutionary accelerator technology

- Huge hydrogen pump speed
- Hydrogen reversibly pumped (i.e., it comes back out at activation, i.e., when you heat them)
- Gases like CO, CO_2, O_2 and N_2 diffuse into the interior of the getter material. High temperature activation promotes further diffusion into the material (these gasses are not reversibly pumped)
- Noble gases are not pumped at all (He, Ne, Ar, Kr, Xe)
- The chemical bonds of the gas molecules are broken on the surface of the NEG
- Various gas atoms are chemisorbed forming oxides, nitrides, and carbides.
- Water vapor and hydrocarbons are “cracked” on the surface of the NEG

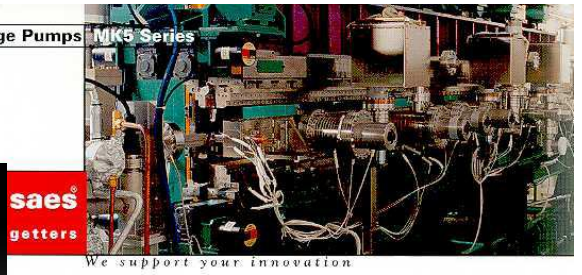
NEGs must be “activated”, i.e., heated

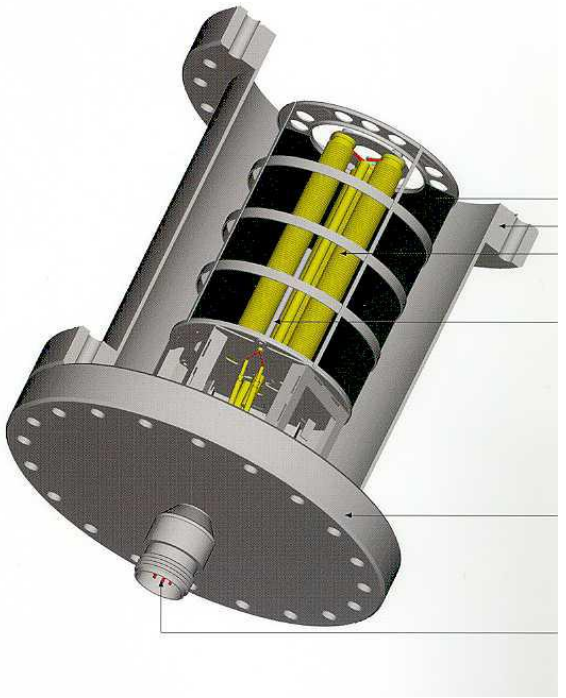
- NEGs made of alloys composed of titanium , vanadium, aluminum, zirconium, iron
- NEGs rely on surface area, more surface area means more pumping and capacity
- Commercial NEG material sintered to a substrate which can also serve as the heater
- NEGs coatings can be applied to the inner walls of chambers and beam pipes directly





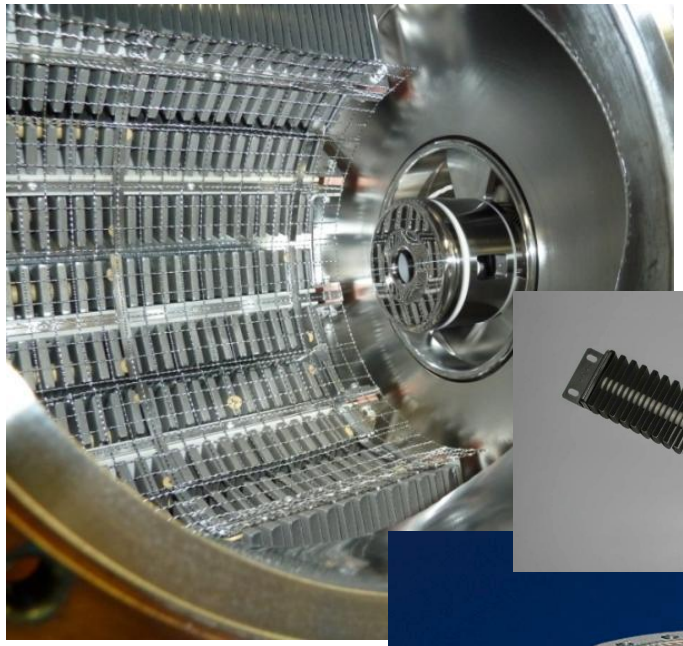
Typical NEG cartridge from SAES Getters

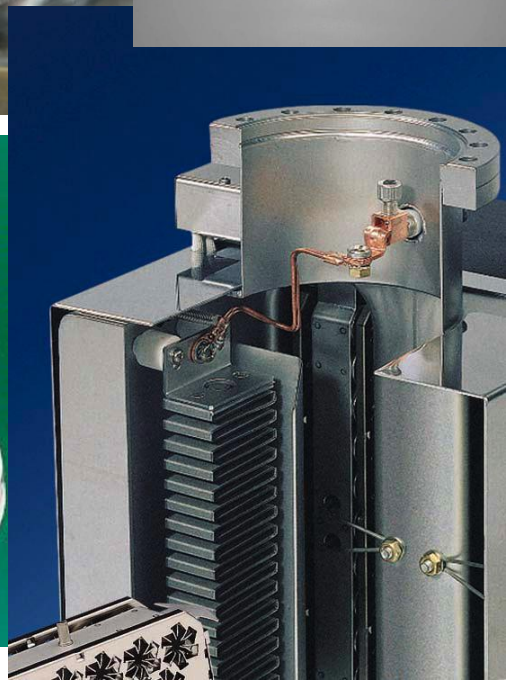




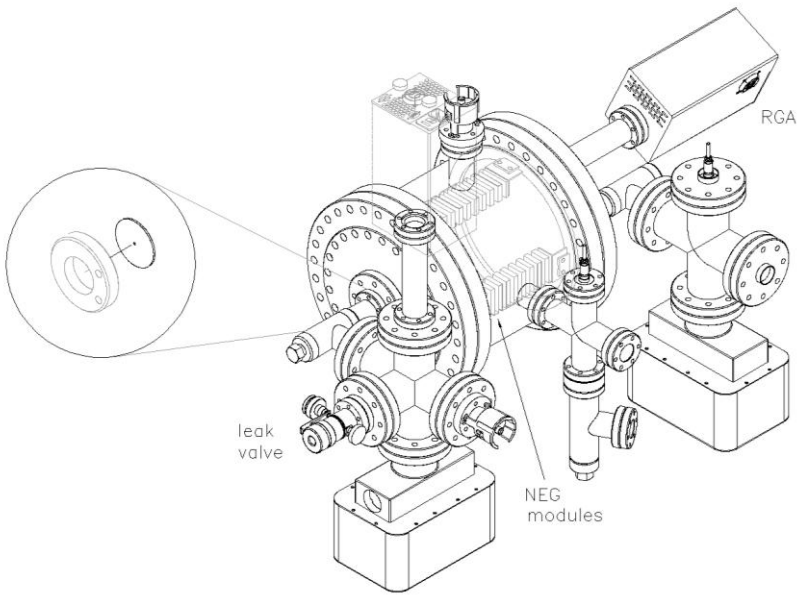
NEG Benefits

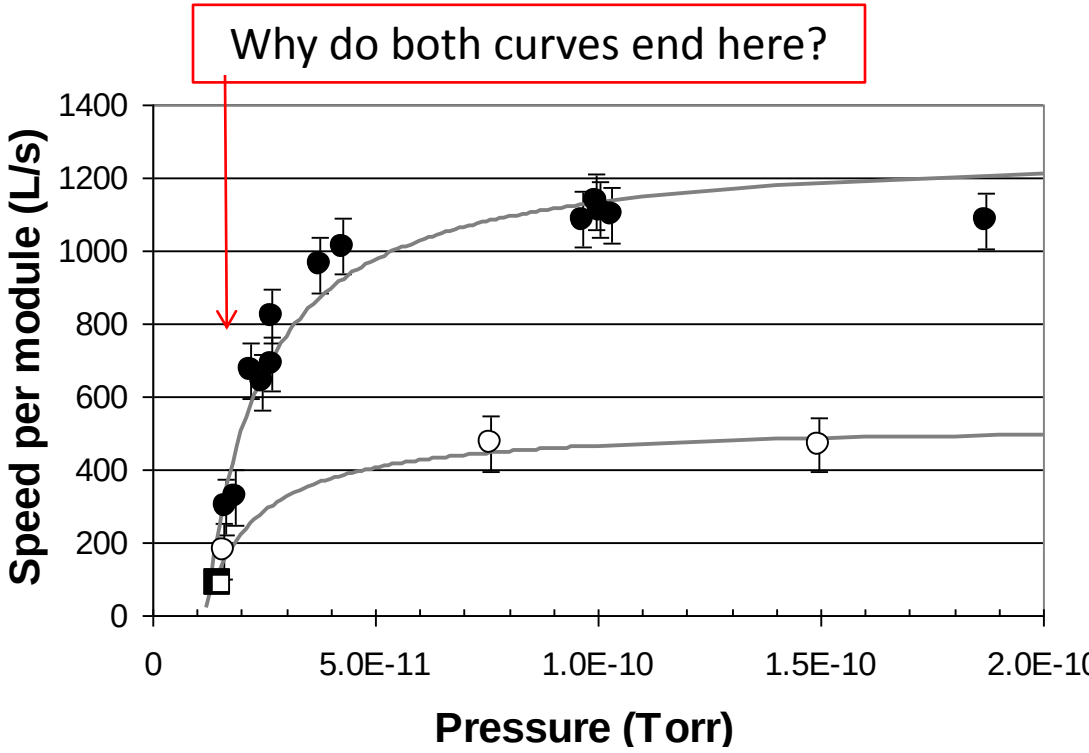
- Once they are activated, they don't need electricity
- Massive hydrogen pump speed
- Relatively easy to get put where you want/need them
- Flange-mounted cartridges, modules, sheet and homemade coatings





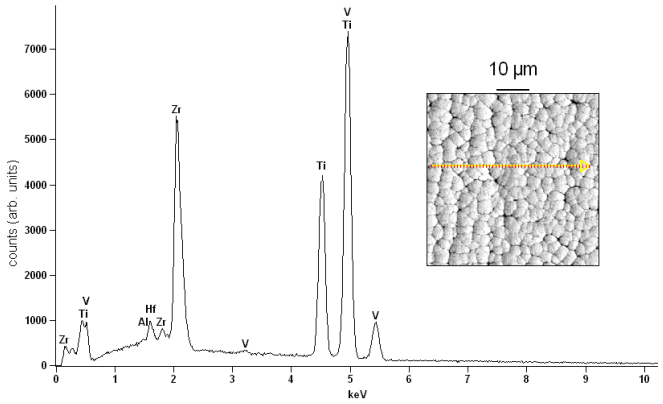
NEG Pump Speed

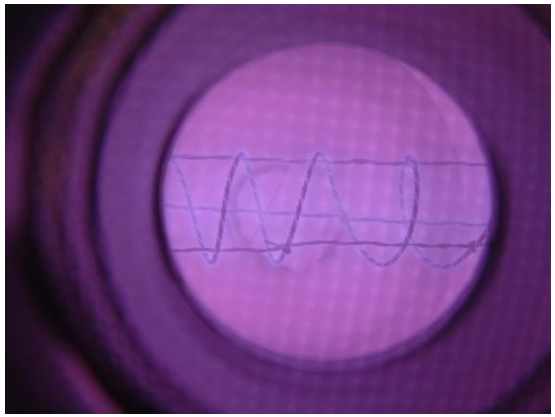




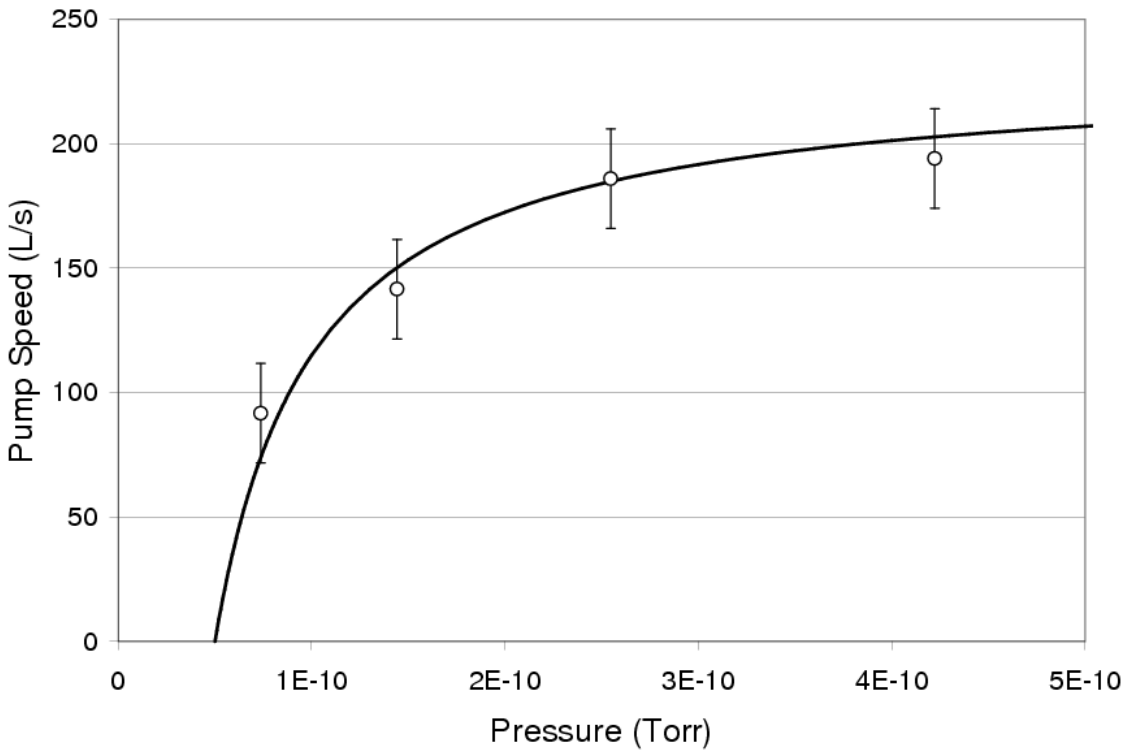
- Full NEG activation better than passive activation via bake
- NEG pump speed very good, at least at high pressure
- NEG pump speed at low pressure goes to zero – a real effect? More likely an indication of gauge limitations

Homemade NEG Coating





"Scrub" chamber walls prior to sputtering, to get good adhesion. Accomplished by reversing polarity on Ti/V/Zr wires



NEG coating turns a gas source into pump

~0.02 L/s·cm^2 : Modest pump speed can be improved

Literature reports ~1 L/s·cm^2

What about Cryopumping?

- Excellent pumping for hydrogen and other gasses, including inert gasses. So a potential replacement for ion pumps and NEG pumps
- Cryosorption: the weak binding force between a gas molecule and a solid surface. The process for pumping H2, He, Ne. Need temps < 12K
- Cryocondensation: associated with the even weaker force which binds molecules together. Process for water and other "air" gasses, like N2 and O2. Need temp < 80K
- Different gasses are pumped at different locations (i.e., temperatures) inside the pump

What about Cryopumping?

Disadvantages:

- Commercial cryo-pumps are appendage pumps (i.e., they do not surround cathode/anode gap)
- Commercial pumps employ a LHe compressor, lots of vibration
- If you lose electricity, the pump warms up and all the captured gas is expelled

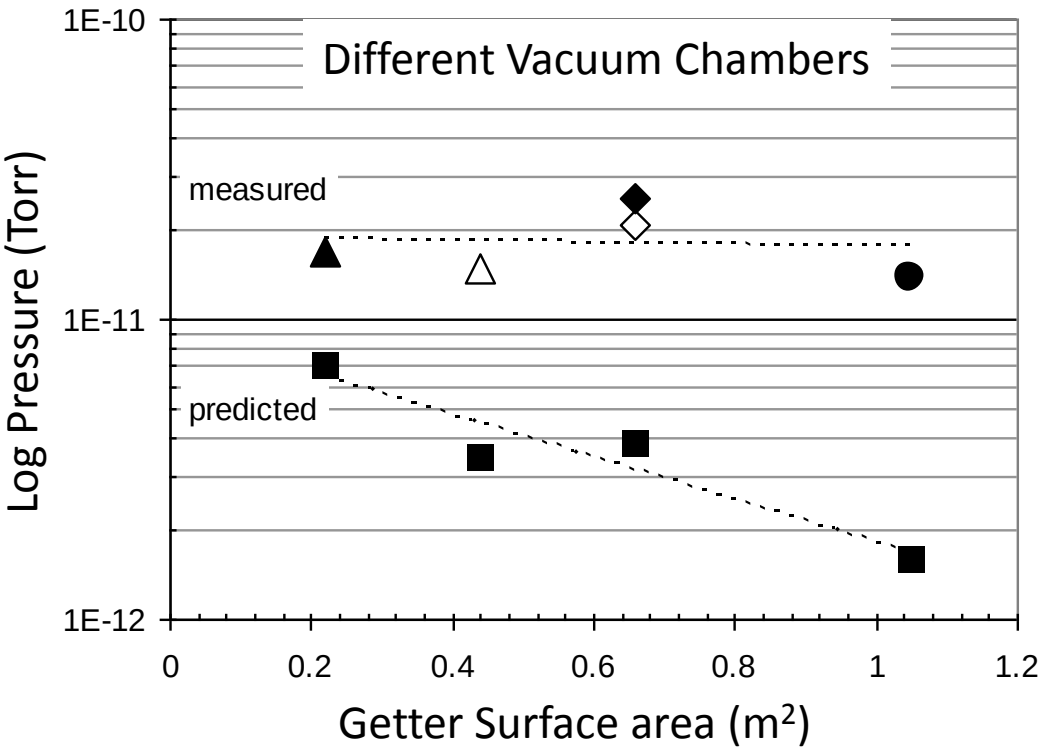
What problems will the cryopump solve?

- Ion pump limitation at low pressure?
- NEG pump limitation at low pressure?
- Much better NEG activation using Cryo-pump as capture pump

Our Vacuum Puzzle

$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{Q}{S} = \frac{q\ A}{S}$$

Q= gas load, q= outgassing rate, A = surface area, S = pump speed



Why is Measured Pressure always higher than Predicted?

- Outgassing rate higher than measured?
- Ion Pump not ON, a source of gas?
- NEG pump speed smaller than SAES says?
- Gauges lying?
- Bookkeeping errors? More surface area than we account for
- Leaks?

Cryopumped gun project

- Investigate adding bakable cryopump into system
  - Leybold Coolvac 2000 BL, special order
  - Cryosorber panel can be chilled with LN_2 during bakeout
  - Isolation valve for regeneration
  - Components ready for assembly
- Can we measure improvement in vacuum due to cryopump?

➢Characterize UHV/XHV gauges

Backup slides

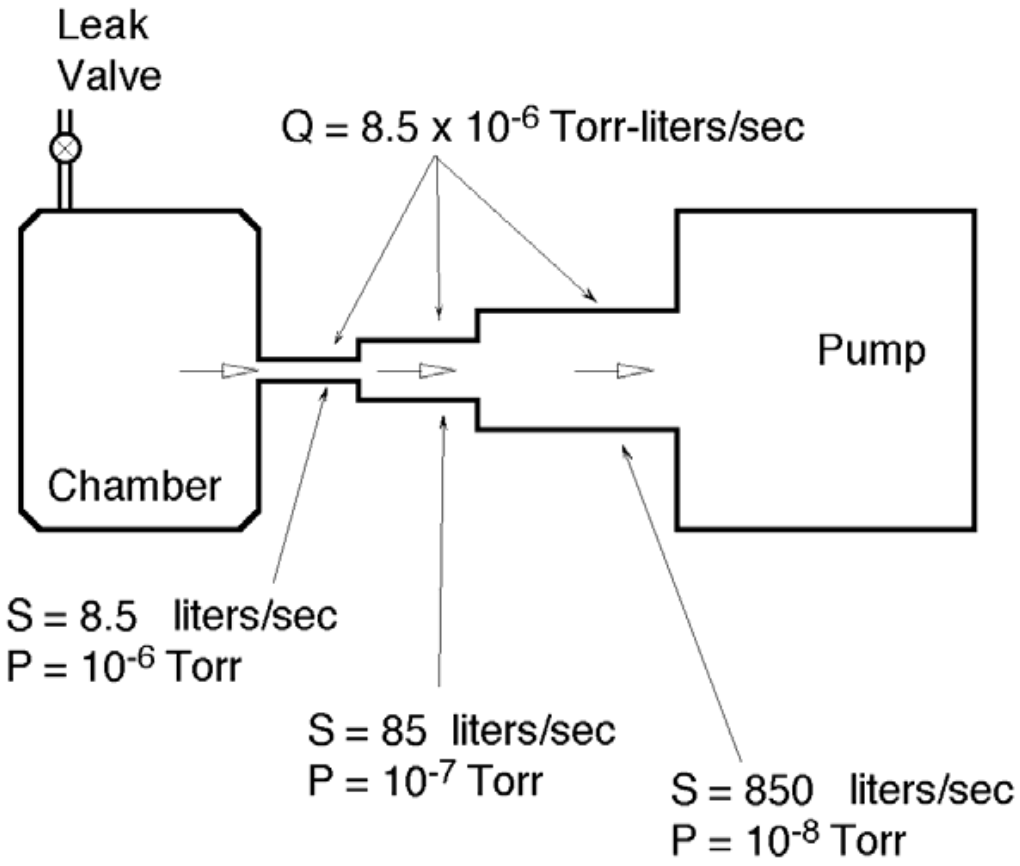
What about the Beamline Vacuum?

$$P_{ult} = \frac{Gas\ Load}{Pump\ Speed} = \frac{Q}{S} = \frac{q\ A}{S}$$

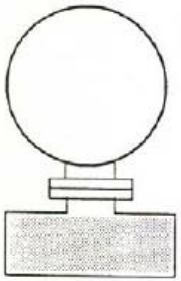
$$Q = P \times S \quad \left(Torr \cdot L/_S\right)$$

Reduce the Impact of Beamline Vacuum

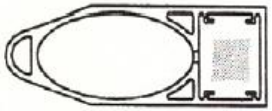
- Bake the Beamline to achieve good pressure
- Conductance limitation



Vacuum system configuration



appendage pump

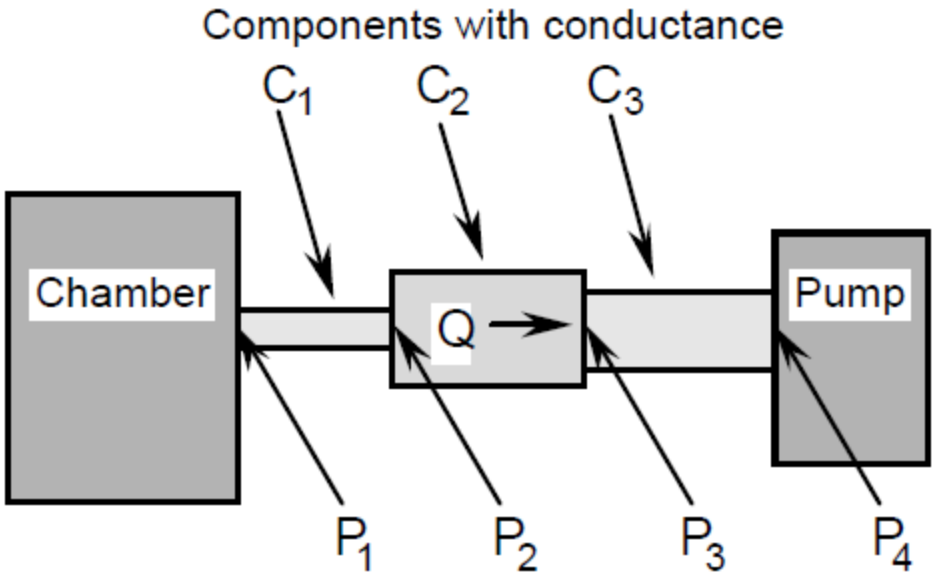


inserted "linear" pump

inserted "total" pump

surface pump/diffusion barrier

Conductance

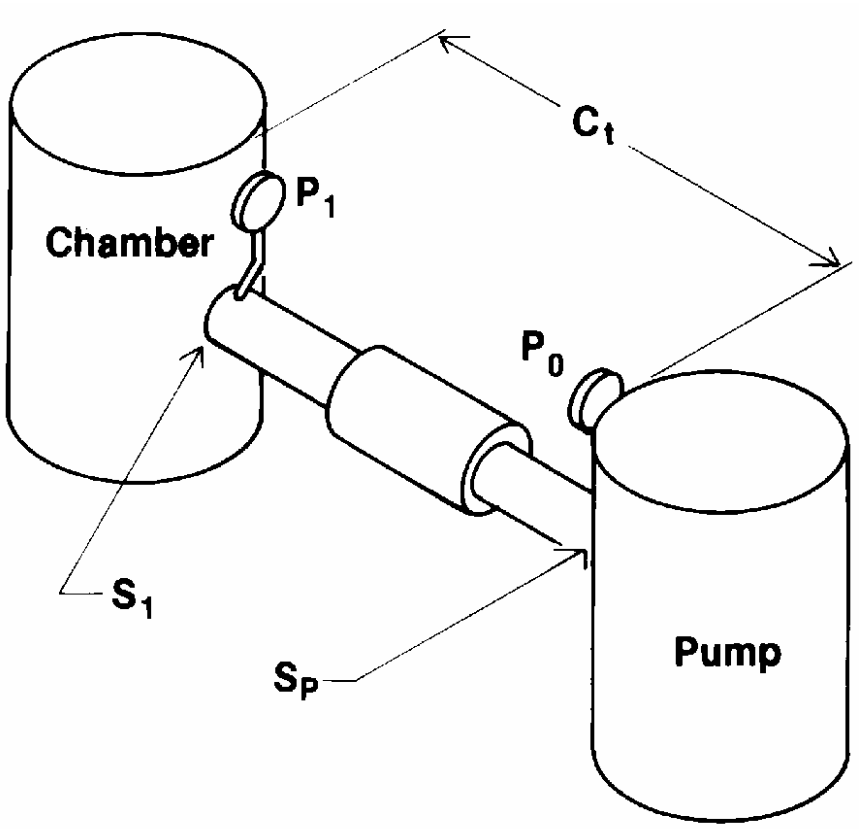


- in series

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

- in parallel

$$C_t = C_1 + C_2 + C_3$$



$$\frac{1}{S_1} = \frac{1}{S_p} + \frac{1}{C_t}$$