Accelerator Vacuum and Mechanical Engineering

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United States Particle Accelerator School @ The College of William & Mary

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The US Particle Accelerator School
Vacuum Fundamentals

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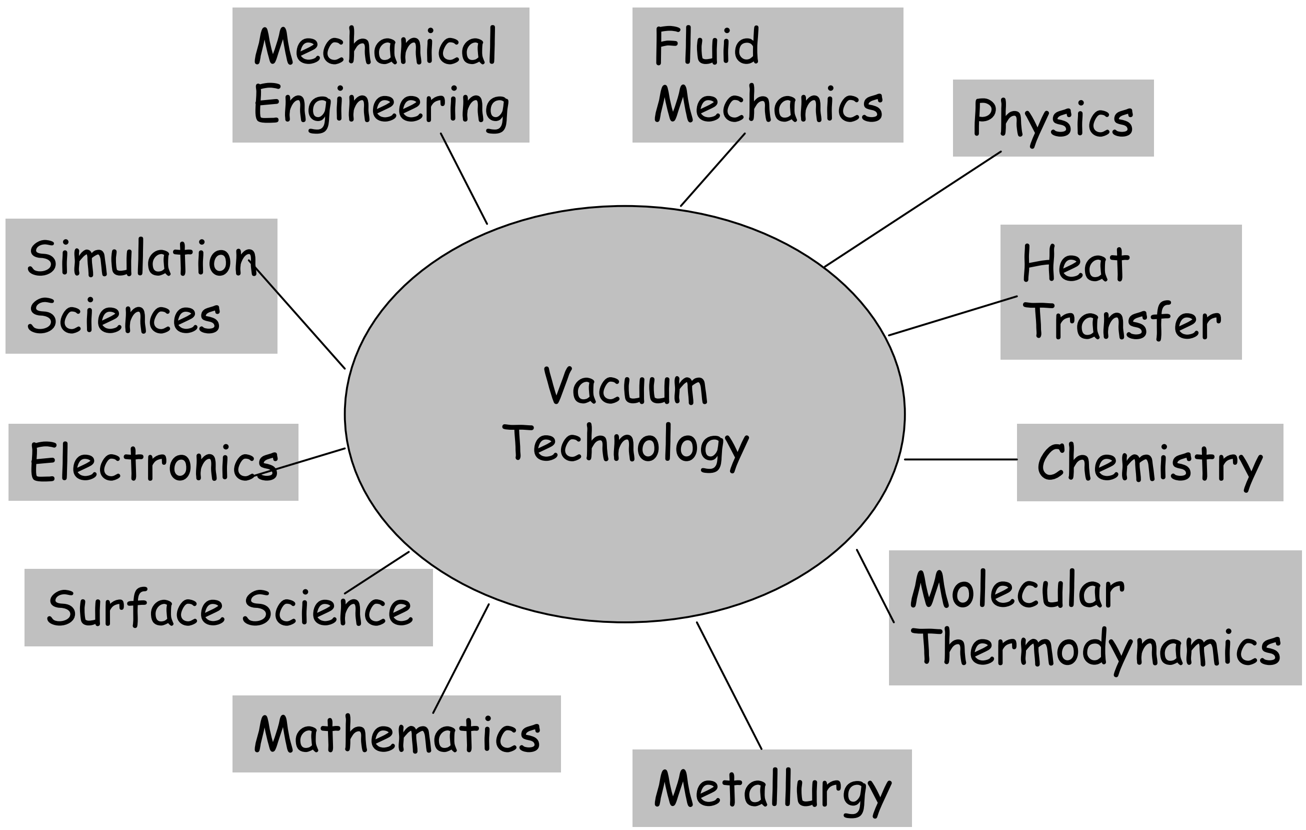
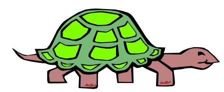
Vacuum is a highly interdisciplinary subject



Kinetic behavior of gas molecules

The behavior of a collection of gas molecules in a vessel is dependent upon the pressure, temperature and composition of the gas.

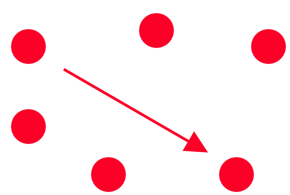
Velocity of gas molecules.



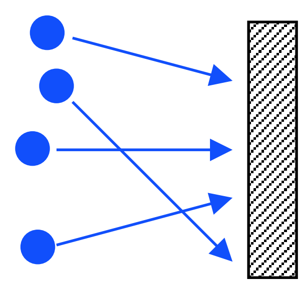
Kr

He

Mean free path



Impingement rate



Gas Laws

Charles' Law

volume vs temperature

Boyle's Law

pressure vs volume

Combined or General Gas Law

pressure vs temperature vs volume

Avogadro's Law

volume vs amount

Ideal Gas Law

pressure vs temperature
vs volume vs amount

> These laws apply to all molecules and atoms regardless of their size

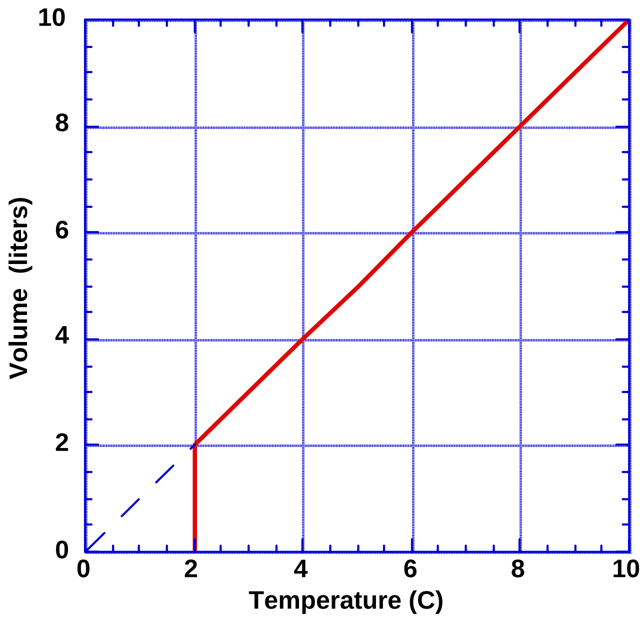
Charles's Law

The volume of a fixed amount of gas at a fixed pressure will vary proportionally with absolute temperature.

$$V \propto T$$

$$\frac{V}{T} = \text{constant}$$

$$\left(\frac{V_1}{T_1}\right) = \left(\frac{V_2}{T_2}\right)$$

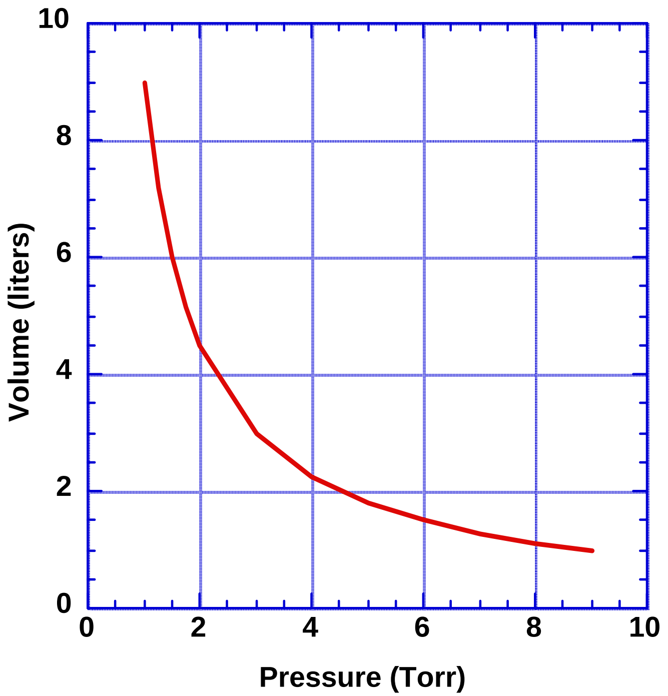


Boyle's Law

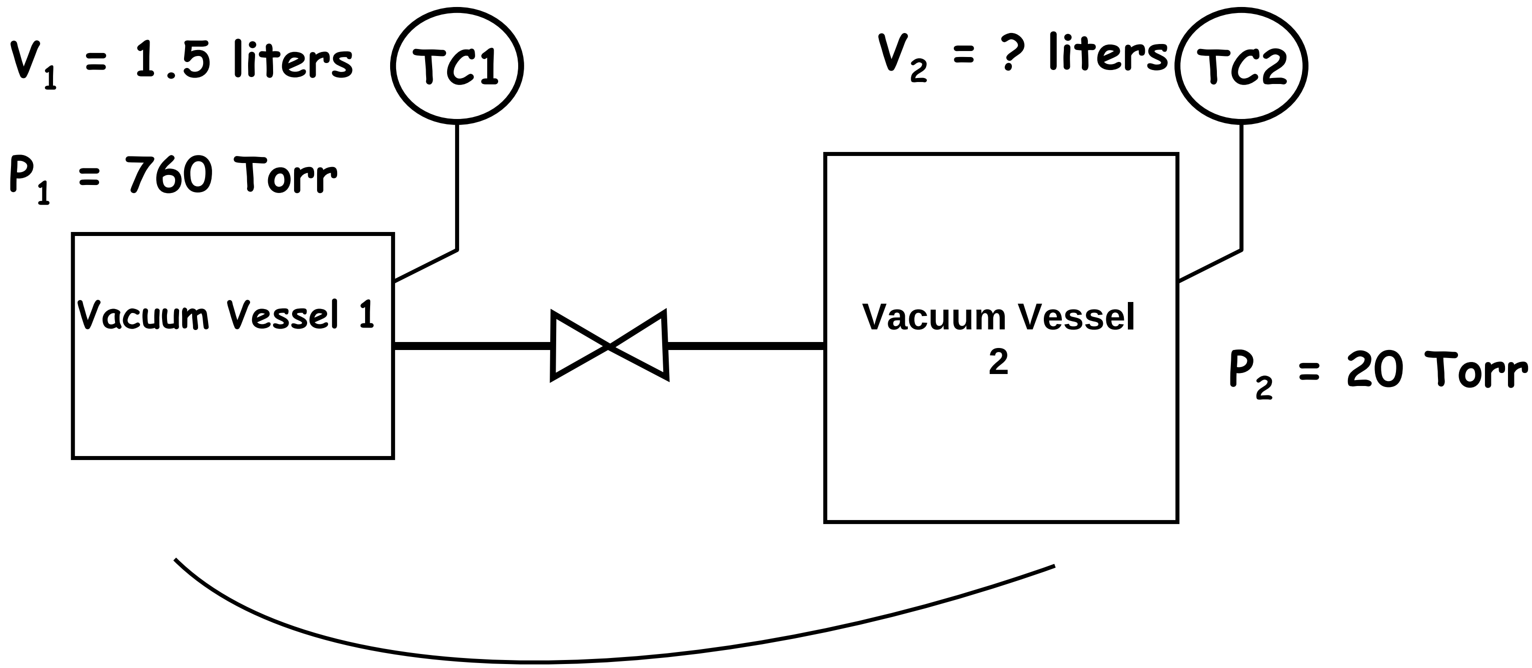
For a fixed amount of gas at a fixed temperature, its pressure is inversely proportional to its volume.

$$V \propto \frac{1}{P} \qquad PV = \text{constant}$$

$$P_1V_1 = P_2V_2$$



Finding volume of a vessel with Boyle's Law



Combined Gas Law

Provides relationship between pressure, volume, and temperature for a fixed amount of gas.

$$\frac{PV}{T} = \text{constant}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Example of combined gas law

P_1 = 100 Torr P_2 = 200 Torr
V_1 = 200 liters V_2 = 80 liters
T_1 = 293 K T_2 = ? K

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{(100\ \text{Torr})(200\ \text{liters})}{293\ \text{K}} = \frac{(200\ \text{Torr})(80\ \text{liters})}{T_2}$$

$$T_2 = 234\ \text{K}$$

Avogadro's Law

The Volume occupied by any gas, at a fixed temperature and pressure, is proportional to the number of moles of that gas.

$$V \propto n$$

N_o = Avogadros' Number = 6.02×10^{23} particles = 1 mole

Ideal Gas Law

Provides relationship between pressure, volume, Temperature, and amount of gas.

$$PV = nRT$$

R = 0.08206 Atm-liter/ K-mole
= 62.36 Torr-liter/K-mole

Units in Gas Law calculations

Gas law calculations may be performed using a variety of pressure units (Torr, Bars, ATM, PSI, Pa, etc.) but the pressure units must remain consistent through the calculation.

$$t = \frac{V}{S_t} \ln \frac{P_1}{P_2} \left(\frac{Torr}{Torr} \right)$$

Temperature must be in absolute units (K,R).

Pressure unit conversions

To convert from: Multiply by:	To:	
Atm	Torr	760
Pascal	Torr	7.5×10^{-3}
mBar	Torr	0.750
PSI	Torr	51.7

Maxwell's Distribution Law

Maxwell determined that for a large population of one type of molecule, there would be a distribution of velocities. There is not one uniform velocity.

$$N_v = 4\pi N\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} v^2 e^{\left(\frac{-mv^2}{2kT}\right)} dv$$

where $N_v dv$ = the number of molecules found in the velocity interval between v and v + dv

v = velocity of the gas molecules (m/sec)

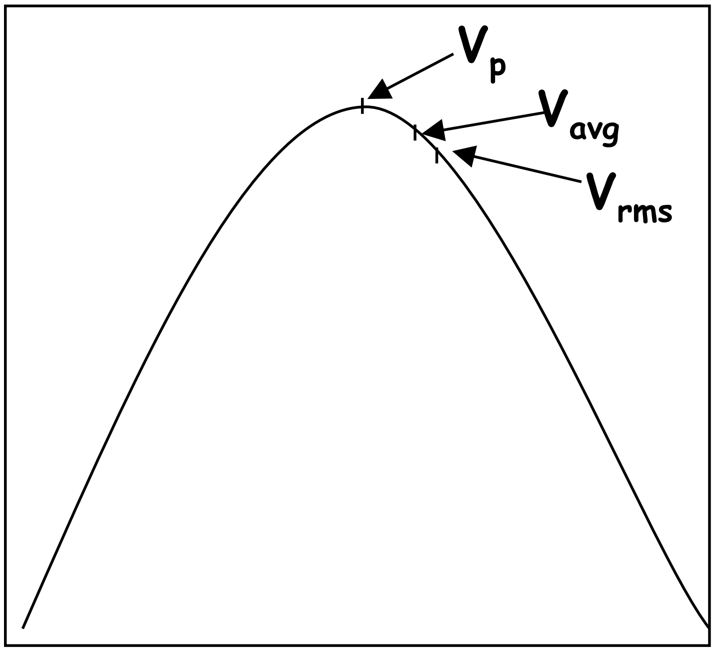
N = the total number of gas molecules

k = Boltzmann's constant (1.38×10^{-23} J/K)

m = mass of the molecule (kg)

T = Temperature (K)

A Typical Maxwell Velocity Distribution



$$v_{rms} = \text{root mean square velocity}$$

$$\approx 1.7\left(\frac{kT}{m}\right)^{\frac{1}{2}} \propto \left(\frac{T}{M}\right)^{\frac{1}{2}}$$

$$v_{avg} = \text{average velocity of population}$$

$$\approx 0.98 v_{rms}$$

$$v_p = \text{most probable velocity}$$

$$\approx 0.82 v_{rms}$$

Velocity of gas molecules

The velocity of gas molecules is independent of the pressure of the gas, and depends only on the molecular weight of the gas and its absolute temperature.

$$\bar{V} = 1.455 \times 10^4 \sqrt{\frac{T}{M}}$$

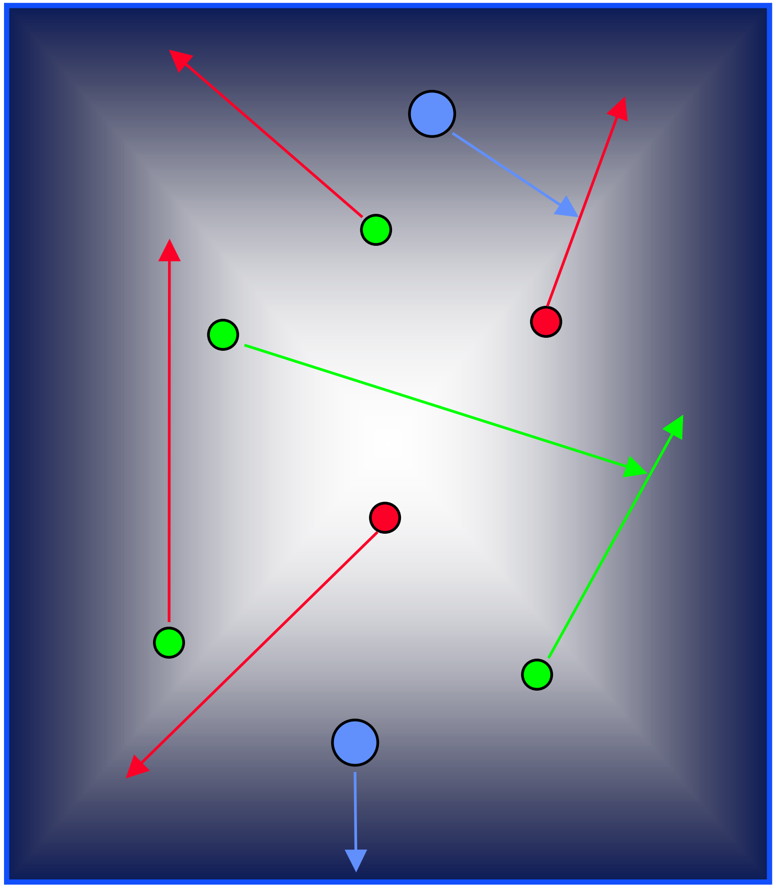
$\bar{V}$ = average velocity (cm/sec)
T = absolute temperature (K)
M = molecular weight of gas, (g/mole)

Mean free path

The mean free path is the average distance that a gas molecule can travel before colliding with another gas molecule.

Mean Free Path is determined by:

- Size of molecule
- Pressure
- Temperature



Mean Free Path Equation

$$\lambda_i = \frac{kT}{\sqrt{2}\pi P d_i^2}$$

λ_i = mean free path of gas species "i" ($^{cm}/_{sec}$)
k = Boltzmann's constant (1.38 x 10^{-23} Joules/K)
T = Temperature (K)
P = Pressure (Pa)
d_i = gas species diameter (cm)

Gas Flow

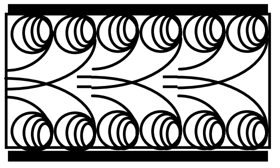
The flow of gases in a vacuum system is divided into three regimes. These regimes are defined by specific value ranges of a dimension-less parameter know as the Knudsen number.

$$K_n = \frac{\lambda_a}{a}$$

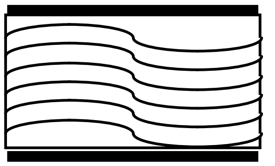
λ_a = mean free path
a = characteristic dimension of flow channel (typically a pipe radius)

Gas Flow

Viscous Flow : $Kn = \frac{\lambda_a}{a} < 0.01$



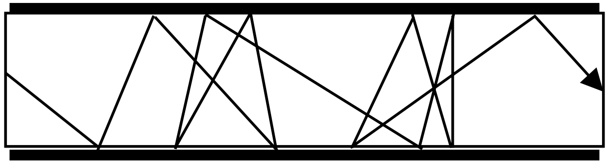
Turbulent



Laminar

Transition Flow : $0.01 < Kn < 1.0$

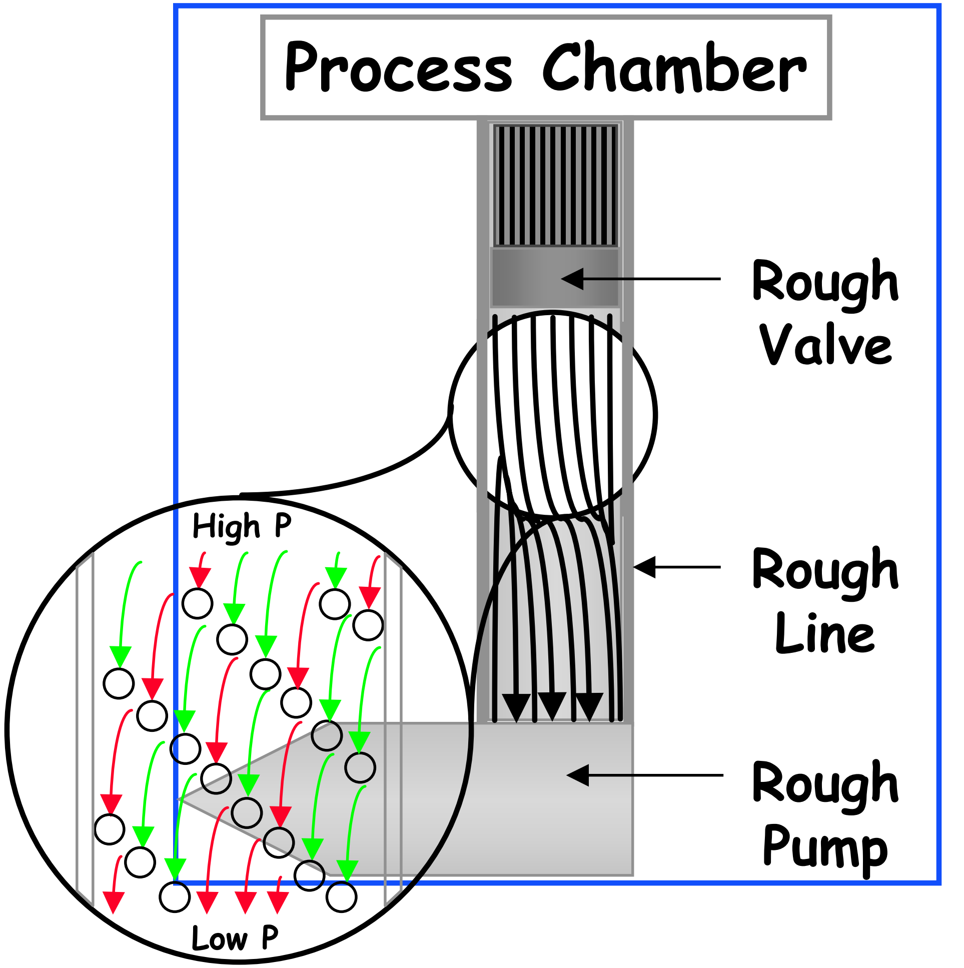
Molecular Flow : $Kn > 1.0$



Molecular

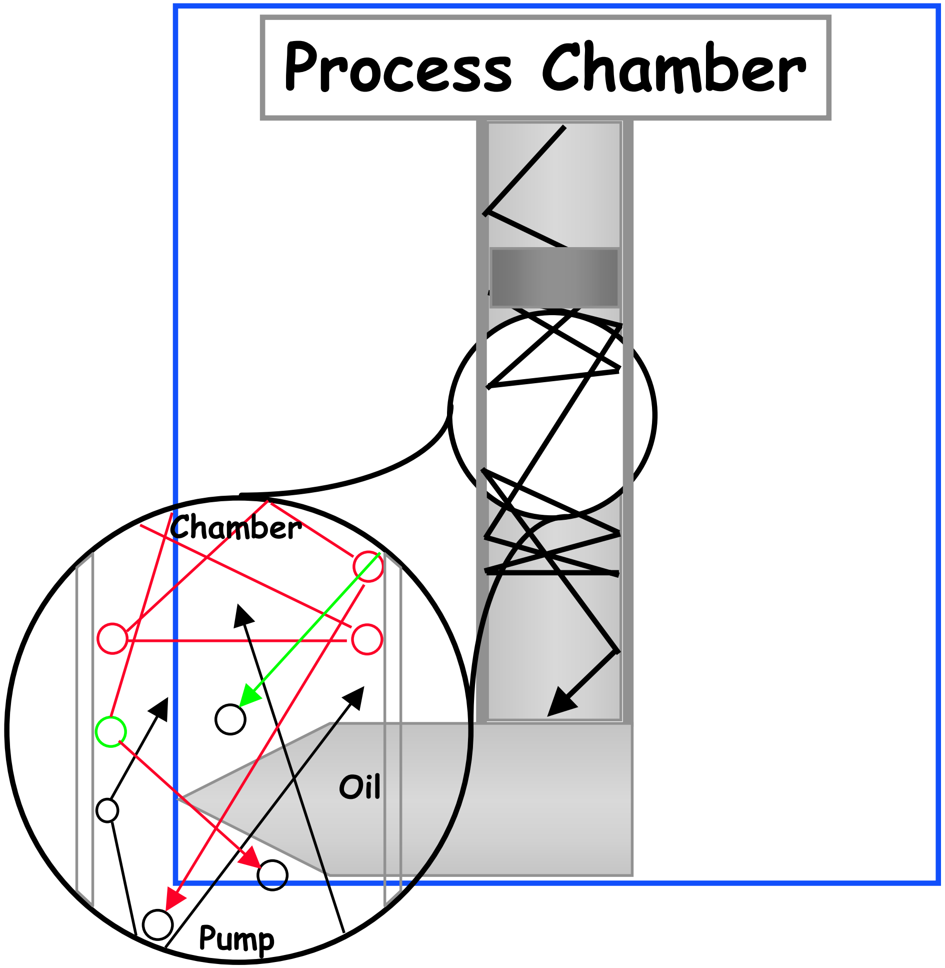
Viscous Flow

- Viscous Flow
  - Molecules travel in uniform motion toward lower pressure
  - Random motion of a molecule is influenced in the direction of the mass flow
  - Molecular motion "against" mass flow unlikely



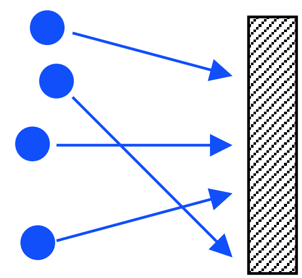
Molecular Flow

- **Molecular Flow**
  Molecules move randomly in either direction - to or away from rough pump and vacuum pump
  - Oil molecules will Backstream (move up the rough line) in this flow regime



Gas Flux Density incident on a Surface (impingement rate)

$$\upsilon = N\left(\frac{kT}{2\pi m}\right)^{1/2}$$



$$\text{where } N = \frac{PN_o}{RT}$$

$$= \text{density of molecules per m}^3$$

$$\upsilon = 10^3\,\frac{PN_o}{RT}\left(\frac{kT}{2\pi m}\right)^{1/2}$$

liters/m^3 conversion

Gas Flux Density (Impingement rate)

The number of gas molecule collisions with the inner surface of a container is given by:

$$\upsilon = 3.5 \times 10^{22} \frac{P}{\sqrt{MT}}$$

υ = particle flux density (molecules/sec cm^2)
P = pressure (Torr)
M = molecular weight of gas (g/mole)
T = absolute temperature (K)

Residence time

Residence time is the average amount of time a molecule stays on a surface, and is a function of the molecular weight of the gas and the temperature of the surface.

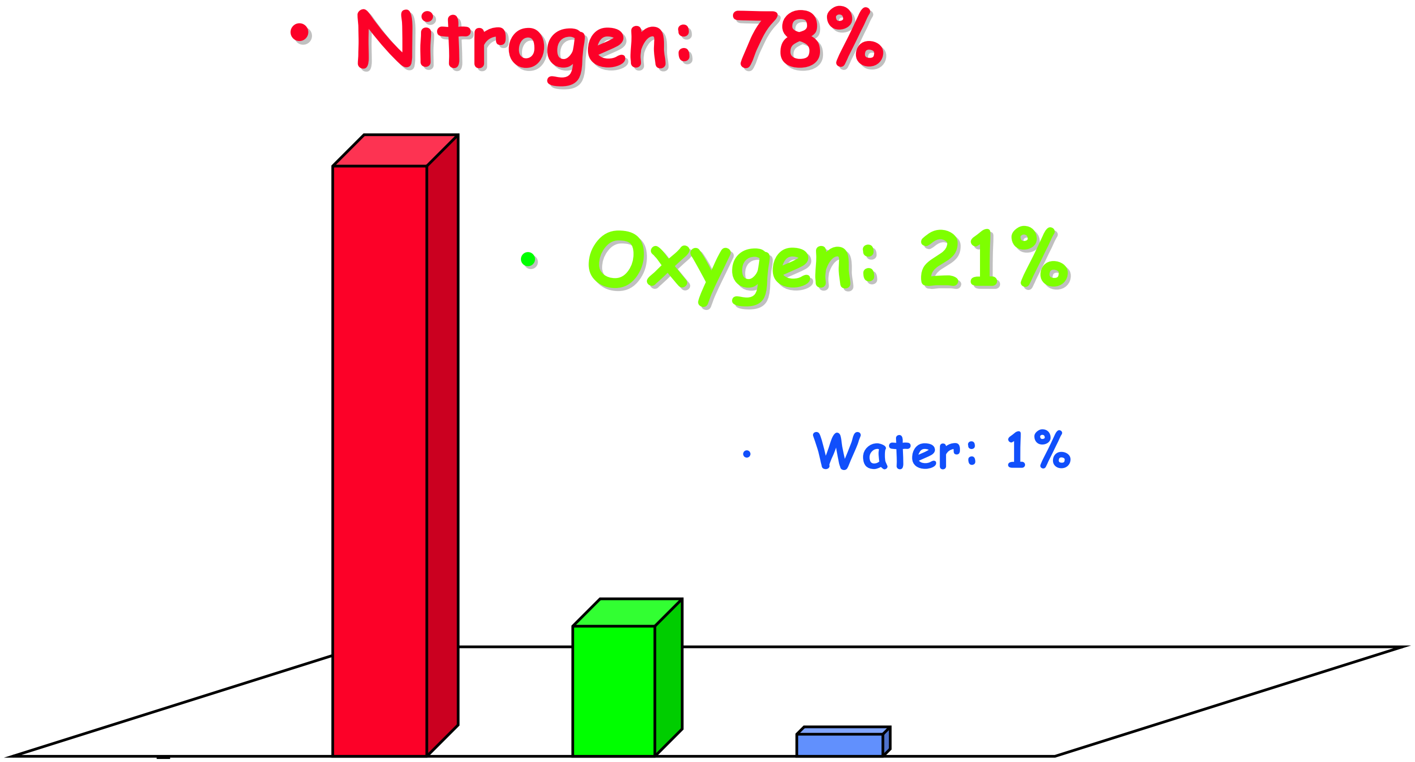
$$t = t_o e^{\left(\frac{Q}{RT}\right)}$$

where t_o = time of oscillation in the absorbed state (typically 10^{-12} to 10^{-13} sec)

Q = activation energy

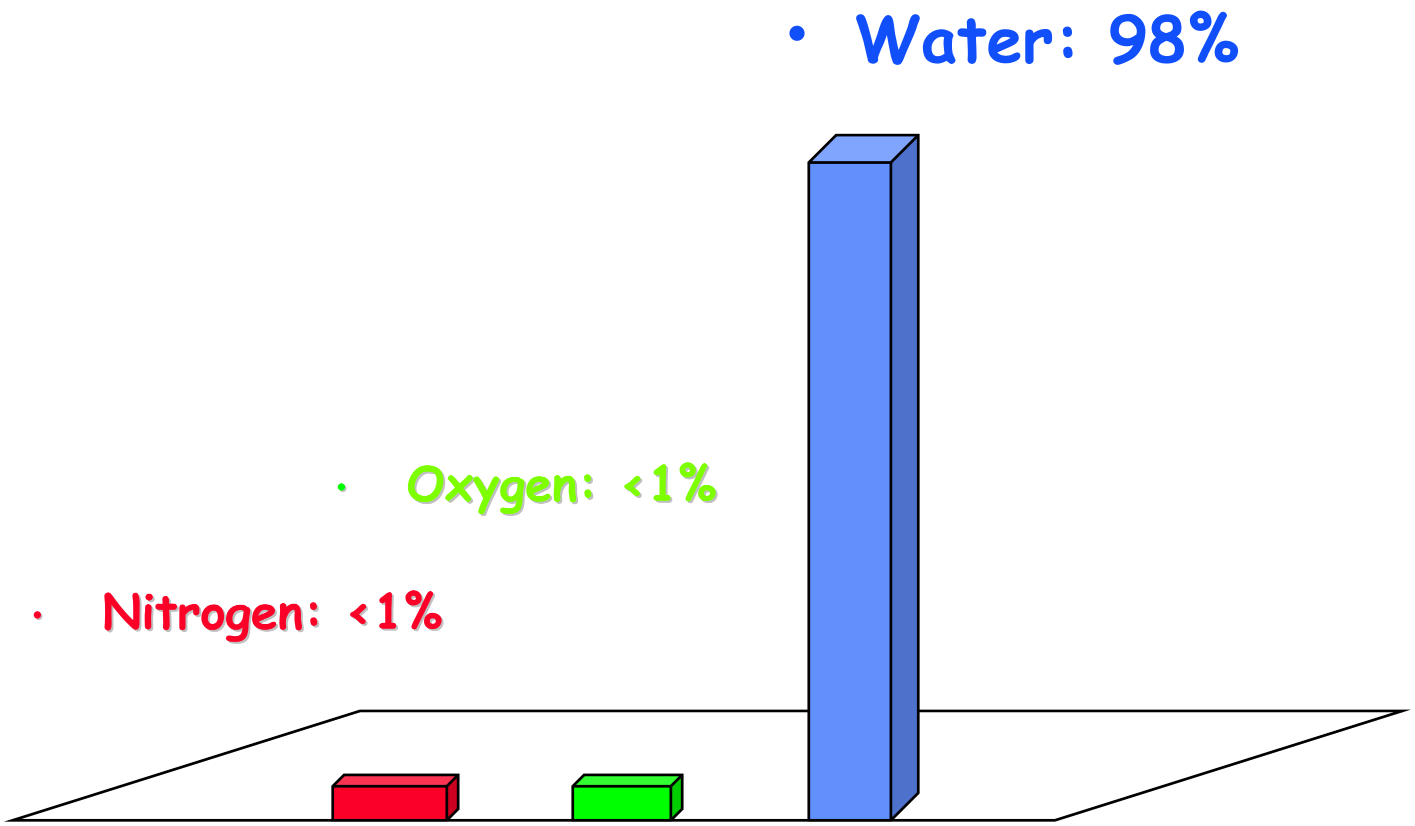
T = temperature (K)

Composition of Atmosphere



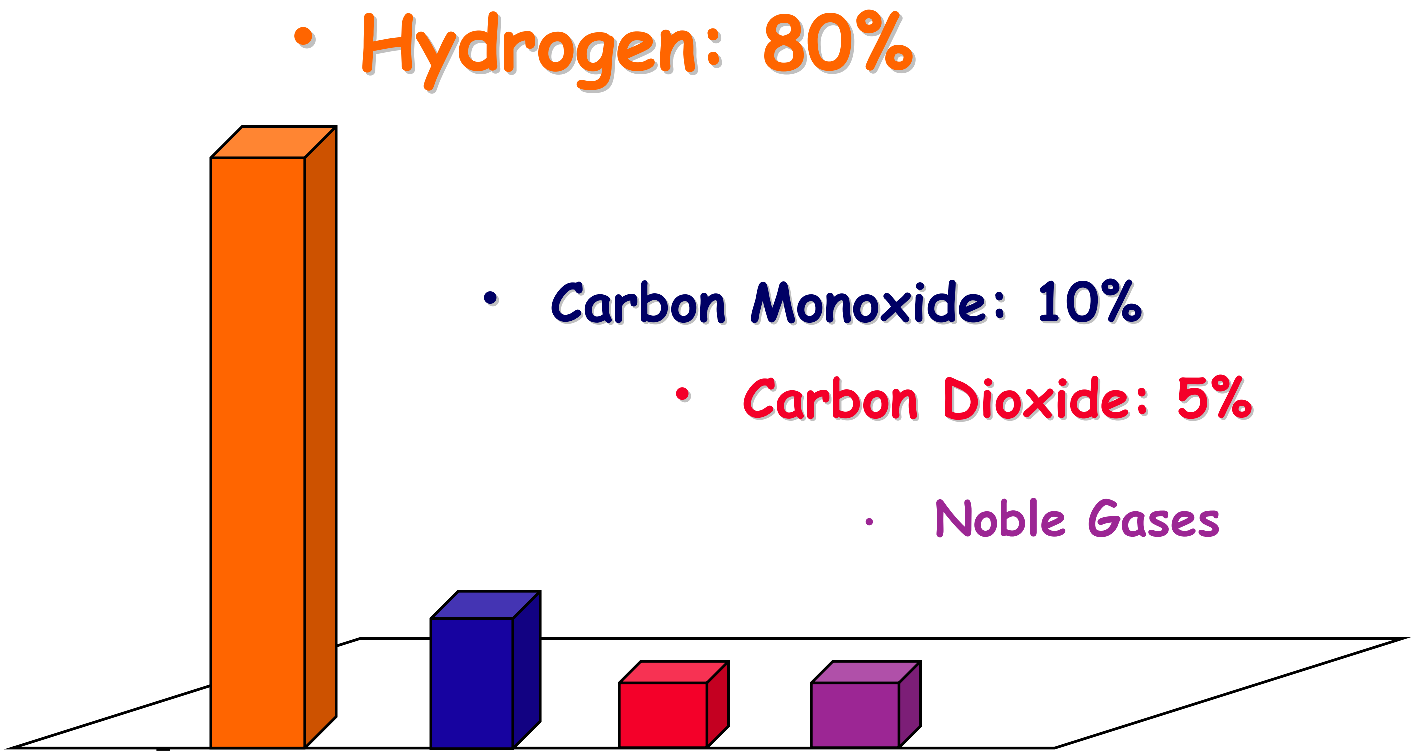
Pressures Above 10^{-3} Torr

Composition of Atmosphere



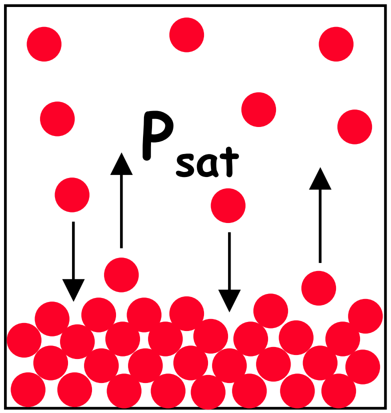
Pressures 10^{-3} Torr to 10^{-6} Torr

Composition of Atmosphere

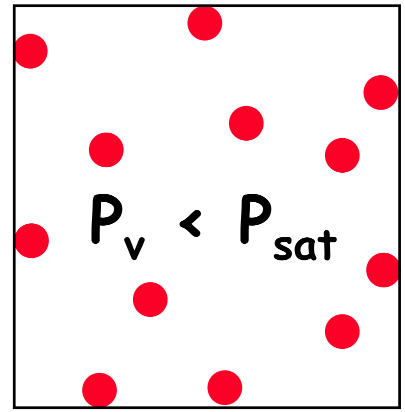


Pressures 10^{-6} Torr to ????

Vapor Pressure



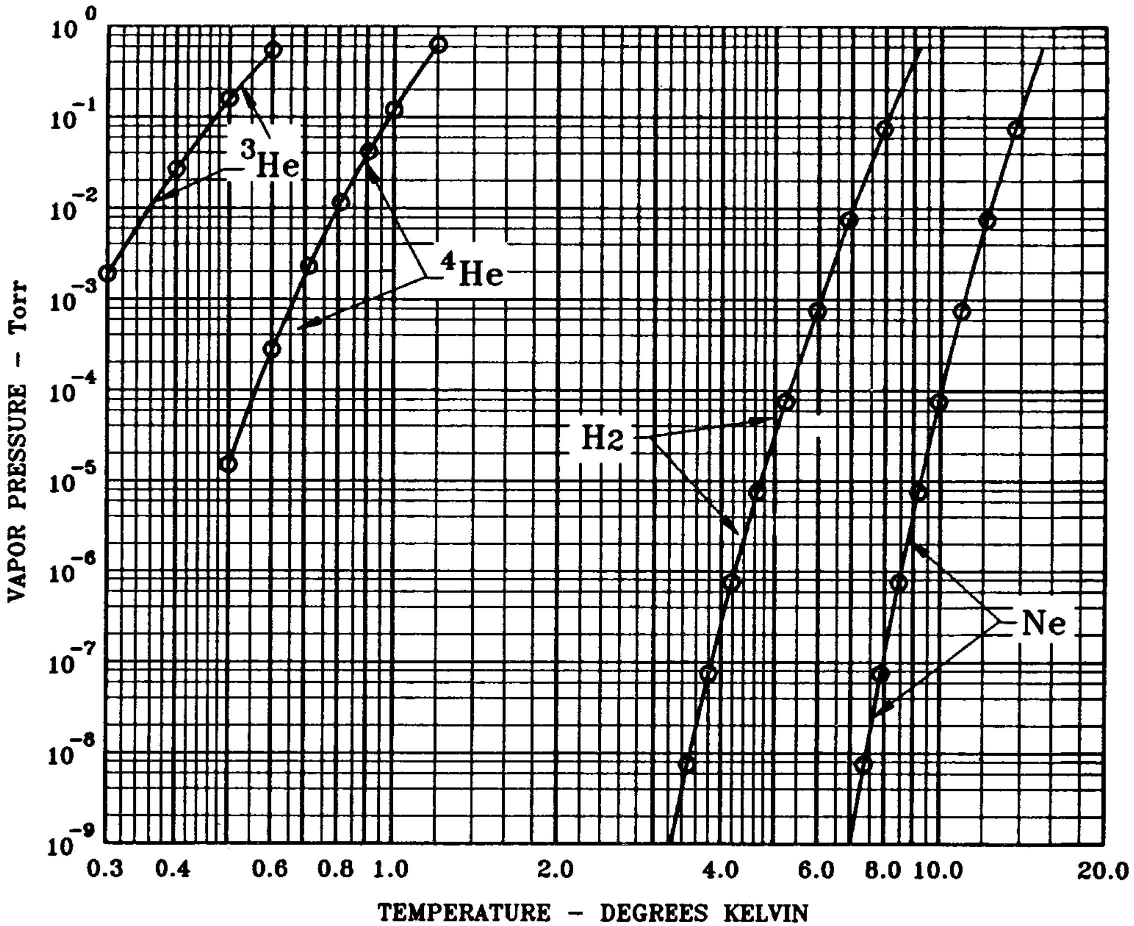
In this case, the gas above the bulk is considered to be saturated.



In this case, there is not sufficient bulk material to support a saturation vapor pressure

- Vapor pressure is an important concept as it relates to cryopumps.
- At thermal equilibrium the net flux of particles at the surface of bulk material is zero.
- Each element has a specific saturation pressure for a given temperature.
  The saturation pressure is also referred to as the saturation vapor pressure, equilibrium vapor pressure, or just vapor pressure.

Vapor Pressure Curve



Pumping Speed

Defined as a measure of volumetric displacement (liters/sec, cu.feet/minute, cu.meters/minute)

- It is the volume of gas flowing past a point per unit time.
- Pumping speed is independent of pressure.
- Pumping speed is an abstract concept used to describe the behavior of gas in a vacuum system.

$$S = \frac{dV}{dt} = \frac{Q}{P}$$

Throughput

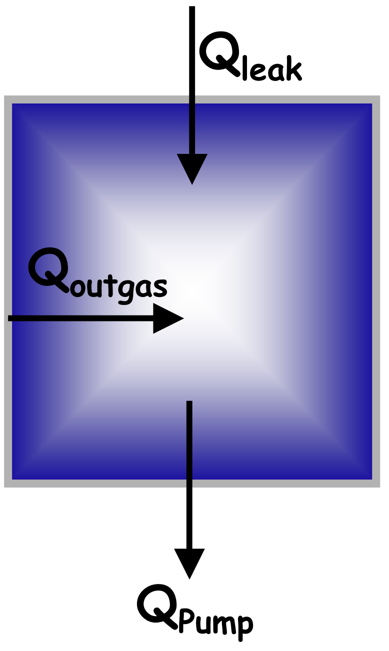
Defined as a measure of gas flow rate (Torr-liters/sec)

- For constant pumping speed throughput varies with pressure:

$$Q = \frac{d(PV)}{dt} = SP$$

- Under dynamic conditions:

$$\frac{d(PV)}{dt} = Q - S(P - P_o)$$



Conductance

Defined as a measure of ease with which abstract volumes can pass from one place in a vacuum system to another.

- Conductance is an abstract concept used to describe the behavior of gas in a vacuum system.
- Conductance is specific to a particular geometrical configuration.
- Conductance is specific to the actual gas species and temperature.
- When the mean free path of a gas species in a system is less than the dimensions of the system the conductance is pressure dependent.

Conductance under Molecular Flow

Aperture

$$C = 3.64\sqrt{\frac{T}{M}}\,A \qquad \text{(liters/sec)}$$

where A = the aperture area (cm^2)
T = Temperature (K)
M = molecular weight (grams/mole)

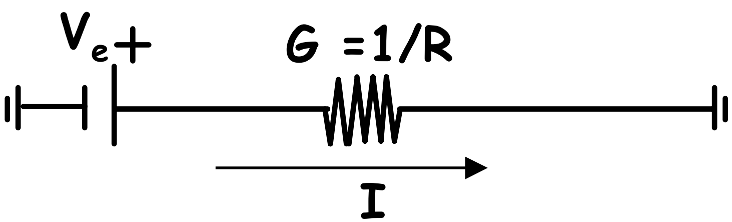
Long Tubes (L $\geq$ 10D)

$$C = 3.81\sqrt{\frac{T}{M}}\,\frac{D^3}{L} \qquad \text{(liters/sec)}$$

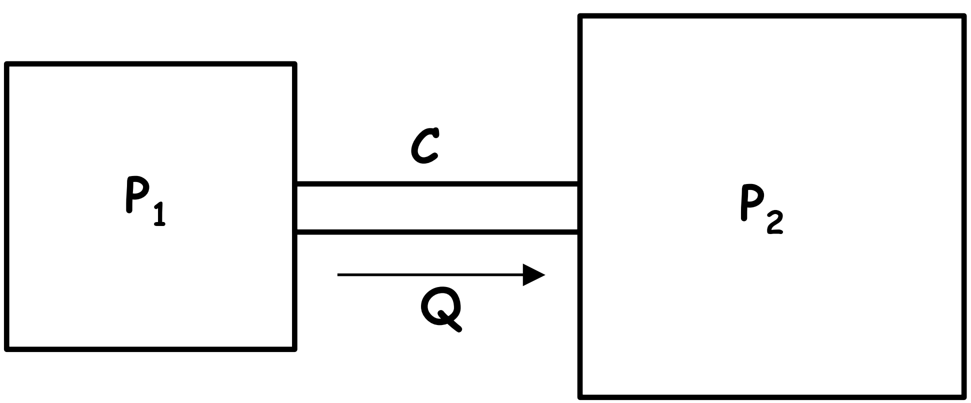
where D = pipe diameter (cm)
L = pipe length (cm)

Electrical Analogy (Ohm's Law)

A vacuum system operating in the molecular flow regime can be thought of in terms of an electrical circuit.

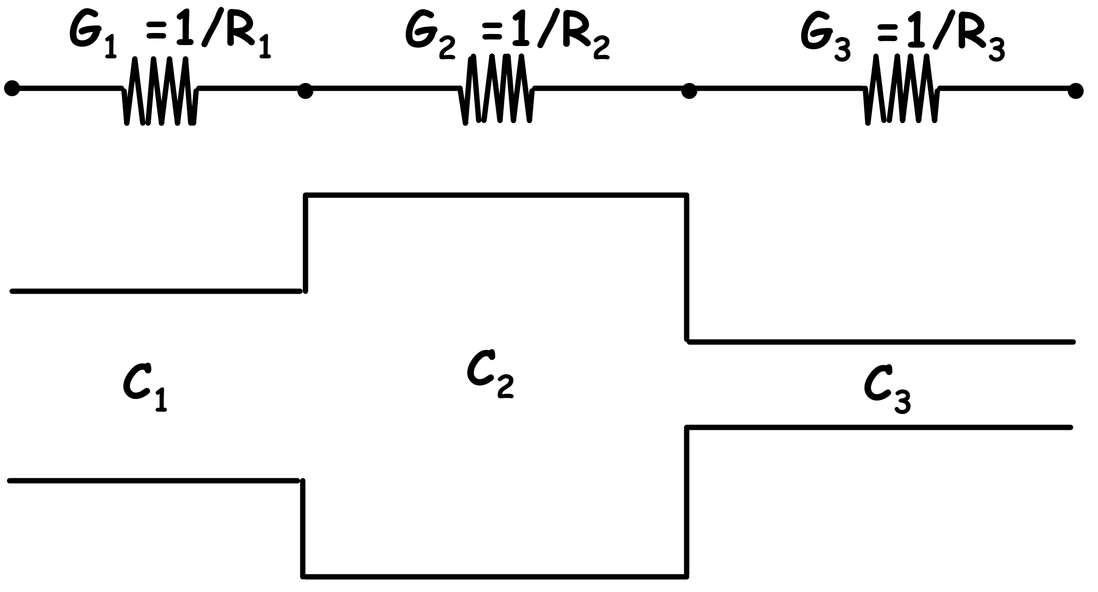


$I = GV_e$



$Q = C(P_1 - P_2)$

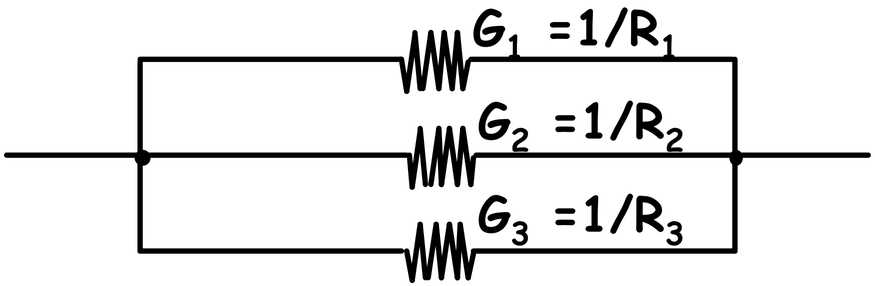
Electrical Analogy (continued)
Conductances in Series



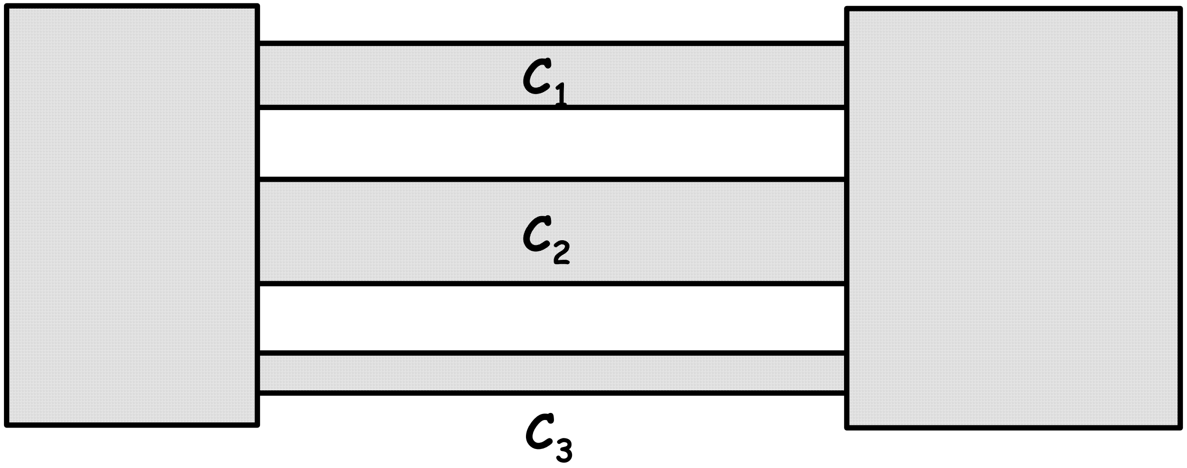
$$\frac{1}{G_e} = \frac{1}{G_1} + \frac{1}{G_2} + \frac{1}{G_3}$$

$$\frac{1}{C_{Total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Electrical Analogy (continued) Conductances in Parallel



$$G_e = G_1 + G_2 + G_3$$



$$C_{Total} = C_1 + C_2 + C_3$$

Dalton's Law

The partial pressures of gases in a mixture behave independently according to the ideal gas laws.

$$P_{Total} = P_{N_2} + P_{O_2} + P_{Ar} + P_{CO_2} + \ldots\ldots + P_n$$

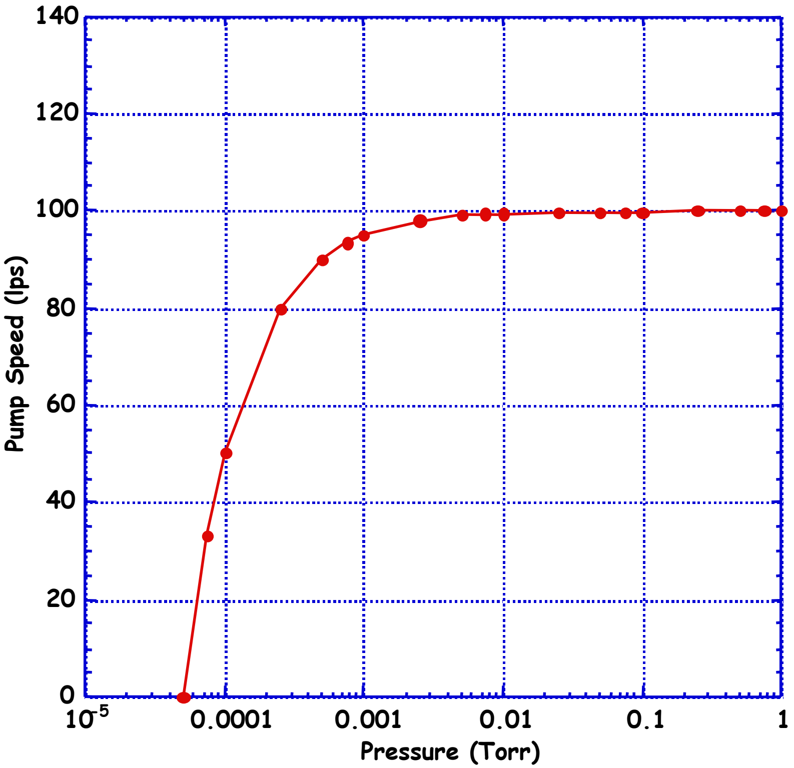
$$P_{Total} = \frac{Q_{N_2}}{S_{N_2}} + \frac{Q_{O_2}}{S_{O_2}} + \frac{Q_{Ar}}{S_{Ar}} + \frac{Q_{CO_2}}{S_{CO_2}} \ldots\ldots + \frac{Q_n}{S_n}$$

Variable Pumping Speed

All pumps have both high and low applicable pressure limits.

- Base or blank-off pressure (P_B) is the minimum pressure a pump will achieve
- At base pressure pumping speed is zero

$$S = S_{max}\left(1 - \frac{P_B}{P}\right)$$

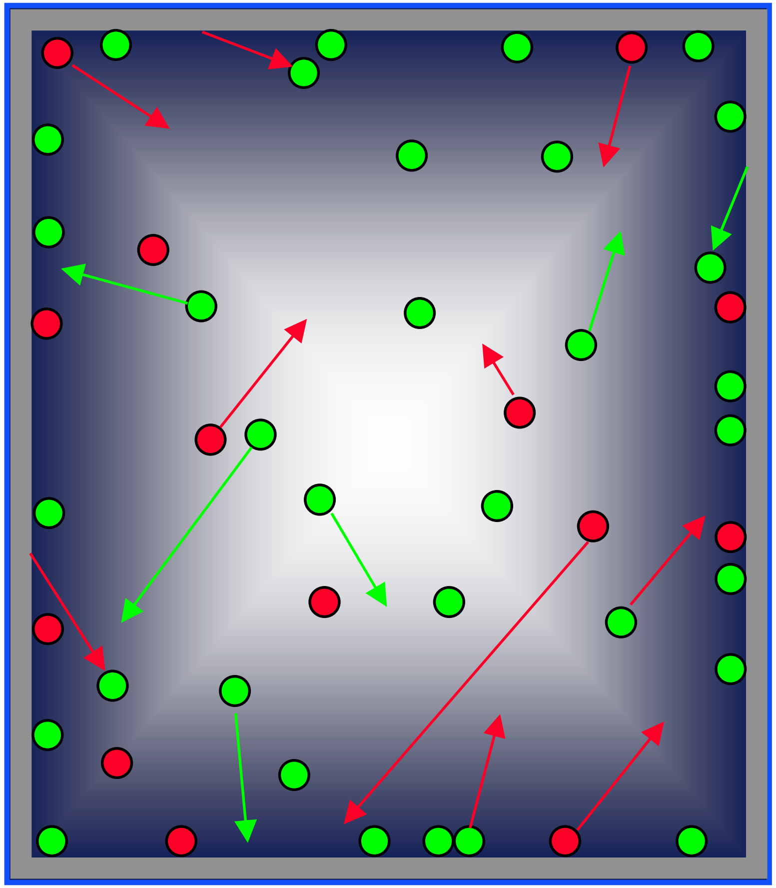


Adsorption and desorption (outgassing)

- **Adsorption** is the arrival of gas molecules on a surface
  - Adsorbed gas molecules exist as molecular layers and in some ways behave like a sheet of liquid
  - Rule of thumb – one monolayer consists of ~10^{15} molecules (atoms) per cm^2

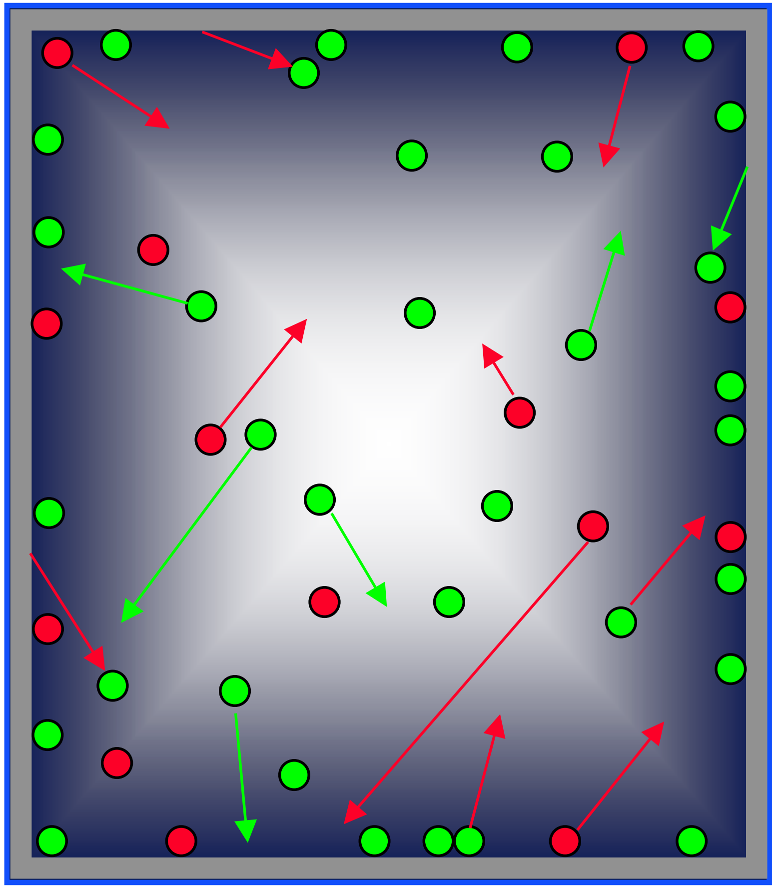
- **Residence time** is the amount of time a gas molecule stays on a surface

- **Desorption** is the departure of gas molecules from a surface
  - The rate of desorption is a function of the activation energy of the sorbent and the temperature of the surface



Significance of Surface Adsorption

Pressure (Torr)	Molecules on Surface / Molecules in Volume	Time to form Monolayer (sec)
10^{-3}	0.5	2.2×10^{-3}
10^{-6}	500	2.2
10^{-9}	500,000	2.2×10^{3}



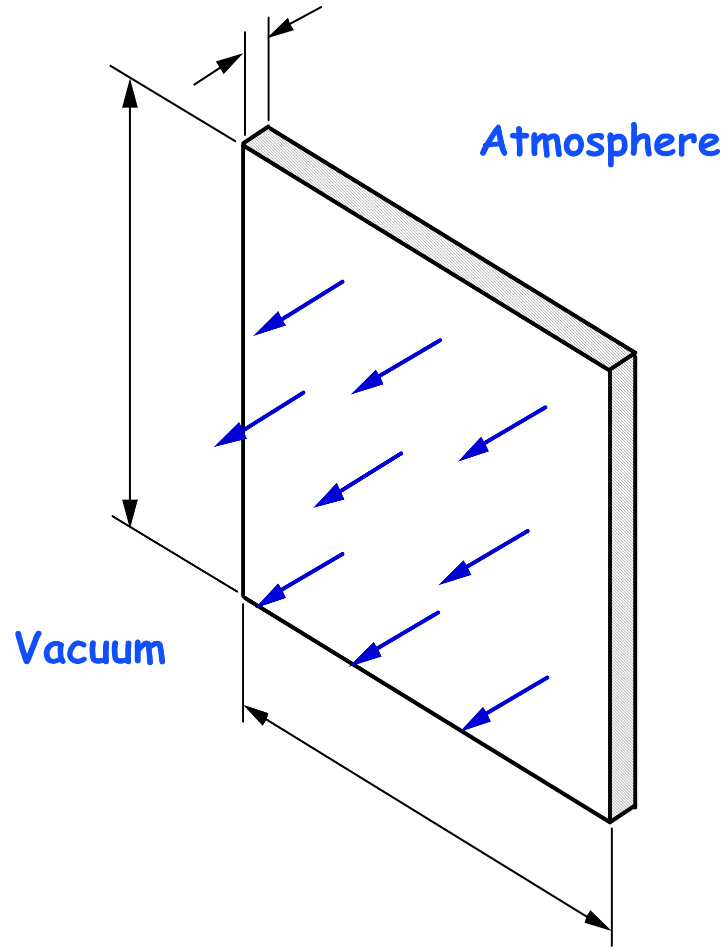
Adsorbed gases affect material properties

- 1 monolayer of adsorbed gas can influence bonding, wettability, and surface chemical reactions (in some cases)
- 1 to 10 monolayers of adsorbed gas affect lubrication and electrical conduction
- 1 to 200 monolayers of adsorbed gas change the absorption of light by a surface
- 200 to 2000 monolayers affect the visual color of surfaces

Permeation is the transfer of a fluid through a solid

- Material combination (fluid & solid)
- Temperature
- Permeation thickness
- Area
- Pressure differential

$$Q = \frac{KA(P_1 - P_2)}{t}$$



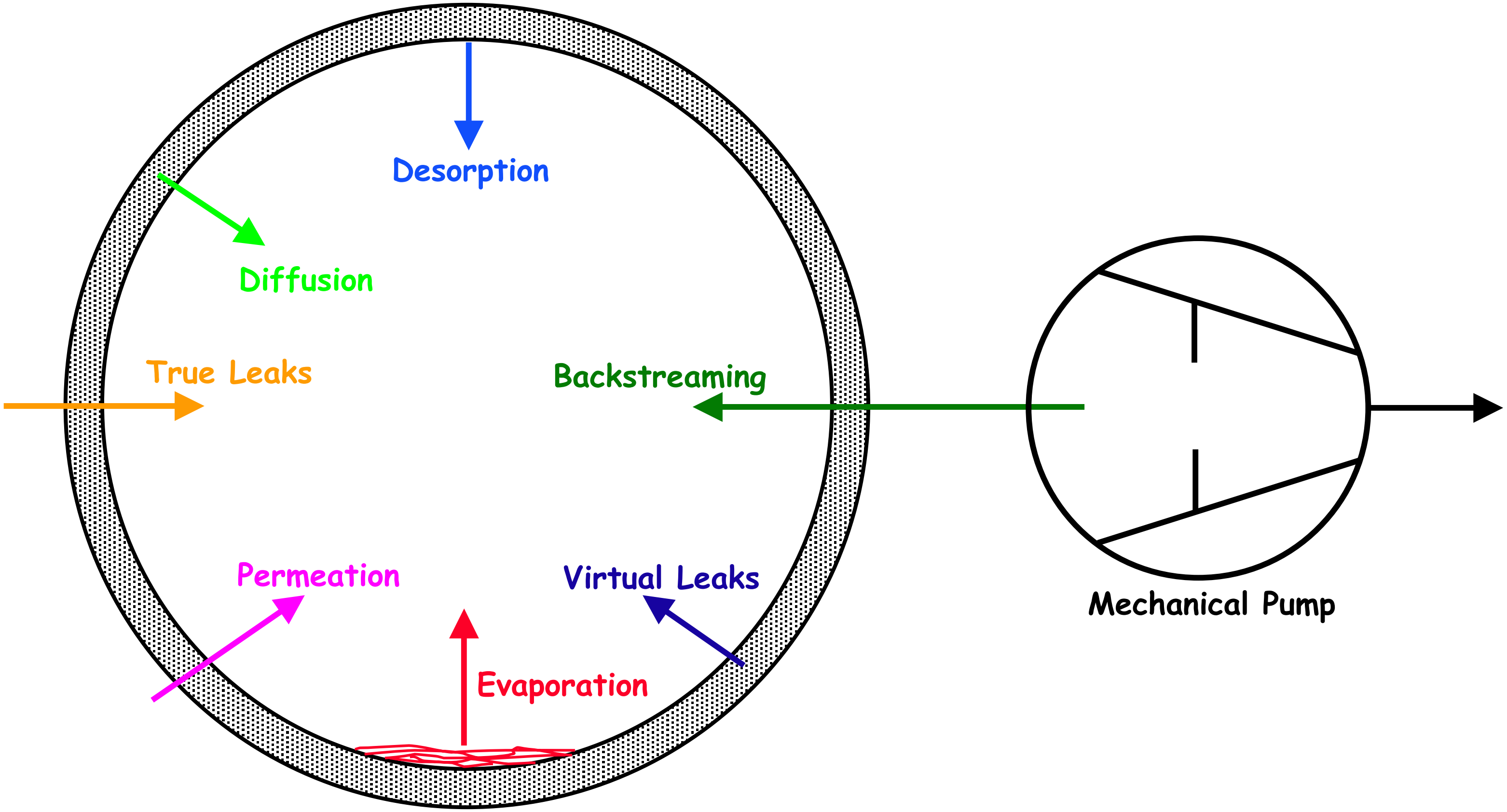
The US Particle Accelerator School
Estimating Gasloads

Lou Bertolini

Lawrence Livermore National Laboratory

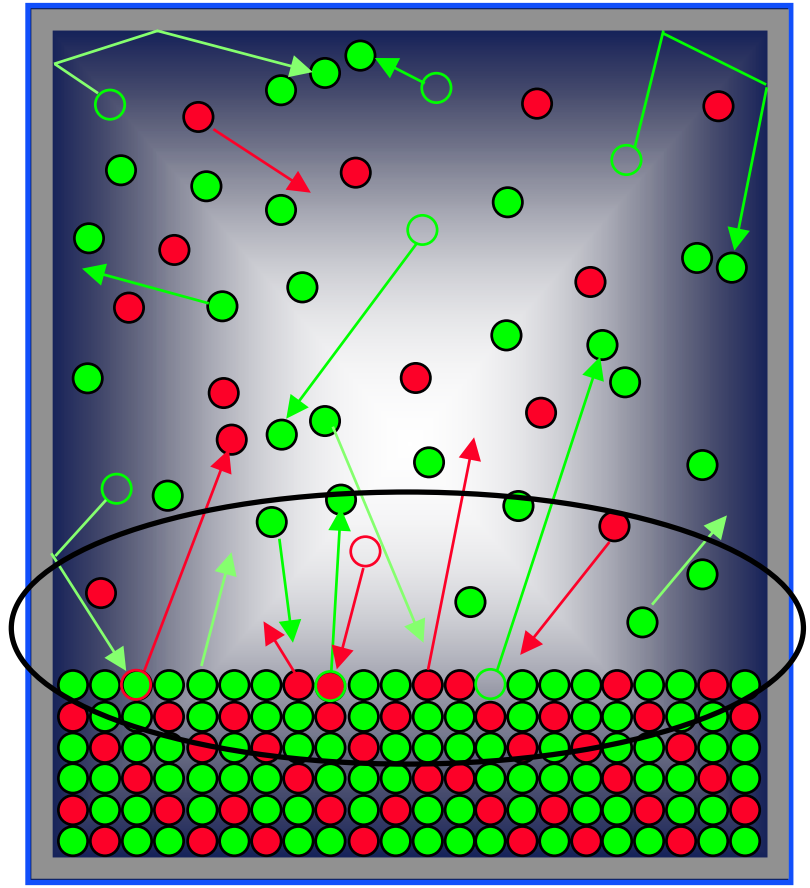
January 19-24, 2004

Sources of Gas in a Vacuum System



Desorption (outgassing)

- Desorption is the evolution of adsorbed gas from the internal surfaces of a vacuum vessel.
- Desorption is a function of :
  - Gas molecule characteristics
  - Surface material
  - Surface treatment
  - Surface temperature
  - Exposure time at vacuum
- High temperature bakeout under vacuum is required to desorb gasses in the shortest possible time.

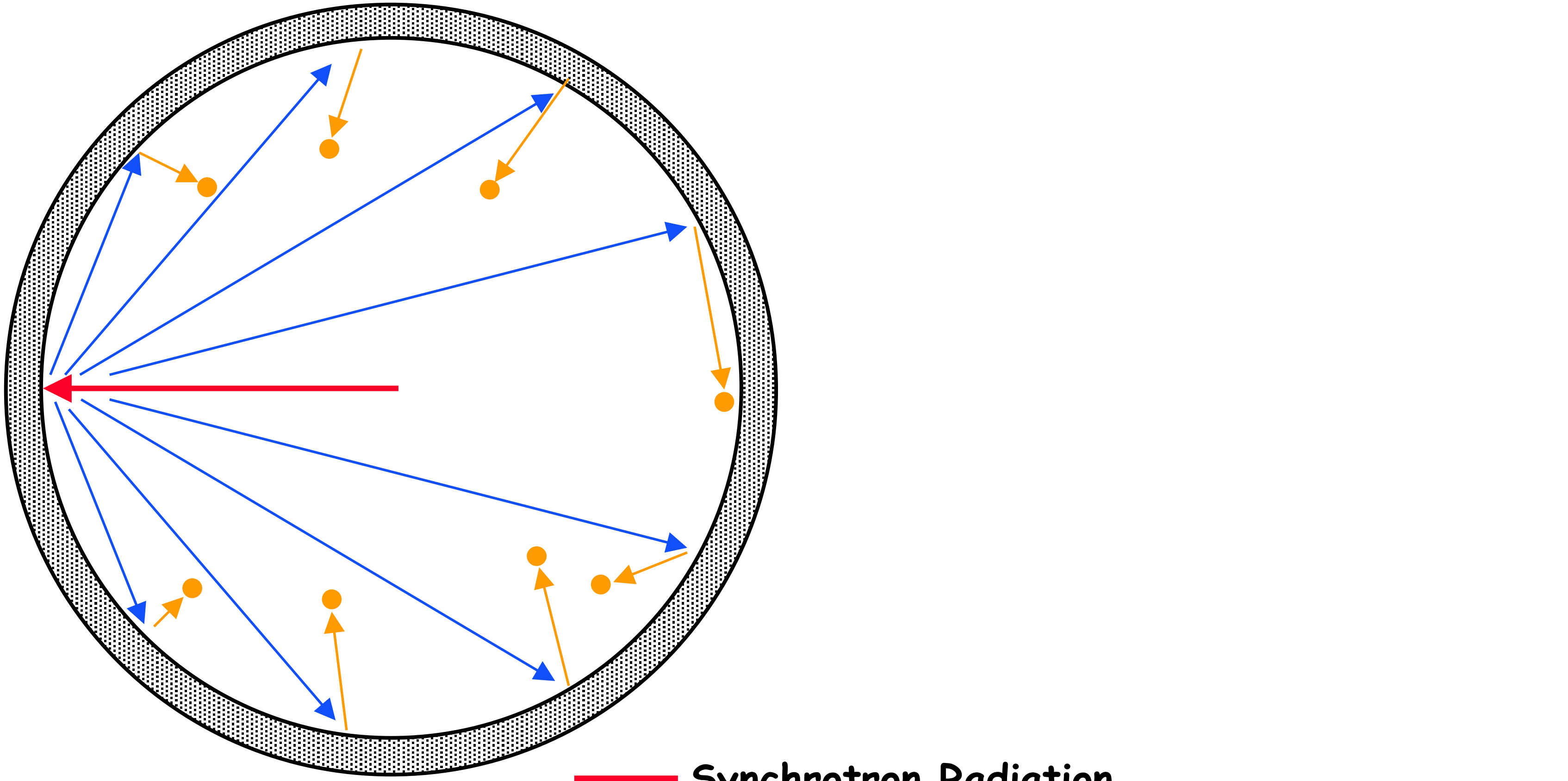


Use Published Desorption Data for comparative purposes only

Metals and Glasses	Desorption Rate (mBar-l/sec- cm^2 x 10^{-10}) 1 hr @ vacuum	4 hrs @ vacuum
Aluminum	80	7
Copper (mech. polished)	47	7
OFHC Copper (raw)	266	20
OFHC Copper (mech. polished)	27	3
Mild Steel, slightly rusty	58,520	199
Mild Steel, Cr plate (polished)	133	13
Mild Steel, Ni plate (polished)	40	4
Mild Steel, Al spray coating	798	133
Molybdenum	67	5
Stainless Steel (unpolished)	266	20
Stainless Steel (electropolished)	66	5
Molybdenum glass	93	5
Pyrex (Corning 7740) raw	99	8
Pyrex (Corning 7740) 1 mo. At Atm.	16	3

Ref. "Modern Vacuum Practice", Nigel Harris, pg 240

Photon Stimulated Desorption



Photon Stimulated Desorption

$$N_{\alpha} = \frac{(P_{SR})(l)(6.242 \times 10^{15}\ \text{KeV/Joule})}{\varepsilon}$$

where N_{a} = photon dose (photons/sec)

P_{SR} = Synchrotron Radiation Power (Watts/cm)

l = element length (cm)

ε = average photon energy = $0.308(2.218\ E^3/r)$ (keV/photon)

E = beam energy (GeV)

r = magnetic bend radius (m)

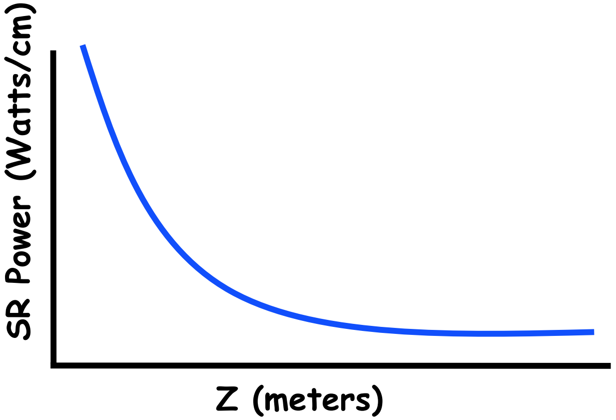
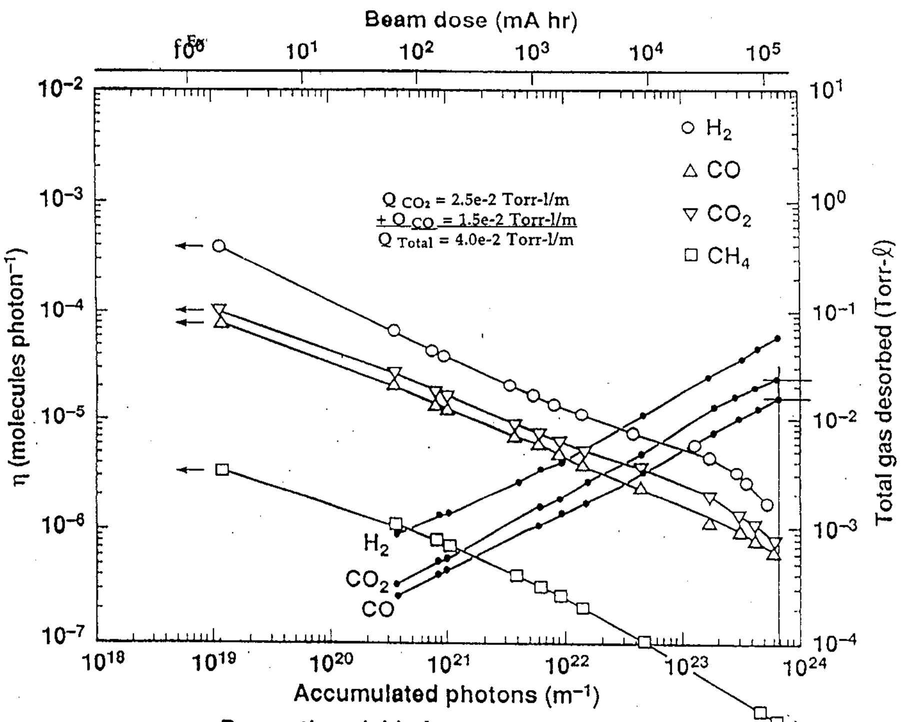


Photo-desorption rates vary with dose



Desorption yields from copper chamber (C10100) with glow discharge cleaning

"Eta-Leveling"

$$\eta_i = \eta_{base}\left(\frac{Peak\ P_{SR}}{P_{SR_i}}\right)^n$$

where η = photo-desorption coeff. (molecules/photon)

P_{SR} = Synch. Rad. Power (Watts/cm)

Photon Stimulated Desorption

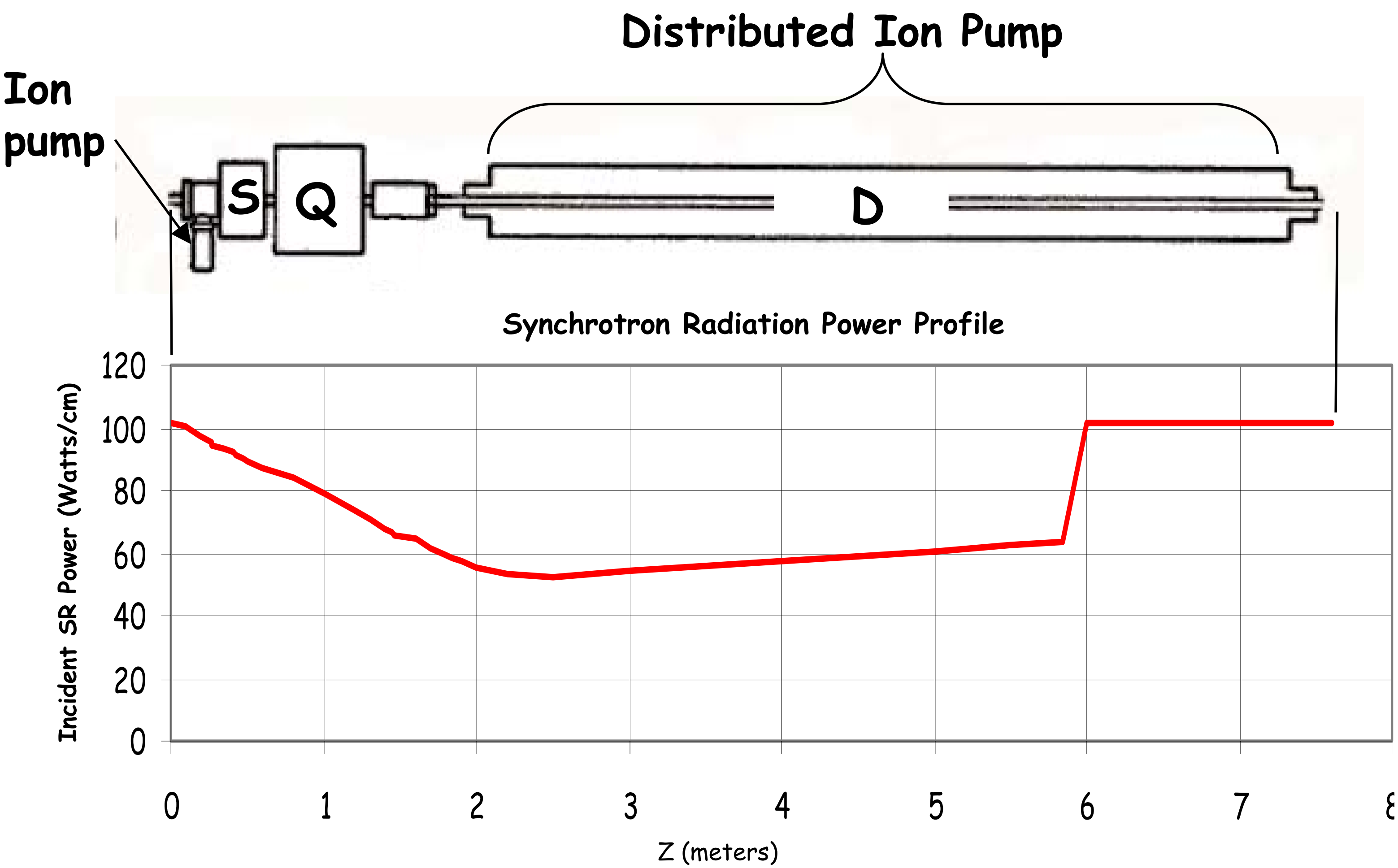
$$Q_i = N_\gamma \eta_i \left(\frac{22.4 \text{ liters x } 760 \text{ Torr}}{6.02 \text{ x } 10^{23} \text{ molecules}} \right)$$

where Q_i = Photon Stimulated Desorption (Torr - liters/sec)

N_γ = Photon Dose (photons/sec)

η_i = Photo - desorption Rate (molecules/photon)

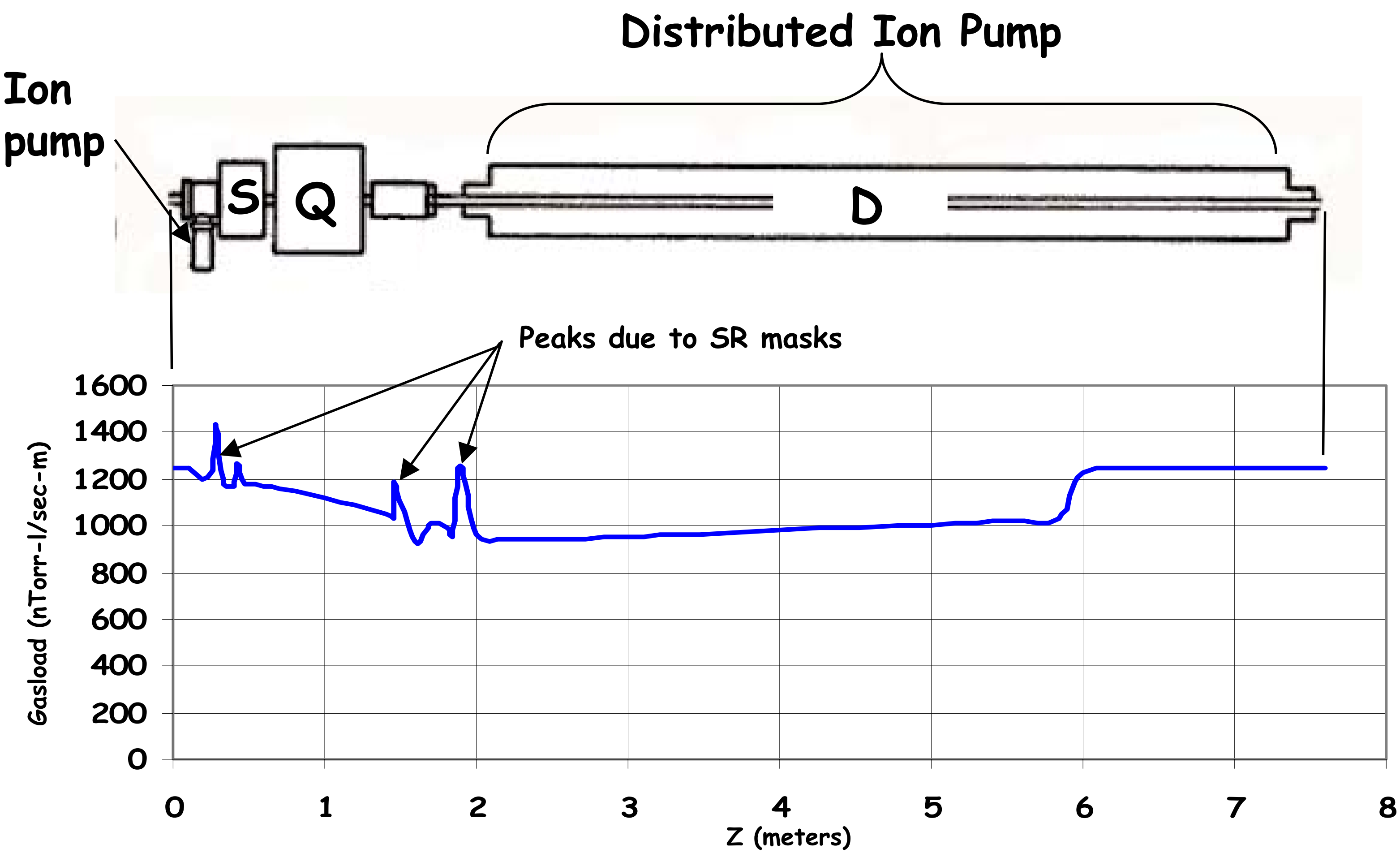
Photo-desorption Example Calculation – PEPII HER Arc Section



Example Gasload Worksheet

Z (m)	Element Length (m)	Power (Watts/cm)	η_i (molecules/photon)	N_γ (photons/sec)	Q_i (Torr-l/sec)	Q_i (Torr-l/sec)	Q_i (nTorr-l/sec)
0.00000		101.805					
0.10000	0.10000	100.484	2.014E-06	2.0781E+18	1.184E-07	5.800E-09	124.18
0.19280	0.09280	97.941	2.043E-06	1.8797E+18	1.086E-07	5.382E-09	113.98
0.25910	0.06630	95.848	2.067E-06	1.3142E+18	7.684E-08	3.845E-09	80.68
0.27690	0.01780	94.744	2.081E-06	3.4877E+17	2.052E-08	1.032E-09	21.55
0.34040	0.06350	93.679	2.094E-06	1.2302E+18	7.284E-08	3.683E-09	76.52
0.40390	0.06350	92.022	2.114E-06	1.2085E+18	7.225E-08	3.683E-09	75.94
0.42520	0.02130	90.919	2.128E-06	4.005E+17	2.411E-08	1.235E-09	25.34

Photo-desorption Example Calculation –
PEPII HER Arc Section Photo-desorption Profile



Evaporation

$$Q_E = 3.639\sqrt{\frac{T}{M}}\left(P_E - P\right)A$$

where Q_E = gasload due to evaporation (Torr-liters/sec)
T = temperature (K)
M = molecular weight (grams/mole)
P_E = vapor pressure of material (Torr)
P = pressure (Torr)
A = surface area of material evaporating (cm^2)

Leakage

True Leaks are steady-state gas loads, which limit the ultimate pressure of a vacuum system.

There are two categories of leaks in a vacuum system:

1. External Leaks or True Leaks (Q_{Lt})

   $Q_{Lt} > 10^{-5}$ Torr-liter/sec   laminar flow leak

   $Q_{Lt} < 10^{-8}$ Torr-liter/sec   molecular flow leak

Ref. "Vacuum Technology and Space Simulation", Santeler et al, NASA SP-105, 1966

Leakage (continued)

2. Internal Leaks or Virtual Leaks (Q_{Lv})

$$Q_{Lv} = \frac{P_a V}{et}$$

where Q_{Lv} = gasload due to virtual leak (Torr-liters/sec)

P_a = pressure of trapped gas (Torr)

V = volume of trapped gas (liters)

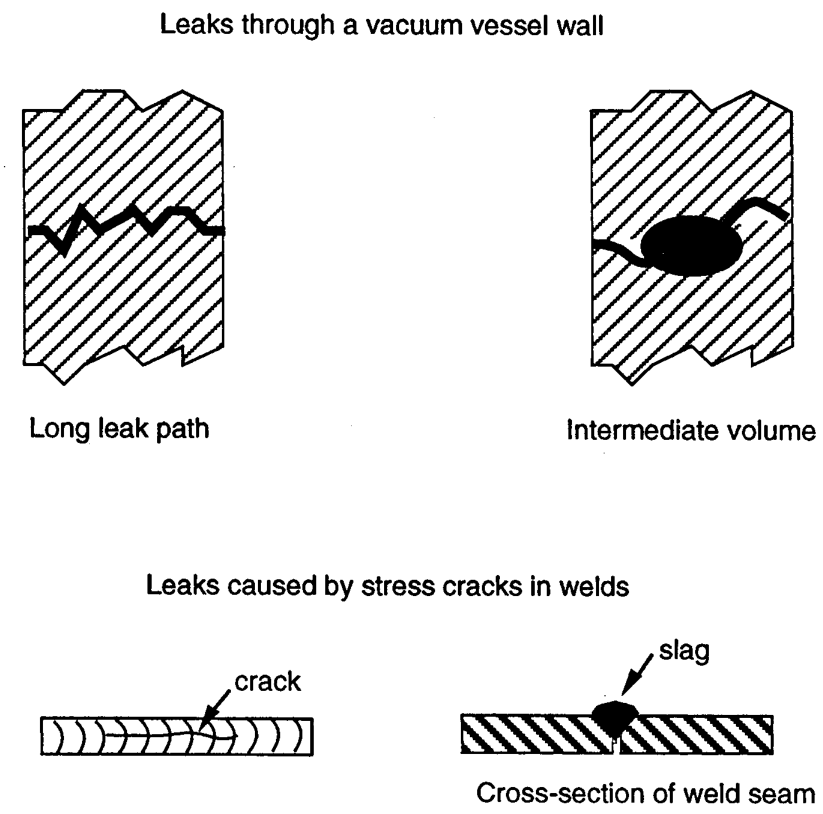
e = 2.7183 base to natural logarithm

t = time (sec)

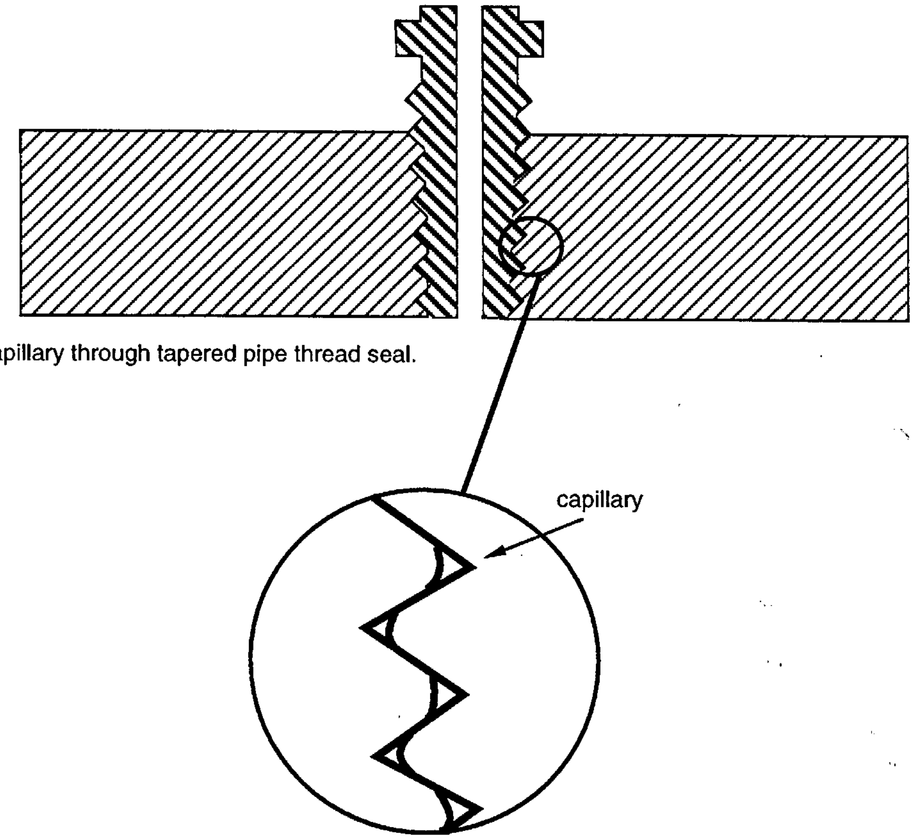
Ref. "Vacuum Technology and Space Simulation", Santeler et al, NASA SP-105, 1966

Examples of True Leaks

Real leak – physical hole or crack in vessel wall allowing gas to enter the vessel



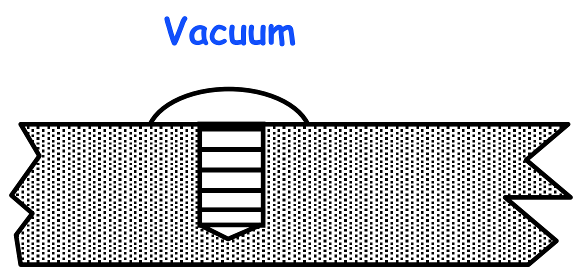
Another example of a true leak



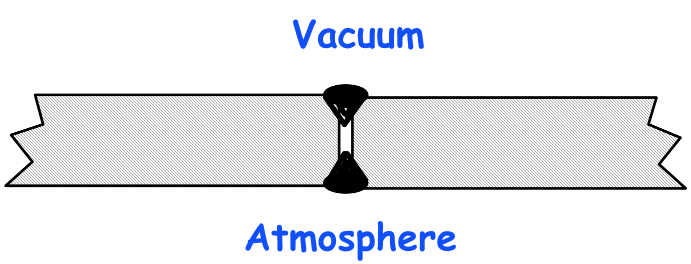
Capillary through tapered pipe thread seal.

Examples of Virtual Leaks

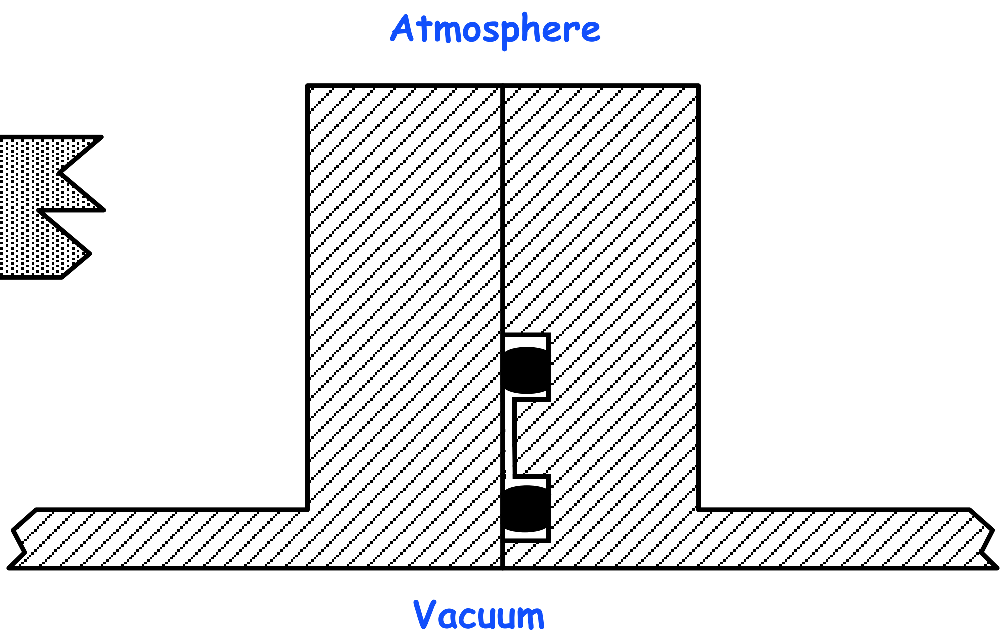
A virtual leak is a volume of trapped atmospheric gas that leaks into the vacuum vessel through holes or cracks that do not go all the way through the vessel wall.



Unvented Screw

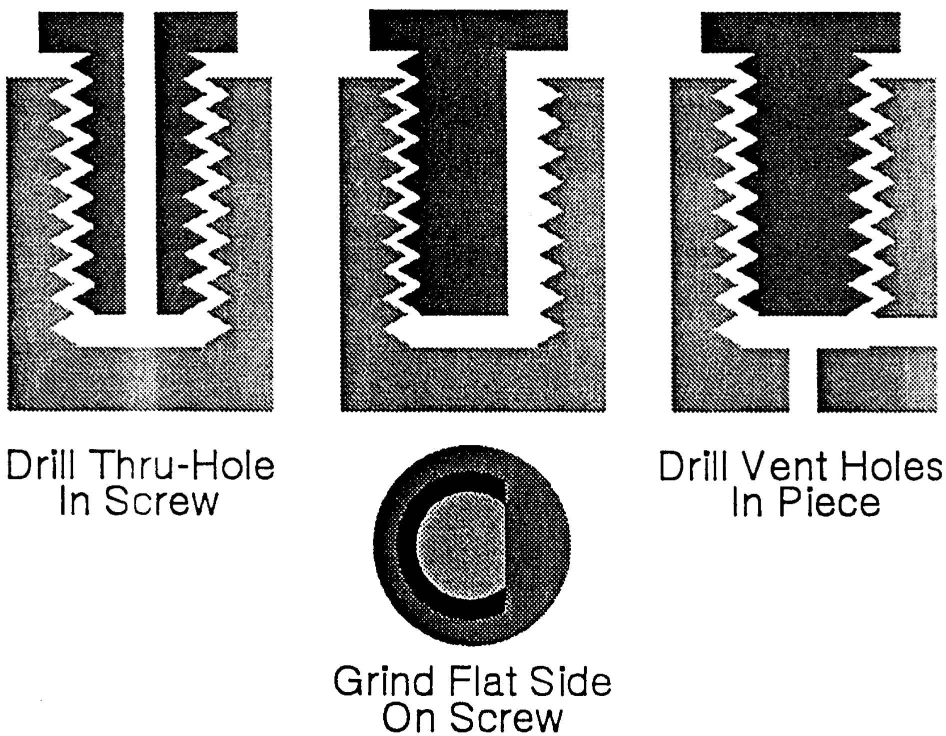


Two Welds in Series



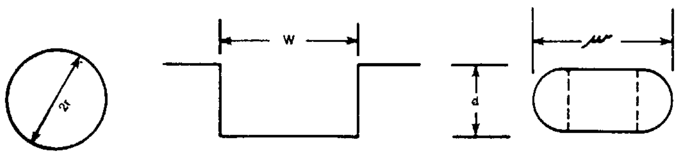
Unvented Double O-rings

Different solutions to blind tapped hole virtual leaks.



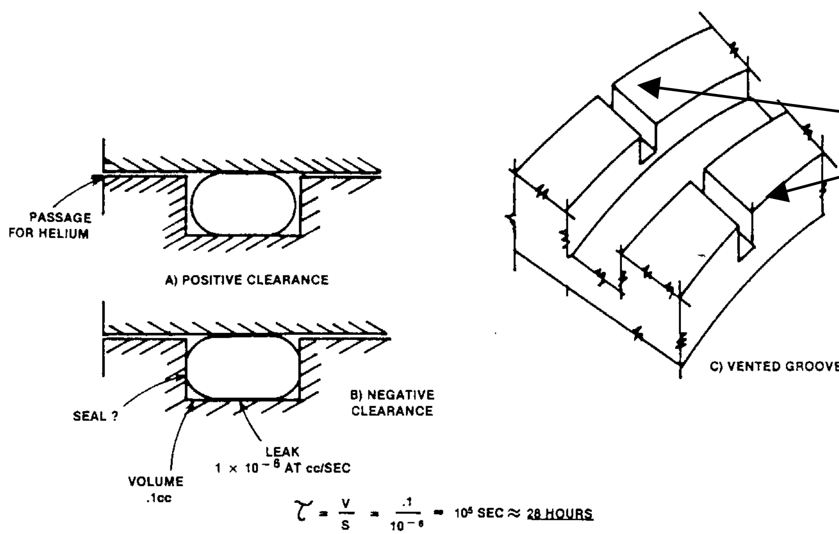
Thread and blind hole venting techniques

Improper sizing of o-rings can also produce virtual leaks.



2r	d	W	w	W - w
.100/.106	.074/.080	.171/.123	.115/.135	-.018/+.008
.135/.143	.101/.107	.157/.163	.157/.181	-.024/+.006
.205/.215	.152/.162	.247/.253	.239/.271	-.024/+.014
.269/.281	.201/.211	.322/.327	.315 .352	-.030/+.012

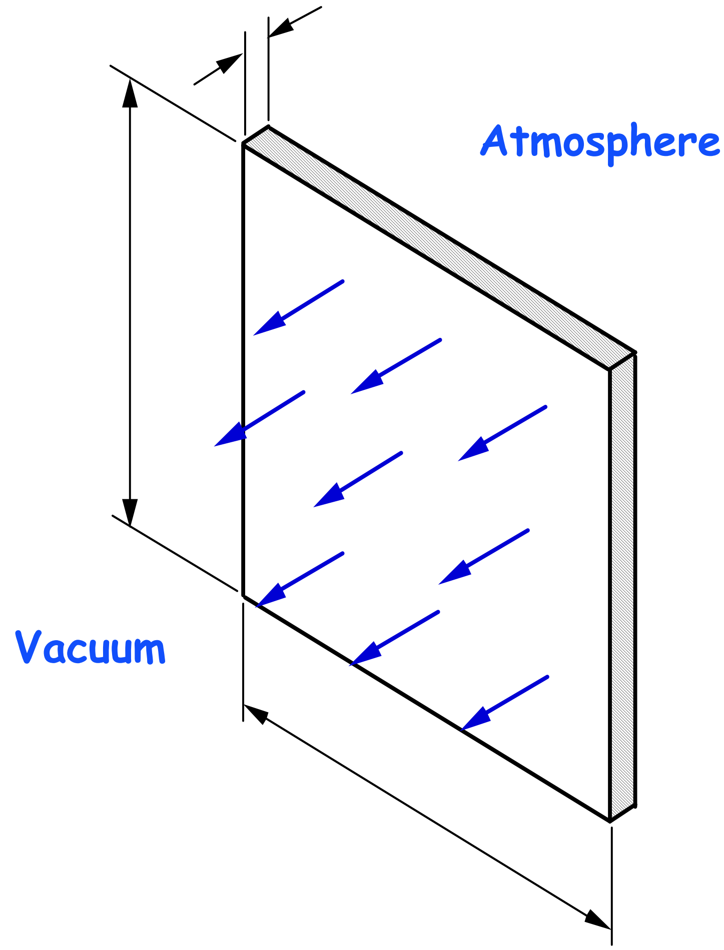
FIG. 3. O-ring seal.



Slot in O-ring groove helps to reduce chance of virtual leak

Permeation is the transfer of a fluid through a solid

- Material combination (fluid & solid)
- Temperature
- Permeation thickness
- Area
- Pressure differential



O-rings

- Fluorocarbon Rubber (Viton , Kalrez)
  Working temperature range -40 to 200^{o}C
  Hardness: Shore A-75

- Nitrile (Buna N)
  Working temperature range -32 to 135^{o}C
  Hardness: Shore A-70

- Silicone Rubber (Silastic, Silplus)
  Working temperature range -115 to 200^{o}C
  Hardness: Shore A-70

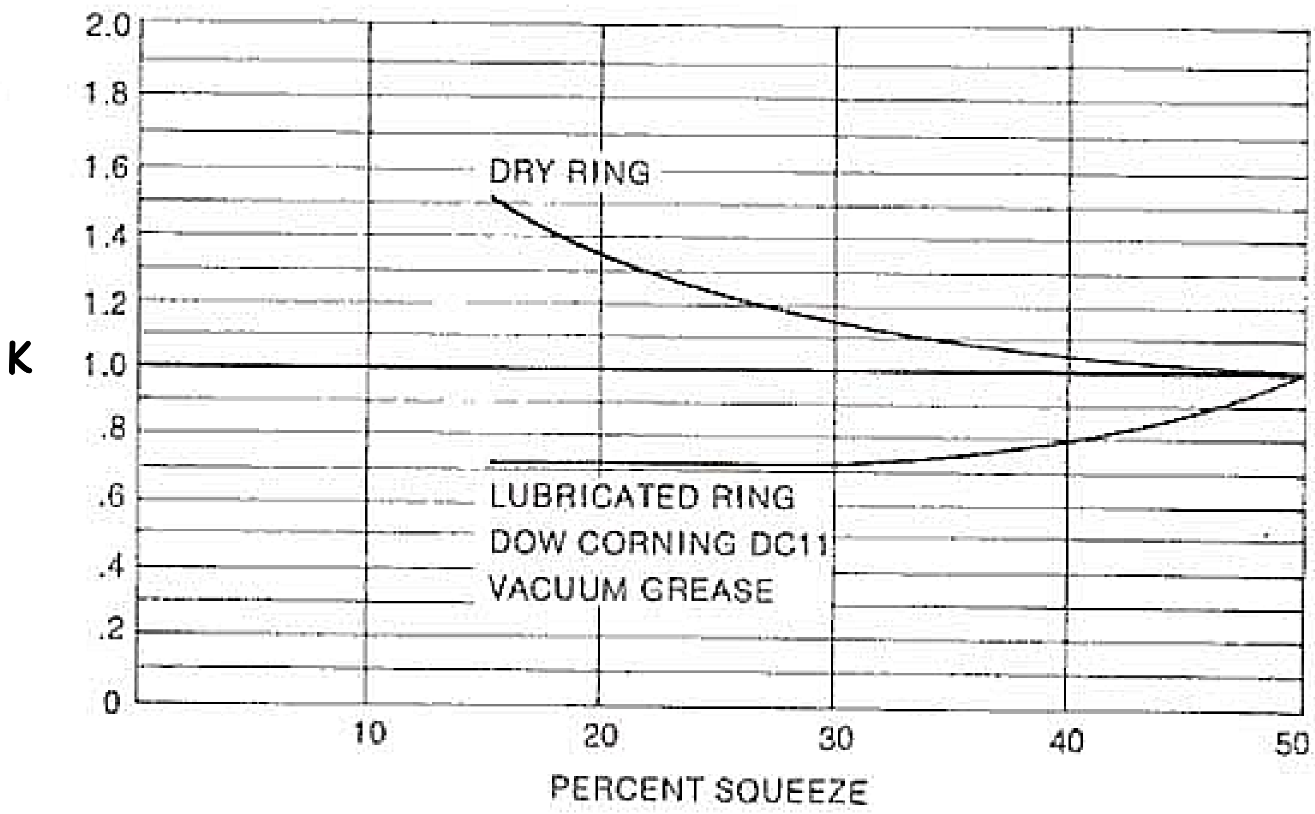
O-ring Permeation Leak Rate Approximation

$$Q_P = 0.7FD(\Delta P)\,K(1 - S)^2$$

where	Q	=	leak rate (std cc/sec)
	F	=	permeability rate for a specific gas through a specific elastomer at a specific temperature (std cc-cm/cm^2 sec bar)
	D	=	o-ring dia. (in)
	ΔP	=	pressure differential across o-ring (psi)
	K	=	factor depending on % squeeze and lubrication (see next slide)
	S	=	% squeeze

Ref. Parker O-ring Handbook

Effect of Squeeze and Lubrication on O-ring Permeability Leak Rate



Ref. Parker O-ring Handbook

Example Calculation of O-ring Permeability

What is the approximate H_2 permeability rate of a 10" diameter Viton o-ring (no lubrication, with a 20% squeeze) at a Δp = 14.7 psi?

$F = 160 \times 10^{-8}$ std cc-cm from Parker Table A2-4

D = 10" diameter

Δp = 14.7 psi

K = 1.35 from Parker Figure A2-2

S = 0.20

$$Q = 0.70FD(\Delta P)K(1 - S)^2$$

$$Q = 0.70\left(160 \times 10^{-8}\ \frac{\text{std cc - cm}}{\text{cm}^2 - \text{sec} - bar}\right)(10'')(14.7\ \text{psi})(1.35)(1 - 0.20)^2$$

$$Q = \left(1.42 \times 10^{-4}\ \frac{\text{std cc}}{\text{sec}}\right)\left(\frac{liters}{1000\ cc}\right)\left(\frac{760\ \text{Torr}}{\text{Std Atm}}\right)$$

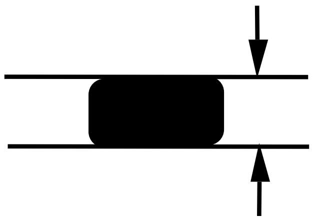
$$Q = 1.08 \times 10^{-4}\ \frac{\text{Torr - liters}}{\text{sec}}$$

O-ring Seal Design Considerations

- The leak rate through an o-ring is dependent on the following:
  1. % squeeze
  2. Lubricated or dry

- Increased o-ring squeeze decreases permeability by increasing the path length the gas has to travel.

- Increased o-ring squeeze also decreases the exposed area available for gas entry.

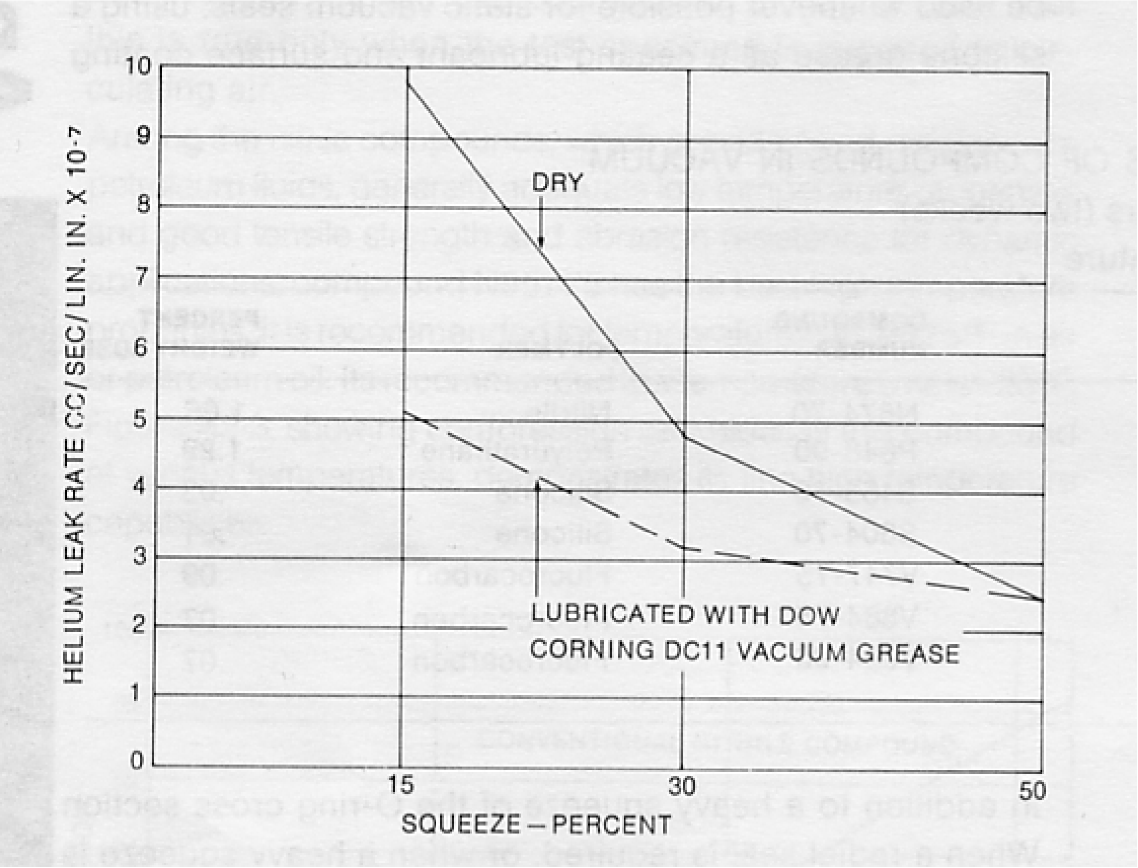


- Increased o-ring squeeze also forces the elastomer into the microscopic irregularities in the sealing surface.

O-ring Seal Design Considerations

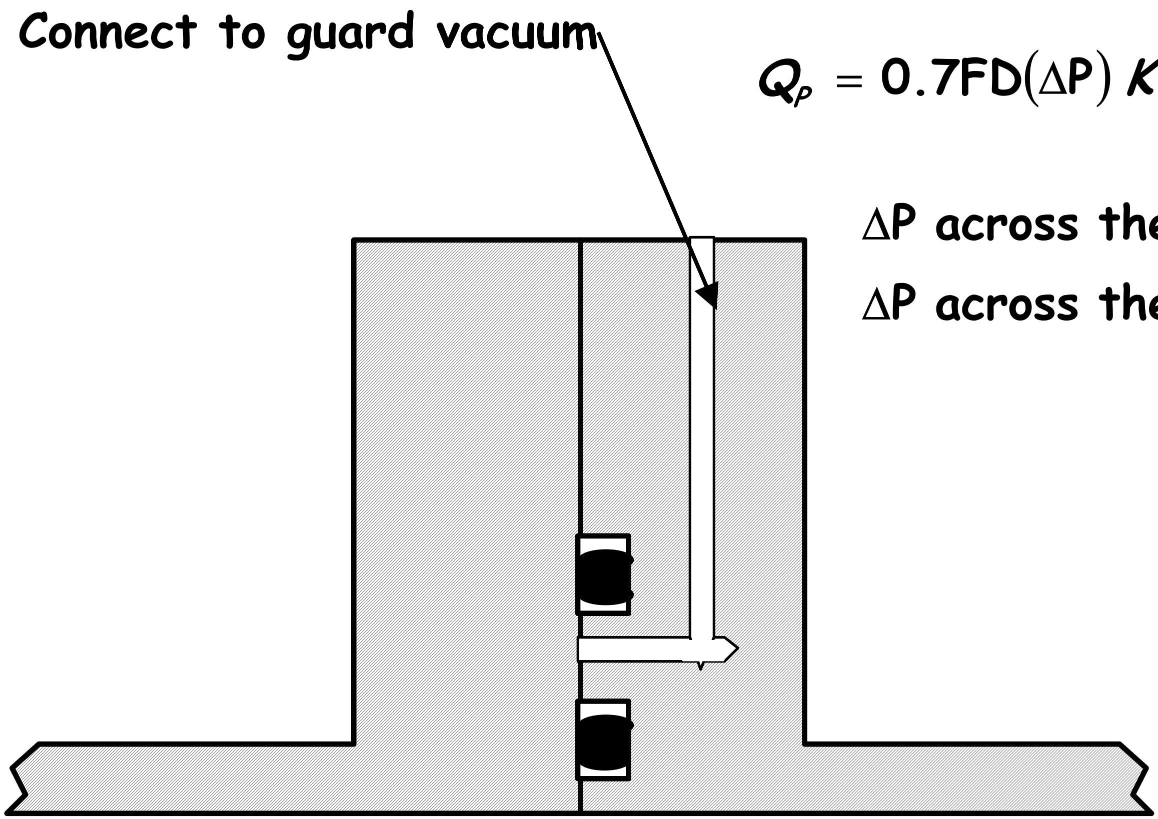
- Face-type o-ring seals are recommended.
- Use as heavy a squeeze as possible on the o-ring cross-section.
- When a heavy squeeze is not possible, then (and only then) consider lubrication.
- A heavy squeeze requires heavy flange construction .
- Two o-rings in series can drastically reduce permeation.

Helium Permeation Rate vs. % Squeeze



Ref. Parker O-ring Handbook

Multiple O-ring Seals

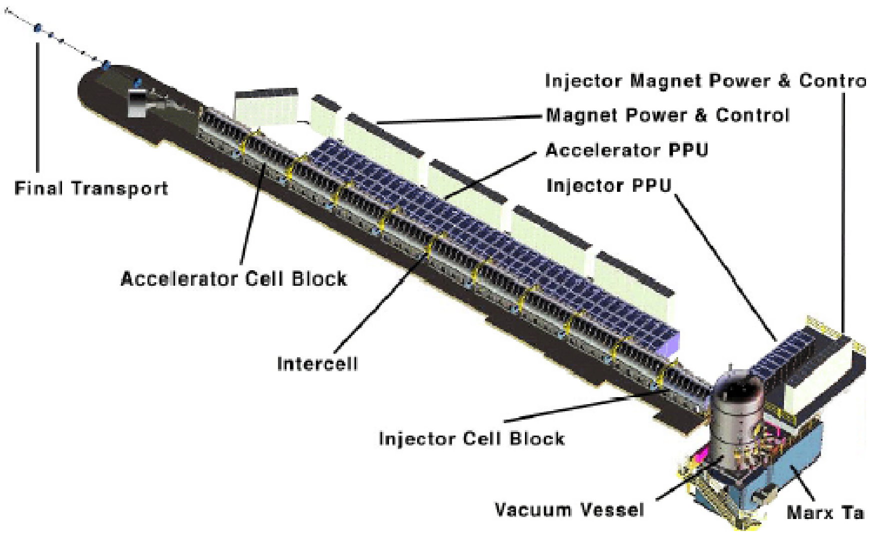


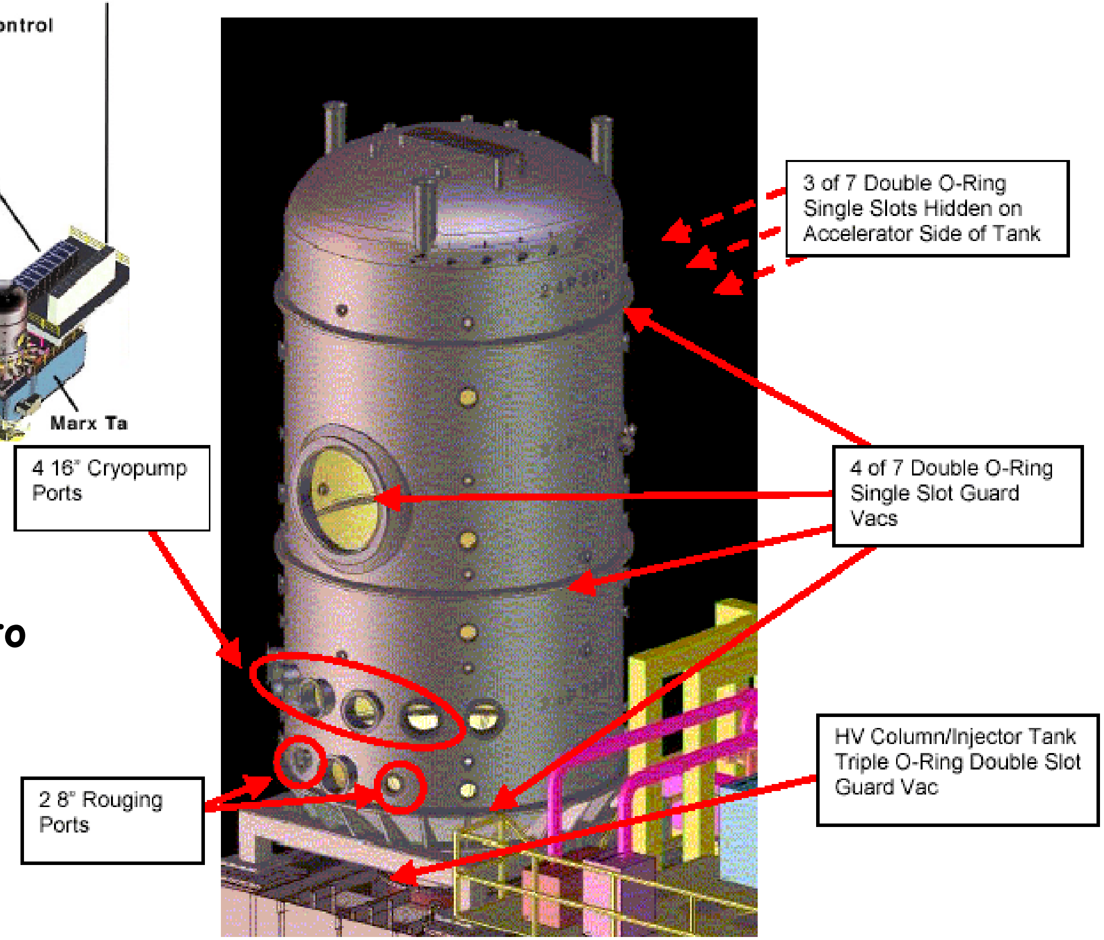
$$Q_P = 0.7FD(\Delta P)\,K(1 - S)^2$$

ΔP across the 1st o - ring = 760 Torr

ΔP across the 2nd o - ring = 10^{-2} Torr

DARHT II Injection Tank - Example of Multiple O-ring Seals





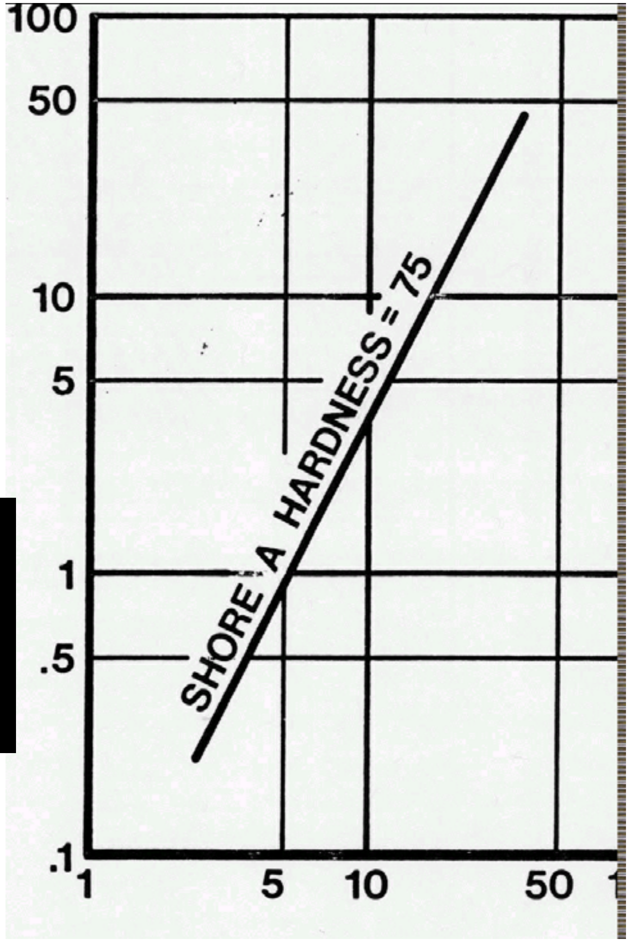
- Design pressure 5 x 10^{-8} Torr
- Guard vacuum between o-rings to minimize permeation
  - Dry mechanical pumps
  - 15 mTorr pressure

Force Required to Compress O-rings

The compression force (per linear inch of o-ring) is dependent on:

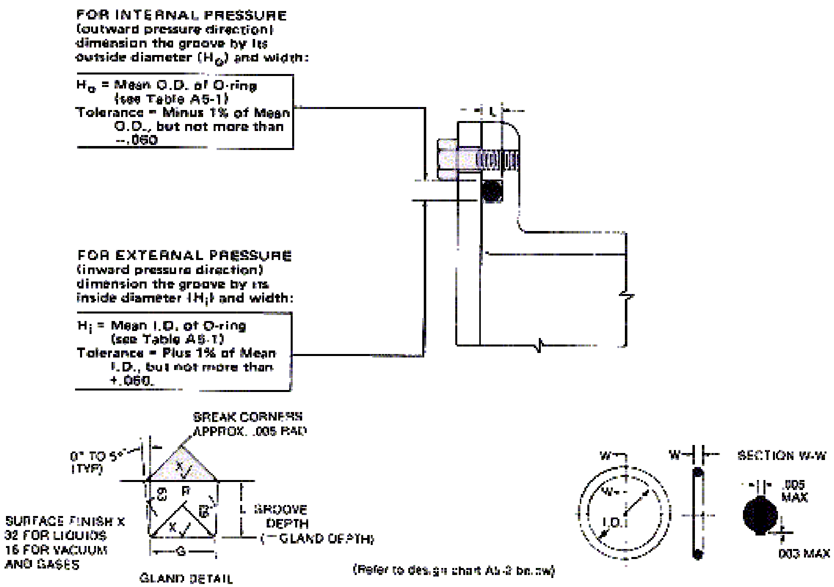
1. Hardness of the o-ring
2. O-ring cross-section
3. % squeeze

Variations in material properties will cause the compression forces to vary though the three attributes are the same.



Typical O-Ring Groove Dimensions

face seal glands



DESIGN CHART A5-2
FOR O-RING FACE SEAL GLANDS
These dimensions are intended primarily for face type seals and low temperature applications.

O-RING SIZE PARKER NO. 2	CROSS SECTION		GLAND DEPTH	SQUEEZE		GROOVE WIDTH		GROOVE RADIUS
	NOMINAL	ACTUAL		ACTUAL	%	LIQUIDS	VACUUM AND GASES	
004 through 050	1/16	.070 ±.003	.050 to 054	.013 to .023	19 to 32	.101 to .107	.084 to .089	.005 to 015
102 through 178	3/32	.103 ±.003	.074 to .080	.020 to .032	20 to 30	.136 to .142	.120 to .125	.005 to 015
201 through 284	1/8	.139 ±.004	.101 to .107	.028 to .042	20 to 30	.177 to .187	.158 to .164	.010 to 025
309 through 395	3/16	.210 ±.005	.152 to .162	.043 to .063	21 to 30	.270 to .290	.239 to .244	.020 to .035
425 through 475	1/4	.275 ±.006	.201 to .211	.058 to .080	21 to 29	.342 to 362	309 to .314	.020 to .035
Special	3/8	.375 ±.007	.276 to .286	.082 to .108	22 to 28	.475 to .485	.419 to .424	.030 to .045
Special	1/2	.500 ±.008	.370 to .380	.112 to .138	22 to 27	.638 to .645	.560 to .565	.030 to .045

"0" preferred

A5-13

Ref. Parker O-ring Handbook

The US Particle Accelerator School
Vacuum System Design Calculations

Lou Bertolini

Lawrence Livermore National Laboratory

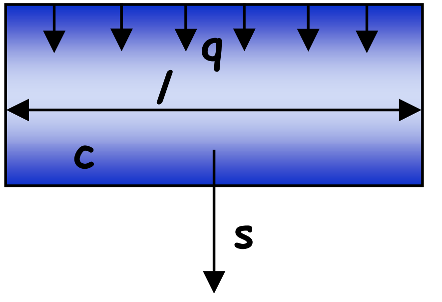
January 19-24, 2004

Vacuum System Design . . . Motivation

- The goal is to develop a numerical model of the vacuum system whether simple or complex.
- This effort is undertaken to provide an understanding of the critical issues (e.g. conductance limiting components, surface outgassing rates and leak rates) in order to design the most cost-effective pumping system.
- Simple pumping calculations can lead to over-designing the pumping system which can escalate the costs for a large accelerator system.

Calculating Steady-State Pressure Profiles using VACCALC

$$\frac{d}{dz}\left(c\frac{dP}{dz}\right) - sP + q = 0$$



where z = axial beamline length (m)

c = conductance m(liters/sec)

s = pumping speed (liters/sec)/m

q = gasload (nTorr - liters/sec)/m

Ref. "A Method for Calculating Pressure Profiles in Vacuum Pipes", Sullivan, SLAC, 1993

VACCALC Input

- Each beampipe element is described by the following characteristics:
  1. Lumped or distributed values.
  2. Length (m)
  3. Axial conductance (liters/sec)
  4. Outgassing rate (nTorr-liters/sec)
  5. Pumping speed (liters/sec)

- Segment length (Δz) is specified for all elements

- 10,000 segments max. per pipe.

Sample VACCALC Input File

Segment Length — Segment Node Numbers — Length — Outgassing load — Pumping Speed — Conductance

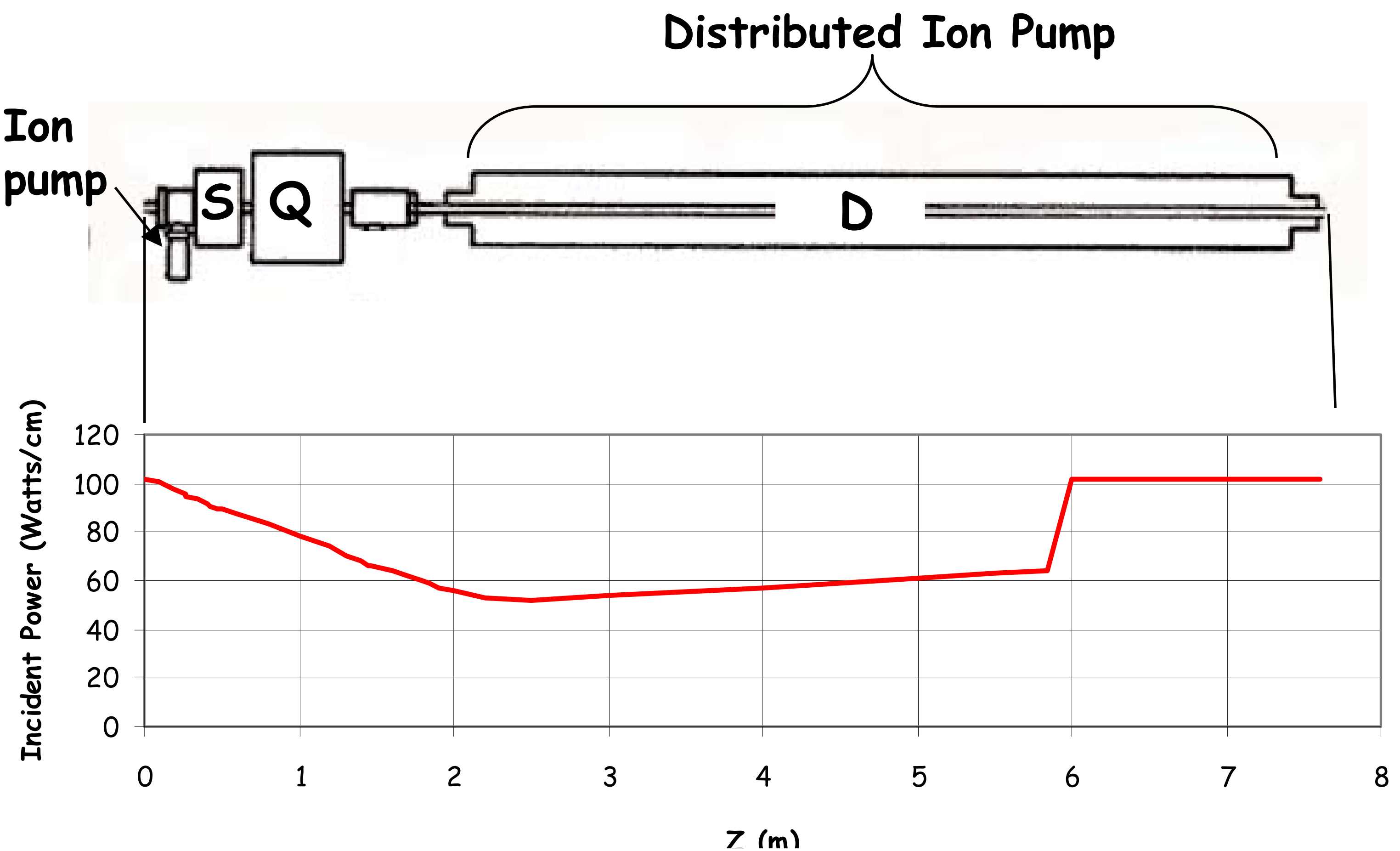
```
Model of LCLS Undulator Beam Pipe
0.005
2                Segments
First Segment
   0.00    0.00    1    2    LIN    20
Pump             L           0.1     0.15537    0.00785    1.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    1.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    1.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    1.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    1.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    1.00
ENDPIPE
Second Segment
   0.00    0.00    2    3    LIN    20
Pump             L           0.1     0.15537    0.00785    2.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    3.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    4.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    5.00
Undulator        L           4.9     0.00317    0.39781    0.00
Pump             L           0.1     0.15537    0.00838    1.00
ENDPIPE
```

VACCALC Output

- VACCALC produces an Excel Spreadsheet output file called "VACCALC.tsv" which includes the following:

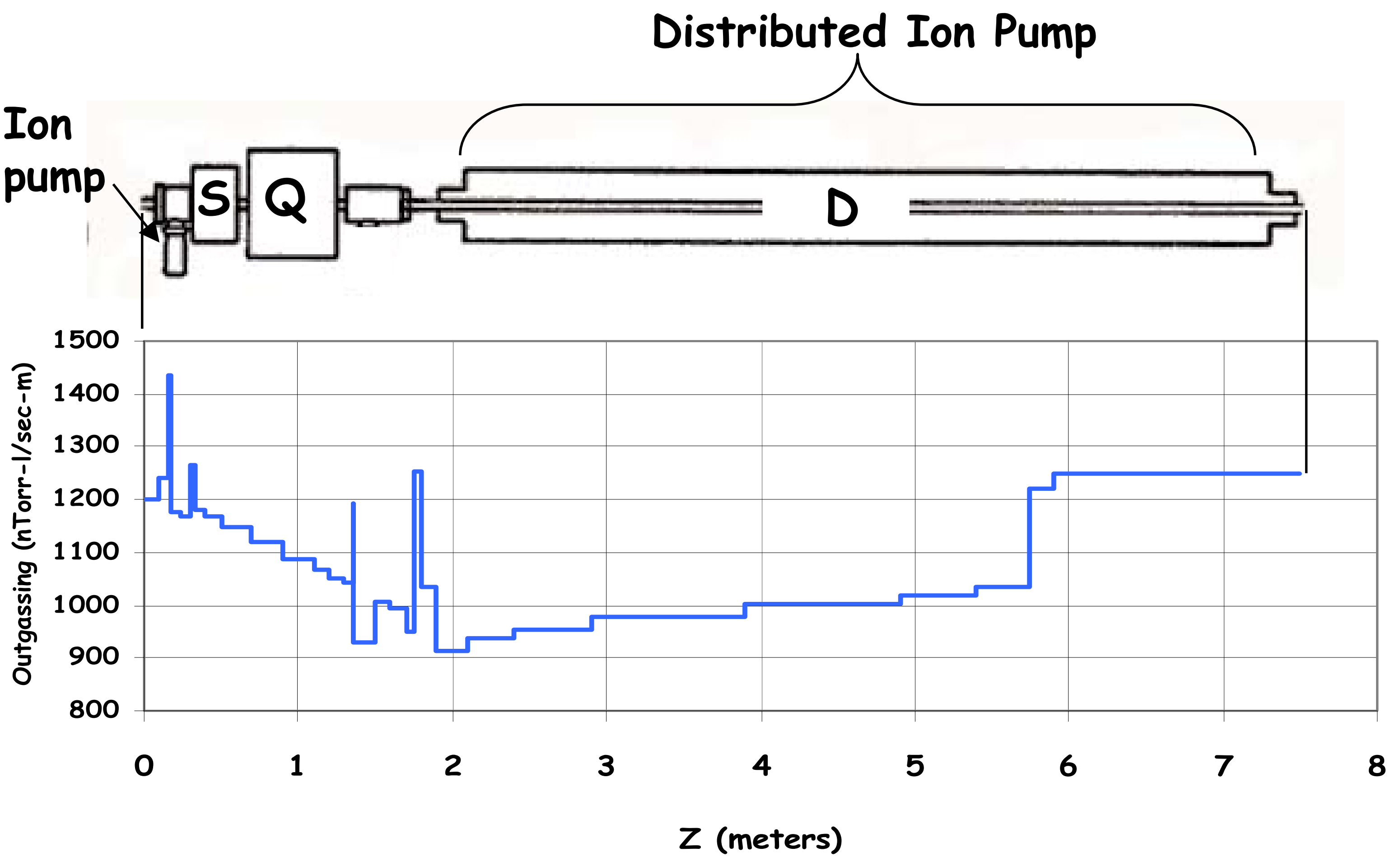
  1. Pressure (nTorr) vs. Z (meters)
  2. Average Pressure along piping segment (nTorr)
  3. Axial Conductance (liters/sec-m) vs. Z (meters)
  4. Gasload (nTorr-liters/sec-m) vs. Z (meters)
  5. Pumping Speed (liters/sec-m) vs. Z (meters)

VACCALC Example – PEPII HER Arc Section
Synchrotron Radiation Power Profile

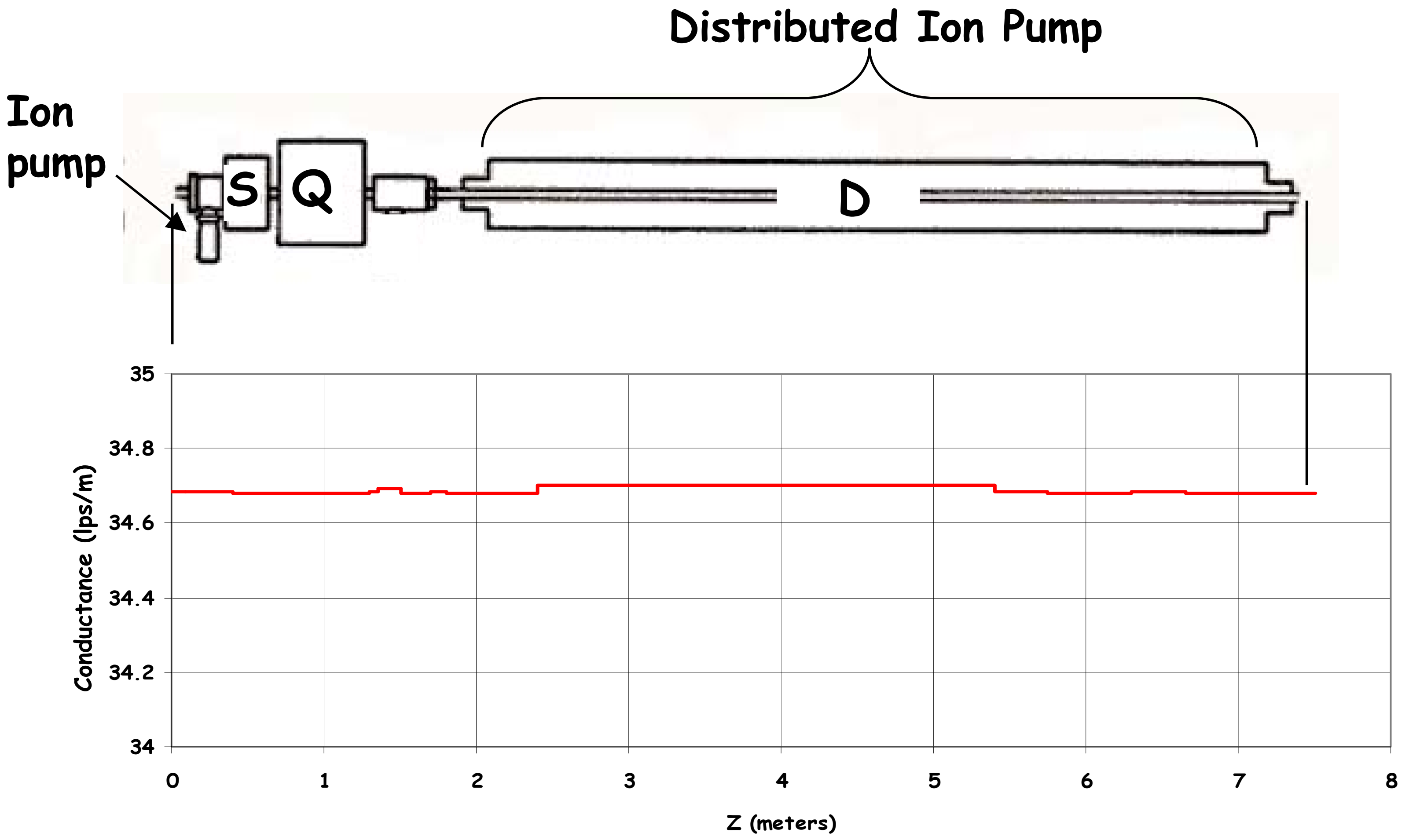


VACCALC Example - PEPII HER Arc Section

Graphical Representation of Input Gasload Profile

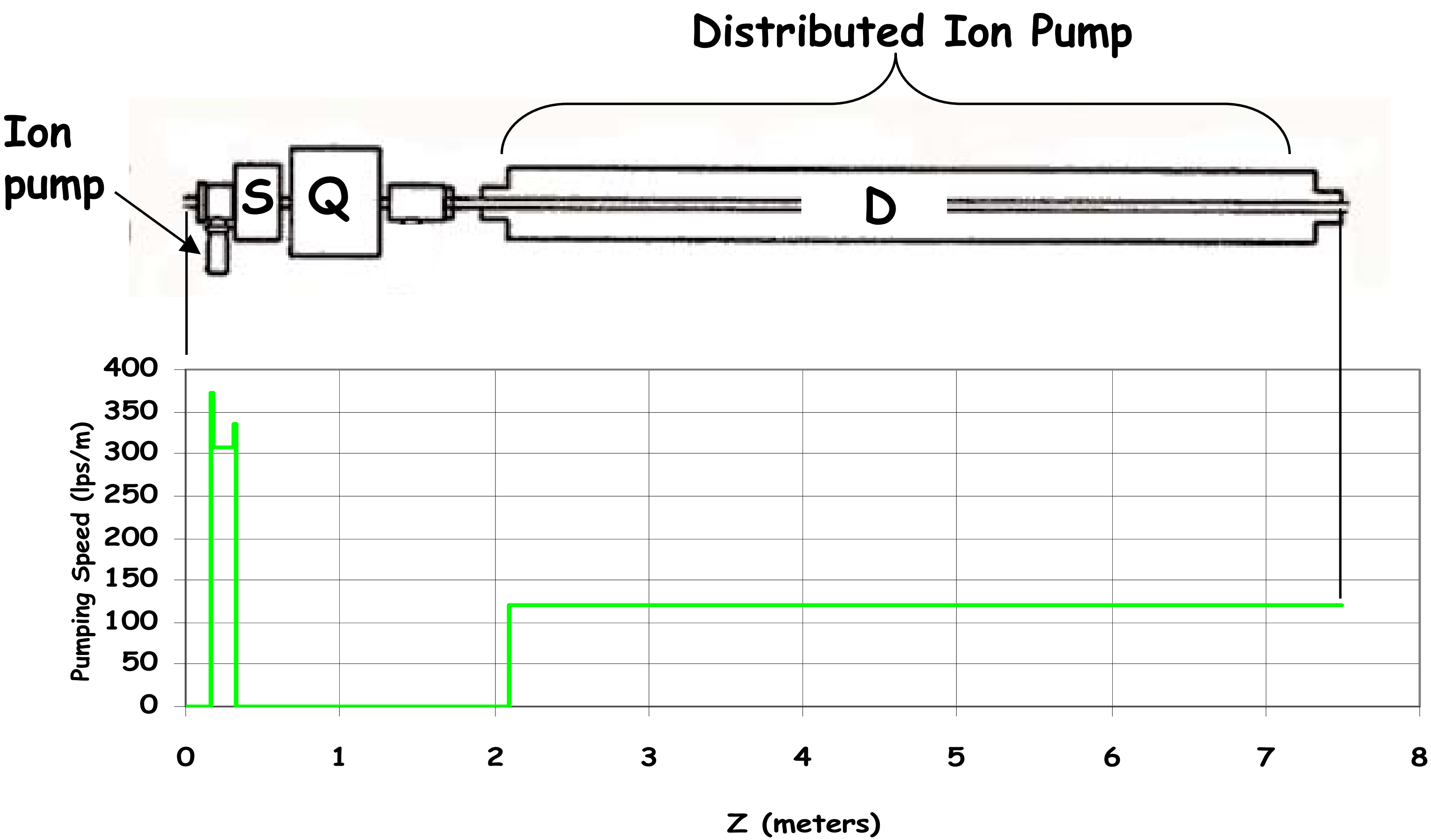


VACCALC Example – PEPII HER Arc Section
Graphical Representation of Input Conductance Profile



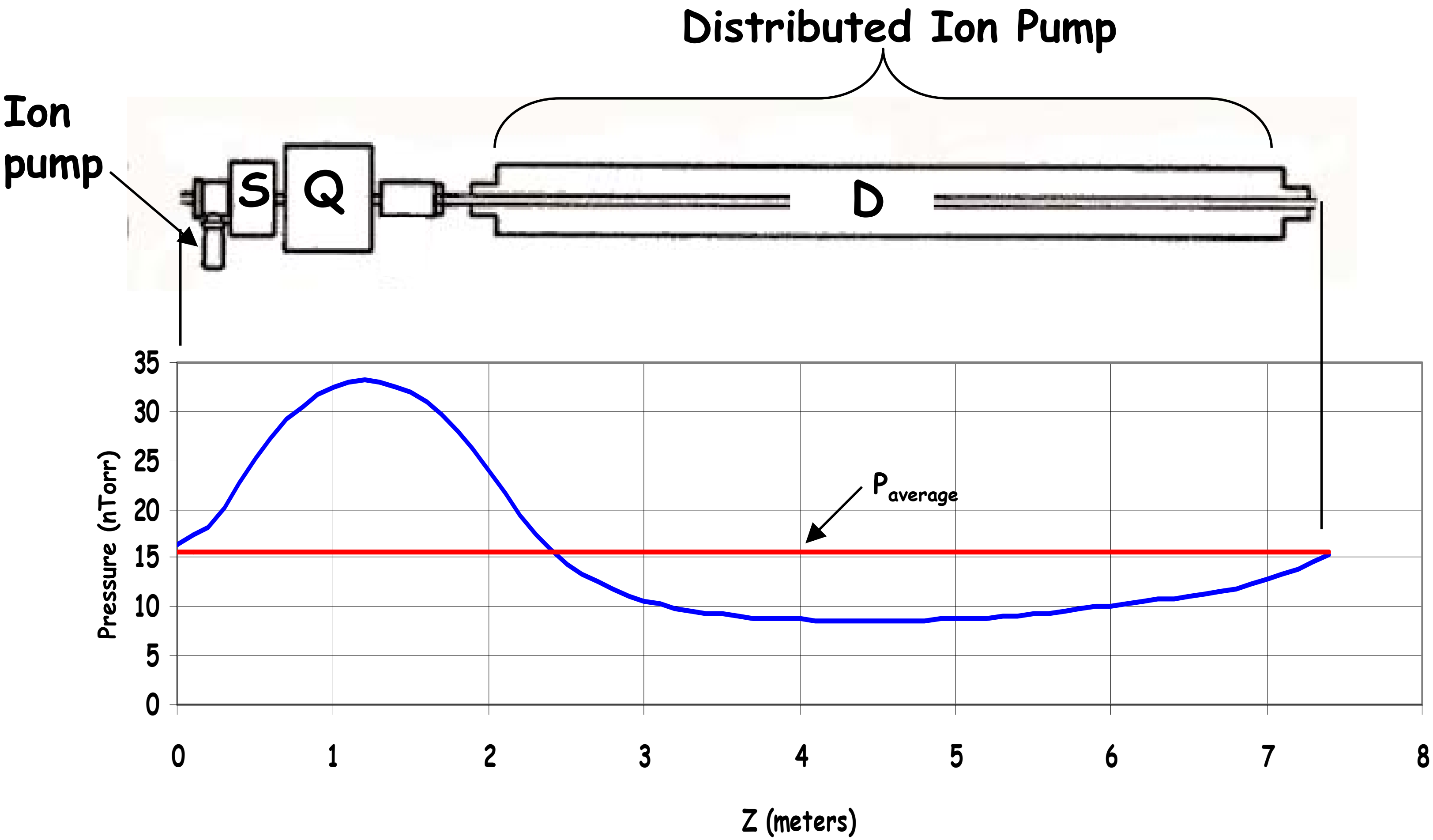
VACCALC Example – PEPII HER Arc Section

Graphical Representation of Input Pumping Profile



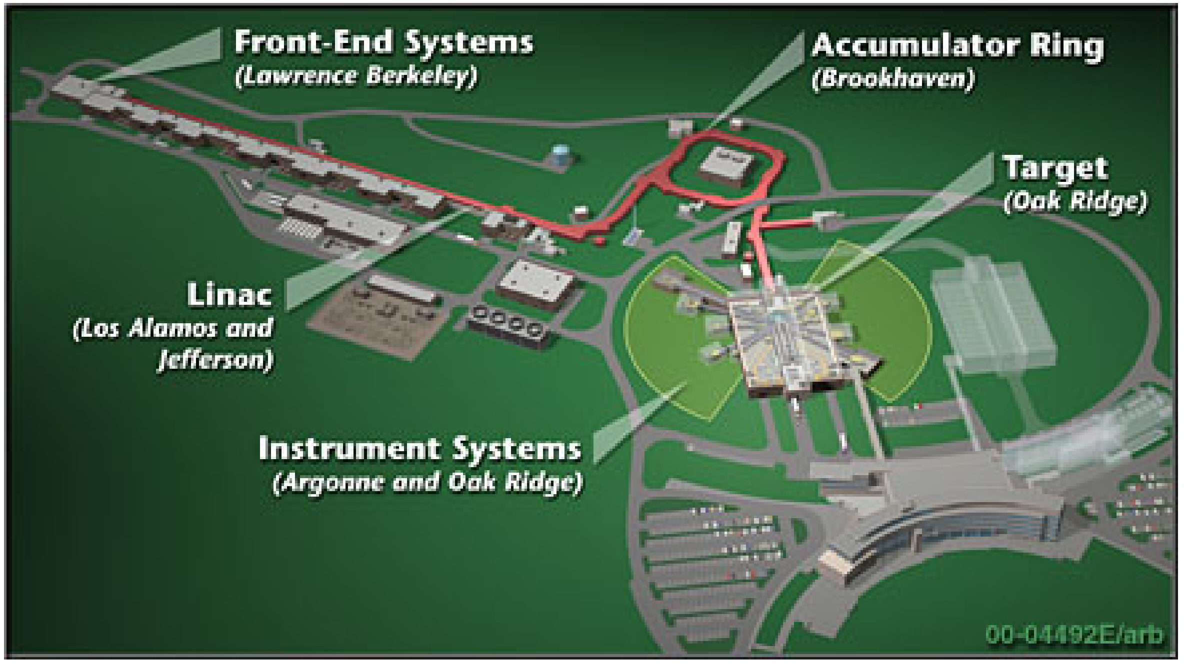
VACCALC Example – PEPII HER Arc Section

Graphical Representation of Output Pressure Profile



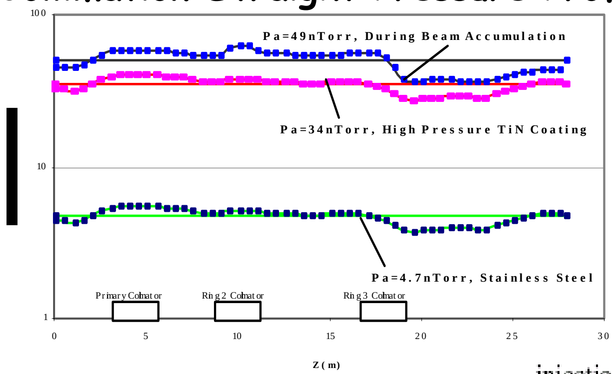
VACCALC Example – Spallation Neutron Source Accumulator Ring

Pressure profiles were developed using VACCALC by Ping He of Brookhaven National Laboratory.

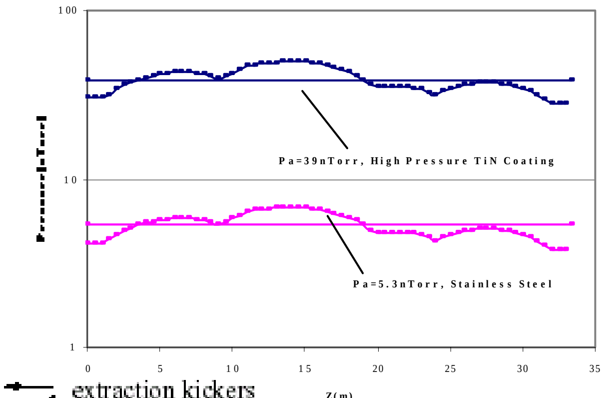


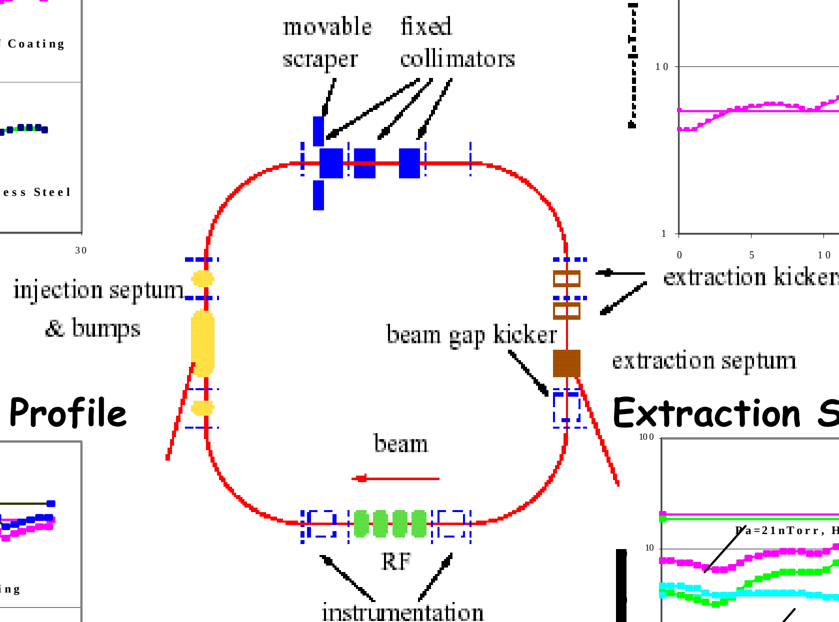
Spallation Neutron Source Accumulator Ring Pressure Profiles

Collimation Straight Pressure Profile

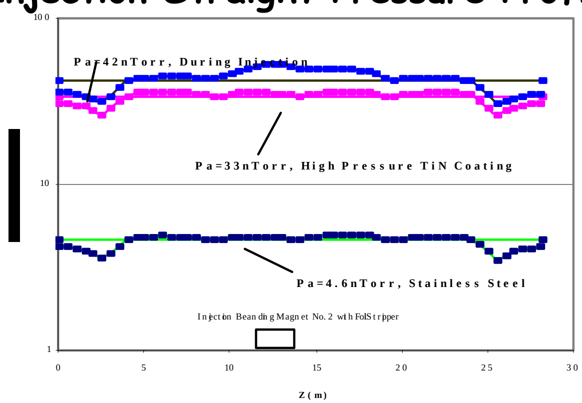


Arc Pressure Profile

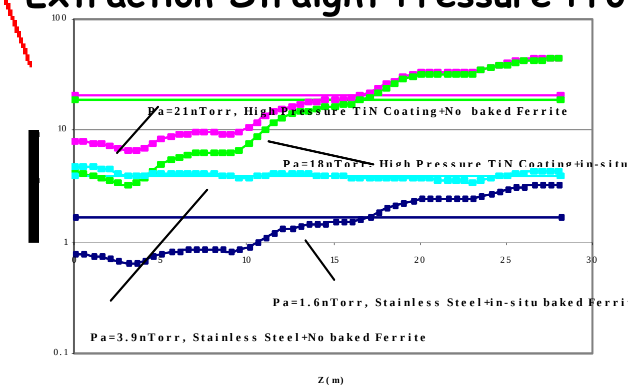




Injection Straight Pressure Profile



Extraction Straight Pressure Profile



Ref. "Pressure Distribution Simulation for SNS Ring Vacuum Systems", He, et al, BNL,

Designing a system using a more complicated numerical model

- In the mid-1990's, we at LLNL started using numerical modeling to design the vacuum systems for the APT RFQ and linac.

- Later we used it to design the vacuum systems for the Spallation Neutron Source linac.

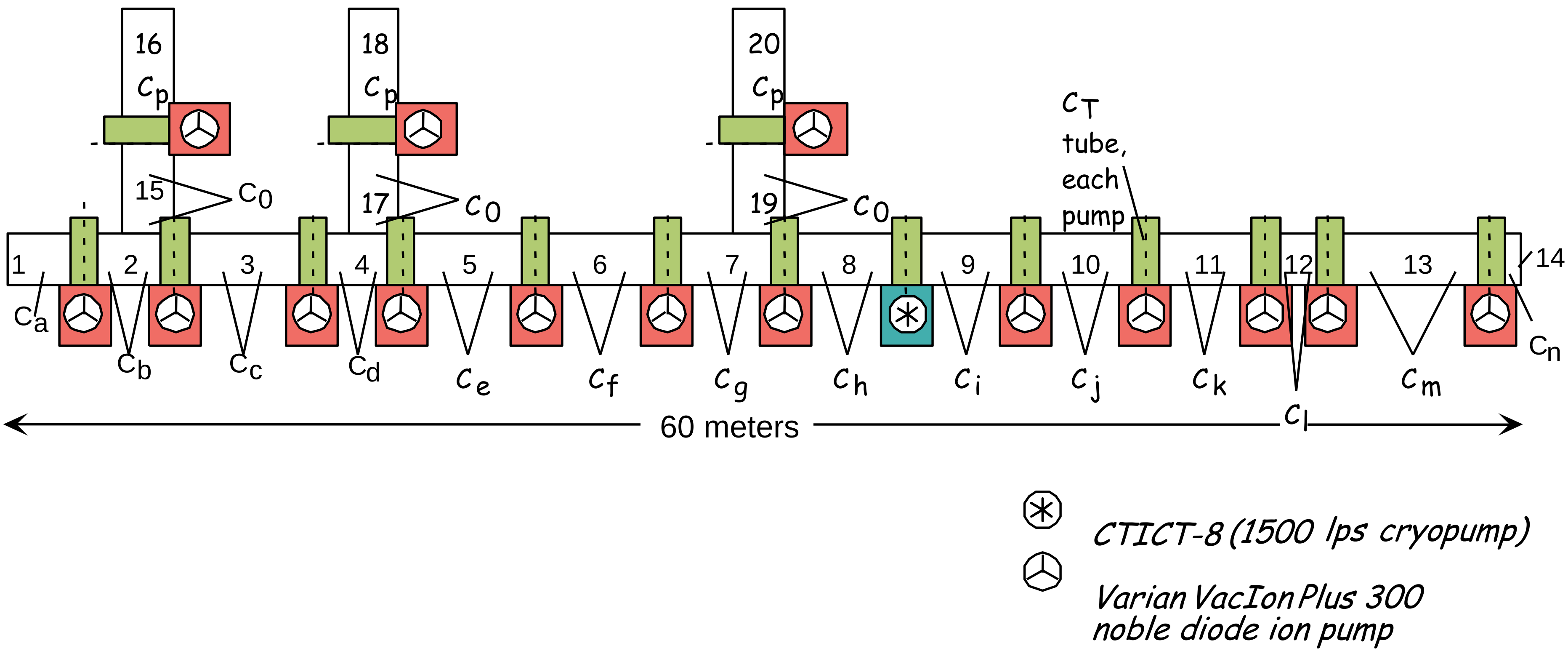
Typical features of a more complicated numerical model

- Pressure histories are solved for each sub-volume.
- We can save the pumpdown history for specific sub-volumes of interest.
- We can employ separate time-dependent outgassing rates for pre- and post-conditioned surfaces.
- We can employ pressure-dependent pump speeds.
- We can do parametric studies of pump speeds and pump distribution,
- We can even run partial-pressure cases.

Simple example: distributed pumping along a beam tube

20 sub-volumes interconnected with 16 conductances C_a - C_p

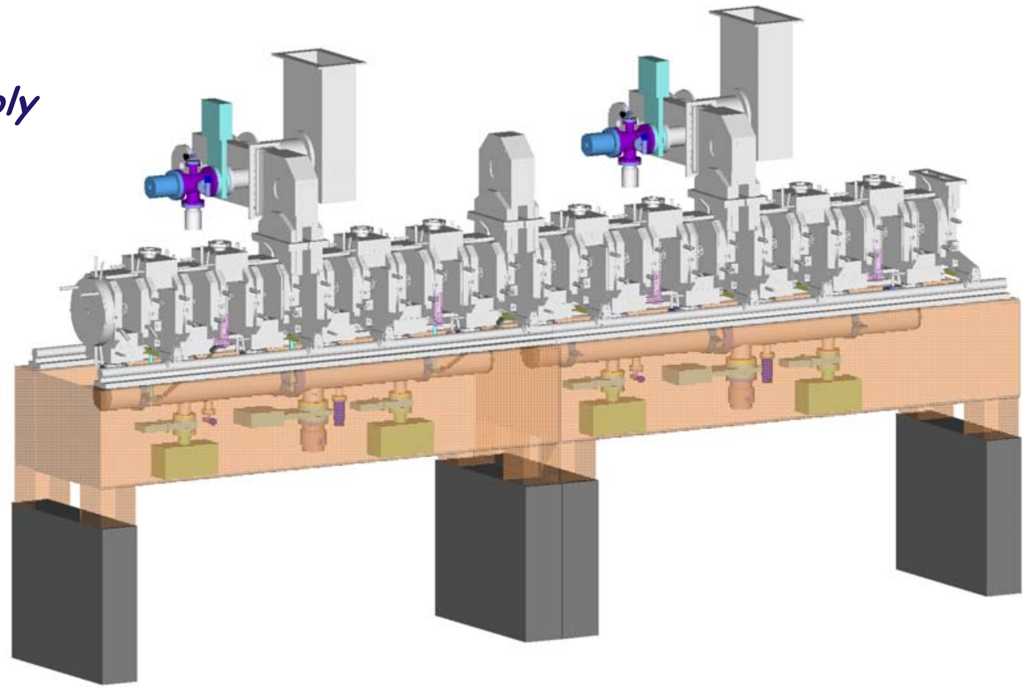
and pumped with 15 ion pumps and 1 cryo pump



Complex example: Pumping using a manifold along an rf linac

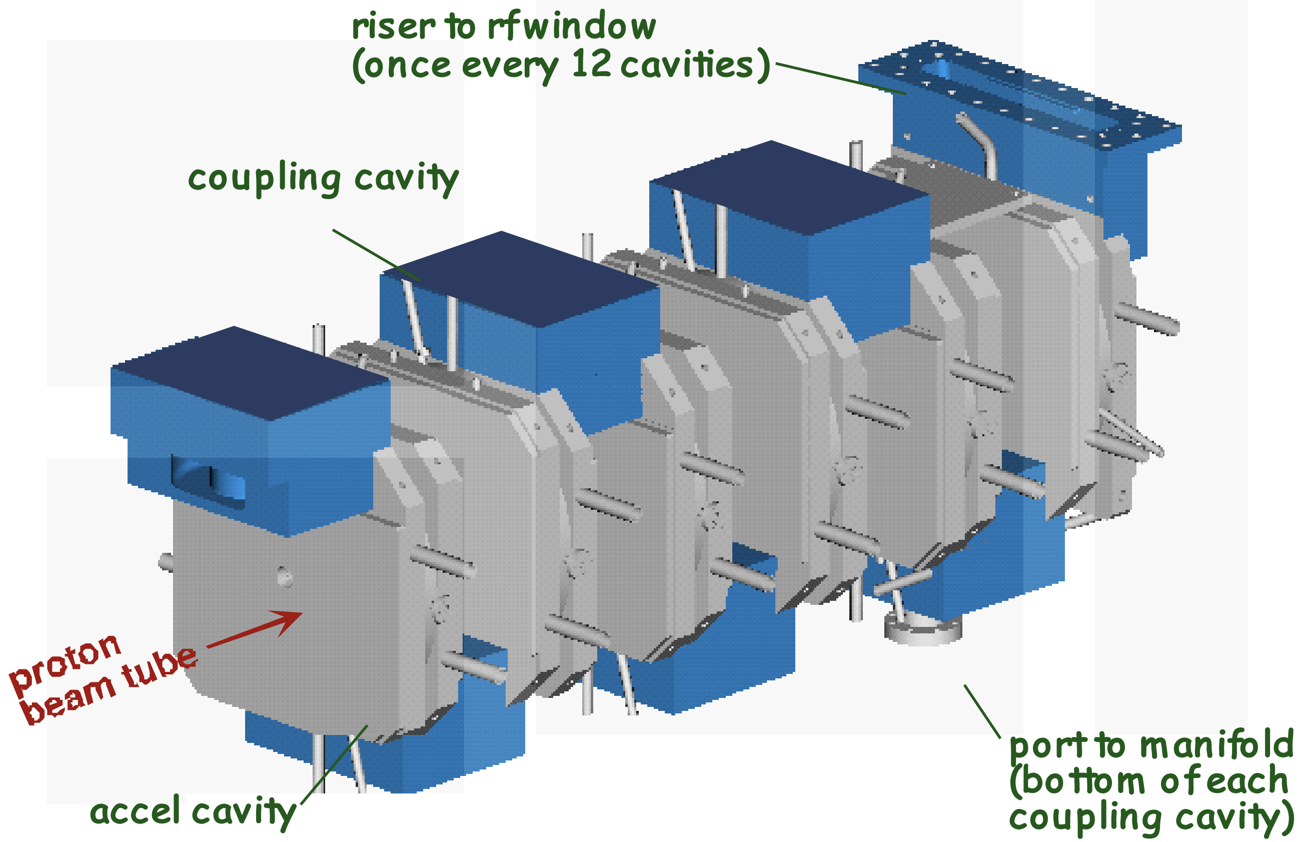
Model the first twelve cavities with a length of 2.5 meters (per manifold) and extrapolate results to the full length (10's to 100's of meters)

rf window assembly with separate pumping system

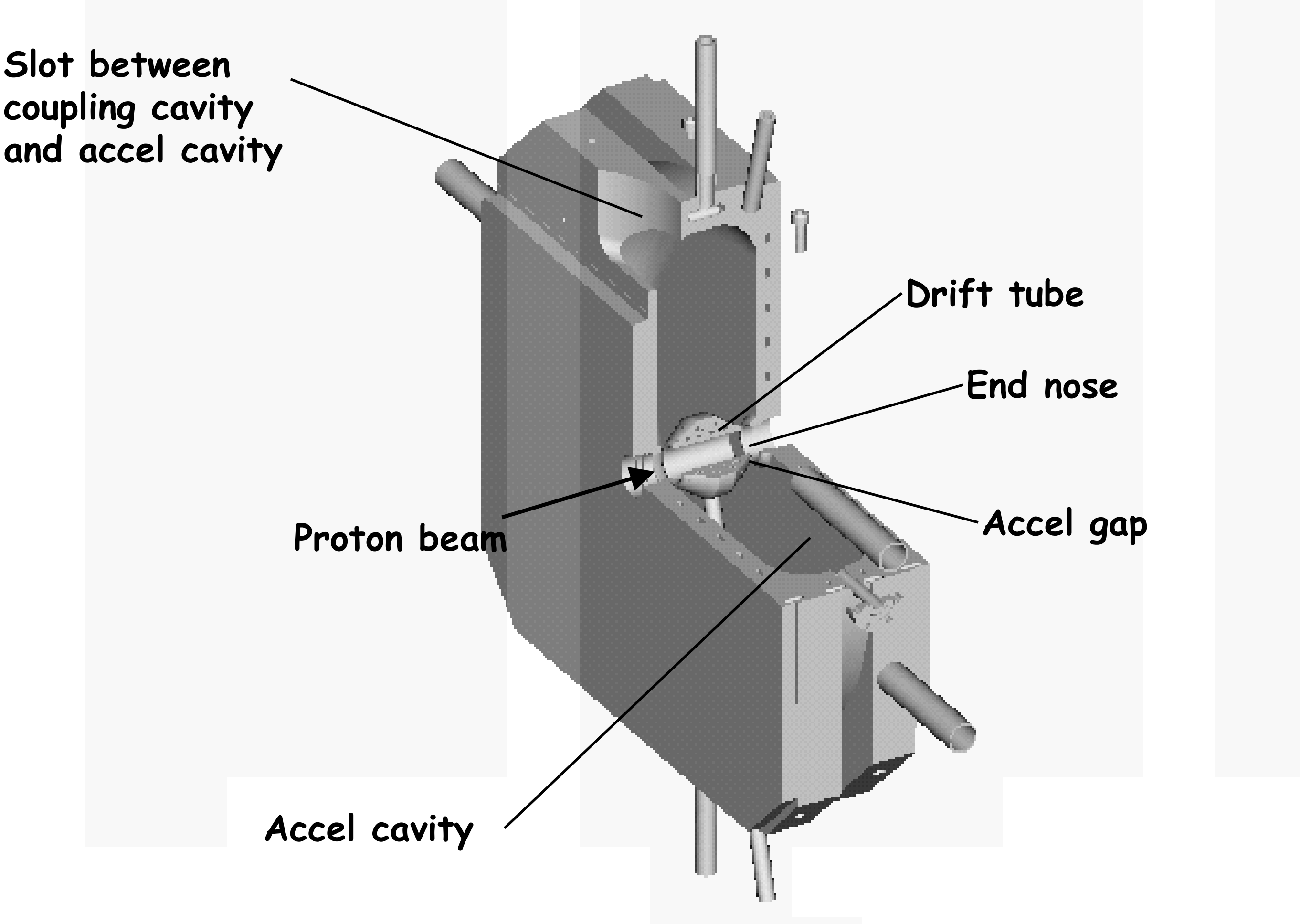


Detail of the first six cavities of an rf linac

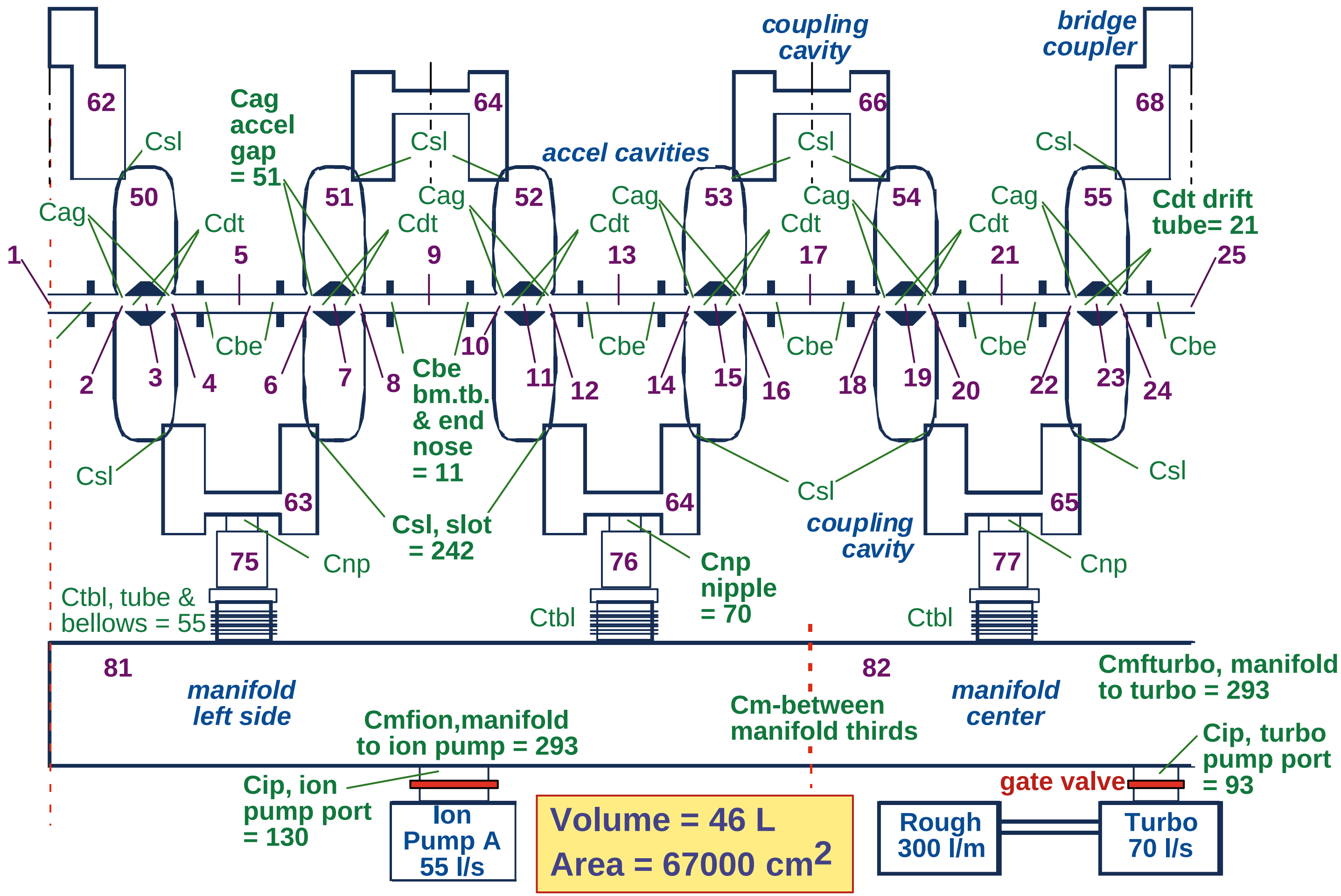
Goal: Pump through the coupling cavities and accel cavities to maintain the operating pressure of 10^{-6} Torr within the beam tube



Internal cavity detail included in the model



For twelve cavities, conductances interconnect 83 sub-volumes (half-symmetry)



N ordinary differential equations must be solved simultaneously for each time where N = the number of sub-volumes

Gasload balance is the heart of the numerical model.

$$V_n \frac{dP_n}{dt} = \sum Q_{in} - \sum Q_{out}$$

where V_n = volume of the nth sub-volume (liters)

P_n = pressure of the nth sub-volume (Torr)

there are N pressures to solve for at each time t (sec)

Q_{in} = leakage or outgassing into volume n (Torr-liters/sec)

Q_{out} = $C_{nm}(P_n - P_m)$ where m is the adjacent sub-volume

C_{nm} = your favorite conducatance formula for the resistive component between sub-volumes n and m (liters/sec)

or Q_{out} = $S_p P_n$ where S_p is pressure-dependent pump speed

Pressure history for each pump phase is found for each of the N sub-volumes.

- Model solves for pressure with N coupled differential equations (for each N sub-volumes) during each time for each pumping phase:
  - Roughing phase from atmospheric pressure down to 50 mTorr
  - Turbopumping phase from 50 mTorr to 10^{-6} Torr
  - Ion pumping phase down to base pressure

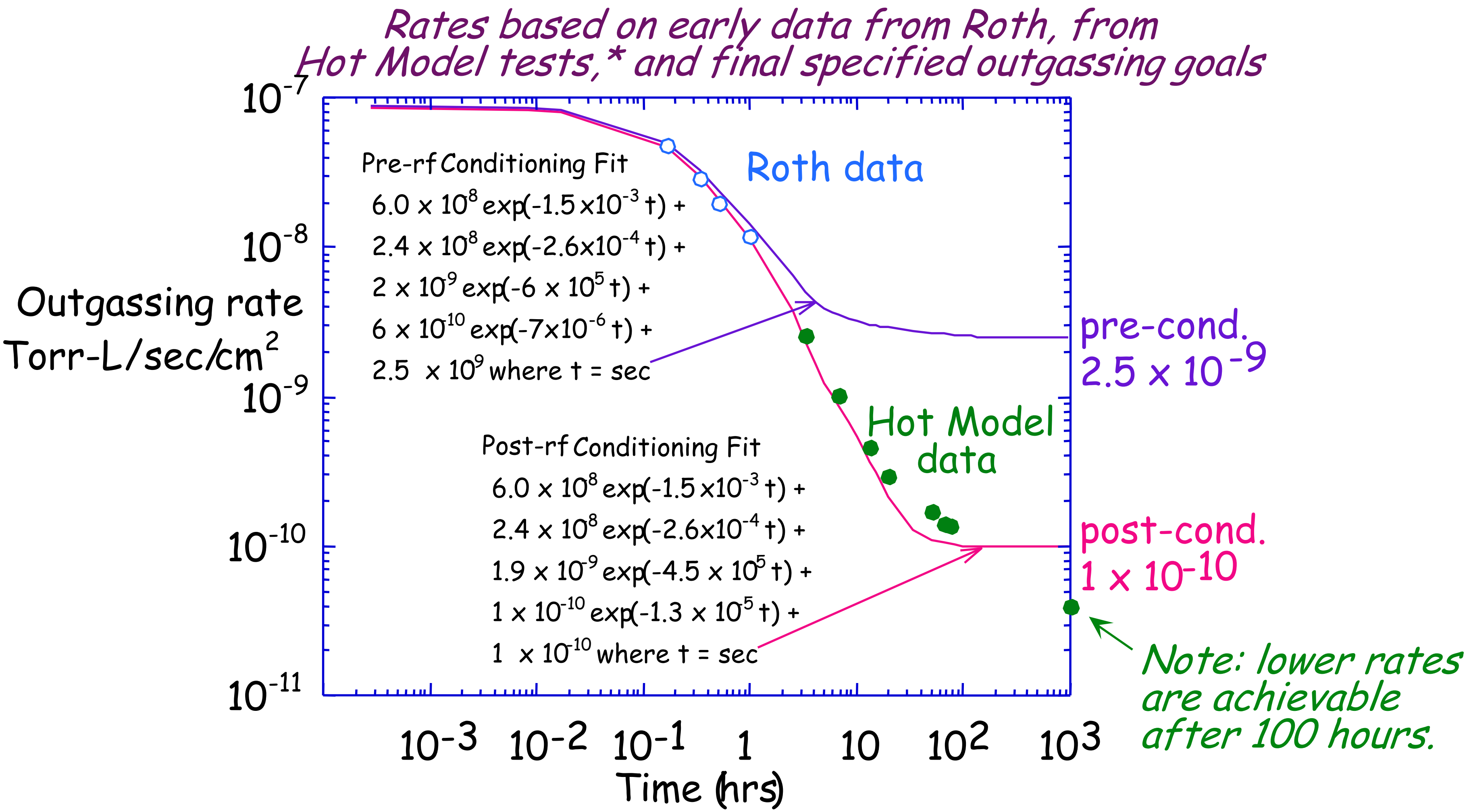
- Note that the choice of pump type depends on the design and operational requirements.

- Note that the final time for the pumpdown history should be chosen based on characteristics of outgassing data and operational requirements.

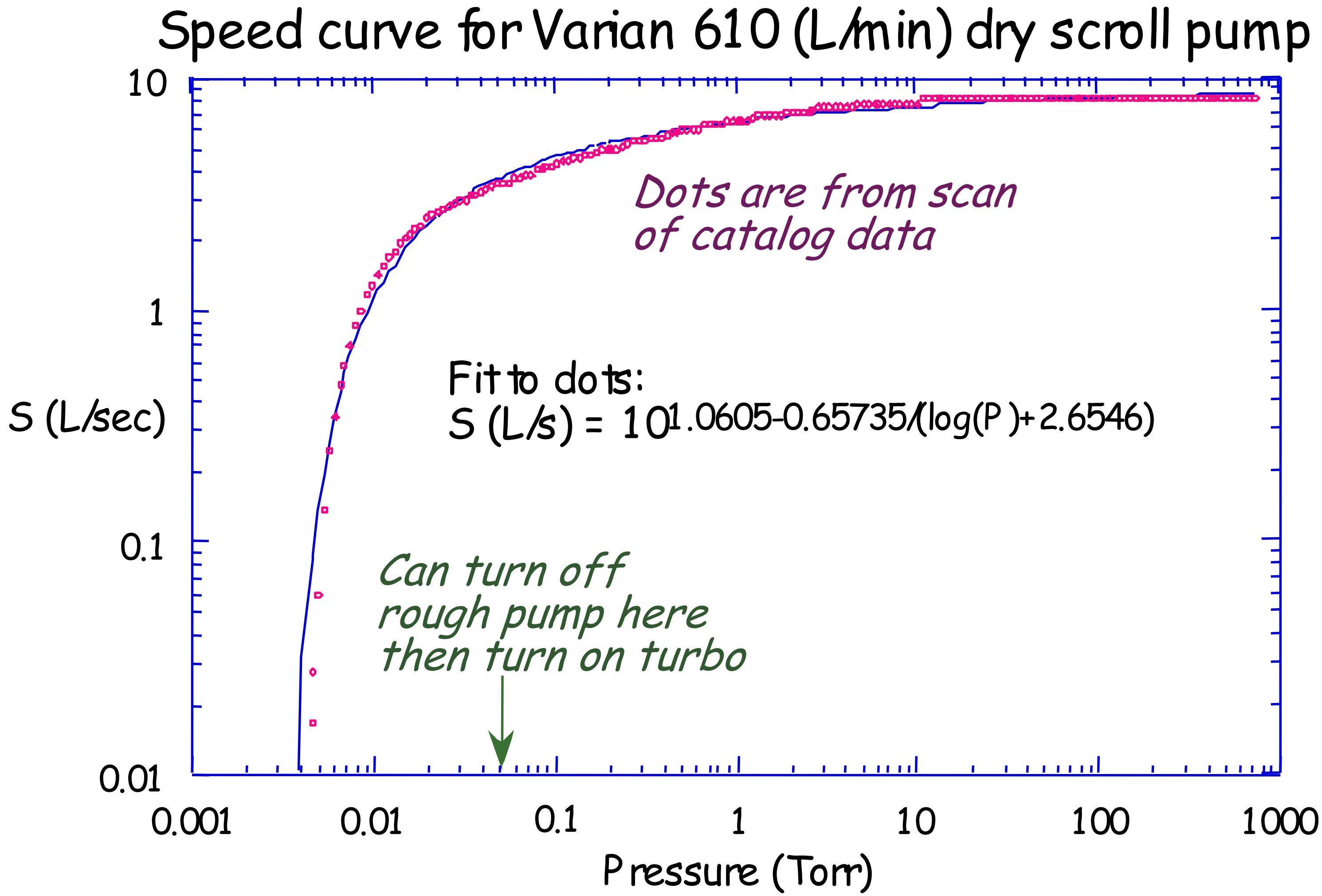
The software tool to solve the model depends on the number of sub-volumes and the speed of your computer.

- You can build your own solver routine using your favorite language and computer.
- You can use a routine like rkfixed from MathCad.
- You can use a routine like NDSolve from Mathmatica.
- We have solved small problems (N<10 sub-volumes) using MathCad on a PC in less than one hour.
- For larger problems, it is worth learning Mathmatica.
  - Example: N = 83 sub-volumes with tress separate pumping phases, the computer processing time was 4.5 min on a 266 MHz G3 PowerMac.
  - With MathCad, the problem would have taken days due to the overhead needed to MathCad more user friendly with a cleaner output.

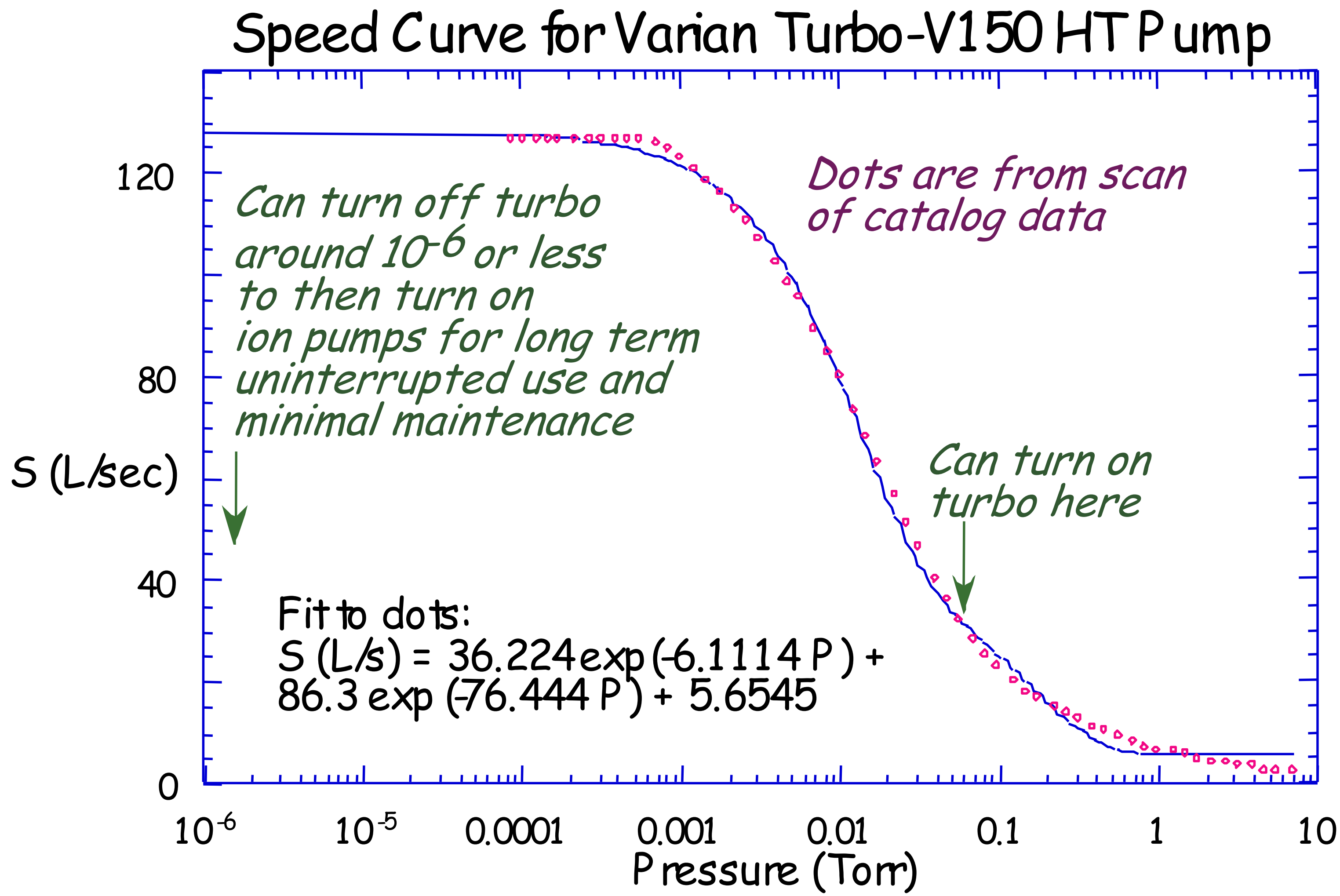
Model can include multiple time-dependent outgassing rates for pre-and post-conditioned surfaces.



Pressure dependence of speed for a Varian dry scroll pump

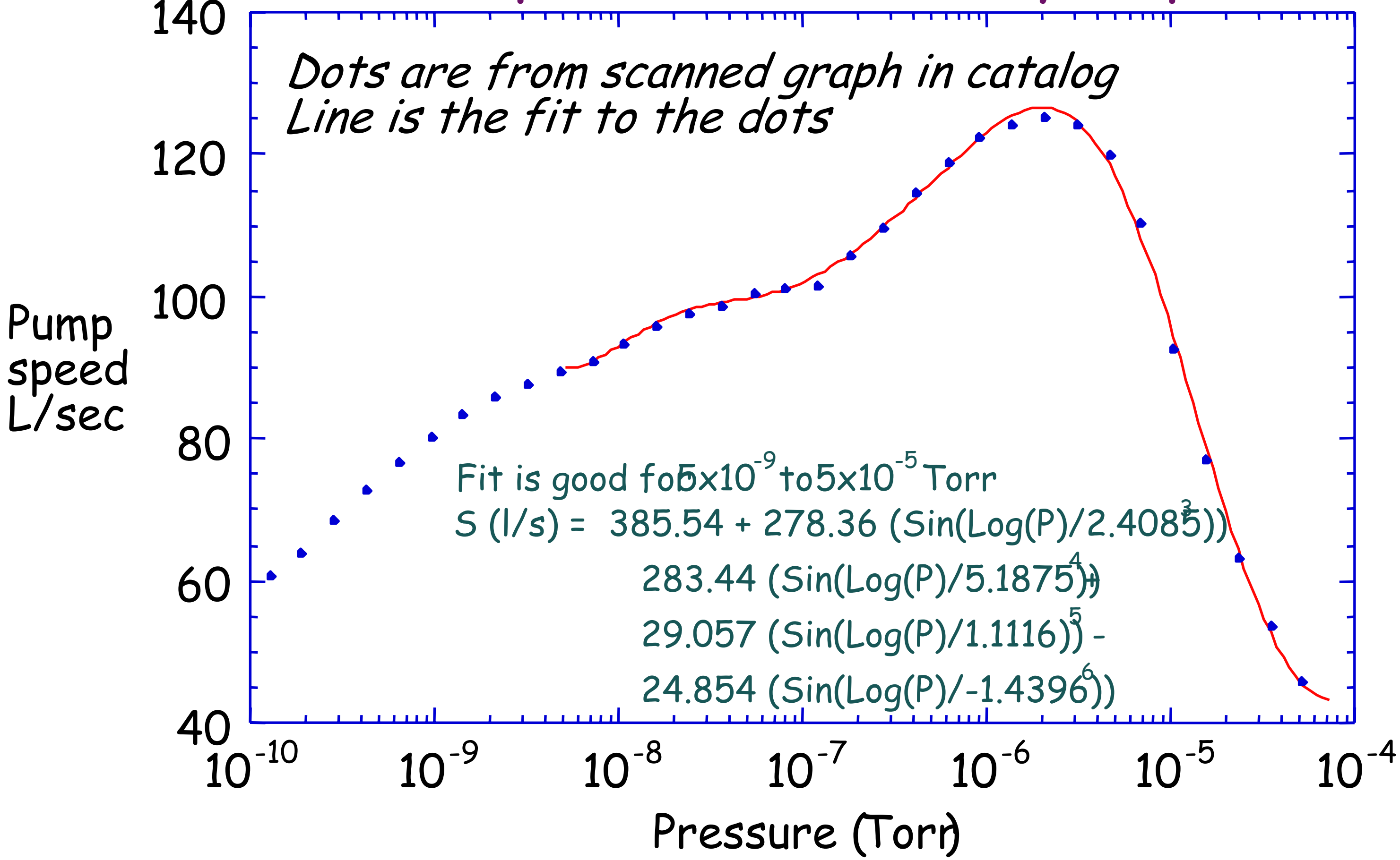


Pressure dependence of a speed for a Varian turbomolecular pump

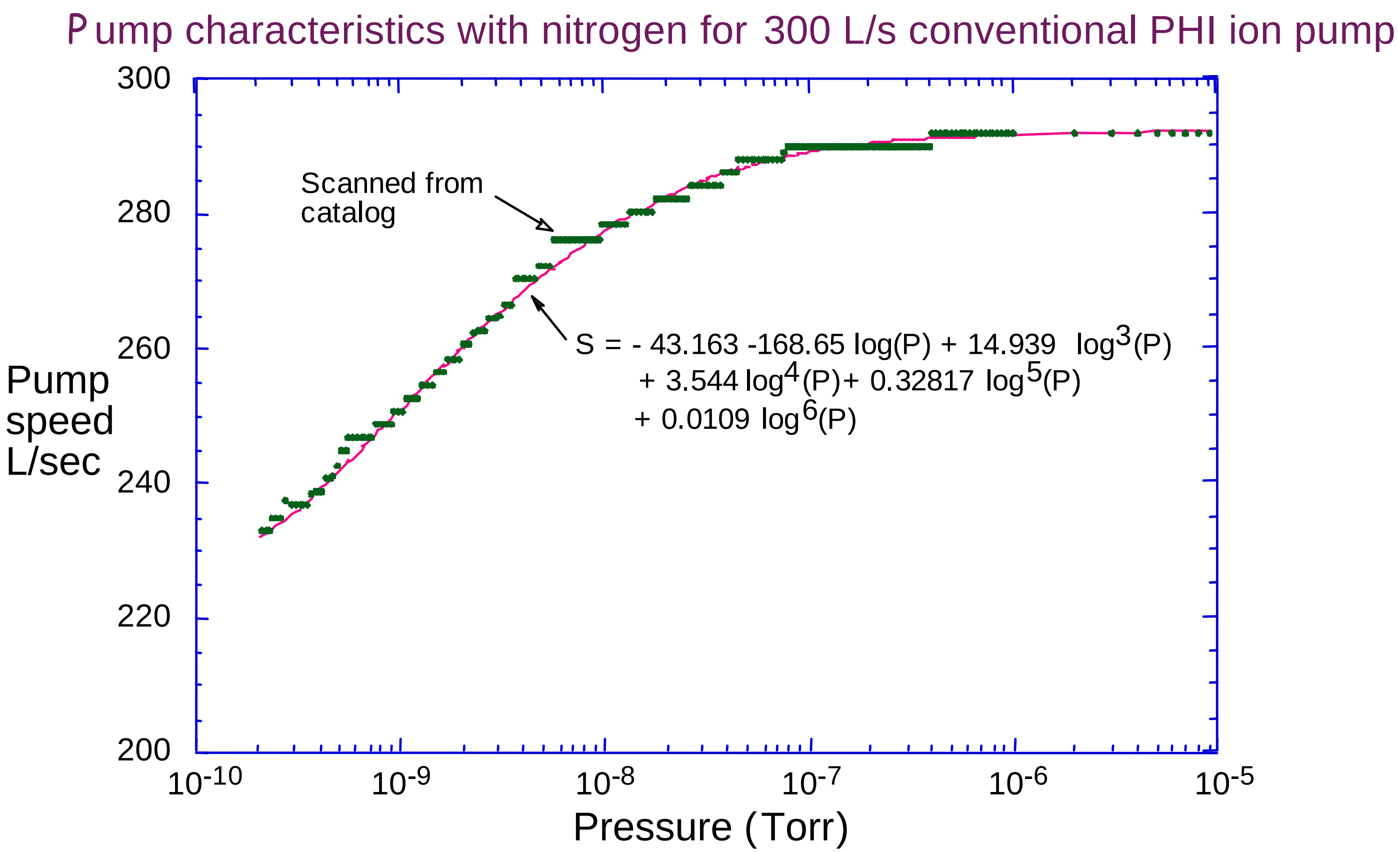


Pressure dependence of a speed for a Varian Starcell ion pump

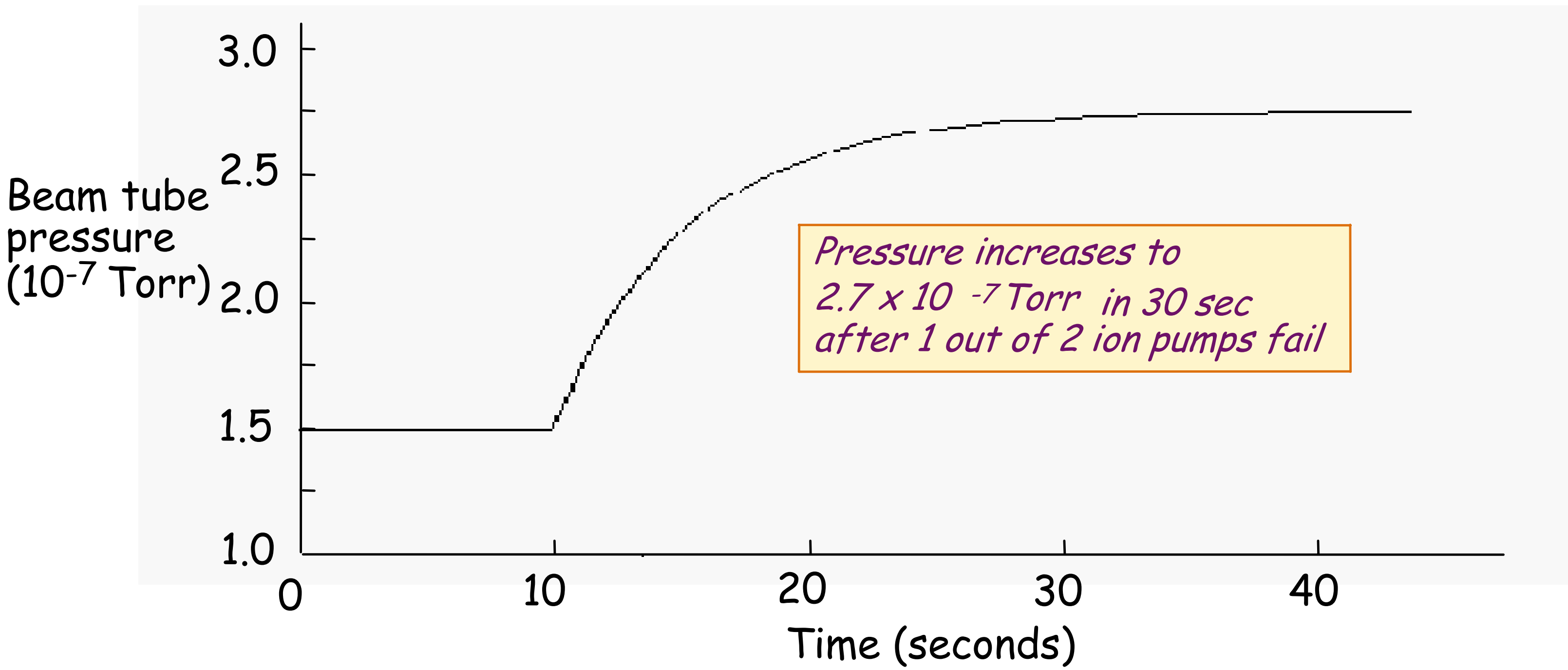
An input of constant nominal speed of 150 L/sec would have predicted an erroneously low pressure



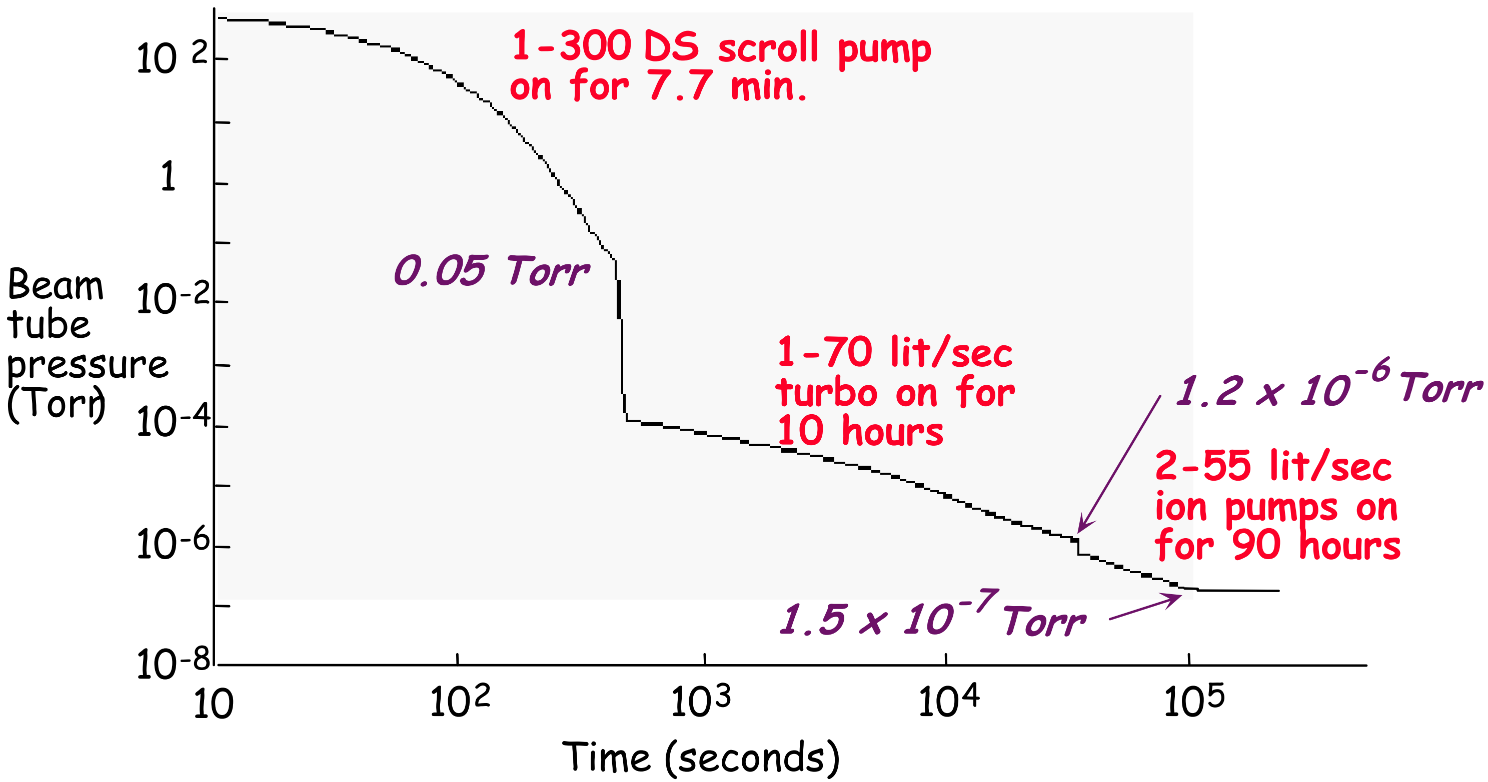
All ion pumps are not alike



System response to a perturbation can be studied such as a failed pump.



After the optimal system is chosen, then plot the entire pressure history.



The US Particle Accelerator School
Mechanical Vacuum Pumps

Lou Bertolini

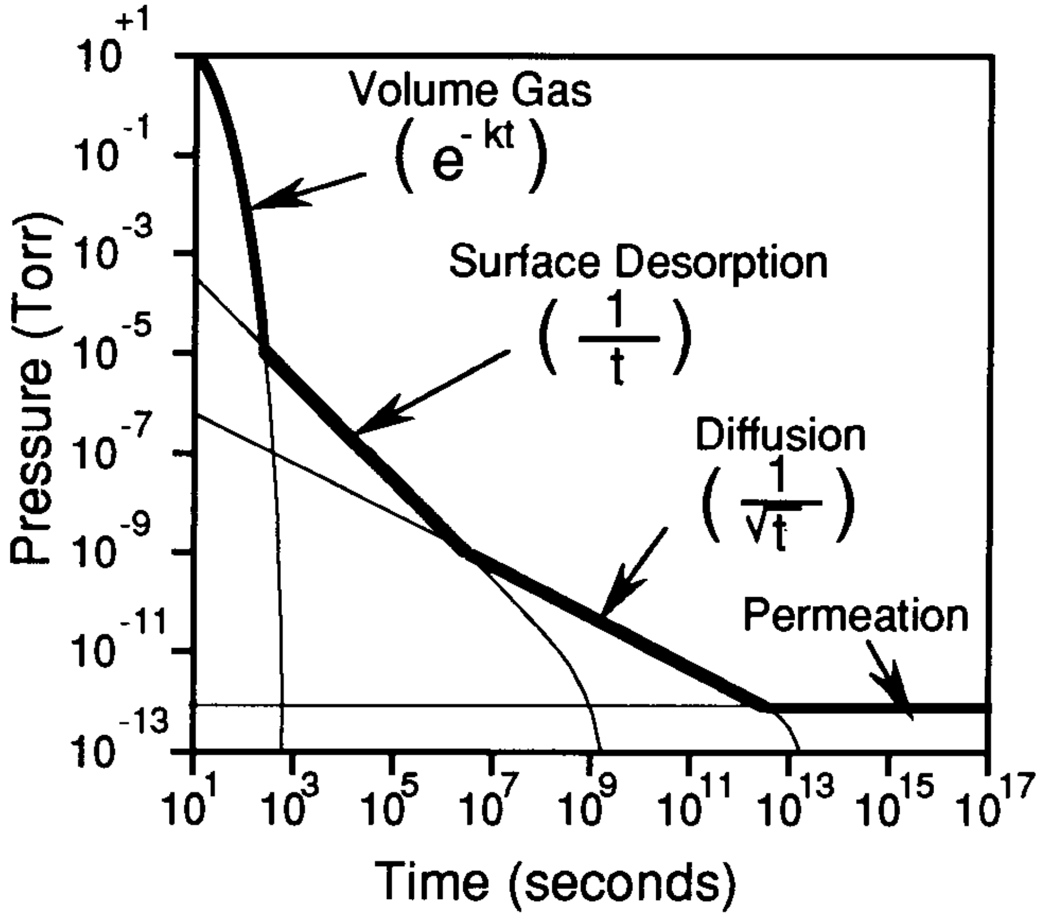
Lawrence Livermore National Laboratory

January 19-24, 2004

Mechanisms for Pumping

- Throughput mechanisms:
  - Positive displacement: Molecules are compressed into a smaller volume, raising the pressure
  - Momentum transfer: Molecules are given a preferred direction by very fast moving surfaces or oil molecules
- Capture mechanisms:
  - Chemical combination: Molecules react with active metal surfaces and are converted to a solid
  - Condensation: Molecules land on a very cold surface and freeze into a solid
  - Adsorption: Molecules land on a surface and remain there
  - Absorption: Molecules land on a surface and dissolve into the bulk material
  - Ionization & burial: Molecules are ionized and accelerated into a surface with enough energy to burrow in

Evacuation of a Vacuum System



Comparison of Mechanical Roughing Pumps

Type	Advantages	Disadvantages
Rotary Vane	Low Ultimate Pressure Low Cost Reliable	Source of Backstreaming Oil & Hazardous Waste
Rotary Piston	High Pumping Speed Low Cost	Noisy Source of Vibration
Scroll	Clean Low "clean" Ultimate Pressure	Permeable to light gases Clean applications only
Diaphragm	Quiet Easy to work on	Low Pumping Speed High Ultimate Pressure Requires frequent servicing
Roots Blower	No (Low) Backstreaming Low Ultimate Pressure	Expensive Requires frequent servicing Requires purge gas
Venturi	No moving parts Unlimited pumping Low cost	Limited ultimate pressure

Some Notable Characteristics of “dry” Pumps

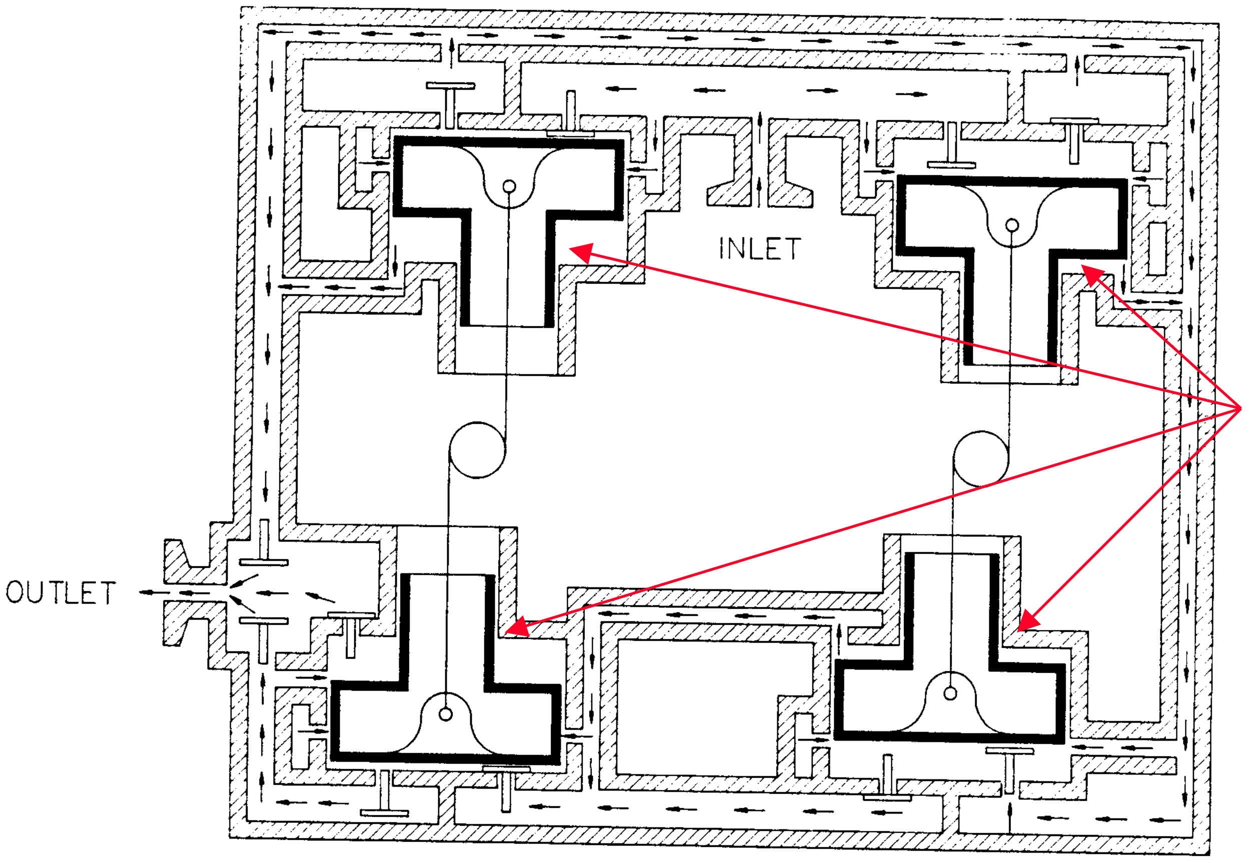
- Oil is often a contaminant in a vacuum system
- Destroys product, increases base pressure, affects sensors
- No oils are exposed to the gas stream
- Pump by positive displacement & momentum transfer
- Operating range 760 Torr to 10^{-2} Torr and lower
- Pumping speeds 2 to >150 CFM
- Lessens concern about malfunctions & trap integrity
- More compatible with corrosive gases than pumps requiring oil
- Expensive compared to oil based pumps ($3,000-$70,000)

"Dry" Pumps, Cont'd.

Several designs & configurations available:

- Multistage Roots
- Claw
- Multistage claw and Roots in series
- Scroll
- Screw
- Diaphragm
- Reciprocating piston
- Molecular drag & diaphragm pump in series

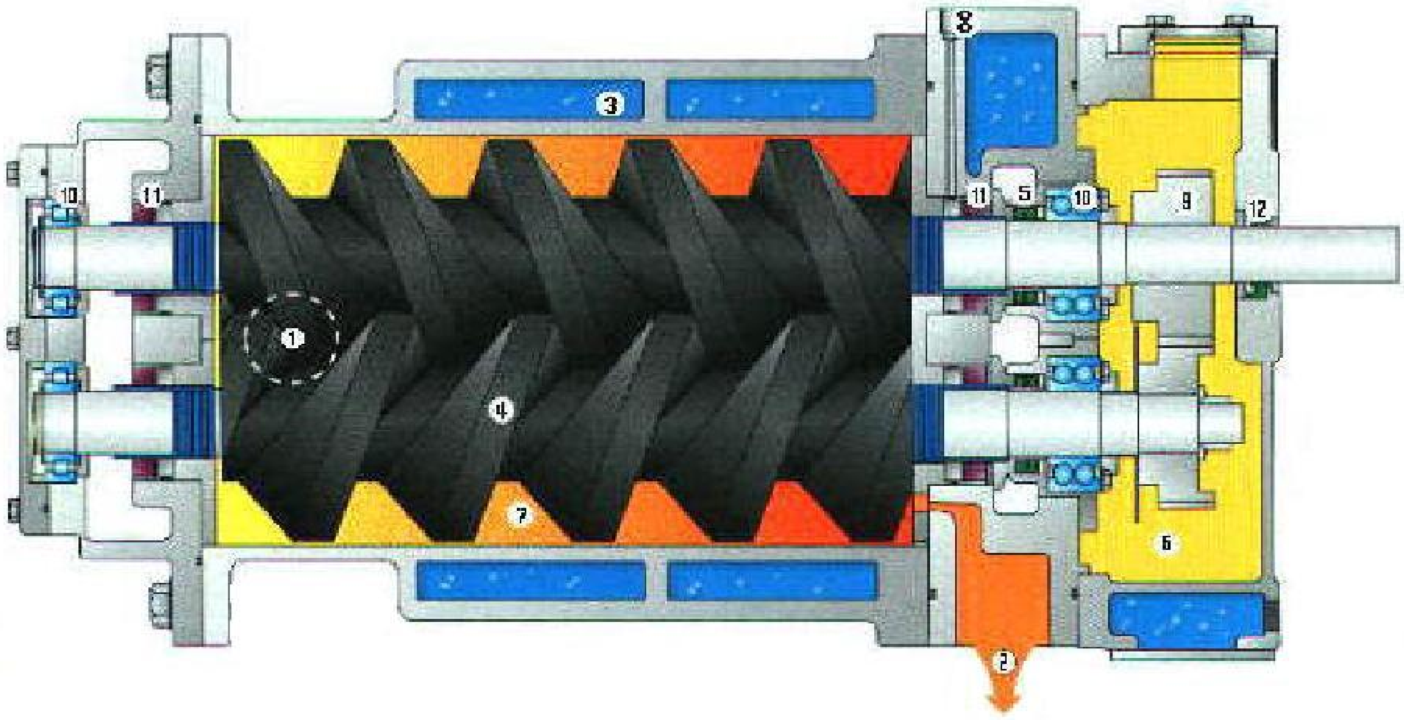
Reciprocating Piston Pump Cross-sectional Drawing



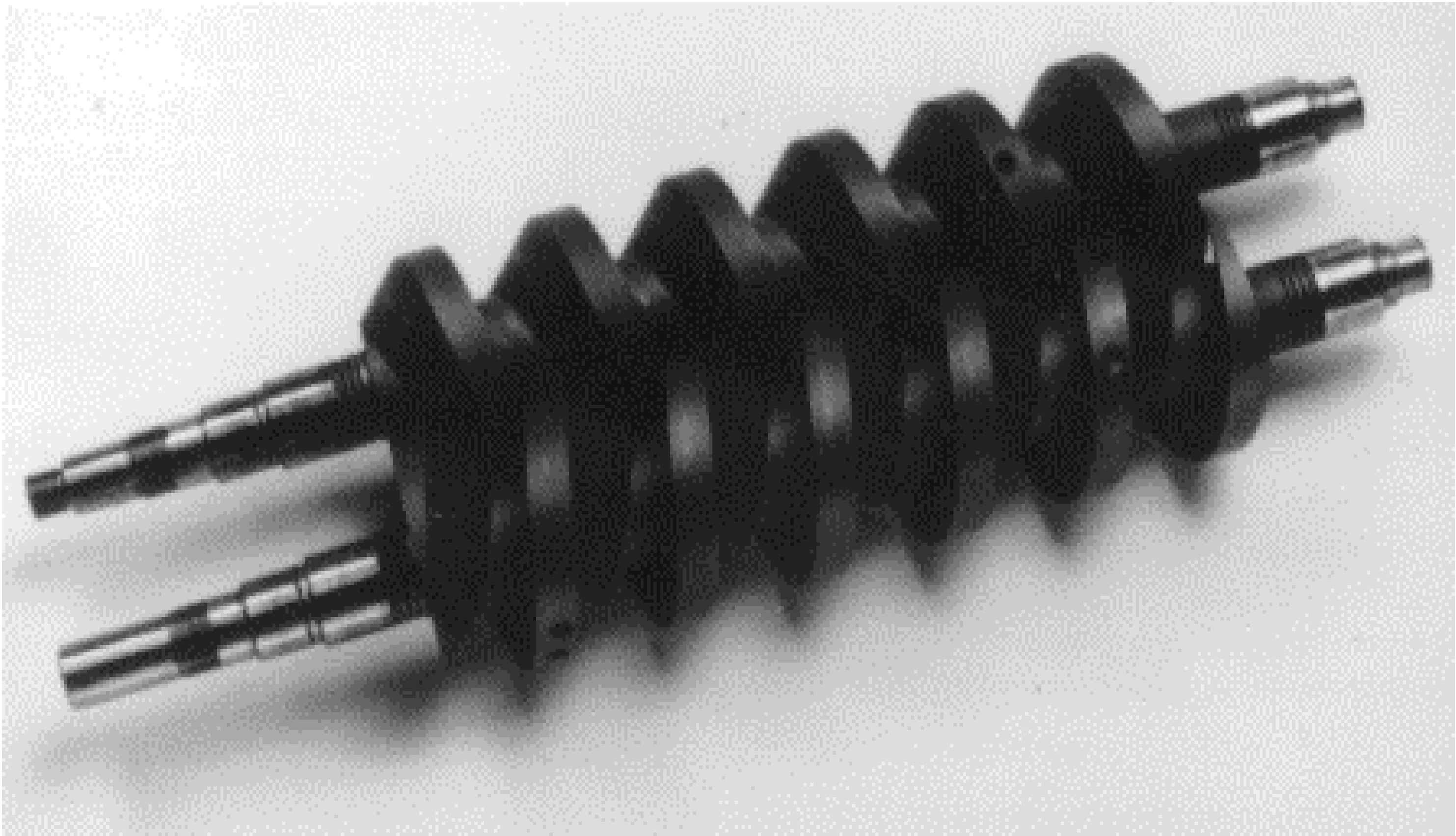
Varian first introduced their Piston "dry" pump in the late 1970's.

Diametrically-opposed Pistons are lined with Teflon.

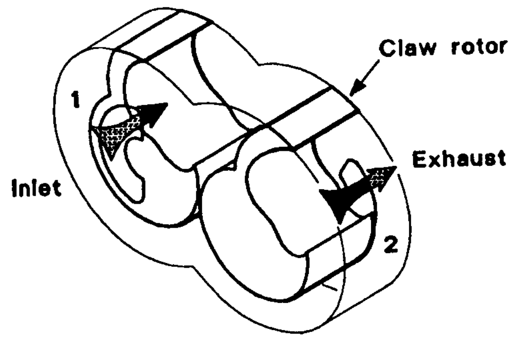
Busch Screw-type Dry Pump

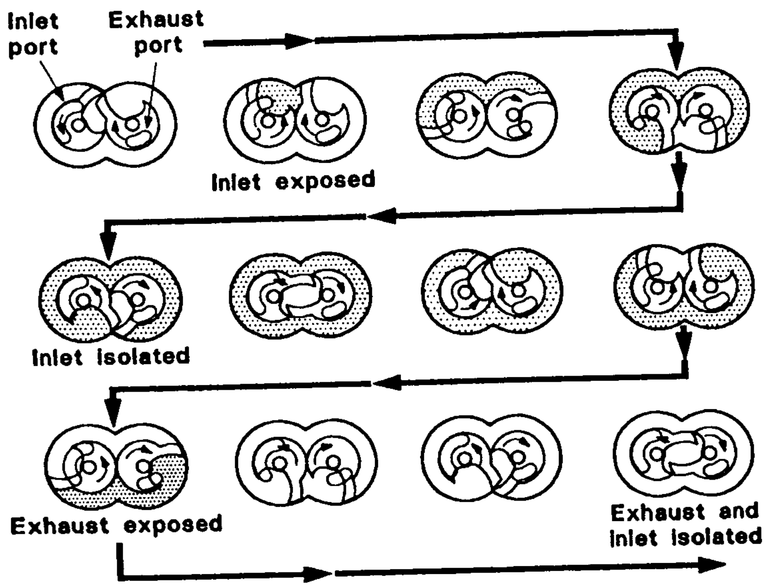


Photograph of Typical Screw Pump Rotors



Claw Mechanism and Operating Cycle

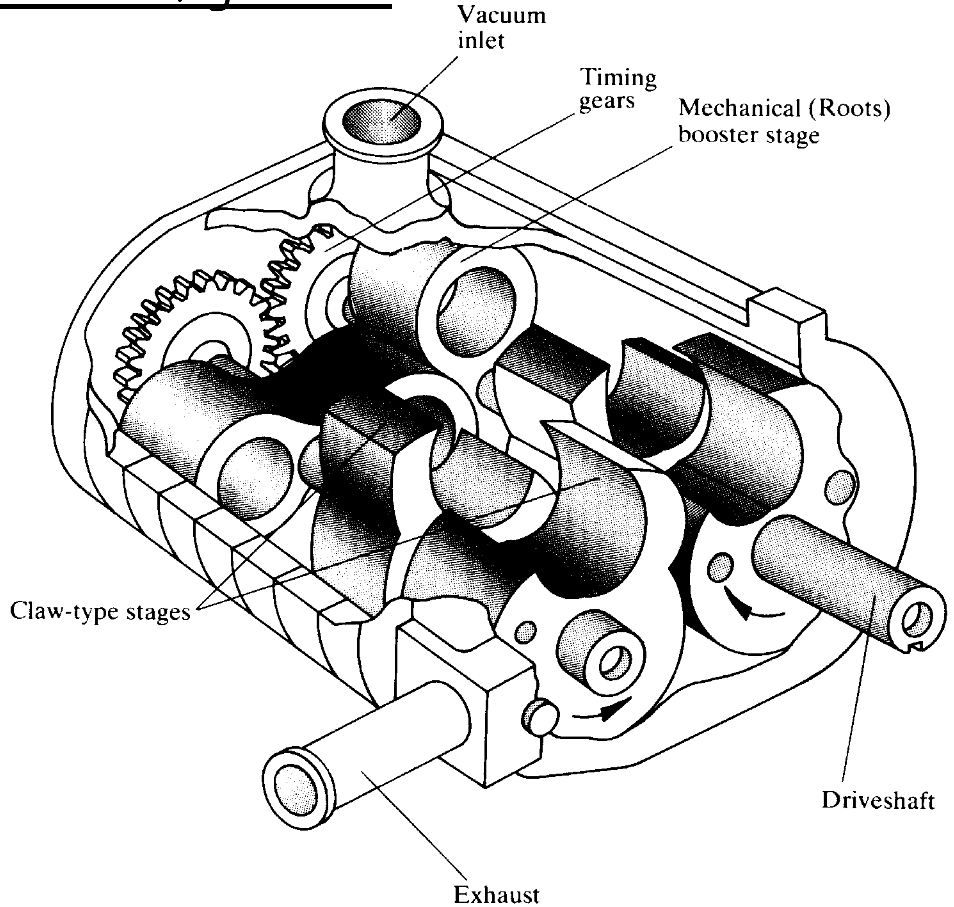




from "Foundations of Vacuum Science and Technology," Lafferty, 1998

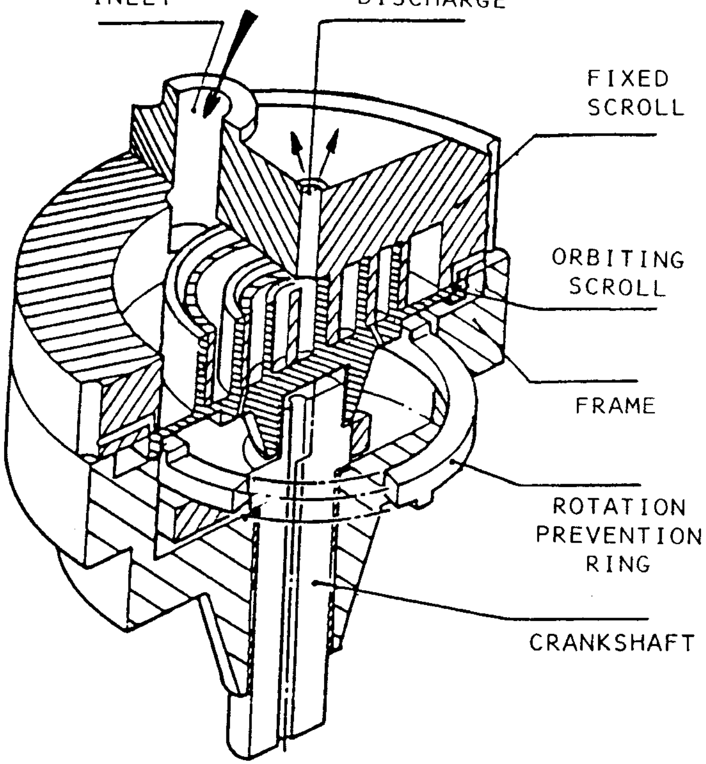
Multi-stage Roots and Claw in Series

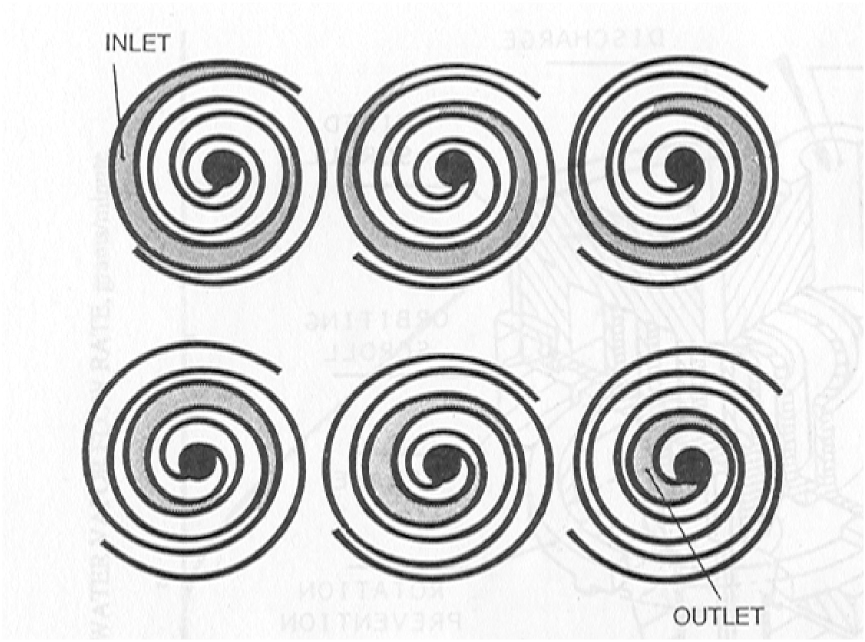
Edwards *Drystar* configuration



from Modern Vacuum Practice, Harris

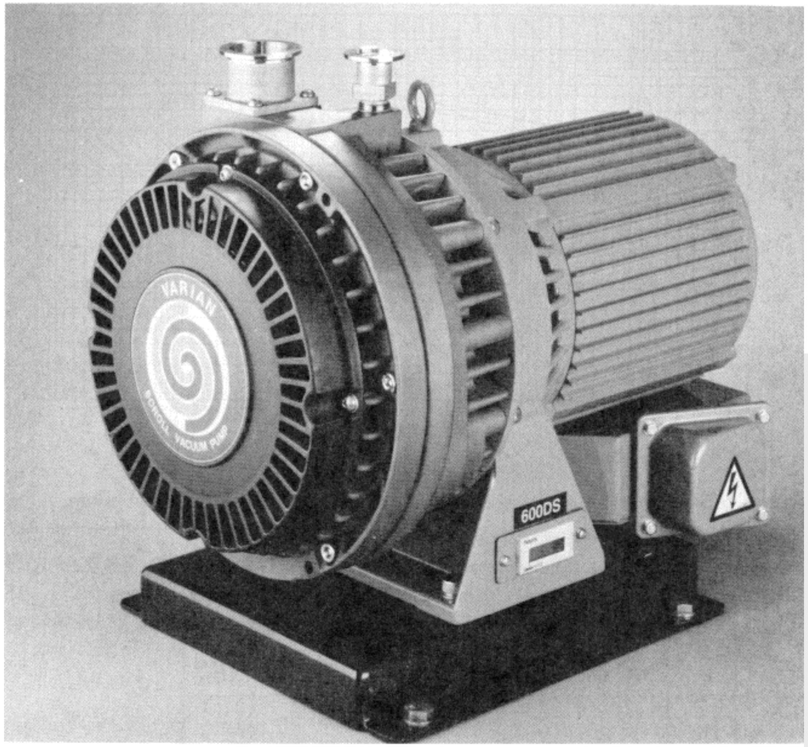
Scroll Pump Cut-away and Operation

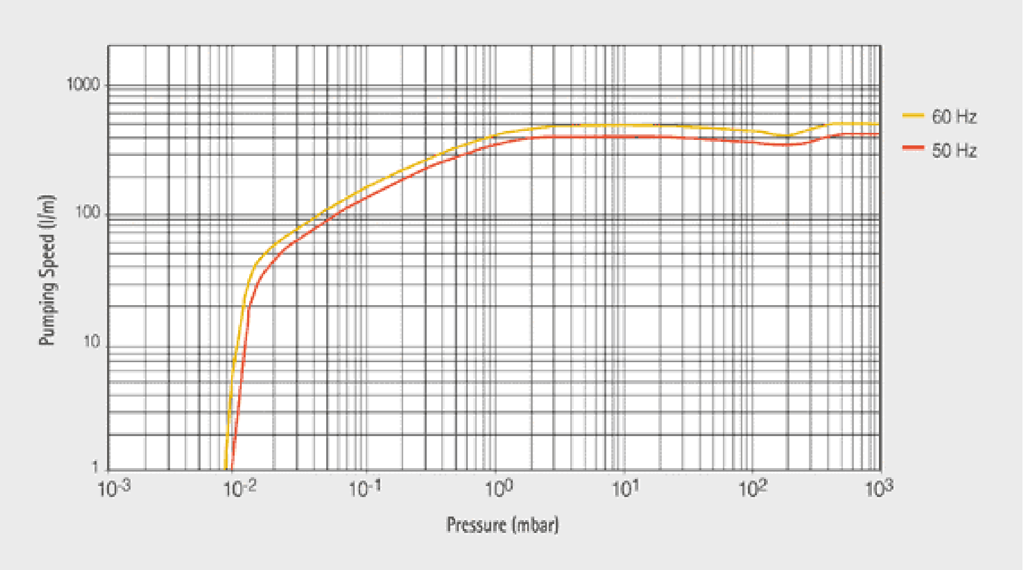




from “High Vacuum Technology,” Hablanian, 1997

Typical Scroll Pump

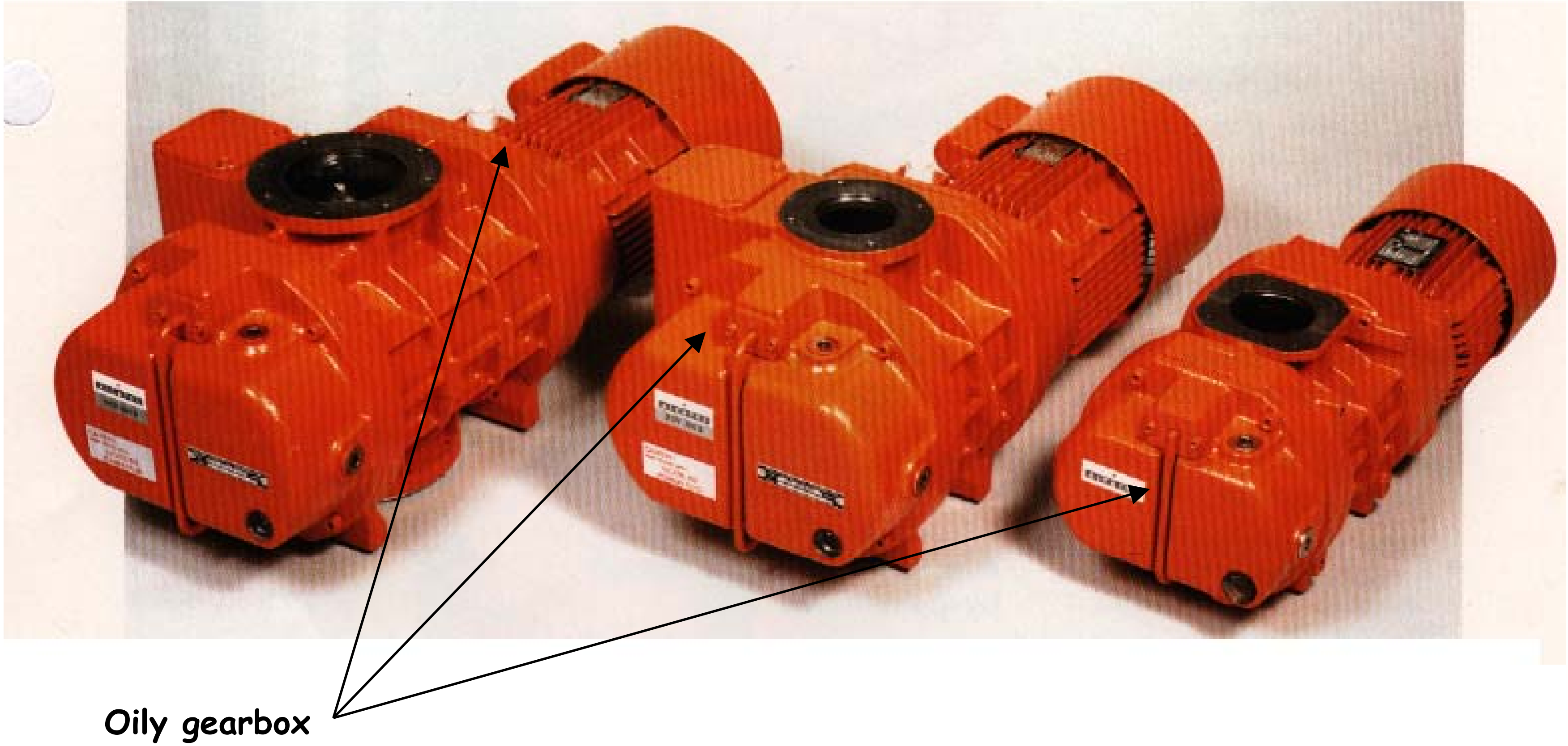




Ref. Varian Vacuum

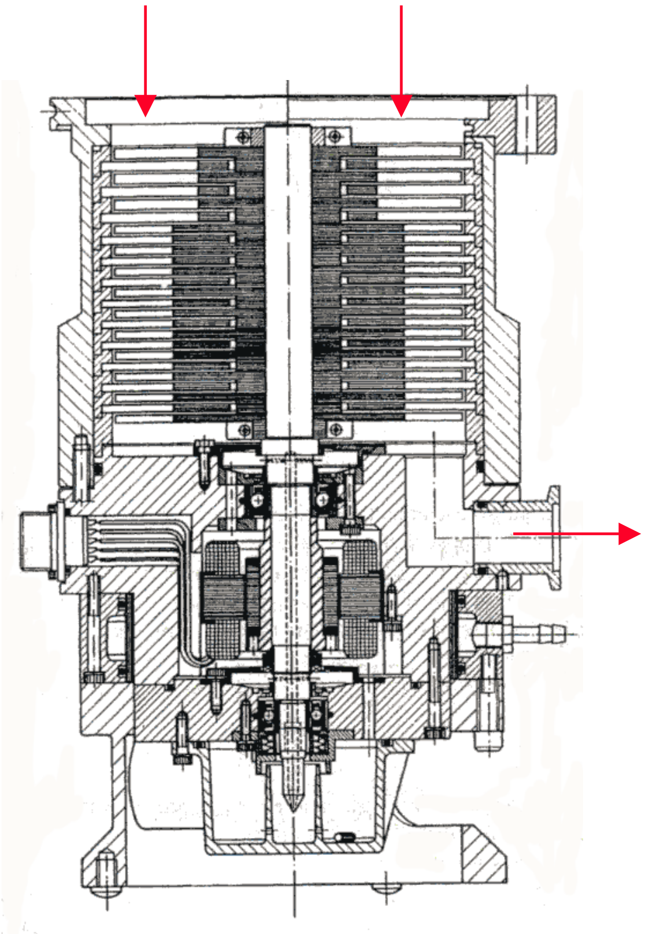
Lobe-type (Roots) Vacuum Pumps

Many consider lobe-type pumps to be "dry". However, pump gearboxes contain oil!



Turbomolecular Pumps

- Turbopumps are axial compressors designed for pumping gases in the molecular flow regime.
- Operating range 10^{-2} to 10^{-10} Torr
- Pumping speed 10 to 10,000 l/s
- Infinite pumping capacity
- Turbopumps are throughput pumps – meaning they have infinite capacity
- Blade rotation speed ranges from 14,000 to 90,000 rpm – making them mechanically vulnerable



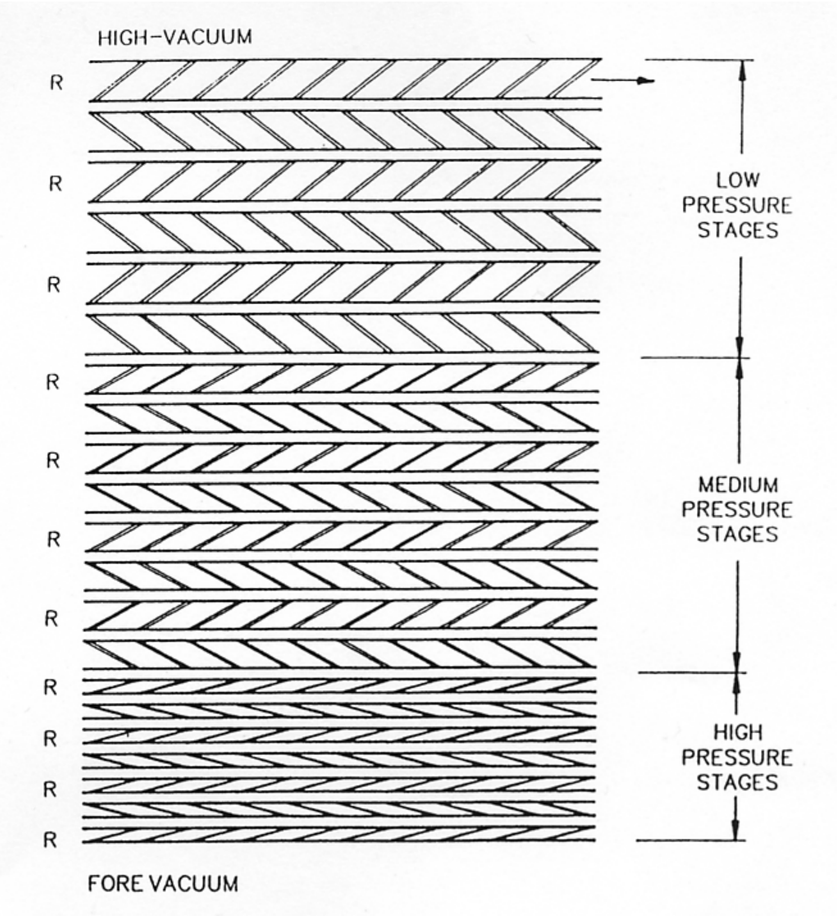
Turbomolecular Pumps, Cont'd.

- Axial compressor type pumps are very flexible designs:
  - # stages can be varied
  - Blade angles varied
  - Hybrid pumps

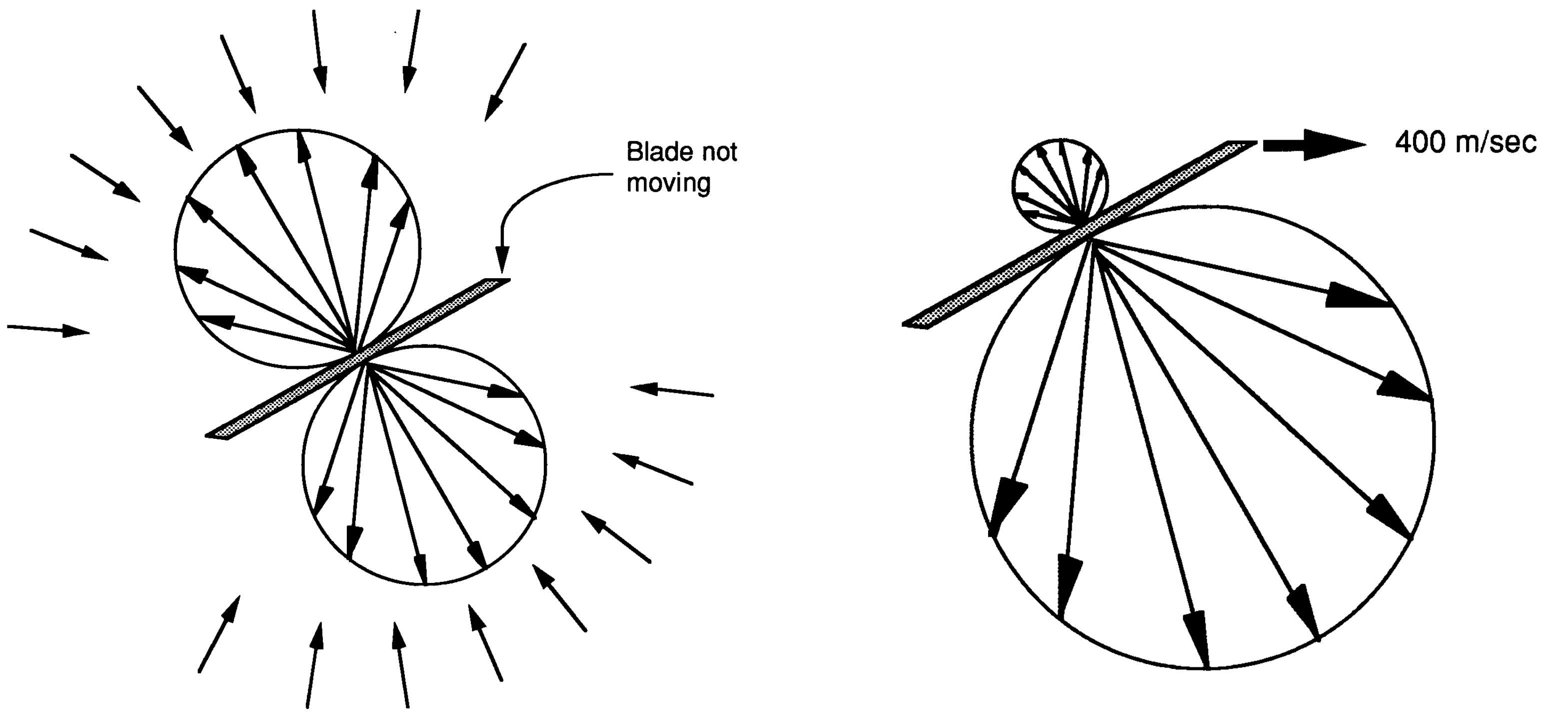
- Molecular flow exists through most of a turbopump; however, transient and sometimes viscous flow occurs at the pump discharge.

- The key parameter of turbopumps is compression ratio, not Δp.

- Typical Compression Ratios:
  - N_2 – 10^8-10^9
  - He – 10^4-10^6
  - H_2 – 10^2-10^5



Rotating Turbomolecular Pump Blades accelerate gas molecules in a preferred direction.



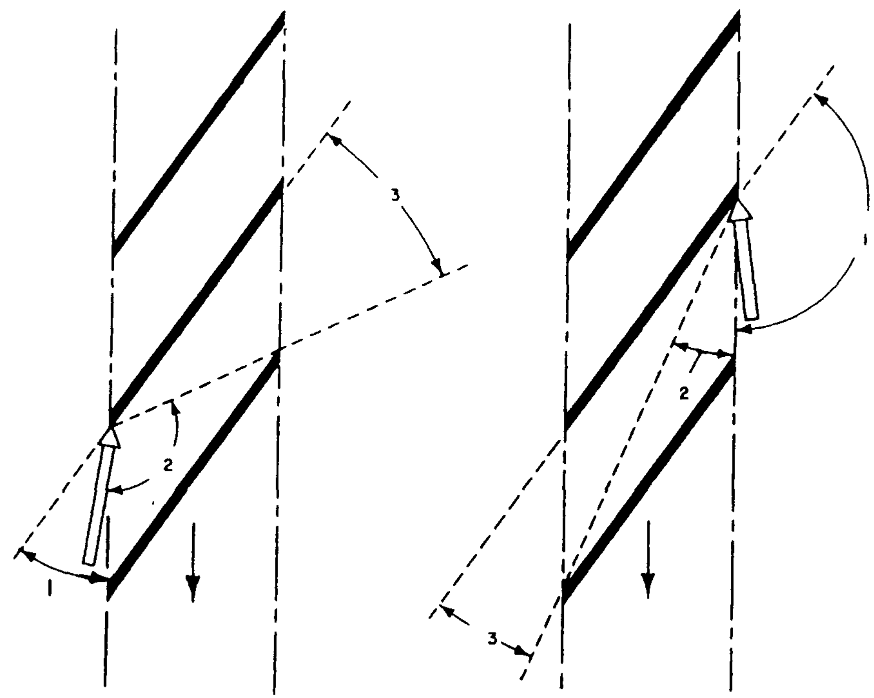
Velocity distribution from moving blades

Turbomolecular Pumping Mechanism

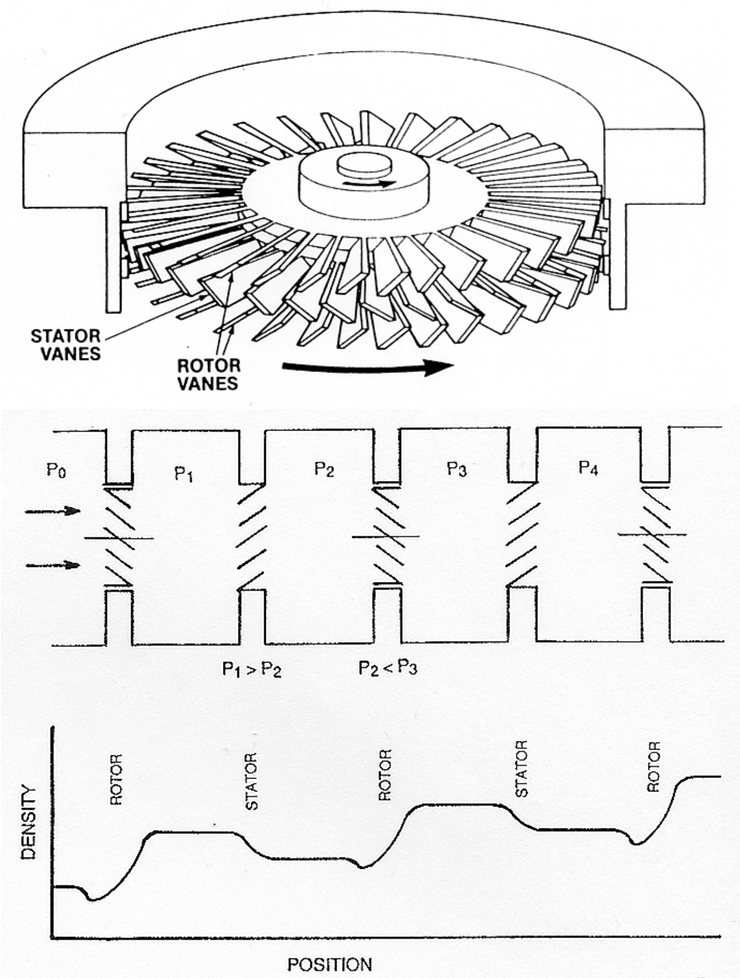
- Another way of looking at it, is to consider the rotors as moving "chevron baffles". Their relative movement gives the baffles a higher conductance in one direction over the other.

- Steep rotor blade angles produce higher conductances, which produces higher pumping speeds.

- Shallow rotor blade angles produce higher compression ratios.



Turbomolecular Pumping Mechanism

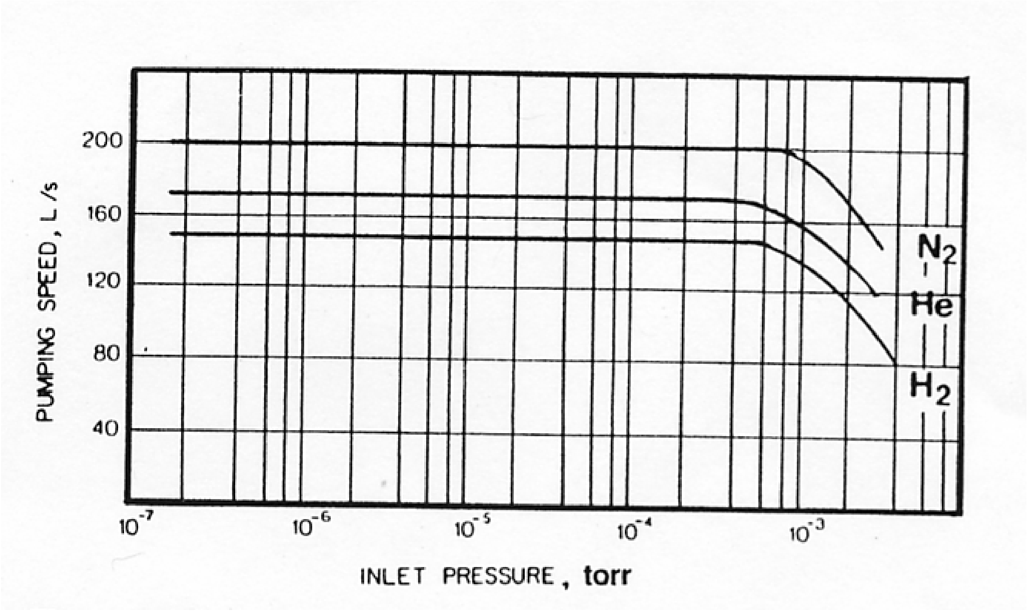


- The stator plays a complimentary role to the rotor.
  1. The stator slows down the gases and,
  2. Increases gas pressure without creating too much of a conductance limitation/
- The stator does it's job in as short a distance as possible.
- Rotors and stators are considered as a "pair" making up a "stage".

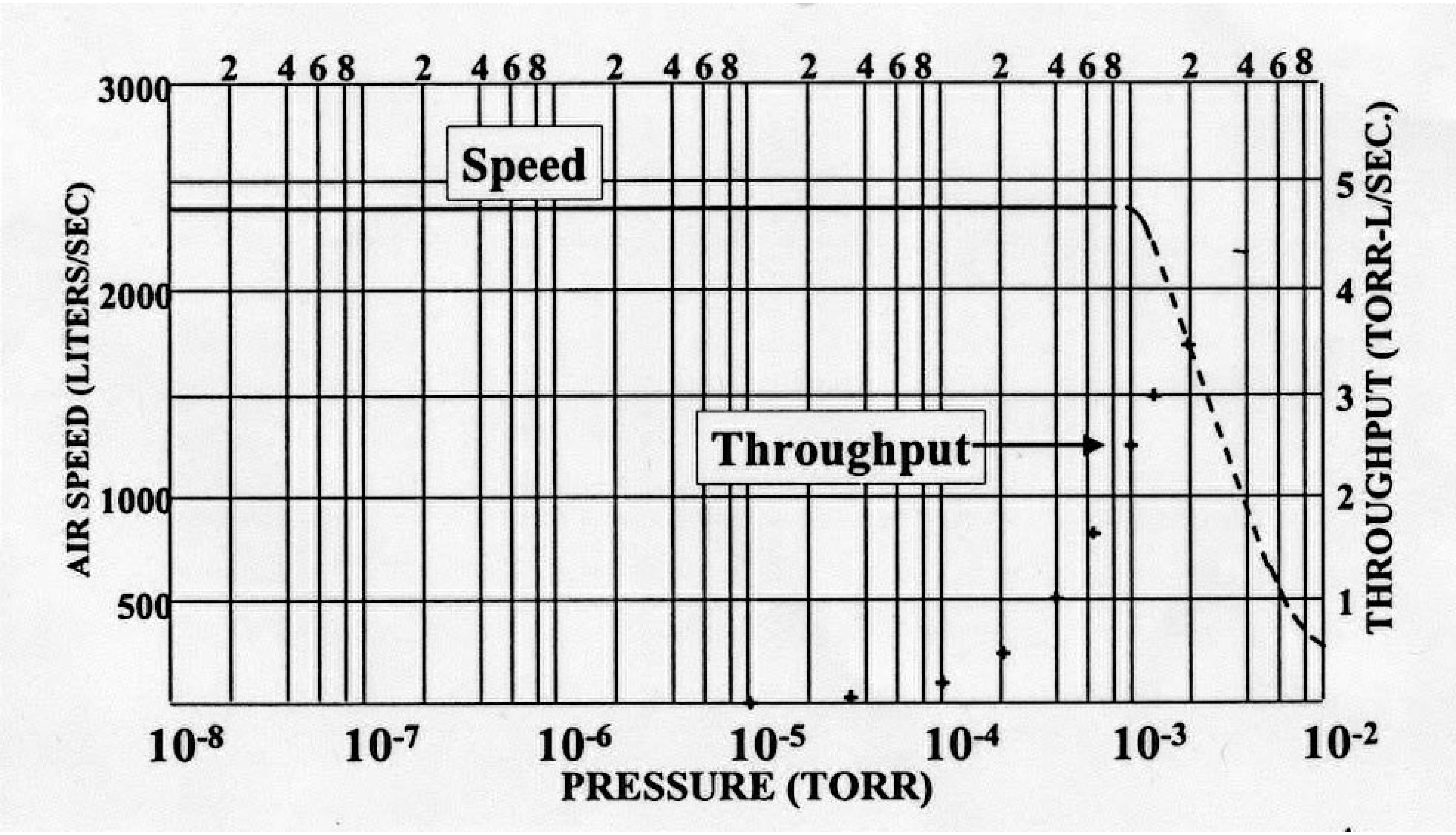
Turbomolecular speeds for different pumps

Pump parameters affecting speed:

1. Rotor diameter and blade height (entrance area)
2. Rotational velocity of blades
3. Blade angle of initial rotor
4. Blade spacing ratio = $\frac{\text{distance between blades}}{\text{blade width}}$



Speed vs.Throughput for a Turbomolecular Pump



Ref. Varian Vacuum

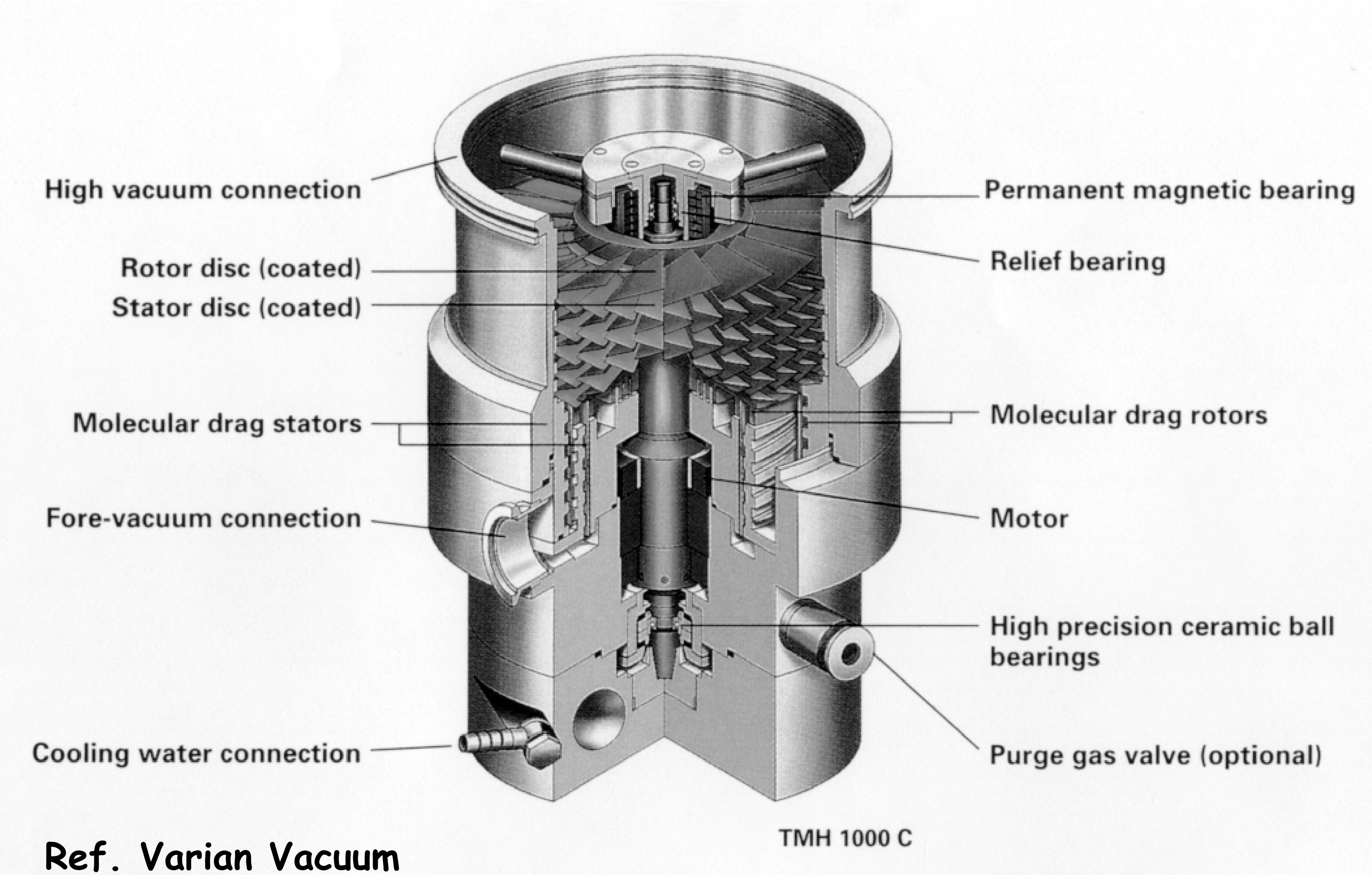
Turbomolecular/Hybrid Pumps are Available in a Multitude of Sizes and Pumping Speeds

Ref. Varian Vacuum

Hybrid Pumps

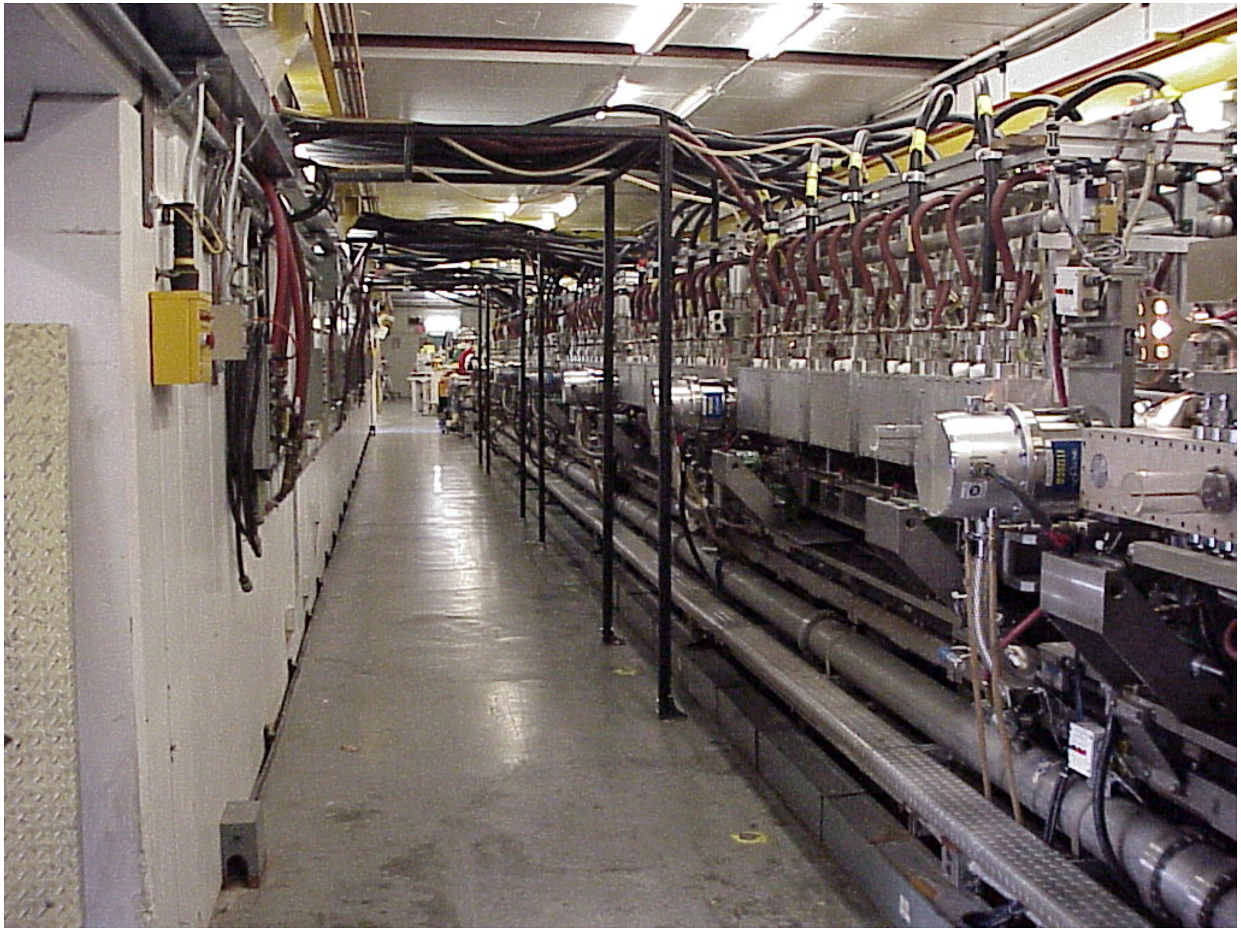
Ref. Varian Vacuum

Cut-away of a Typical Drag Pump



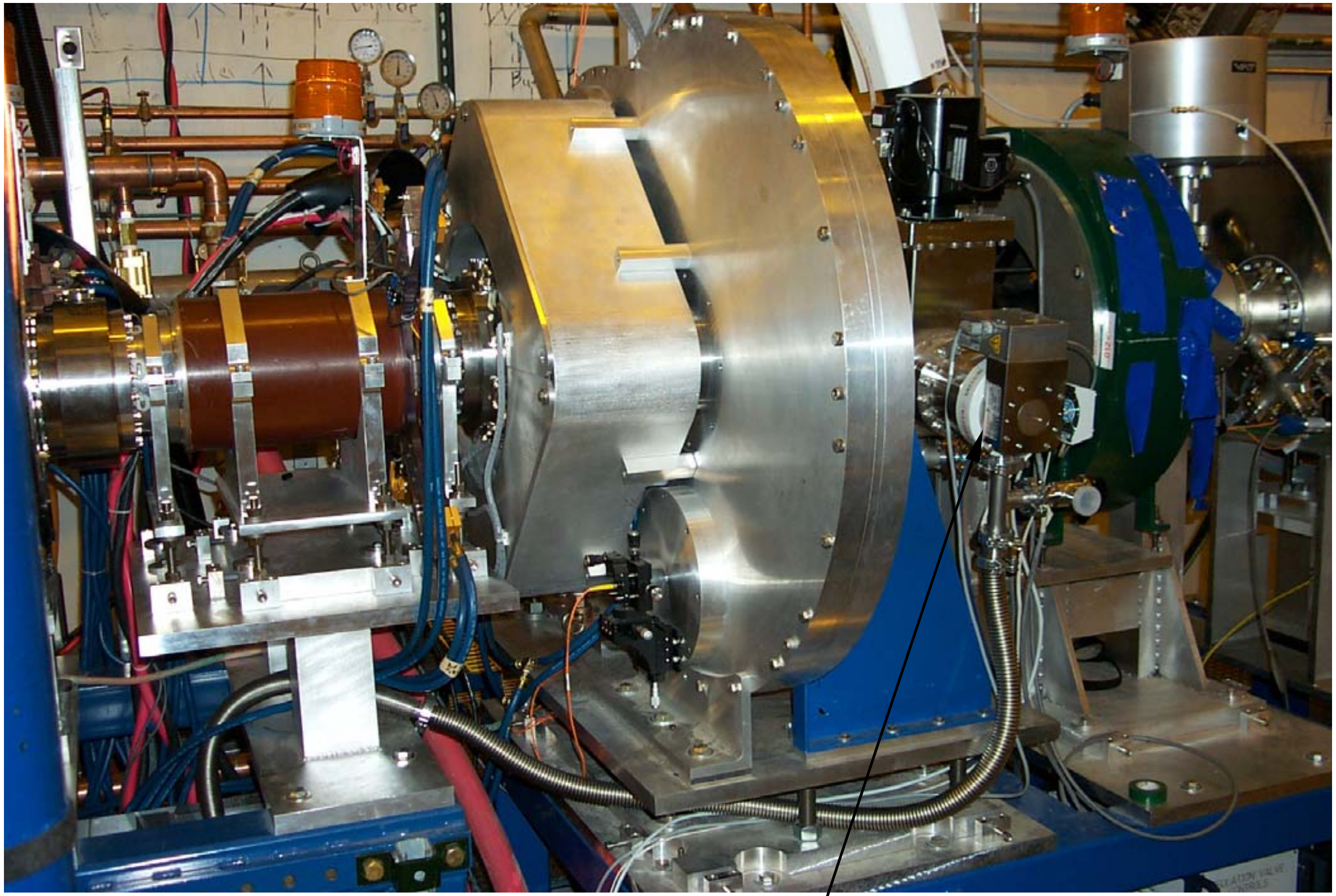
Ref. Varian Vacuum

Example of a Turbomolecular Pumped Accelerator



ETA II @ LLNL

Another example of a Turbomolecular Pumped accelerator component - DARHT II "Debris Blocker".



Turbodrag Pump

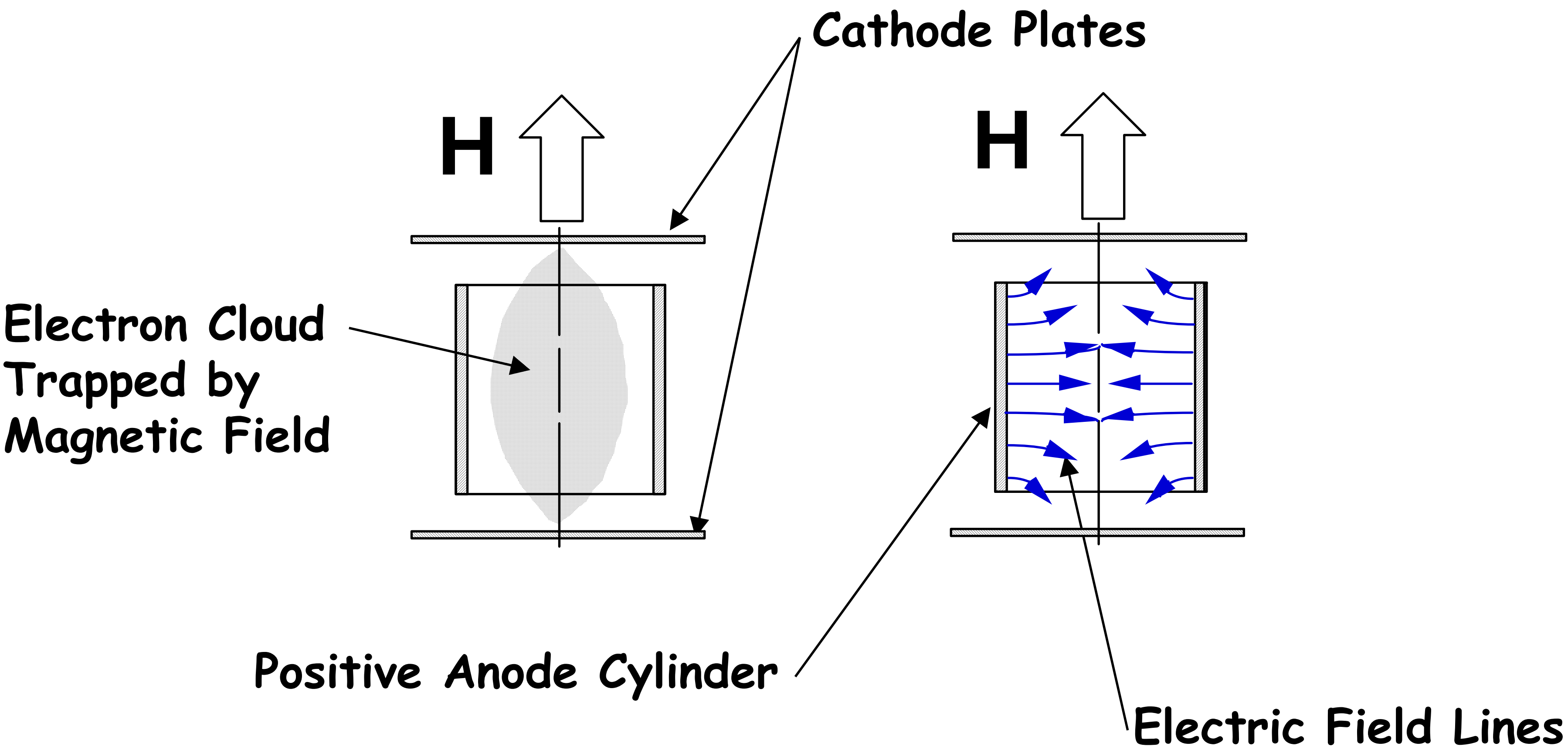
The US Particle Accelerator School
Ion Pumps

Lou Bertolini

Lawrence Livermore National Laboratory

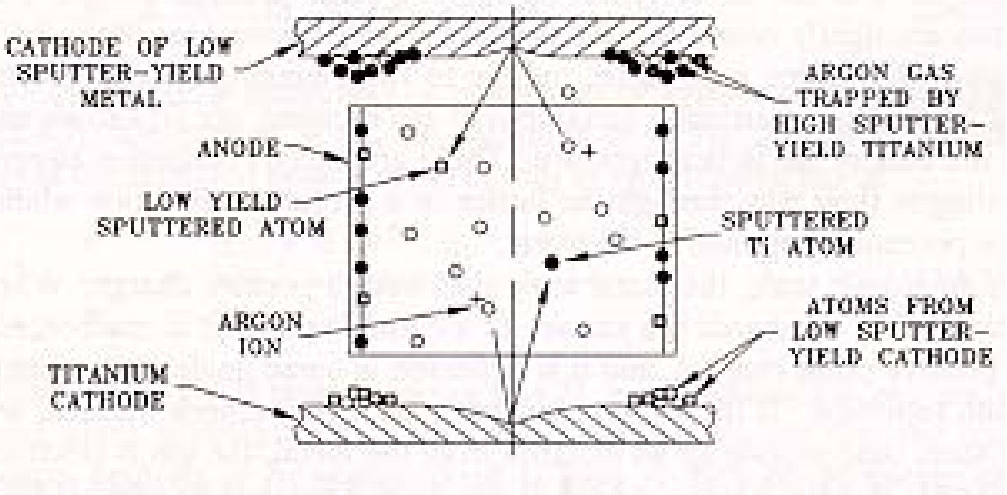
January 19-24, 2004

Penning Cell



Pumping mechanism

- Electrical discharge takes place in crossed electric and magnetic fields.
- The Titanium cathode is bombarded by positive ions.
- Titanium is sputtered on to to the walls of the anode.
- Gas chemisorbs to the sputtered Titanium.
- Gas is buried in the Titanium cathode.



Sputter Ion Pumping Mechanisms

Physisorption - atom burial deep within a lattice, atom burial under sputtered material.

Chemisorption - removal of atoms due to the formation of chemical bonds.

Diffusion - hydrogen diffuses into the bulk of the metal.

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

- Ultra clean
- Quiet
- High pumping speed for water, hydrogen

} Advantages

- Gas species sensitive
- Limited capacity

} Disadvantages

Characteristic Parameter of Penning

Penning Cell Sensitivity

$$S = \frac{I^+}{P}$$

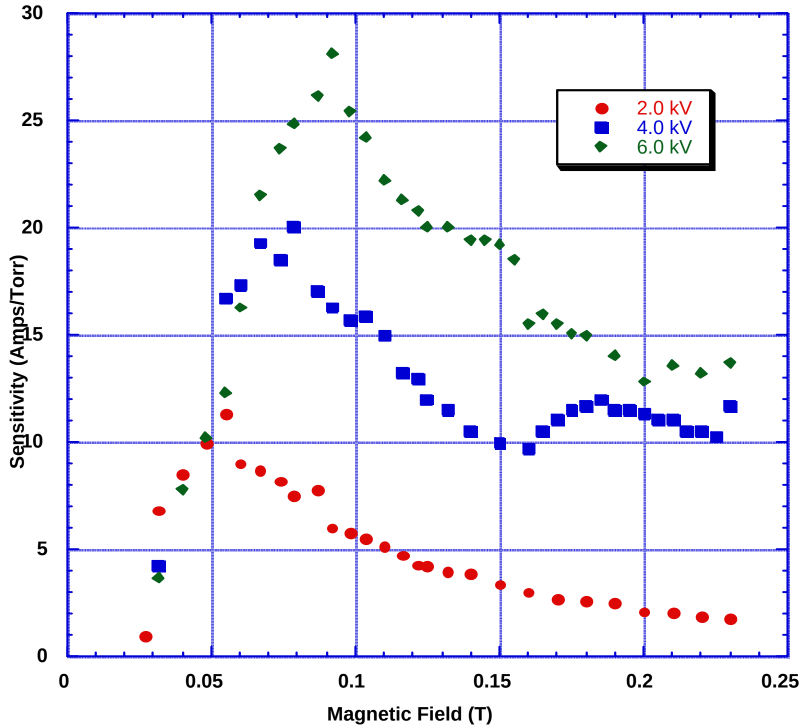
Where I^+ = ion current (Amps)

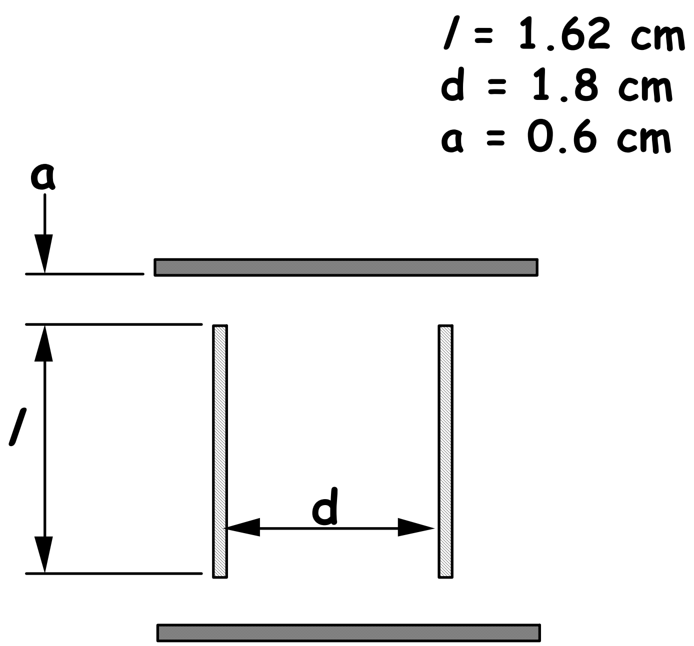
P = pressure (Torr)

Parameters that effect Penning Cell Sensitivity and typical values

Anode Voltage	V	3.0 - 7.0 kV
Magnetic Field	B	0.1 - 0.2 T
Cell Diameter	d	1.0 - 3.0 cm
Cell Length	*l*	1.0 - 3.2 cm
Anode/Cathode Gap	a	0.6 - 1.0 cm
Pressure (P^n)	P	$1.05 \leq n \leq 1.5$ Torr

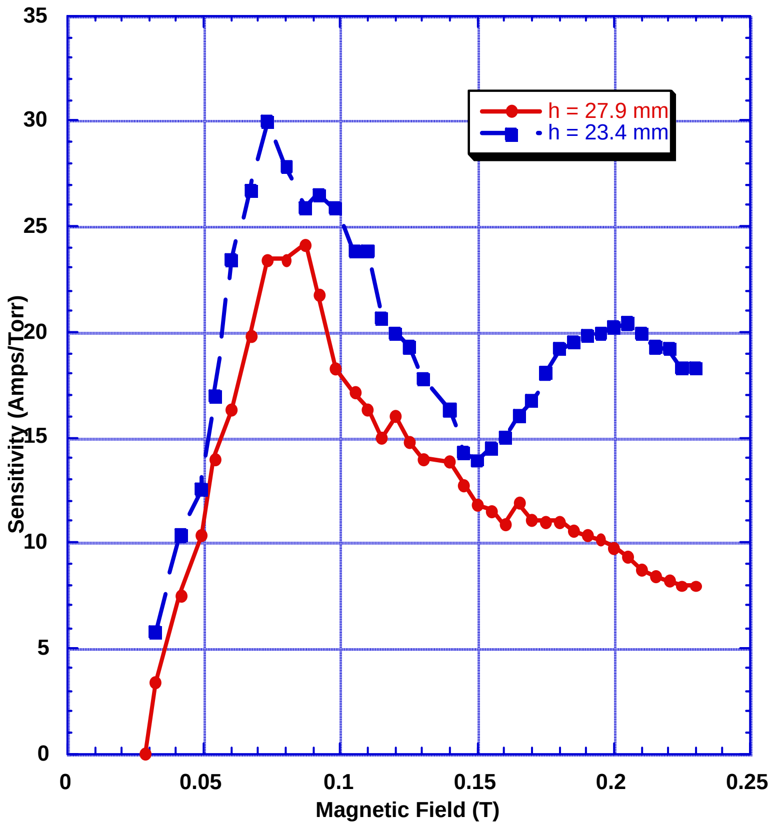
Penning cell sensitivity as a function of magnetic field and anode potential



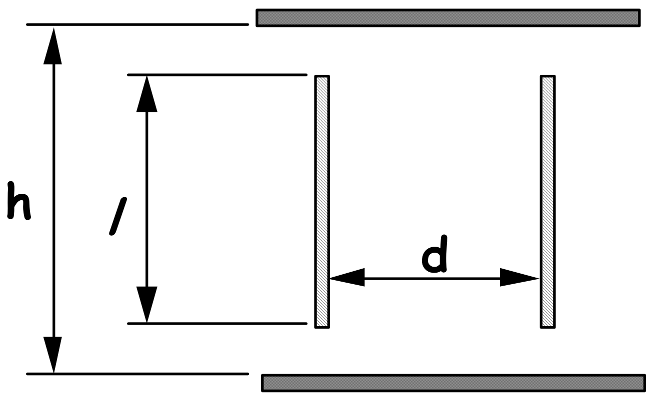


(Ref., Welch, SLAC, 1969)

Penning cell sensitivity as a function of magnetic field and anode-to-cathode spacing



l = 1.62 cm
d = 1.8 cm



(Ref., Welch, SLAC, 1969)

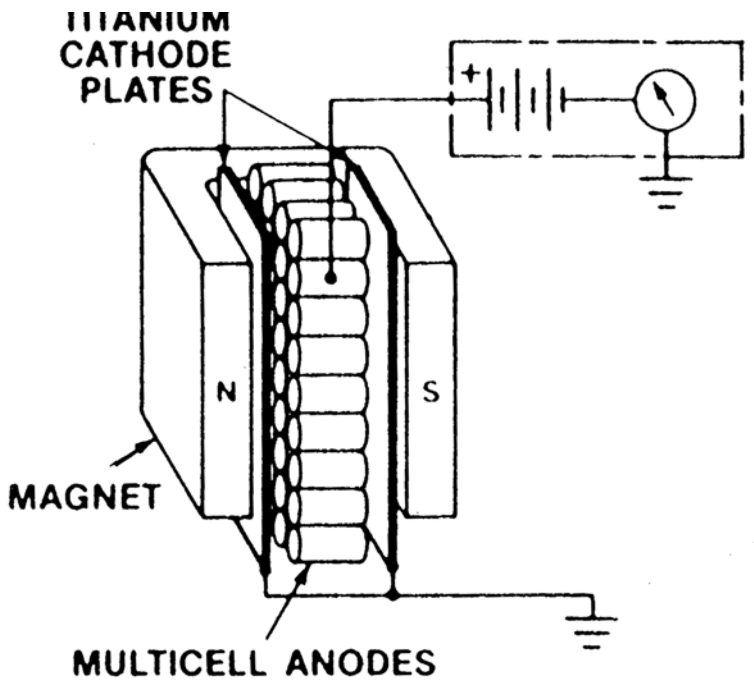
Types of sputter-ion pumps

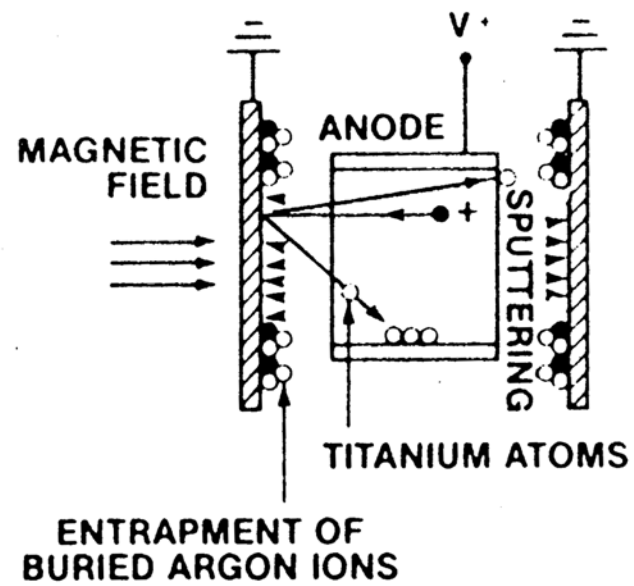
- Diode - best for UHV systems where 98% of the gas is hydrogen. Diodes have the highest hydrogen pumping speed.

- Differential (Noble Diode) – a compromise for hydrogen pumping speed with limited argon stability. This pump has reduced hydrogen pumping speed.

- Triode/Starcell - good hydrogen pumping speed, also pumps argon well. Good choice for pumping down from higher pressures often.

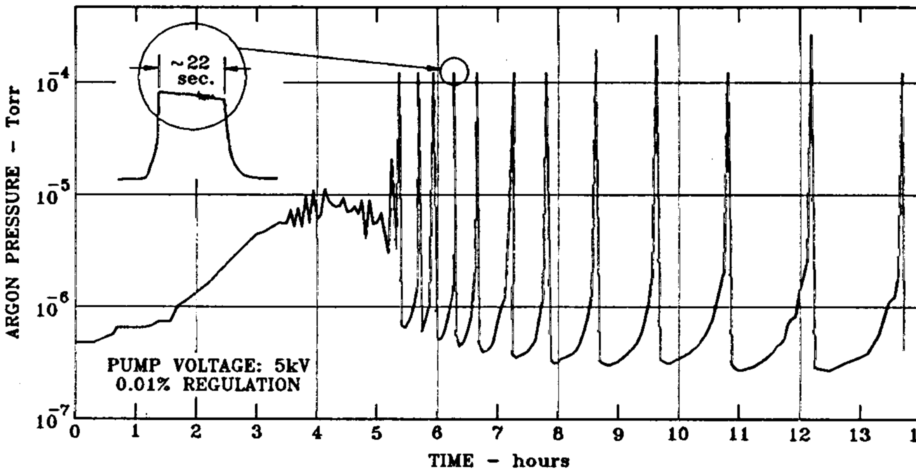
Diode sputter-ion pump





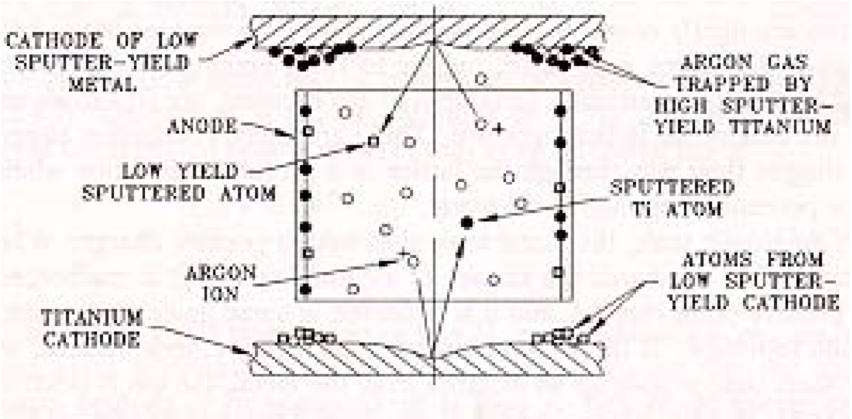
Argon Instability

- Diode ion pumps produce large periodic pressure fluctuations while pumping air or gas mixtures containing inert gases.
- These fluctuations are called "argon instability."
- Argon instability occurs both when pumping air at HV or UHV (1% argon by volume) and pure argon or other inert gases.
- Argon instability occurs when implanted or buried gases are released by sputtering.
- An "argon-stable" pump is one that can pump against a 100% argon leak without becoming unstable.



Differential Ion (Noble Diode) Pumps

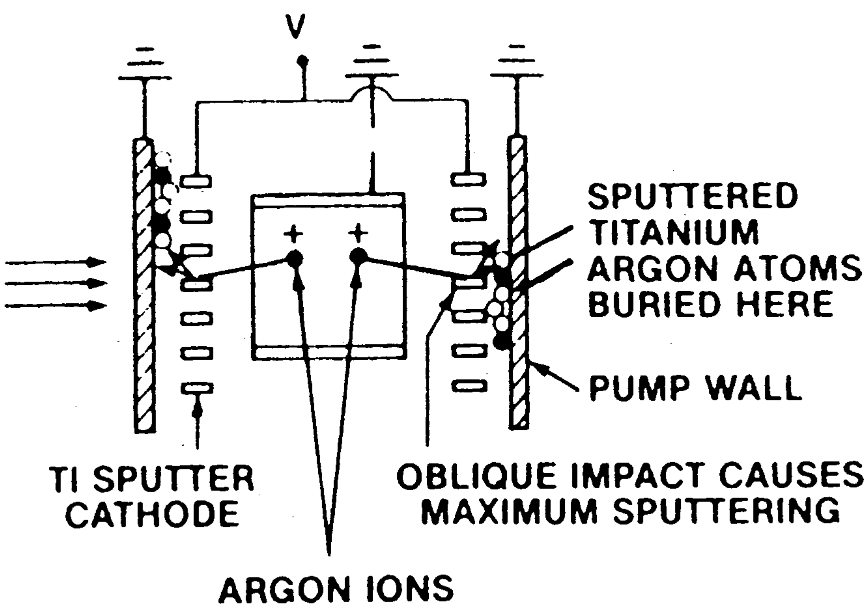
- The differential ion (D-I) pump design provides both air-stability and argon-stability, in a single pump.
- Most inert gases are pumped on the anode structure and at the peripheral areas of the cathode where the sputtering rate is so low that total reemission does not occur.
- These peripheral areas and the anode surfaces are readily reached by energetic reflected neutrals because the neutrals are not affected by the magnetic field.
- With a higher rate of energetic, reflected neutral formation, inert gas pumping speed is increased.
- To achieve high inert gas pumping speeds, differential pumping elements with one cathode chosen for good energetic neutral production (tantalum) and one chosen for its chemical reactivity (titanium) are used.

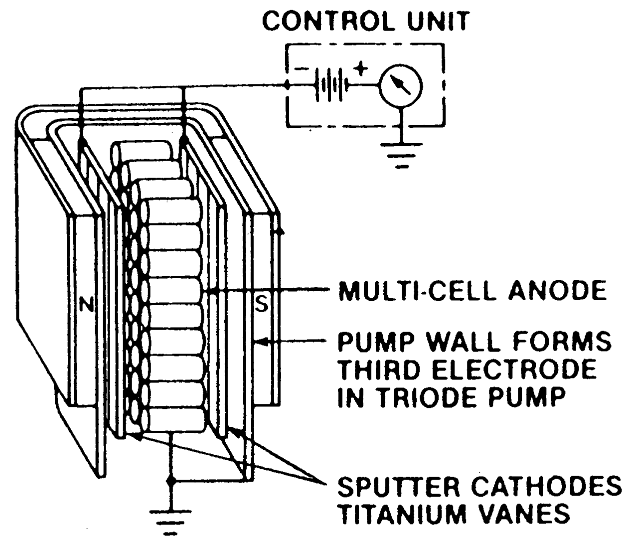


Pumping speeds of ion pumps for various gases compared to air

Gas	Diode	Noble Diode	Triode
H_2	2.5-3.0		2.0
CH_4	2.7		0.9-1.05
NH_3	1.7		
H_2O	1.3		
Air	1.0	1.0	1.0
N_2	0.98		0.95
CO	0.86		
CO_2	0.82	1.0	1.0
O_2	0.55		0.57
He	0.11	0.25	0.3
Ar	0.01	0.2	0.3

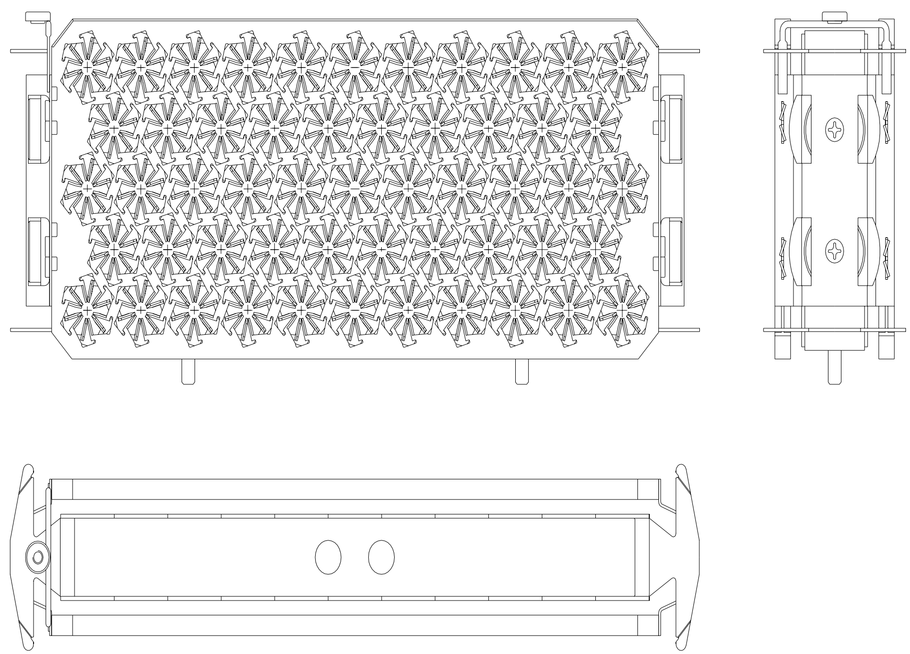
Triode ion pump





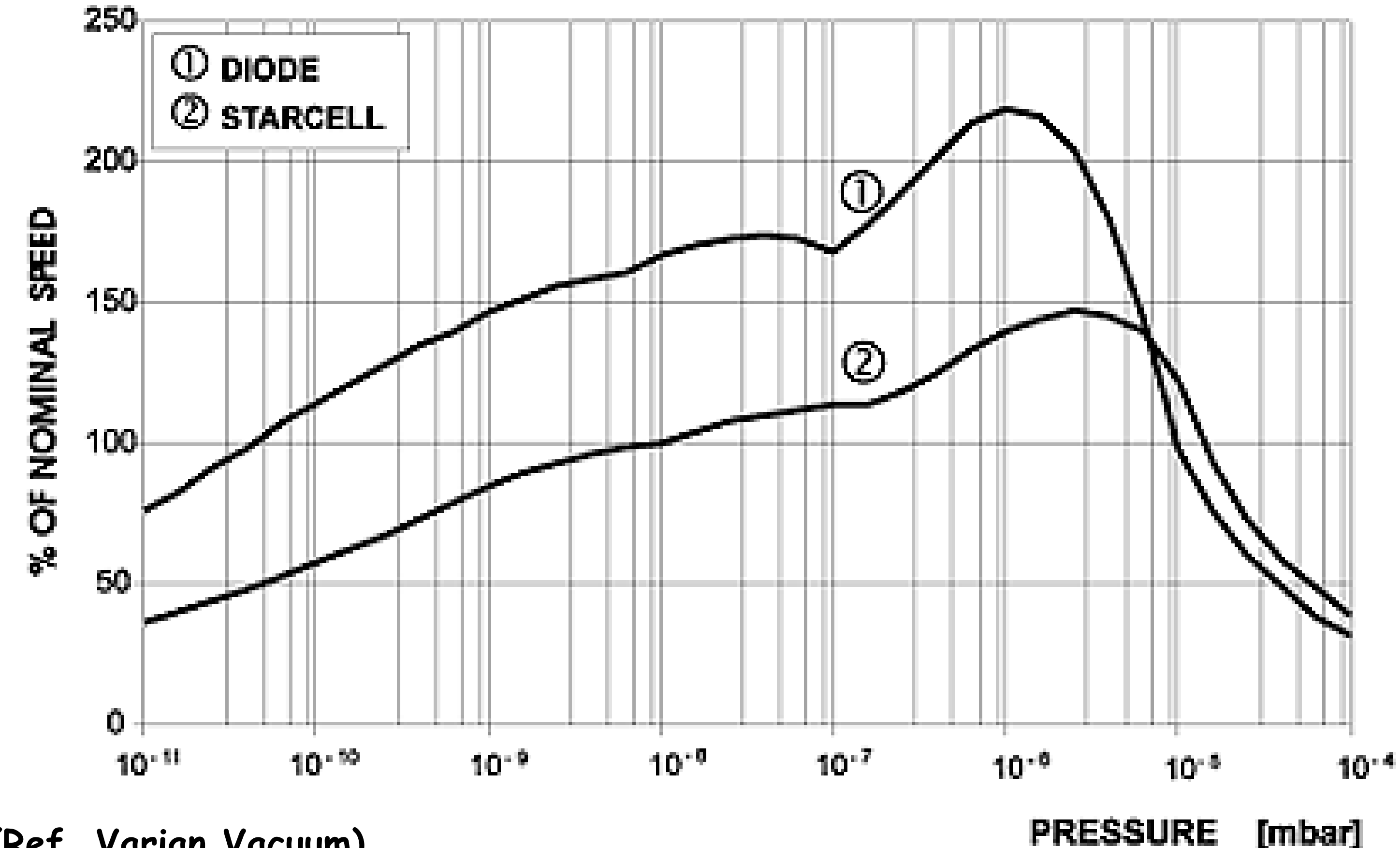
Starcell® Electrodes

- Varian Starcell pump is a variation of the triode design.



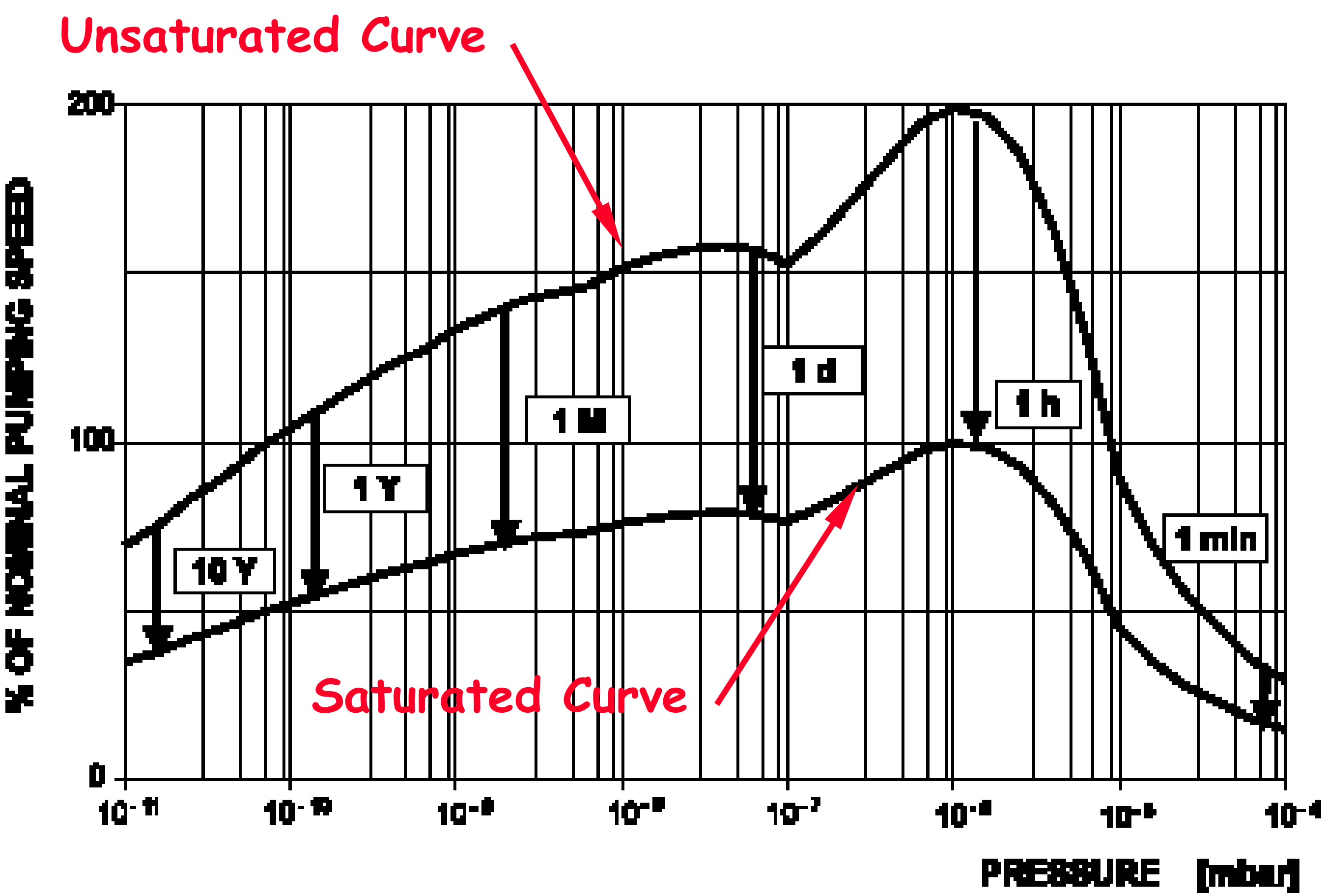
(Ref. Varian Vacuum)

H_2 Pumping Speed curve for an ion pump



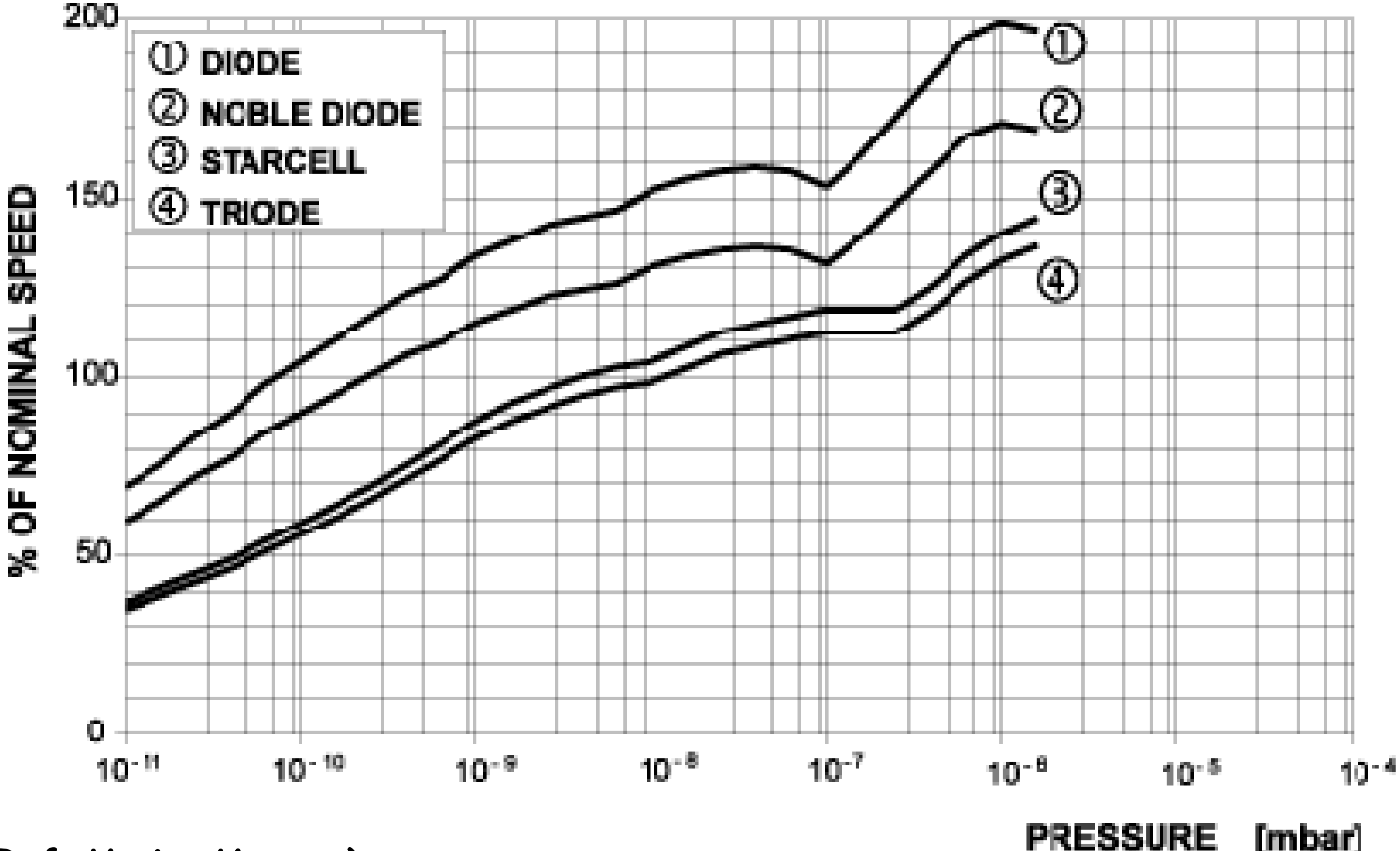
(Ref. Varian Vacuum)

Non-H_2 Pump speed degrades with time



(Ref. Varian Vacuum)

N_2 Speed comparison of different styles of ion pumps



(Ref. Varian Vacuum)

Commercial sputter-ion pumps

(Ref. Varian Vacuum)

Ion Pump Performance for various gases

Gas	Diode	Noble Diode	Triode	Starcell	TSP	NEG
H_2	3	1	1	2	3	4
He	1	3	3	4	0	0
H_2O	3	2	2	2	3	3
CH_4	2	3	3	3	0	0
N_2	3	3	2	2	3	3
O_2,CO,CO_2	3	3	2	2	4	3
Ar	1	3	3	4	0	0

(Ref. Varian Vacuum)

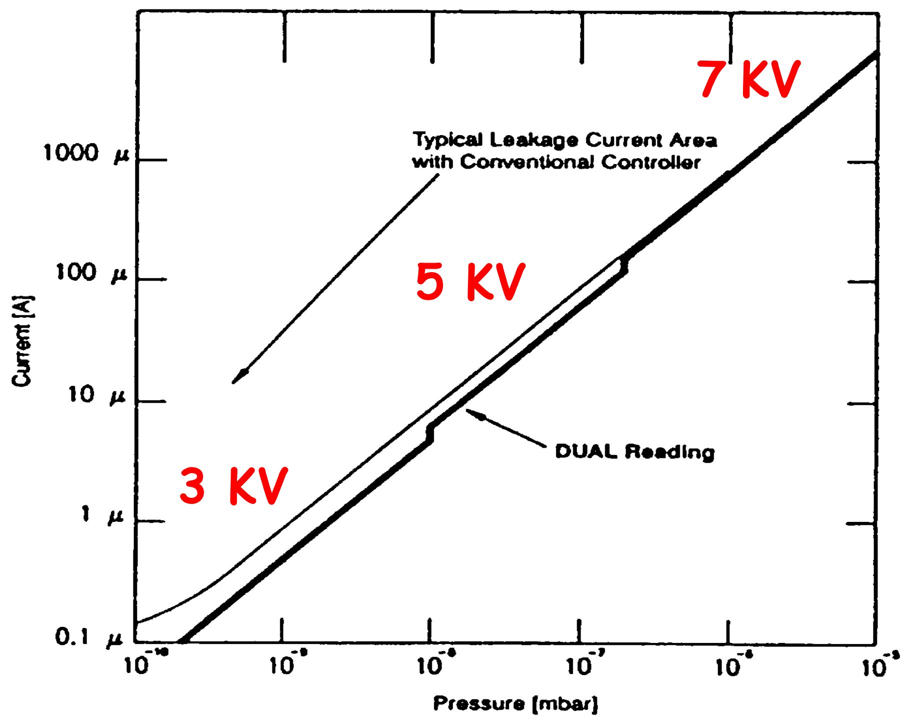
None	0
Poor	1
Good	2
Excellent	3
Outstand.	4

Sputter-ion pump controller

(Ref. Varian Vacuum)

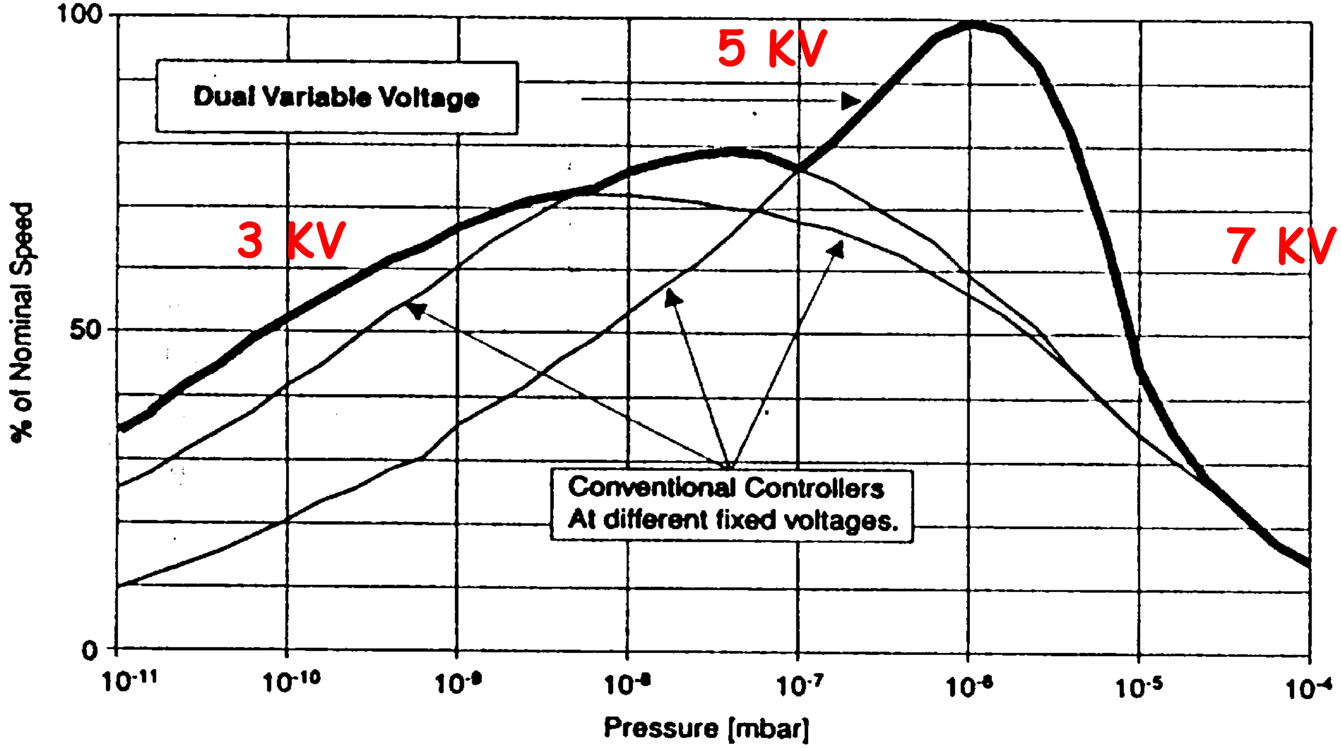
Sputter-ion pump current may be used to measure pressure in the pump body

- Pressure is linearly proportional to current.
- At low pressures (<10^{-9} Torr), the leakage current effects the pressure reading.
- The displayed current is the total of the leakage in the power supply, cable connectors, feedthroughs, insulators, internal discharge, and working current.
- The new controllers with variable voltage capability improve this feature.



(Ref. Varian Vacuum)

"Variable Voltage Control" also improves pump performance

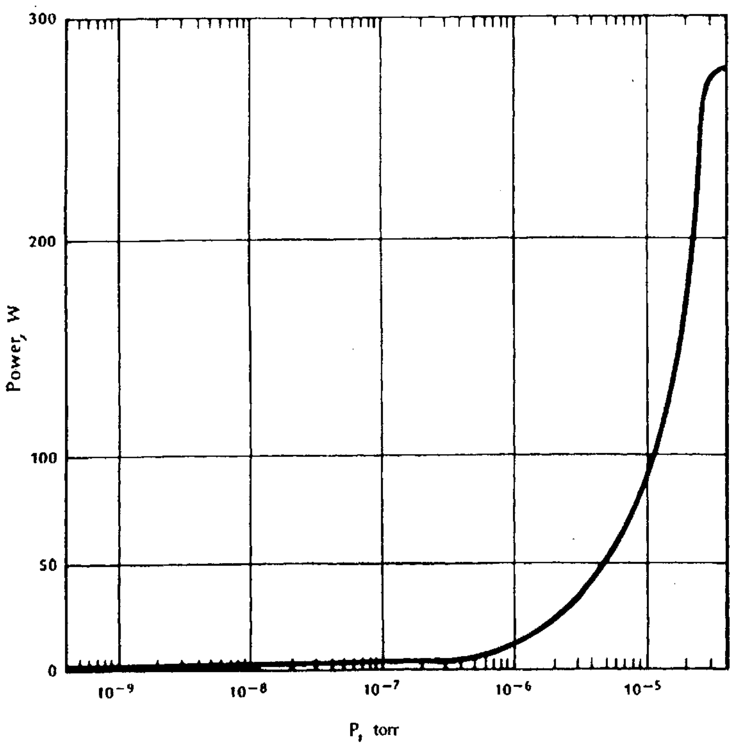


(Ref. Varian Vacuum)

Electrical characteristics of ion pumps

- It is important to match the power supply to the ion pump.
  - Too large a power supply can create overheating in the electrodes.
  - Too small a power supply will not be able to drive the pump at higher pressures.

- The power supply must provide voltage and current to the ion pump under a variety of conditions.



(Ref. Varian Vacuum)

Example – Ion Pumped Vacuum System SNS Linac

Current Design Features:

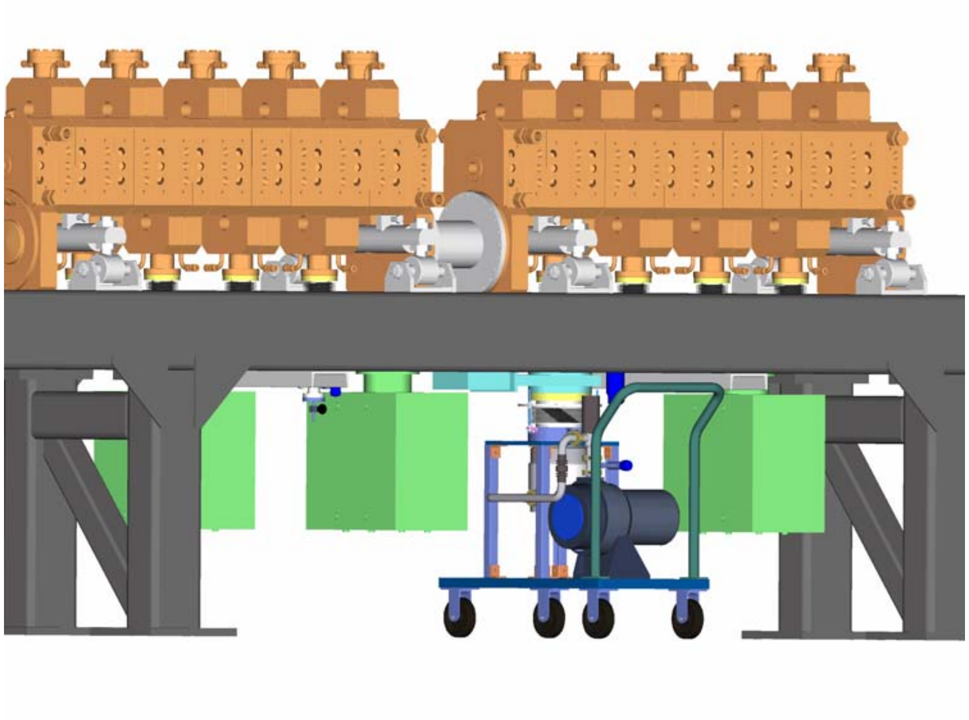
Accelerator Length

DTL: 36.5 m
CCL: 56.5 m

Design Vacuum Level: 10^{-7} Torr (with redundancy)

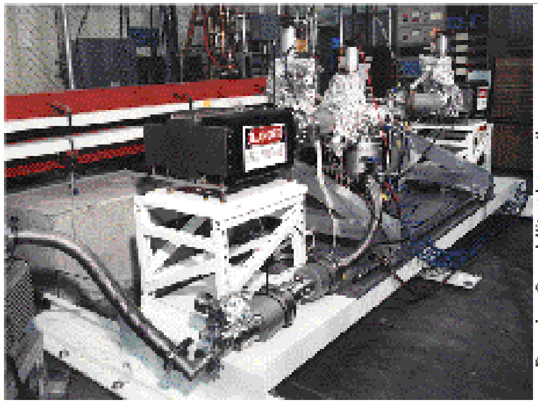
Total Ion Pump Speed: 20,000 L/s

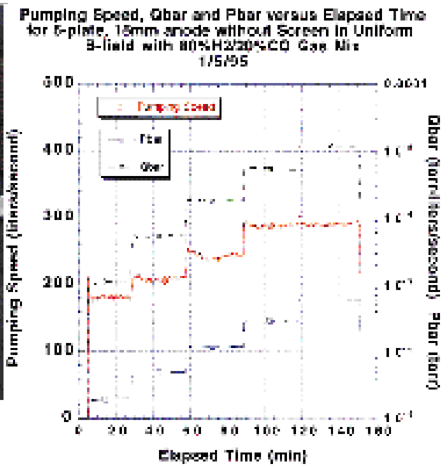
Number of Roughing/Turbo Carts: 15

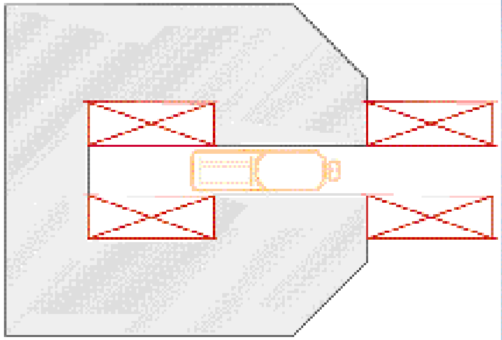


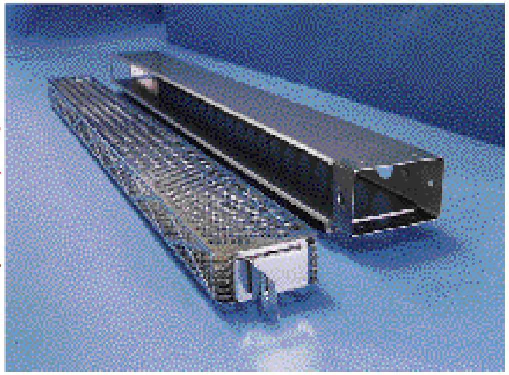
Distributed Ion Pumps (DIPs)

- Distributed ion pumps are often incorporated into storage rings.
- Distributed ion pumps utilize the stray magnetic field of the arc bend magnets.
- They provide effective distributed pumping close to synchrotron radiation gas desorption.

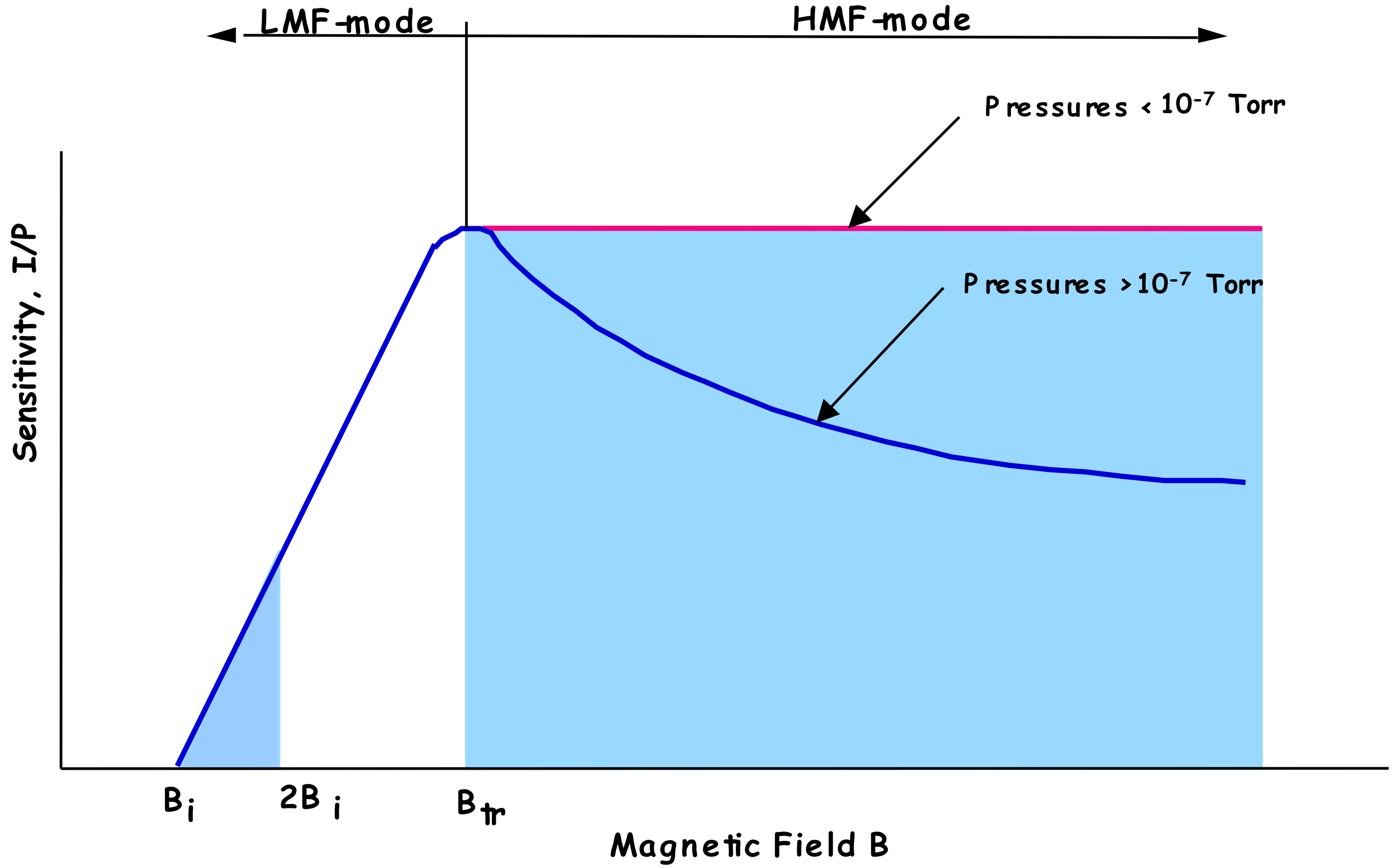








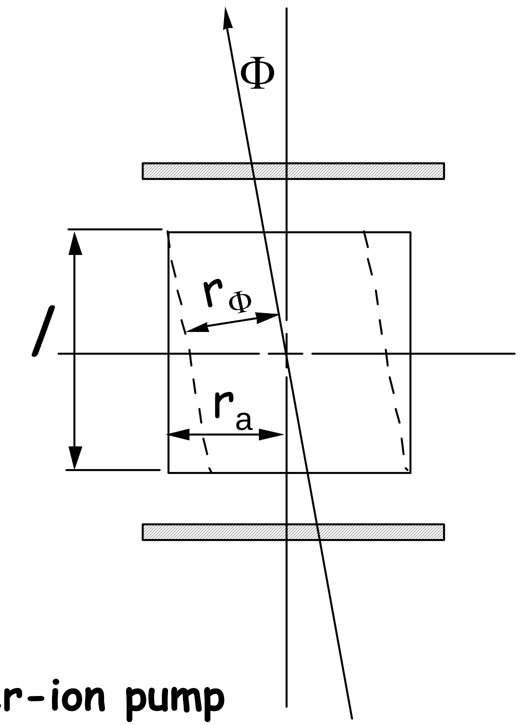
Pump Sensitivity (Discharge Intensity) vs. Magnetic Field



Formalism of Ion Pump Design

In cases where the magnetic field lines are misaligned with the cell axis, the electron cloud will be smaller than the anode radius.

$$r_\Phi = r_a \cos\Phi - 0.5\lambda \sin\Phi$$



Ref. "A new approach for computing diode sputter-ion pump Characteristics", Hartwig and Kouptsidis, JVST, Vol. 11, No. 6, 1974

Formalism of Ion Pump Design (continued)

Magnetic Field at the Ignition Point

$$B_i = \frac{300}{r_a}$$

where a = gap (cm)
r_a = cell radius (cm)
l_a = anode length (cm)
P = pressure (Torr)
U_a = anode voltage (V)
B = magnetic field (Gauss)

Magnetic Field at the Transition to HMF-mode

$$B_{tr} = \frac{7.63\sqrt{U_a}}{r_a P^{0.05}}$$

Effective Cell Length

$$l_{eff} = l_a + 0.5a$$

Formalism of Ion Pump Design (continued)

Unsaturated Nitrogen Pumping Speed of one cell

$LMF - mode,\ B_i \le B \le 2B_i$

$$S_1 = 6.27 \times 10^{-5}\left(1 - \frac{1.5 \times 10^6 P}{1 + 4 \times 10^6 P}\right) P^{0.2} l_{eff} r_a^2 B_i (B - B_i)$$

$LMF - mode,\ 2B_i \le B \le B_{tr}$

$$S_1 = 1.56 \times 10^{-5}\left(1 - \frac{1.5 \times 10^6 P}{1 + 4 \times 10^6 P}\right) P^{0.2} l_{eff} r_a^2 B^2$$

$HMF - mode,\ B \ge B_{tr}$

$$S_1 = 9.1 \times 10^{-4}\left(1 - \frac{1.5 \times 10^6 P}{1 + 4 \times 10^6 P}\right) P^{0.1} l_{eff} U_a \left(1 - 1.5 \times 10^4 \frac{\sqrt{(B - B_{tr})}\, r_a P}{U_a}\right)$$

Saturated Nitrogen Pumping Speed (after Q = 2 x 10^{-6}S Torr-liters/sec)

multiply above equations by $\left(0.75 - \frac{2 \times 10^{-10}}{P}\right)$ valid for $P > 3 \times 10^{-10}$ Torr

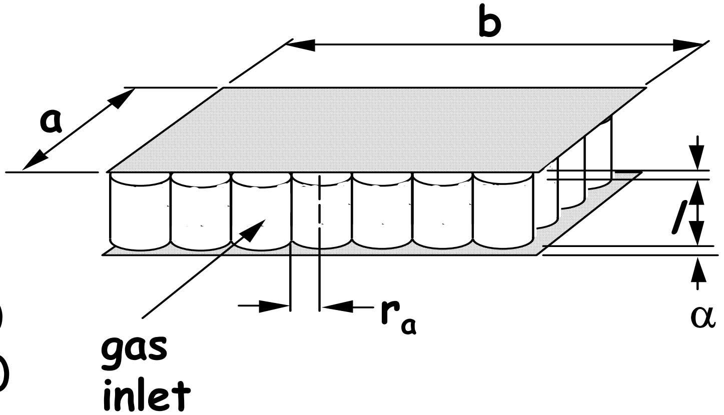
$S_{sat} = 0$ valid for $P < 3 \times 10^{-10}$ Torr

Formalism of Ion Pump Design (continued)

Nitrogen Pumping Speed for n cells

$$S_n = nS_1$$

Effective Nitrogen Pumping Speed due to conductances of the gaps between the anode and the two cathodes.



$$S_{eff} = S_n\left(\frac{\tanh D}{D}\right) \qquad \textit{where} \quad D = \frac{ka}{7.85\alpha}\sqrt{\frac{S_n}{ab}}$$

a = depth of pump unit (cm)

b = length of pump unit (cm)

α = gap (cm)

k = factor = 1 if pump is open on one side

= 0.5 if pump is open on two sides

Formalism of Ion Pump Design (continued)

Effective Nitrogen Pumping Speed for N units at the flange

$$\frac{1}{S_p} = \frac{1}{NS_{eff}} + \frac{1}{C}$$

where S_p = effective nitrogen pumping speed (liters/sec)

N = number of pumping units

C = conductance of the pump chamber (liters/sec)

The US Particle Accelerator School
Non-evaporable Getter Pumps

Lou Bertolini
Lawrence Livermore National Laboratory

January 19-24, 2004

Non-evaporable Getters (NEG)

- NEG is available only from:
  SAES Getters S.p.A.
  Via Gallarate, 215
  20151 Milano Italy

  SAES Getters U.S.A., Inc.
  1122 E. Cheyenne Mountain Blvd.
  Colorado Springs, CO 80906

Non-evaporable Getters (NEG)

- Bulk Getters - gases diffuse into the interior of the getter material.

- Gases are categorized into four families based on their interactions with NEGs:
  1. Hydrogen and its isotopes - sorbed reversibly.
  2. CO, CO_2, O_2, and N_2 - sorbed irreversibly.
  3. H_2O, hydrocarbons - sorbed in a combination of reversible and irreversible processes. Hydrocarbons are sorbed very slowly.
  4. Rare gases - not sorbed at all.

NEG Pumping Characteristics

Hydrogen

- Hydrogen does not form a stable chemical composition with a NEG alloy. It diffuses rapidly into the bulk of the getter and is stored as a solid solution.

- Sievert's Law describes the relationship between H_2 concentration within its NEG and its equilibrium pressure.

$$\text{Log}\, P = A + 2 \log q - \frac{B}{T}$$

q = H_2 concentration in NEG, Torr - liters/gram

p = H_2 equilibrium pressure, Torr

T = getter temperature, K

A, B constants for different NEG alloys

NEG Pumping Characteristics

CO, CO_2, O_2, N_2

- Active gases are chemisorbed irreversibly by NEGs.
- The chemical bonds of the gas molecules are broken on the surface of the NEG.
- The various gas atoms are chemisorbed forming oxides, nitrides, and carbides.
- High temperatures do not break these chemical bonds. High temperatures promote diffusion into the bulk of the NEG.

NEG Pumping Characteristics

H_2O and Hydrocarbons

- Water vapor and hydrocarbons are "cracked" on the surface of the NEG.
- H_2, O_2, and C are chemisorbed irreversibly.
- However, hydrocarbons sorption efficiency below 500°C is extremely low.

NEG Pumping Characteristics

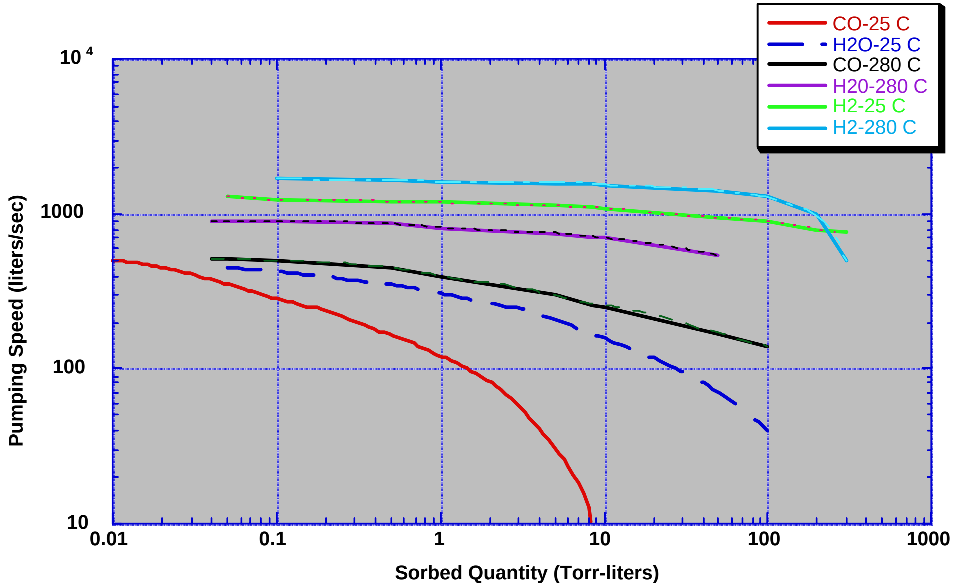
Rare gases

- NEGs do not sorb Ar, He, Kr, Xe.
- Ion pumps are required in combination with NEGs for pumping rare gases.

NEG Pumping Characteristics

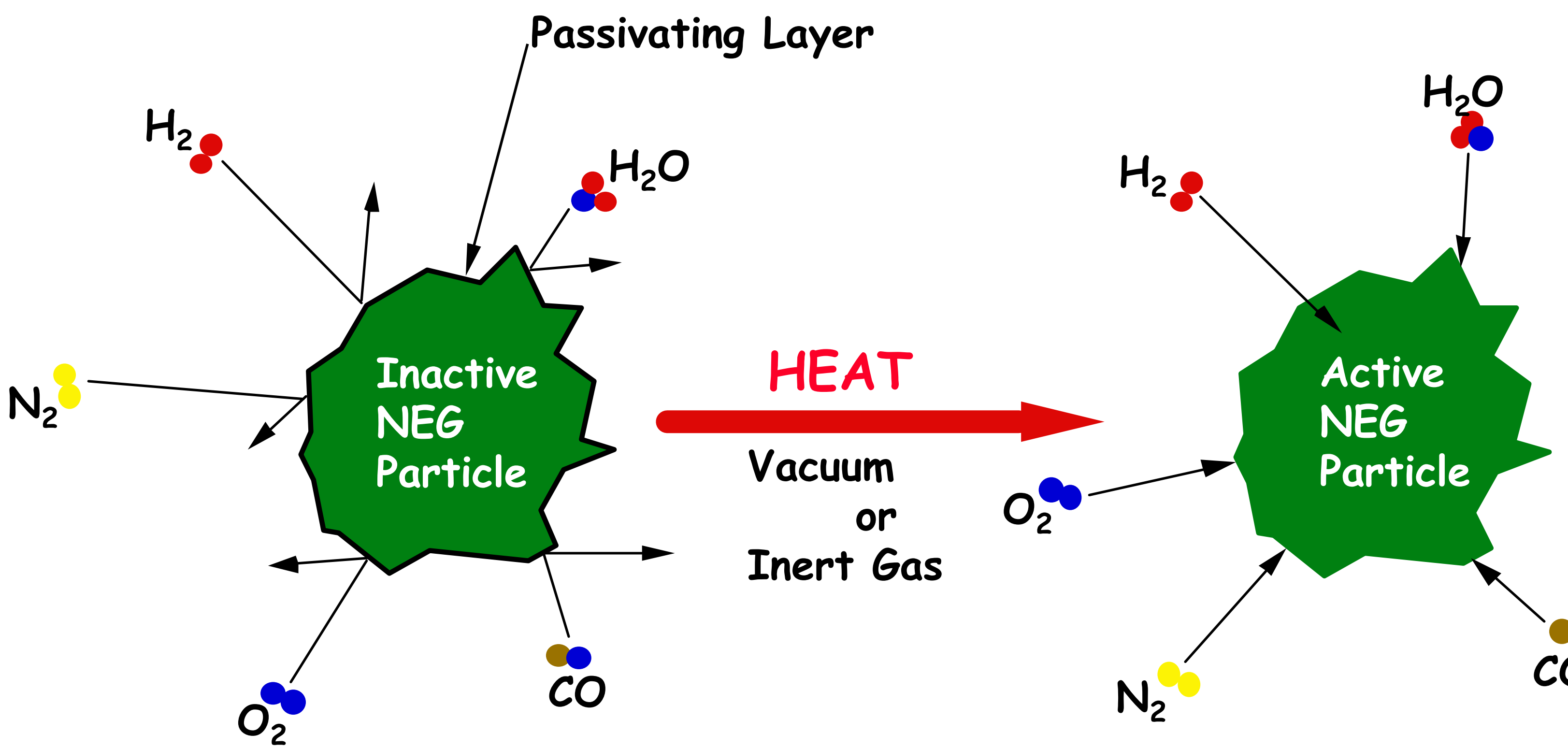
- Below pressures of 10^{-5} Torr, NEG pumping speeds do not vary.

- Pumping speeds do, however, vary with NEG temperature.



Ref. SAES Getters

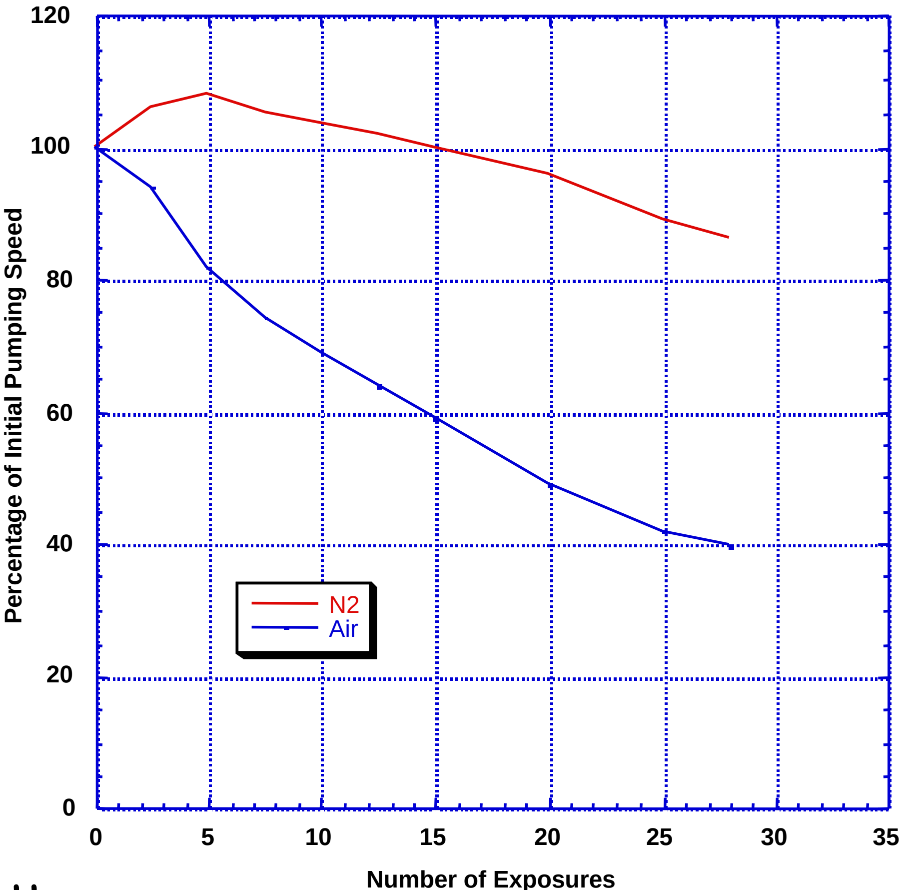
Activation Process for NEG



Ref. SAES Getters

Venting NEG Pumps

- NEG pumping speed deteriorates due to successive exposures to air or N_2.
- Further improvement can be obtained if Argon is used as a protective gas.
- NEG pumps should never be exposed to air while at temperatures greater than 50°C.



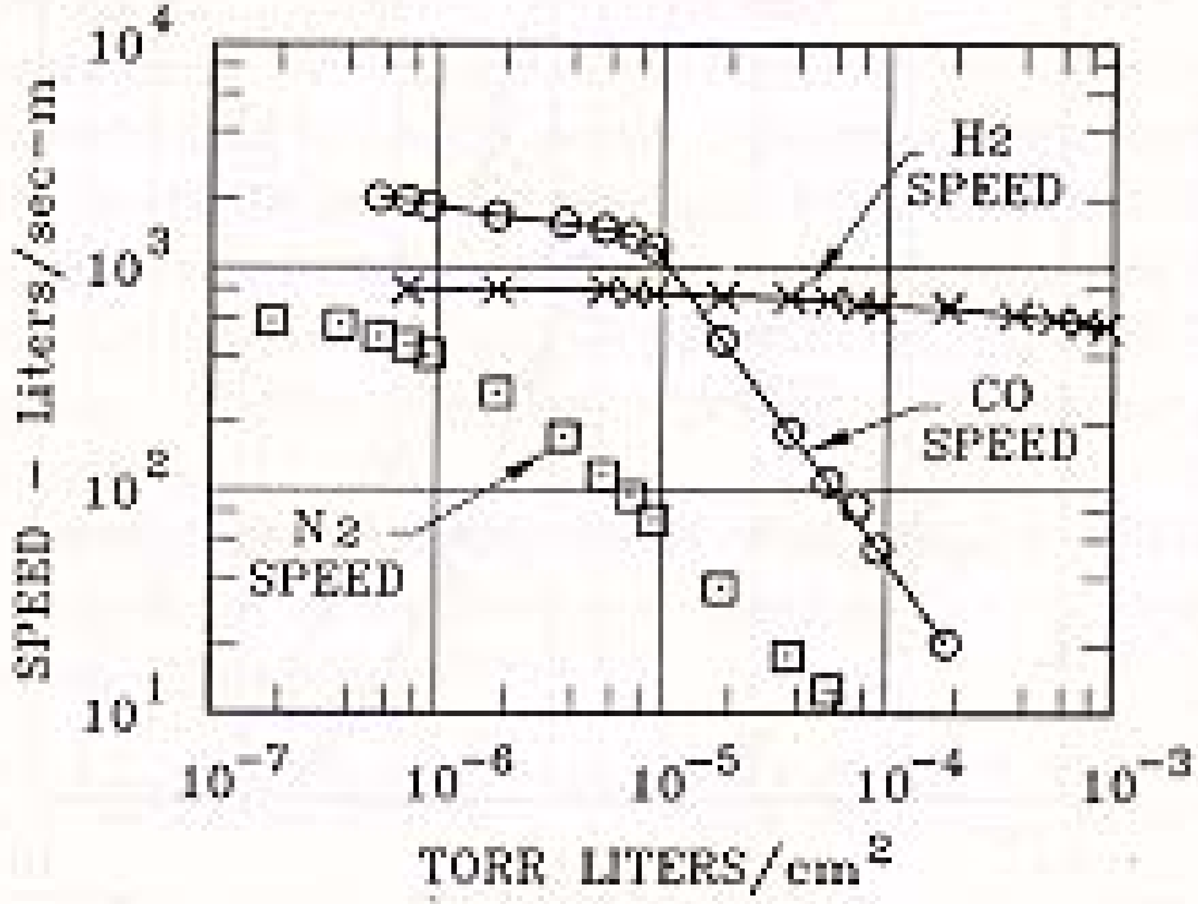
Ref. SAES Getters

SAES ST101® Non-evaporable Getter

- Metal alloy made up of 84% Zr, 16% Al.
- First Zirconium based getters alloy introduced and still widely used today after 30 years.
- The operating temperature range of ST101 is 0 to 450°C.
- ST101 chemisorbs CO, CO_2, H_2O, N_2, and O_2 at high rates.
- ST101 activates at temperatures from 550 to 900°C.

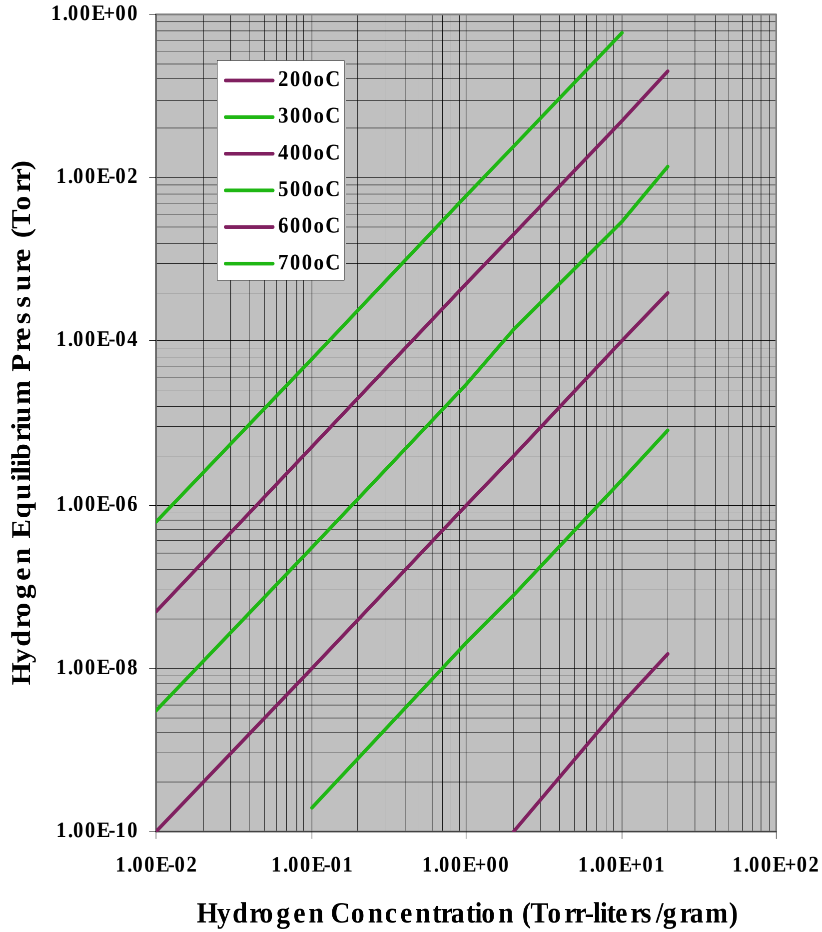
Ref. SAES Getters

SAES ST101® Non-evaporable Getter Sorption Plot



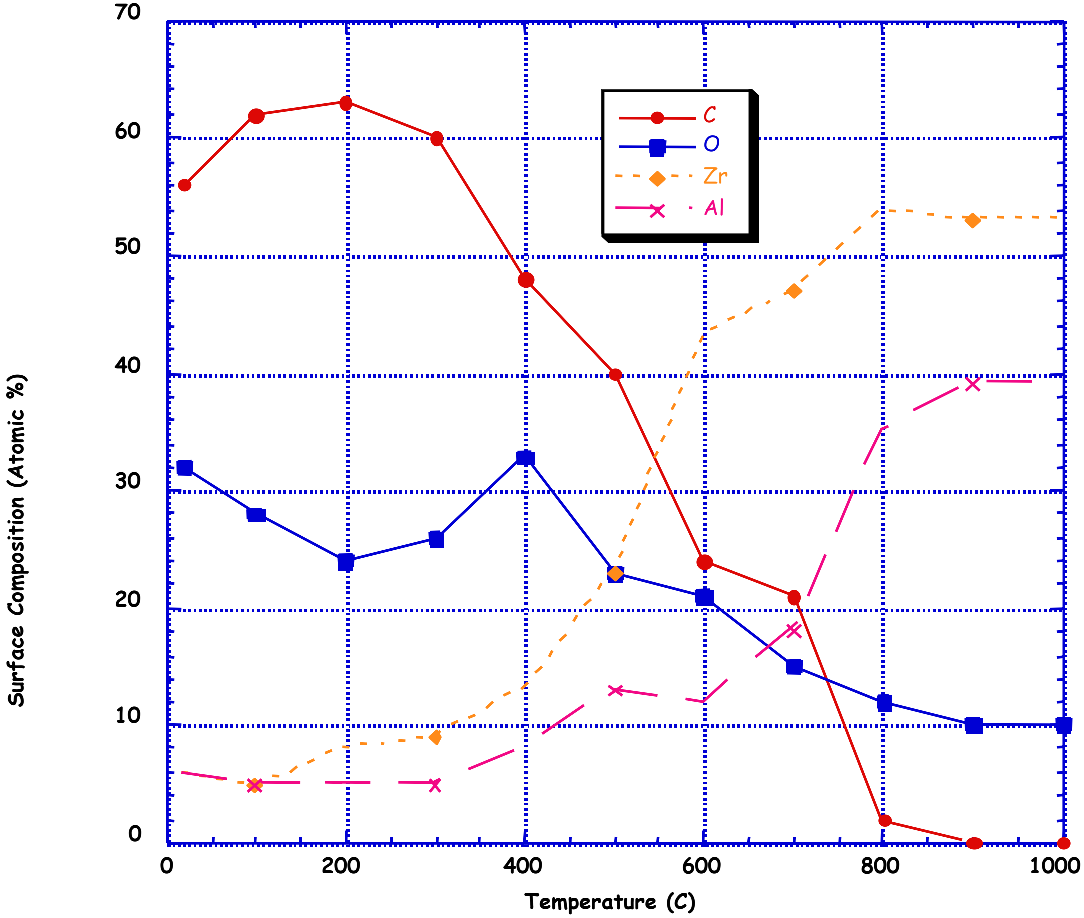
Ref. SAES Getters

SAES ST101® Non-evaporable Getter Hydrogen Equilibrium Pressure



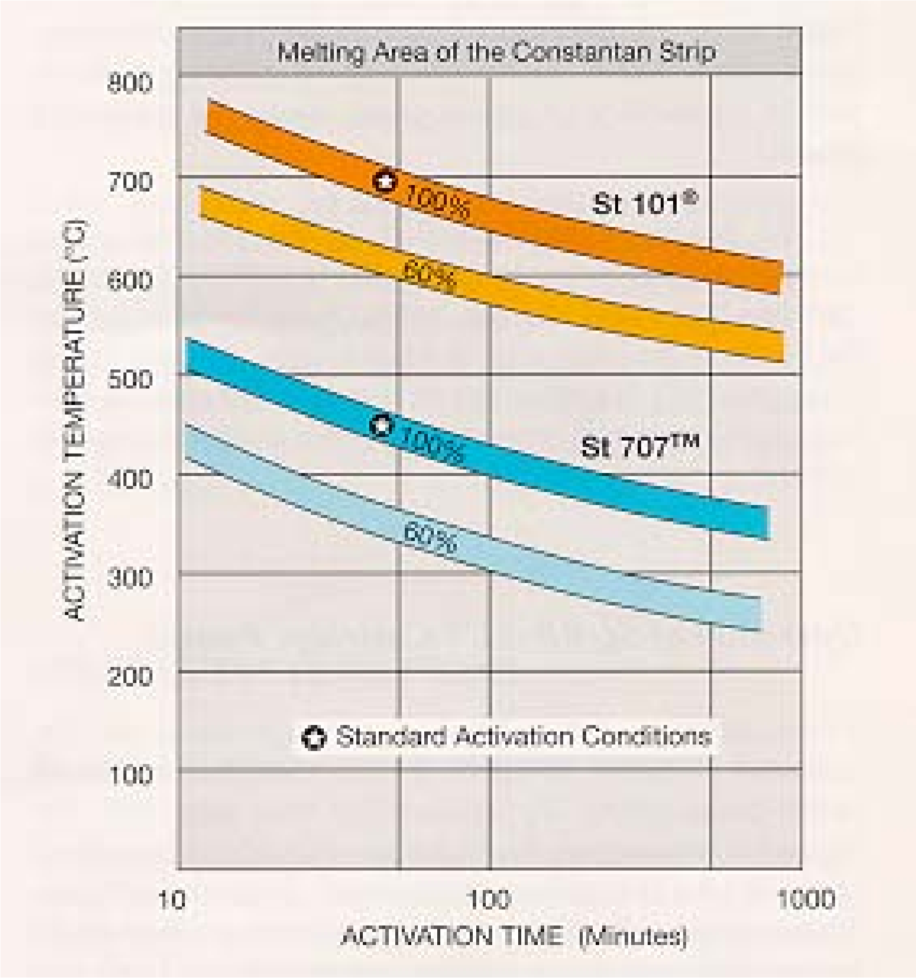
Ref. SAES Getters

SAES ST101® Surface Composition vs. Activation Temperature



Ref. SAES Getters

Activation Efficiency for ST101® and ST707™



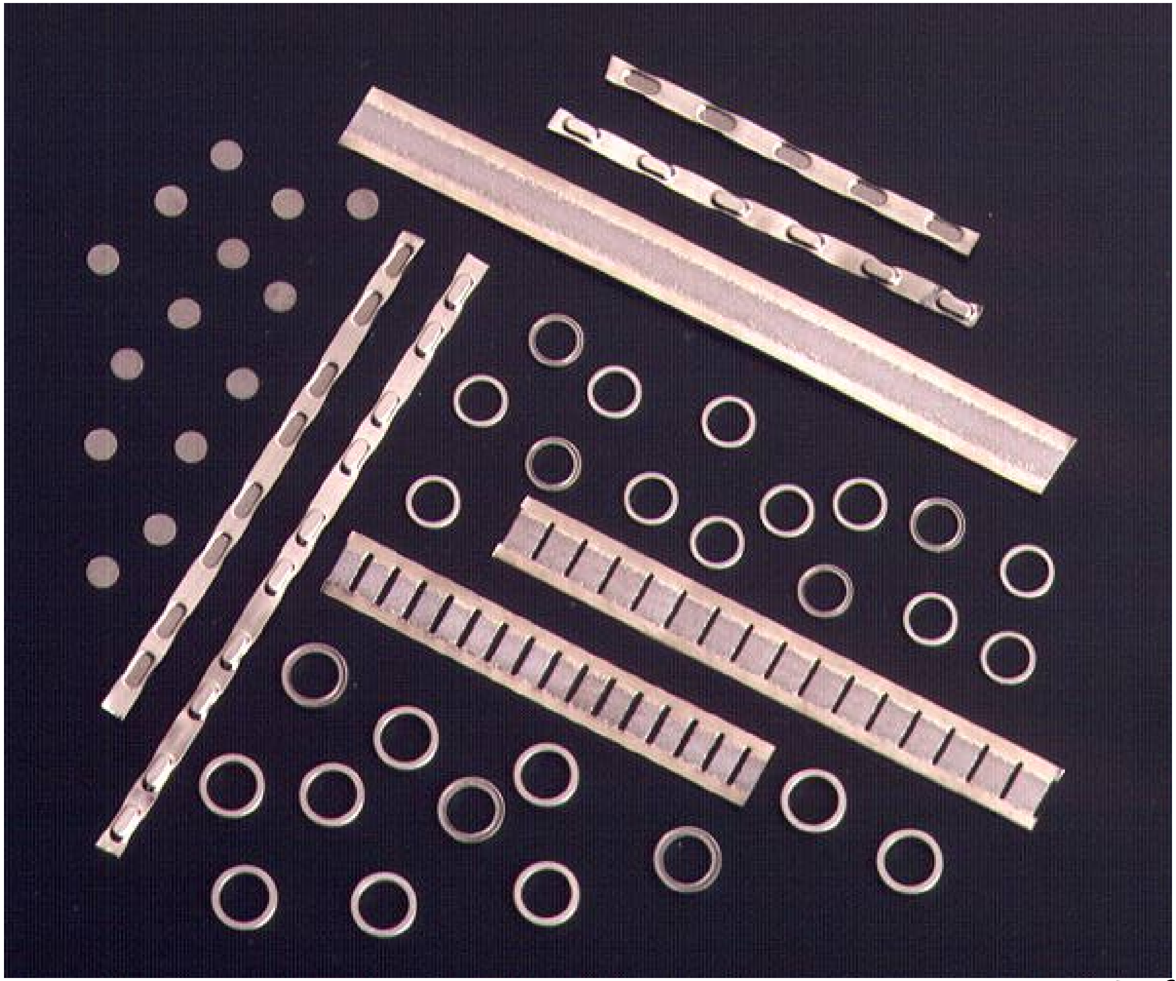
Ref. SAES Getters

SAES ST707™ Non-evaporable Getter

- Metal alloy made up of 70% Zr, 24.6% Va, and 5.4% Fe.
- The operating temperature range of ST707 is 20 to 100°C.
- ST707 chemisorbs CO, CO_2, H_2O, N_2, and O_2 at high rates.
- ST707 comes in a variety of forms (pills, washers, strips).

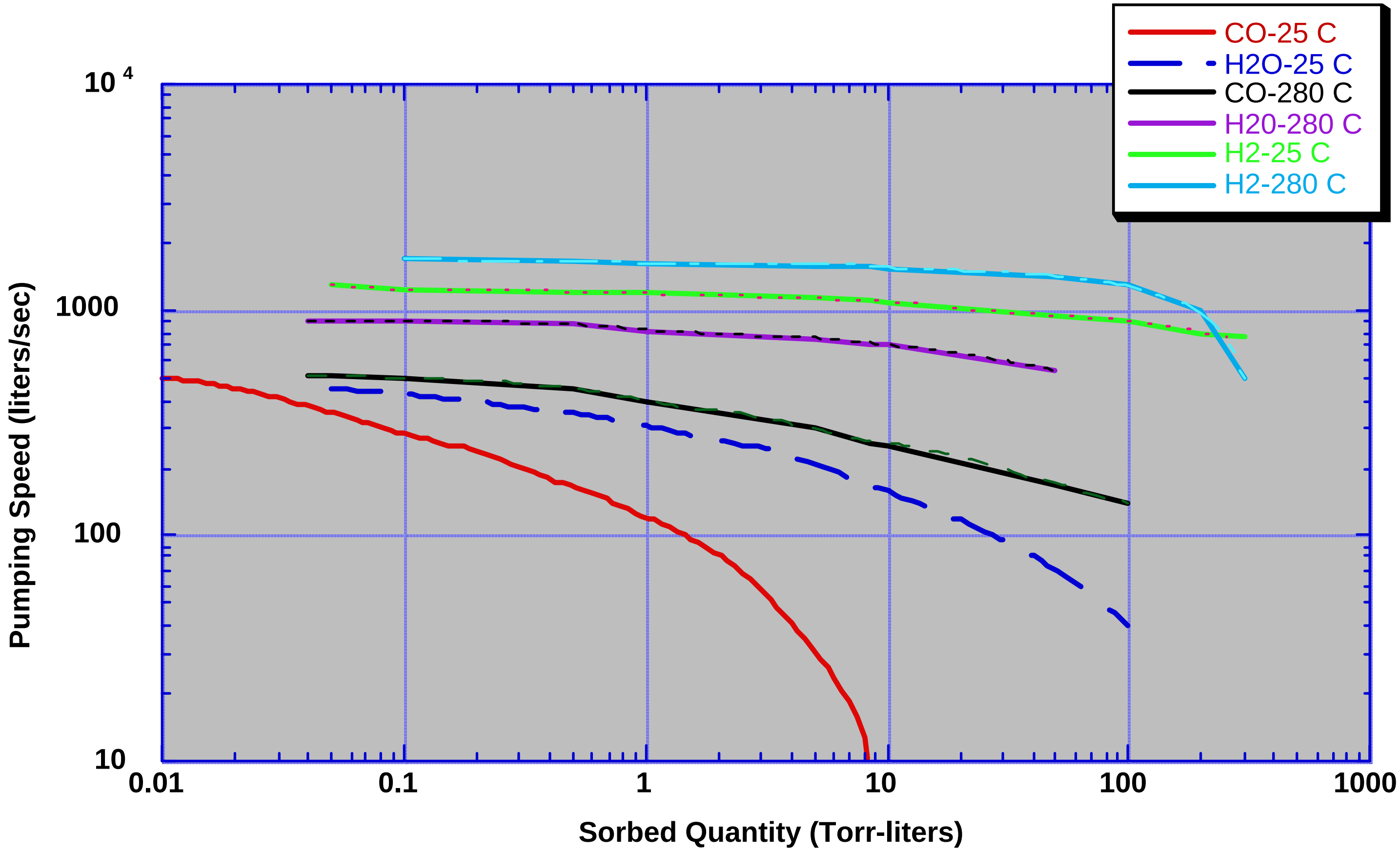
Ref. SAES Getters

SAES ST707™ Non-evaporable Getter



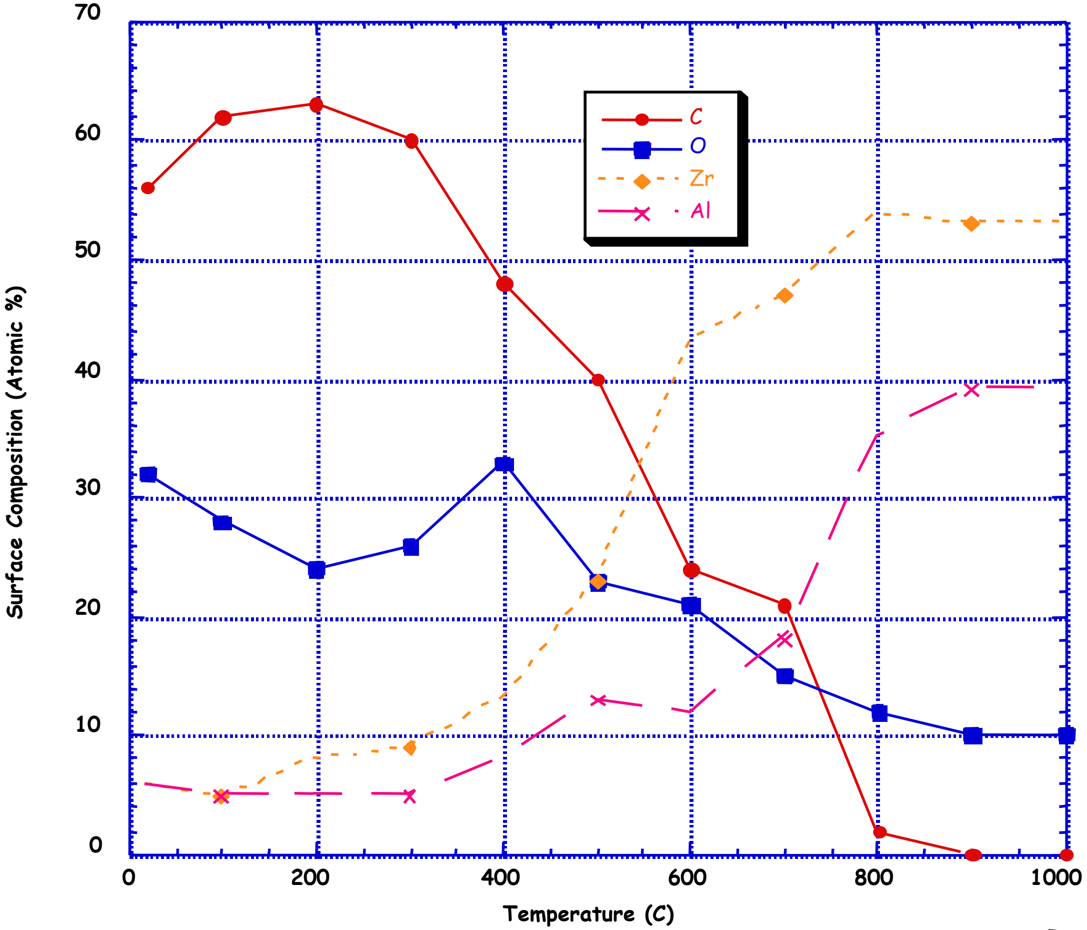
Ref. SAES Getters

SAES ST707™ Non-evaporable Getter Sorption Plot



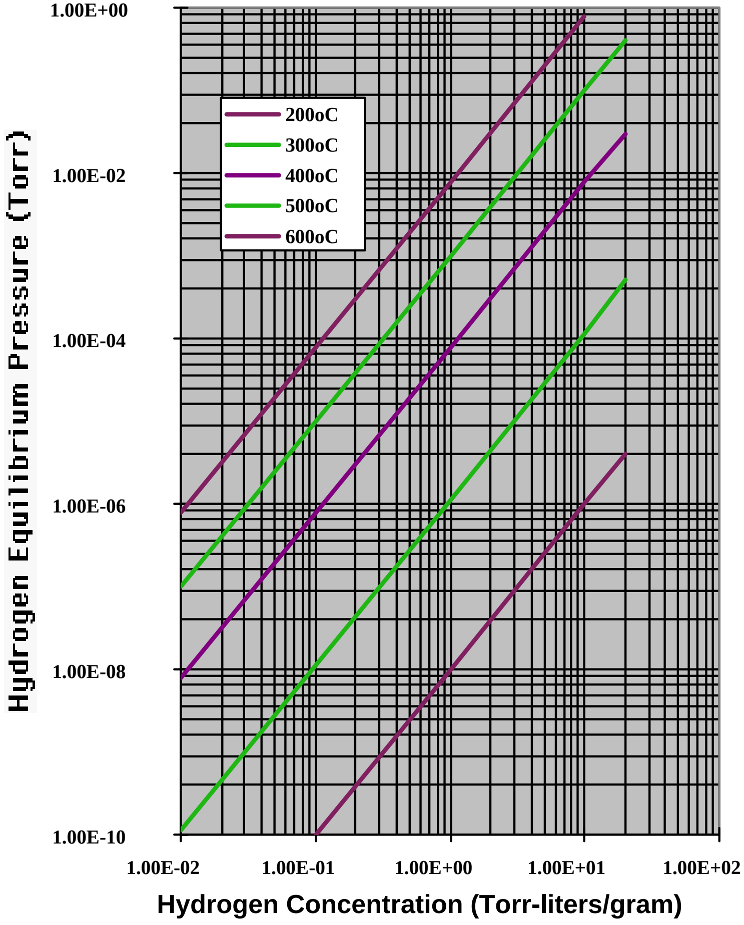
Ref. SAES Getters

SAES ST707™ Surface Composition vs. Activation Temperature



Ref. SAES Getters

SAES ST707™ Non-evaporable Getters Hydrogen Equilibrium Pressure



Ref. SAES Getters

SAES ST172® Non-evaporable Getters

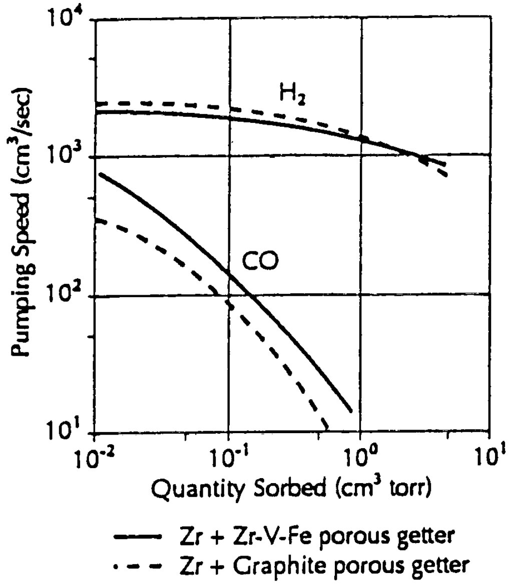
- A porous sintered structure based on a mixture of Zr and ST707 alloy (Zr-V-Fe).
- Sintering process produces a getter with large amounts of surface area, high porosity, and good mechanical strength (less likely to produce dust).
- The alloy is characterized by high diffusity of sorbed gas species.

Ref. SAES Getters

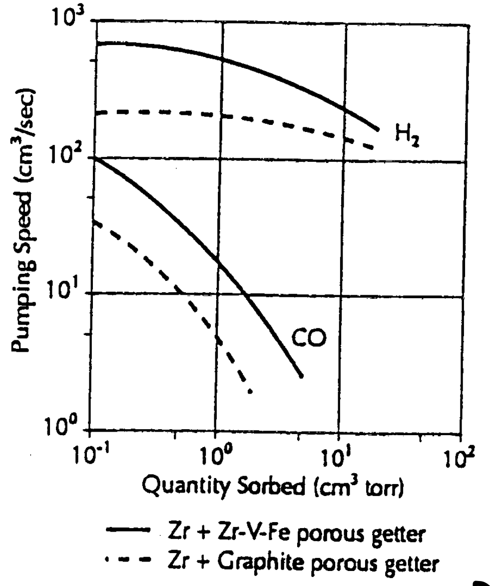
SAES ST172® Non-evaporable Getters

- Highest pumping speeds and capacity are achieved at 800 to 900°C activation temperatures.
- However, ST172 can be activated as low as 400 to 500°C.

900°C



500°C



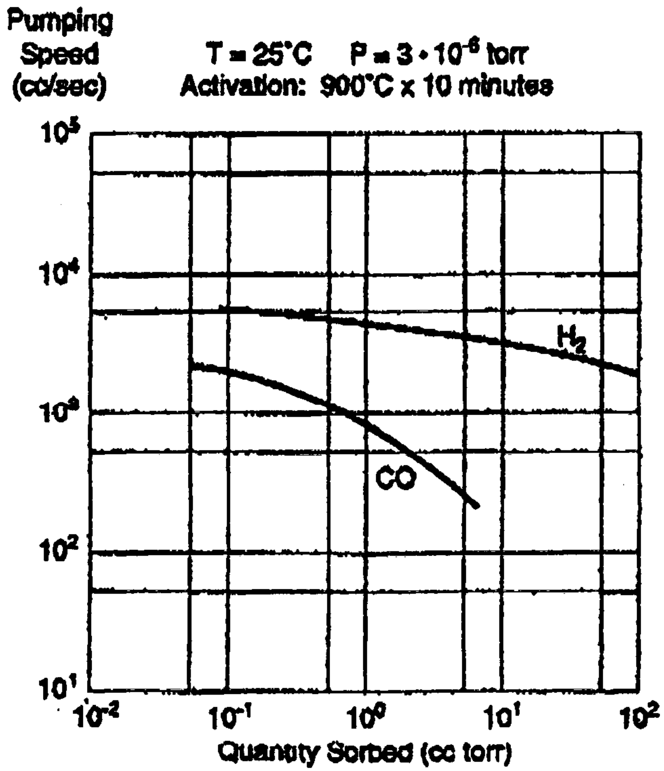
Ref. SAES Getters

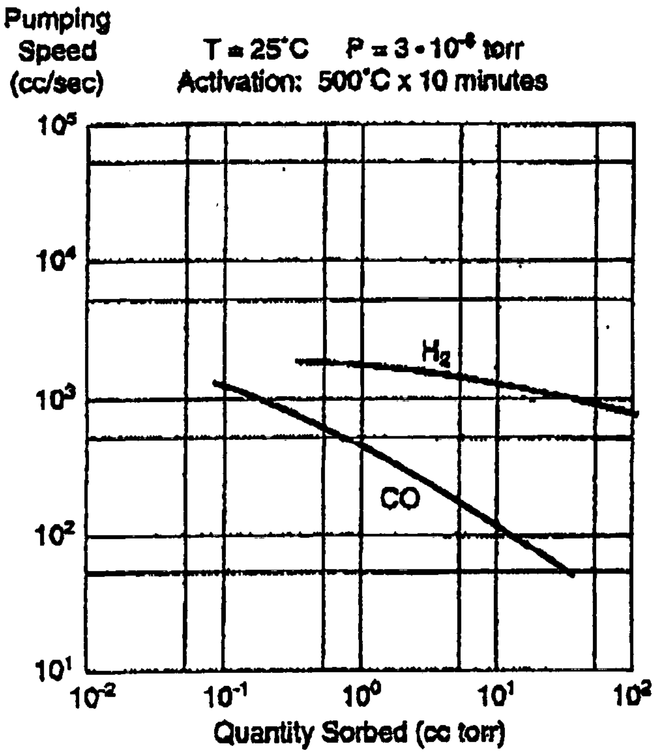
SAES ST175® Non-evaporable Getters

- A porous, sintered structure based on a mixture Titanium and Molybdenum powders.
- Sintering process produces a getter with large surface areas, high porosity, and good mechanical strength.
- This alloy has even higher diffusion rate of sorbed gases than ST172.

Ref. SAES Getters

SAES ST175® Non-evaporable Getter





Ref. SAES Getters

NEG Cartridge Pumps Using ST101® Strip

Ref. SAES Getters

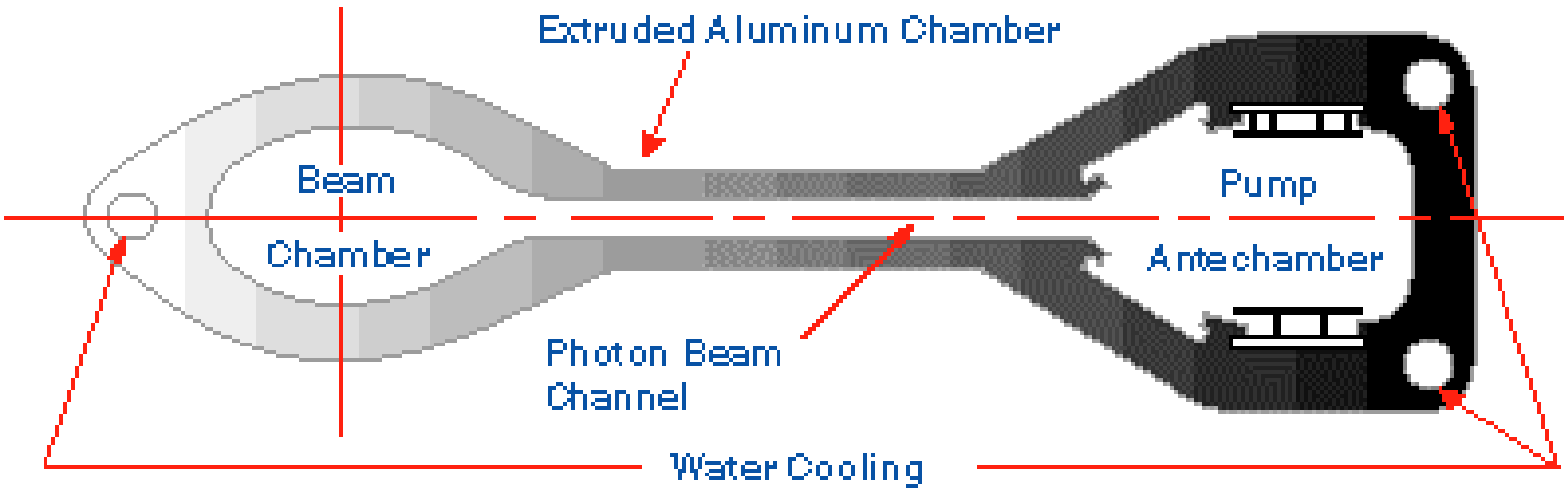
NEG Cartridge Pumps Using Sintered Plates

Ref. SAES Getters

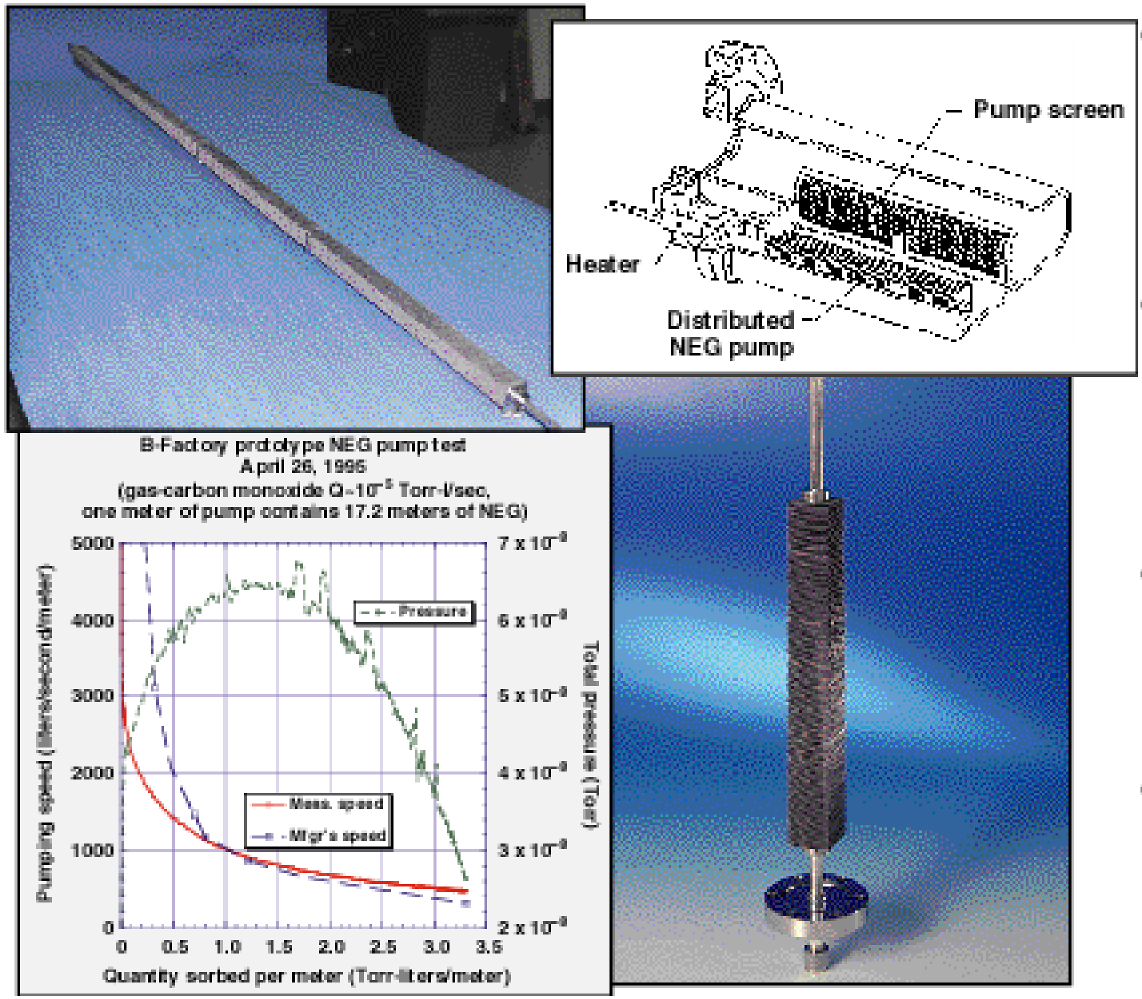
NEG Cartridge Pumps for use in Ion Pumps

Ref. SAES Getters

APS Beampipe with NEG strips

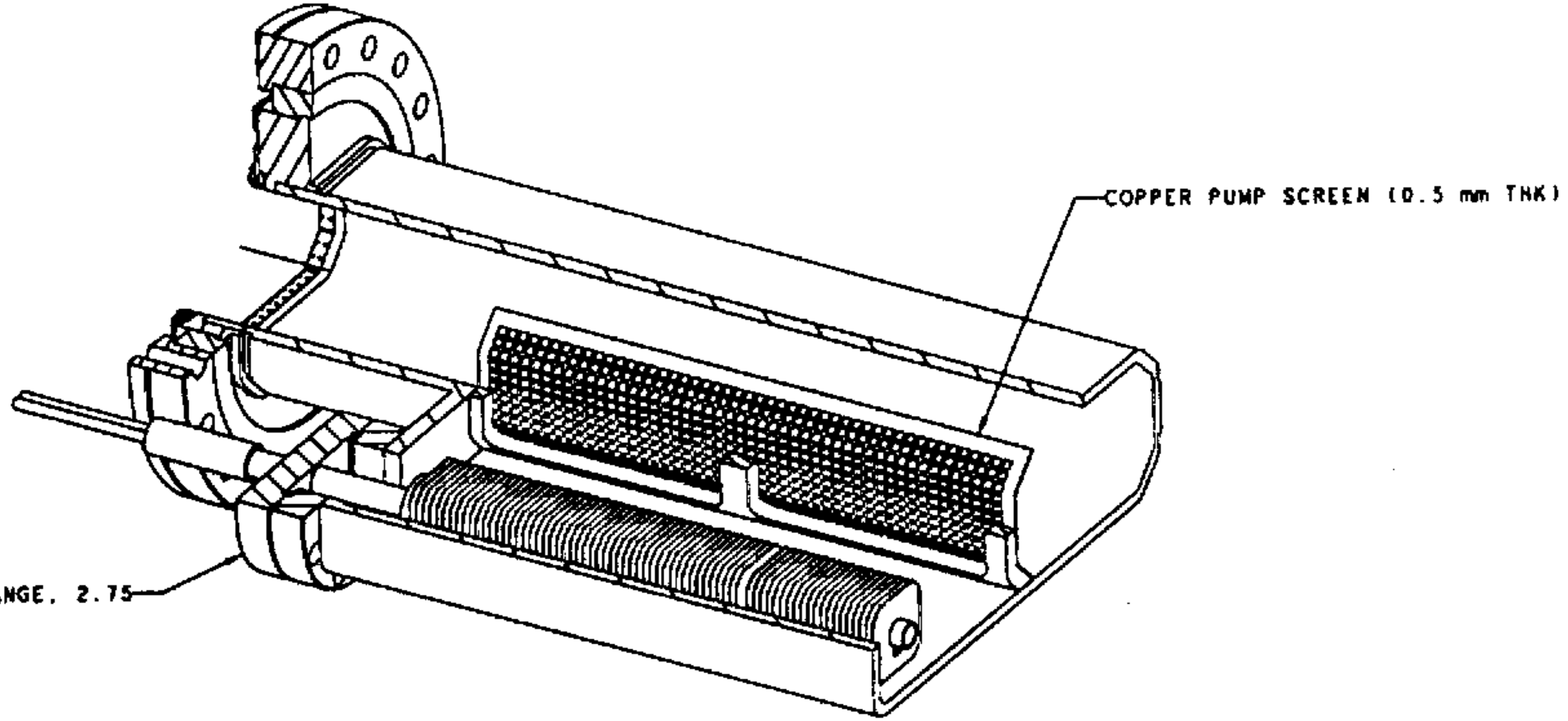


LLNL NEG Pump Design



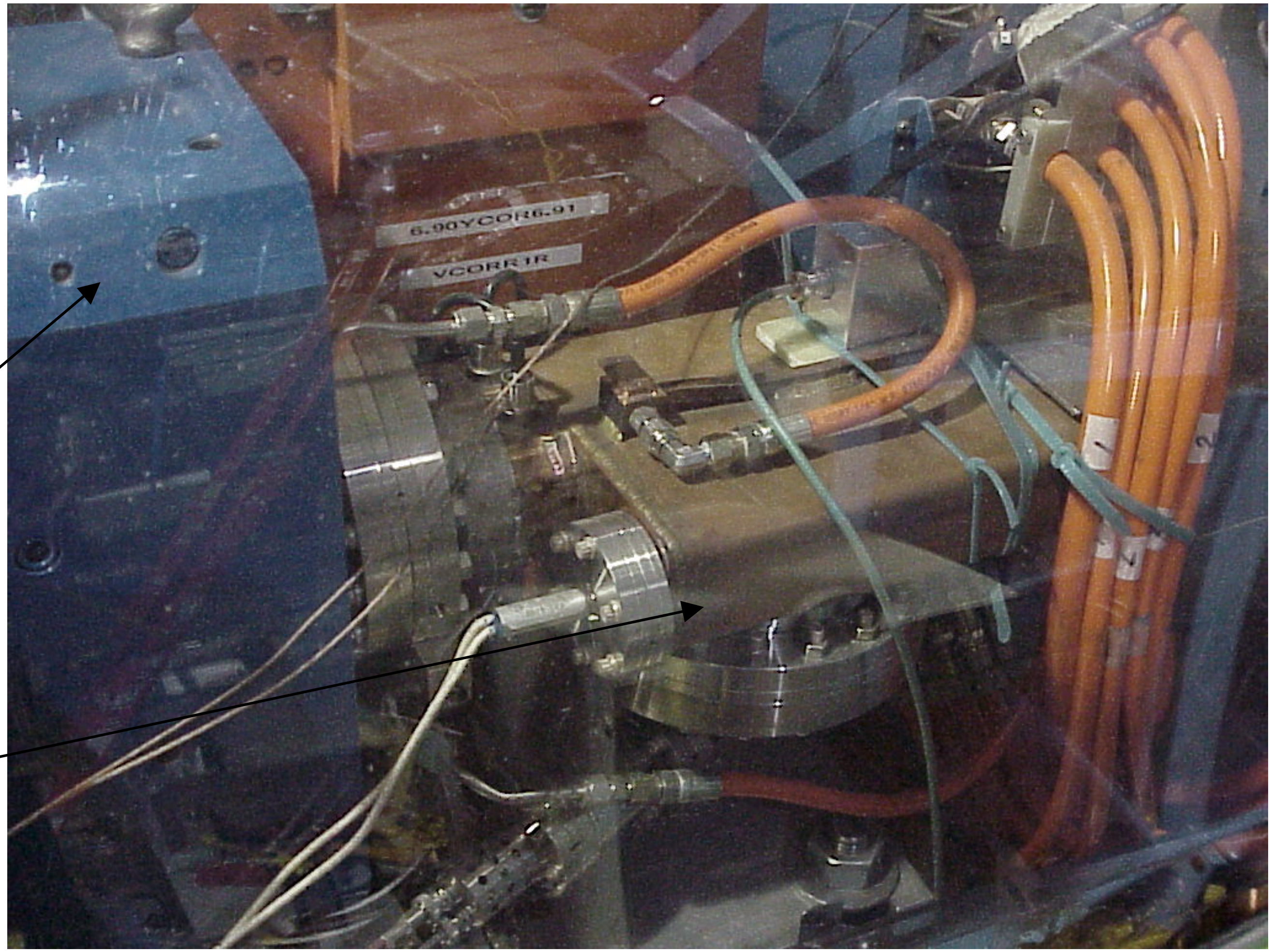
- “Finned” NEG design produces high pumping speeds and high sorption capacity
- Regeneration accomplished with external commercial heater
- Variable fin spacing allows for pump speed adjustment
- Laser is used to cut NEG fins

LLNL NEG Pump in a PEP-II Vacuum Chamber



PEP-II Interaction Region Copper Vacuum Chamber

Q4
Magnet



NEG Pump

Combination Pumping . . . Ion Pumps with TSP or NEG

- Combination pumping produces greater pumping speeds for all gases.
  - TSP and NEG provide high pumping speeds for getterable gases.
  - Ion Pumps provide pumping of argon and light hydrocarbons (usually Noble Diode pumps are chosen).

- Combination pumping can be attained by:
  - Commercial combination pumps
  - Custom built combination pumps
  - Use of multiple types of pumps

- NEGs are used on systems where high constant pump speeds are required.

- TSPs are used on systems with sudden large gas bursts and/or frequent venting takes place.

Commercial Combination Pumps . . .
Ion Pumps with TSP or NEG

Ion Pump with TSP filaments

Ion Pump with NEG cartrdge

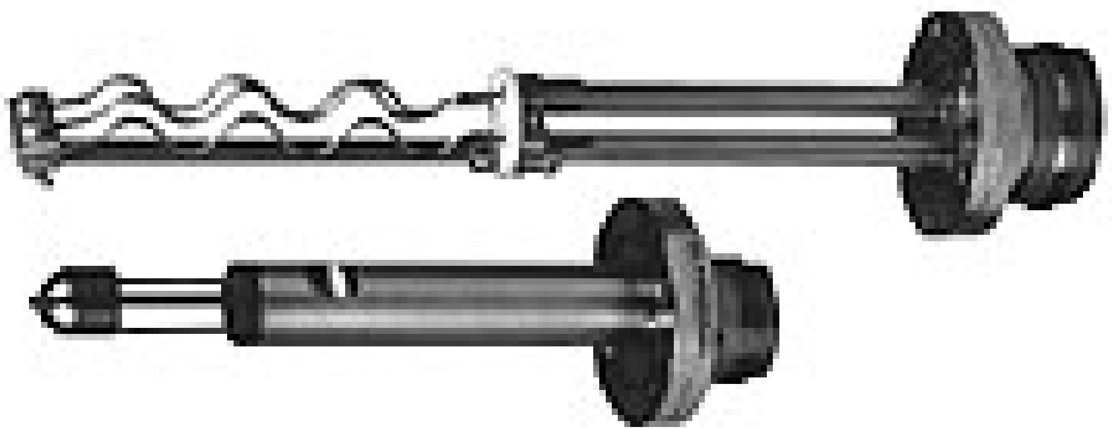
Ref. Varian Vacuum

The US Particle Accelerator School
Titanium Sublimation Pumps

Lou Bertolini
Lawrence Livermore National Laboratory
January 19-24, 2004

Titanium Sublimation Pumping (TSP)

- Gases are pumped by "gettering." "Getterable" gases are pumped at high speeds by chemisorption.
- TSP is very practical and a cost effective mechanism.
- Manufacturers don't sell TSPs; they sell Titanium sources.



Titanium Sublimation Pumping

- "Sticking Coefficients" of gases are important in understanding TSPs.

- Sticking coefficient (α), is the probability that a specific gas molecule, when striking a surface will permanently stick.

$$\upsilon = 3.5x10^{22} \frac{P}{\sqrt{MT}}$$

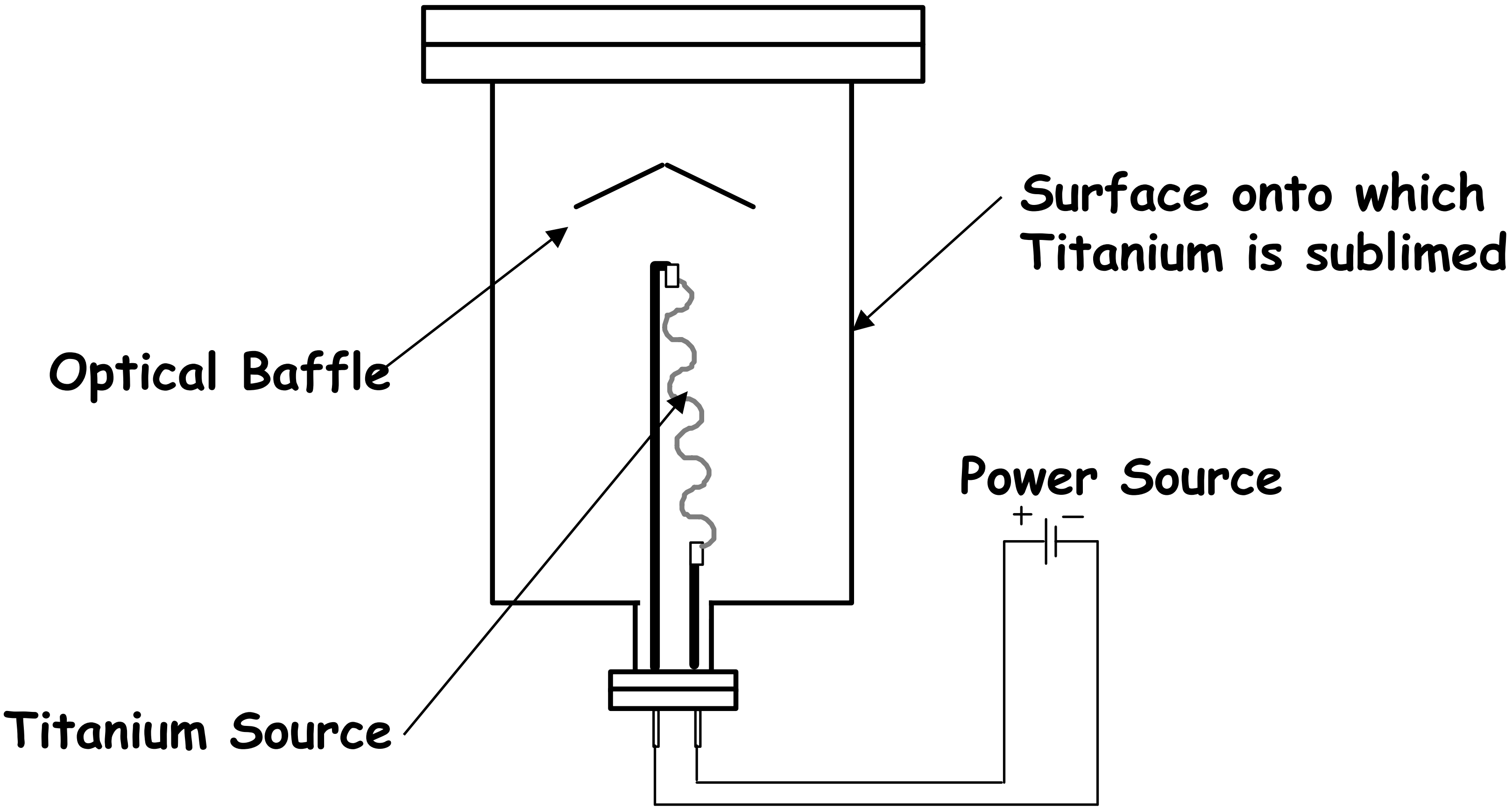
Impingement rate

Titanium Sublimation Pumping

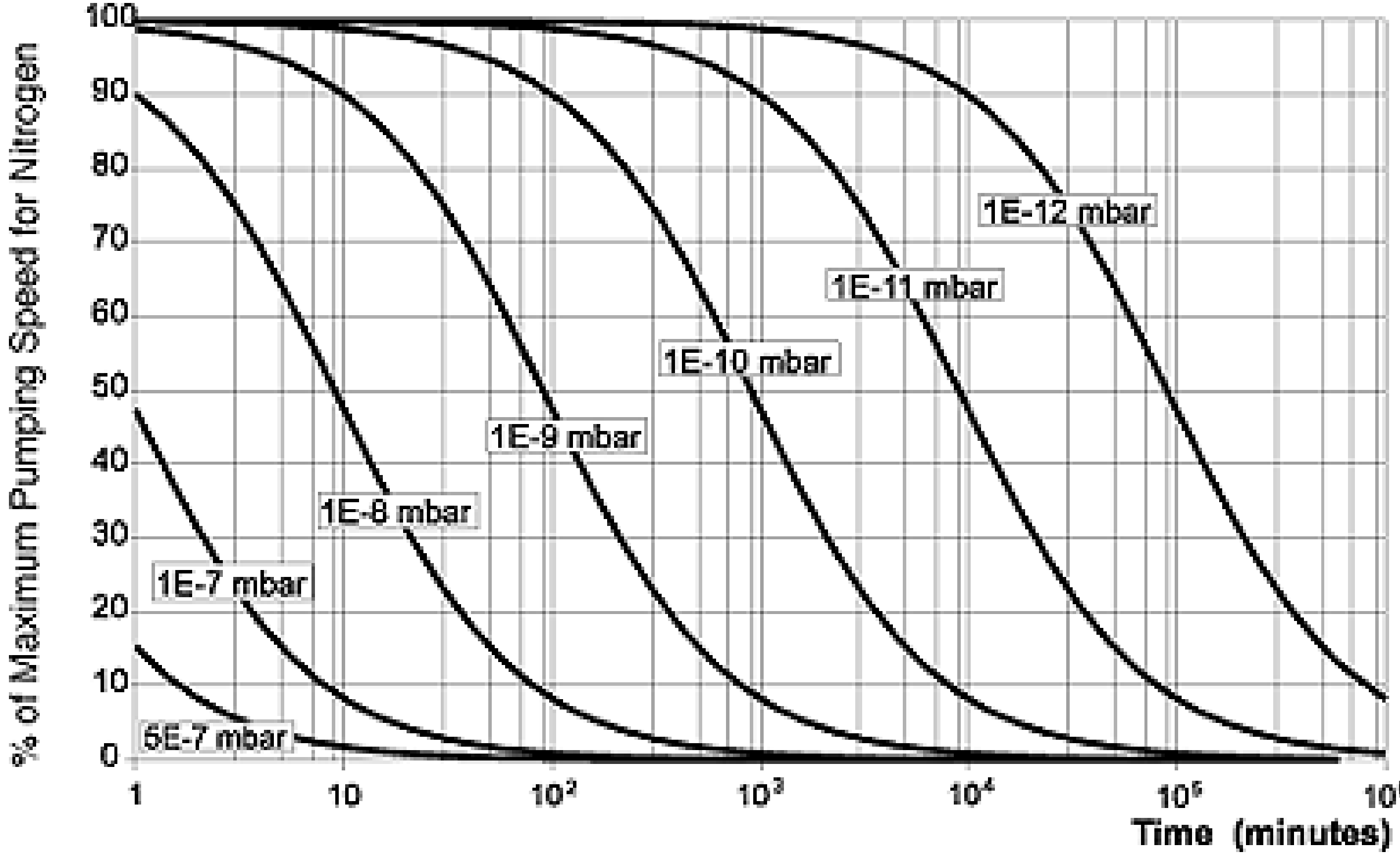
- TSPs are "surface" pumps that are surface conductance limited.
- There is a relationship between the number of active metal energy sites per unit area and the sticking coefficient.
- The sticking coefficient will decrease as the active metal energy sites decrease.

Maintaining a balance between the incident flux of gas and the available chemisorption sites is key to Titanium Sublimation Pumping.

Features of a Titanium Sublimation Pump



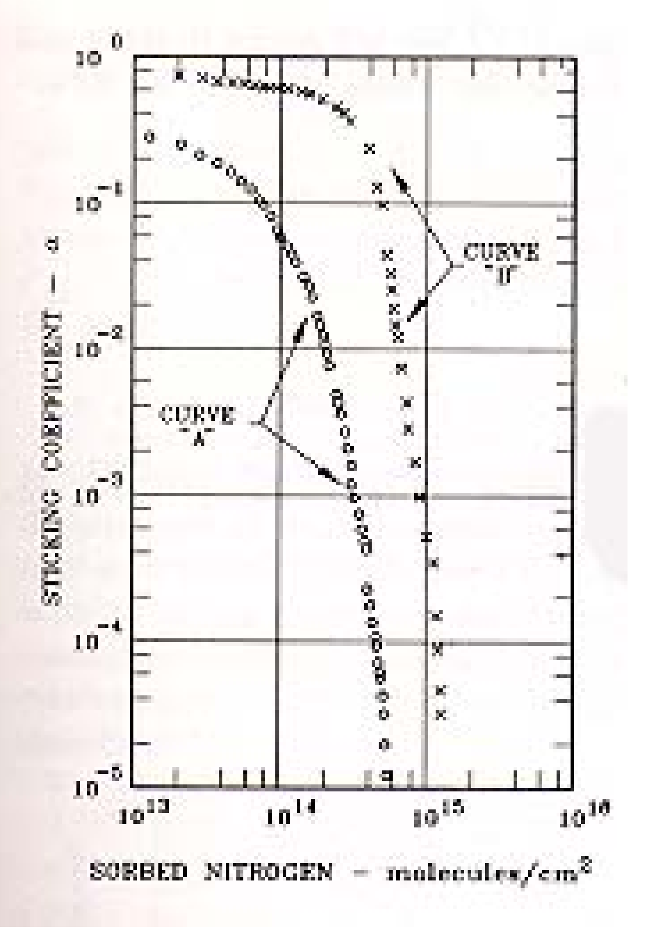
TSP vs. time (at various pressures)



Ref. Varian Vacuum

Sublimation Processes

1. Batch sublimation - periodic sublimation of titanium onto the pumping surface. The titanium film is then allowed to saturate with gas over time.



Curve A – batch layer of 8.0 x 10^{14} Ti atoms/cm^2 deposited on a previously exposed base of 1.7 x 10^{17} atoms/cm^2

Curve B – batch layer of 8.3 x 10^{14} Ti atoms/cm^2 deposited on a previously exposed base of 1.0 x 10^{18} atoms/cm^2

(Ref. "Sorption of Nitrogen by Titanium Films," Harra and Hayward, Proc. Int. Symp. On Residual Gases in Electron Tubes, 1967)

Sublimation Processes

2. Continuous Sublimation - titanium sublimation onto a pumping surface at a constant and continuous rate. Pumping sites are replenished at a rate equal to the rate at which they are occupied.

$$S_s = \alpha_i C_i A_c$$

where S_s = surface pump speed

α_i = sticking coefficient for gas species "i"

C_i = aperture conductance per cm^2 for gas species "i"

A_c = total pumping surface area

Factors that Influence Sticking Coefficient

- Thickness of Titanium film
- Ratio of pumping speed to Titanium sublimation rate
- Surface temperature at the time of sublimation
- Surface temperature at the time of gas sorption
- Film deposition process (batch or continuous)
- Gas species
- Gas desorption and synthesis at Titanium source
- Partial pressures of gases at time of sublimation
- Contamination of film by some gas
- Effects of film annealing
- Variations of surface and bulk diffusion processes

Some have proposed that there is a "pecking order" of gases pumping by Titanium chemisorption

Pumped Gas	Displaced Gas				
	CH_4	N_2	H_2	CO	O_2
CH_4		no	no	no	no
N_2	yes		no	no	no
H_2	yes	yes		no	no
CO	yes	yes	yes		no
O_2	yes	yes	yes	yes	
α_m	$<10^{-3}$	0.3	0.05	0.85	0.95

This is controversial and probably only true for CH_4 and H_2.

Typical Engineering Values for TSP

Test Gas	Max. Sticking Coefficient-α_m		Max. Speed[a] (liters/sec-cm^2)		Max. Capacity of Film- x10^{15} (molecules/cm2) [b]	
	300 K	77 K	300 K	77 K	300 K	77 K
H_2	0.06	0.4	2.6	17	8-230[c]	7-70
D_2	0.1	0.2	3.1	6.2	6-11	-
H_2O	0.5	-	7.3	14.6	30	-
CO	0.7	0.95	8.2	11	5-23	50-160
N_2	0.3	0.7	3.5	8.2	0.3-12	3-60
O_2	0.8	1.0	8.7	11	24	-
CO_2	0.5	-	4.7	9.3	4-12	-

a) Speed calculated at RT
b) Wide vaiations due to film roughness
c) Wide variations due to bulk diffusion into film

(Ref. "Sorption of Nitrogen by Titanium Films," Harra and Hayward, Proc. Int. Symp. On Residual Gases in Electron Tubes, 1967)

Titanium Sublimation Sources

There are three types of sources for sublimating Titanium on pumping surfaces:

1. Filamentary sources

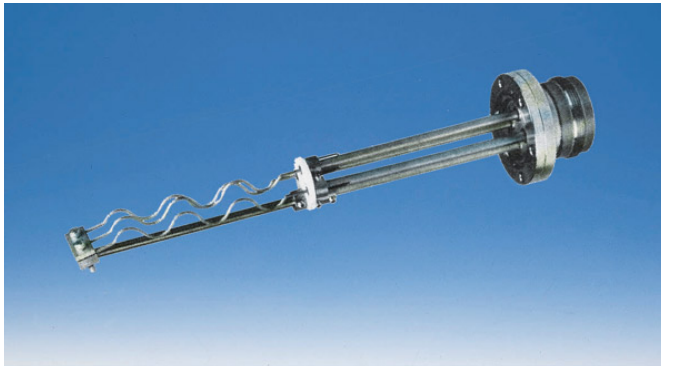
2. Radiantly heated sources

3. Electron-gun sources

Titanium Filamentary Sources

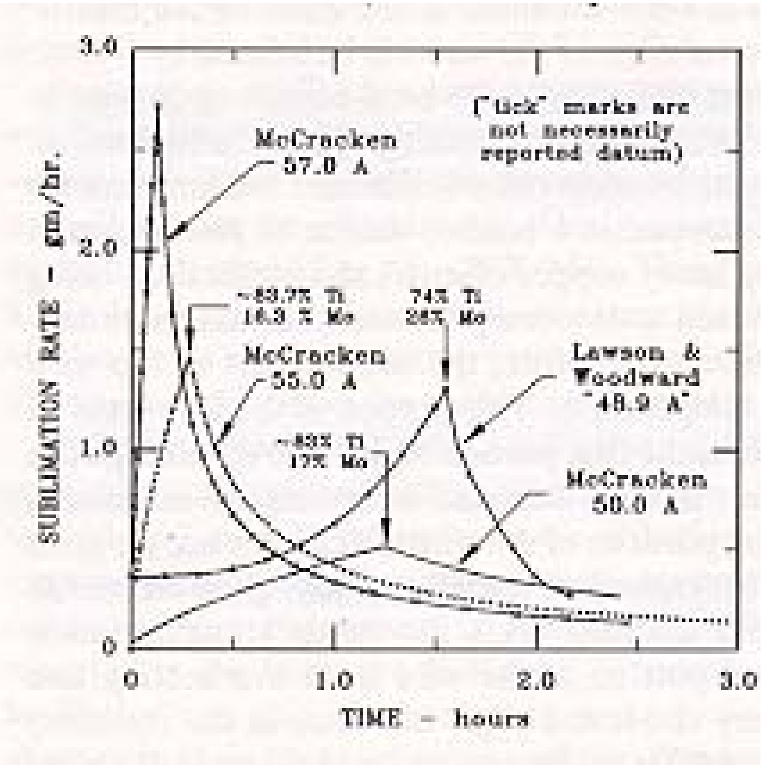
- Titanium has poor mechanical strength at sublimation temperatures.

- Titanium filaments must be coupled with other materials for mechanical strength.
  - One method is to wrap the Titanium filaments on a structural member (Ta or W)
  - The most prevalent solution is to alloy Titanium with Molybdenum (85% Ti; 15% Mo by weight)



Constant current operation of TSPs

- Constant current operation of Titanium filaments produces increases in sublimation rates early in the life of the filament.
- This is probably due to the progressively leaner mixture of Titanium in the filaments.
- Filaments develop rougher surface textures as the mixture changes.
- Rough texture = greater surface area = higher emissivity = lower operating temperature = lower sublimation rates.



Ref. "Properties of Titanium-Molybodenum Alloy Wire as a Source of Titanium for Sublimation Pumps," Lawson and Woodward, Vacuum 17, 205 (1967)

"Titanium Filaments for Sublimation Pumps" McCracken and Pashley, JVST, 3, 96 (1966)

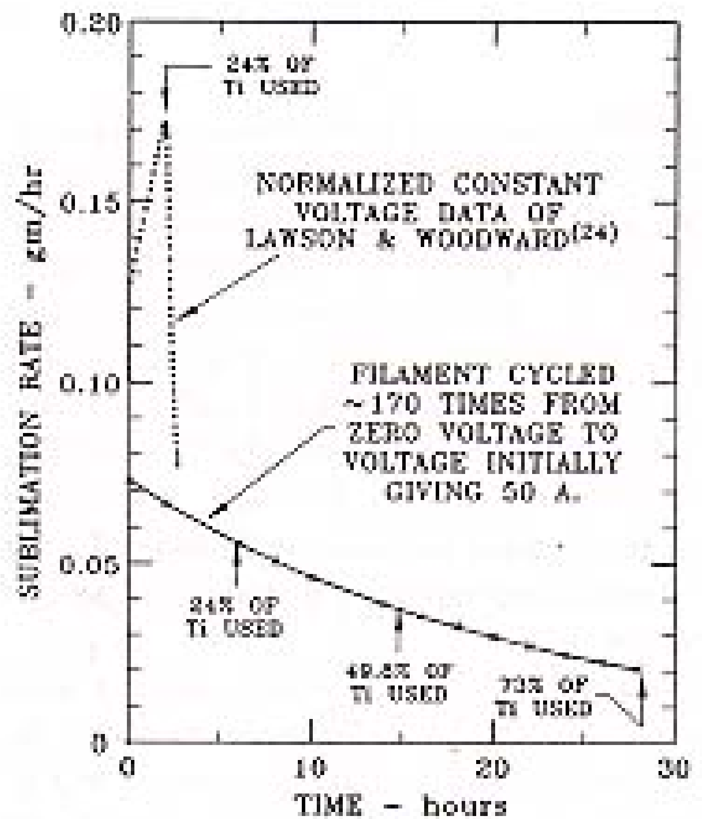
Constant Voltage Operation of TSP Filaments

- Constant voltage operation is rarely done.
- Constant voltage operation in conjunction with RT cycling produces more predictable sublimation rates

$$R(t) = R_o\, e^{-at}$$

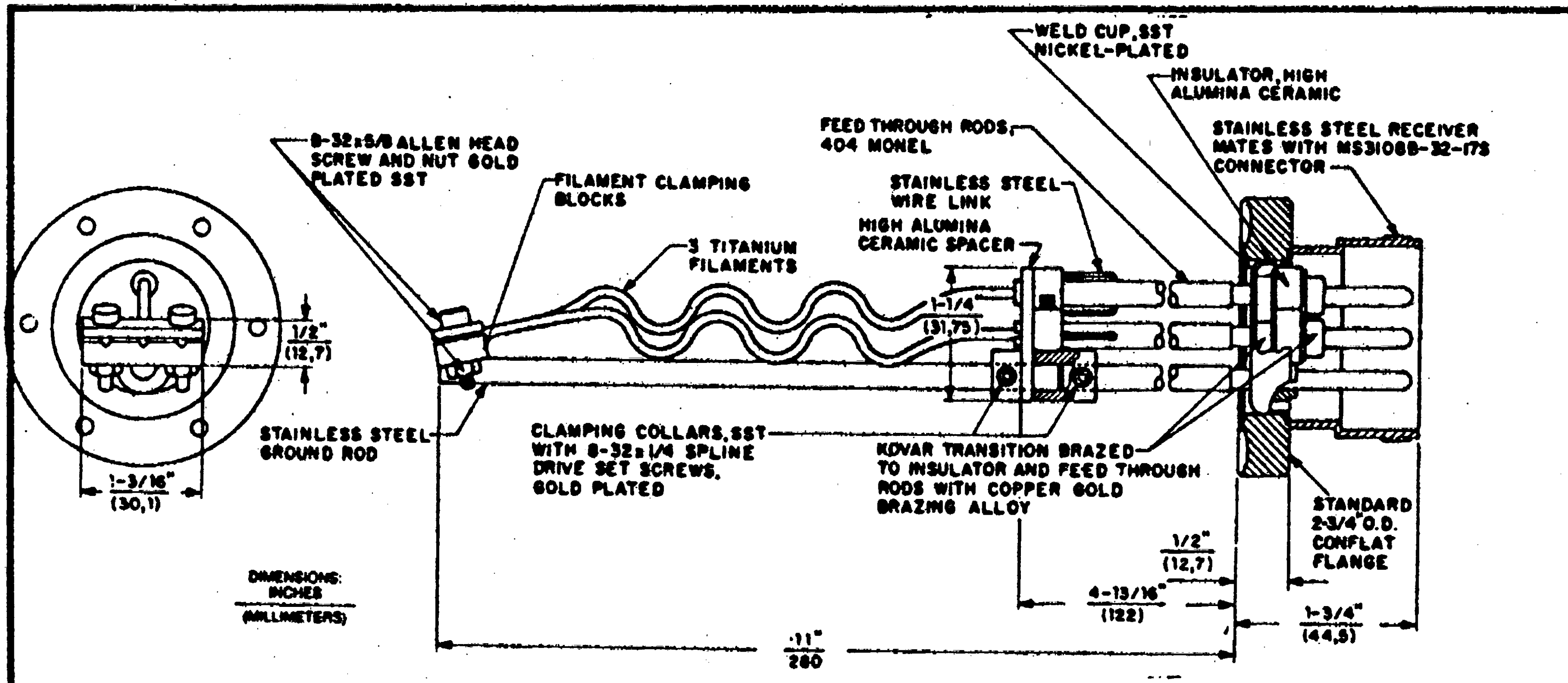
where R_o = initial sublimation rate
a = constant
t = cumulative sublimation time

- Titanium sublimation rates are dependent on Ti and Mo proportions and the number of temperature cycles through the crystalographic transformation temperature.



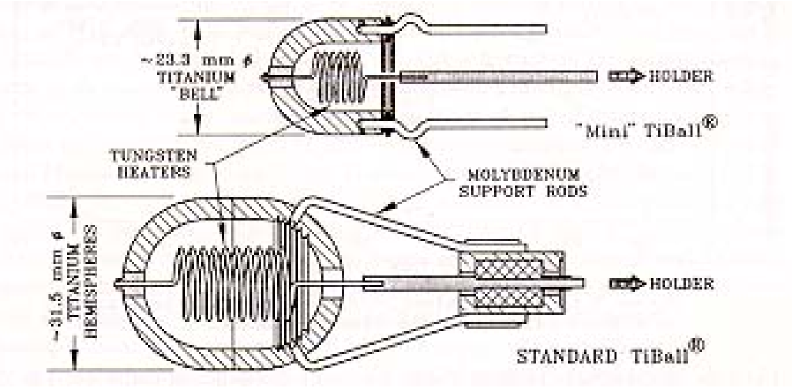
Ref. "Properties of Titanium-Molybodenum Alloy Wire as a Source of Titanium for Sublimation Pumps," Lawson and Woodward, Vacuum 17, 205 (1967)

Titanium Sublimation Cartridge



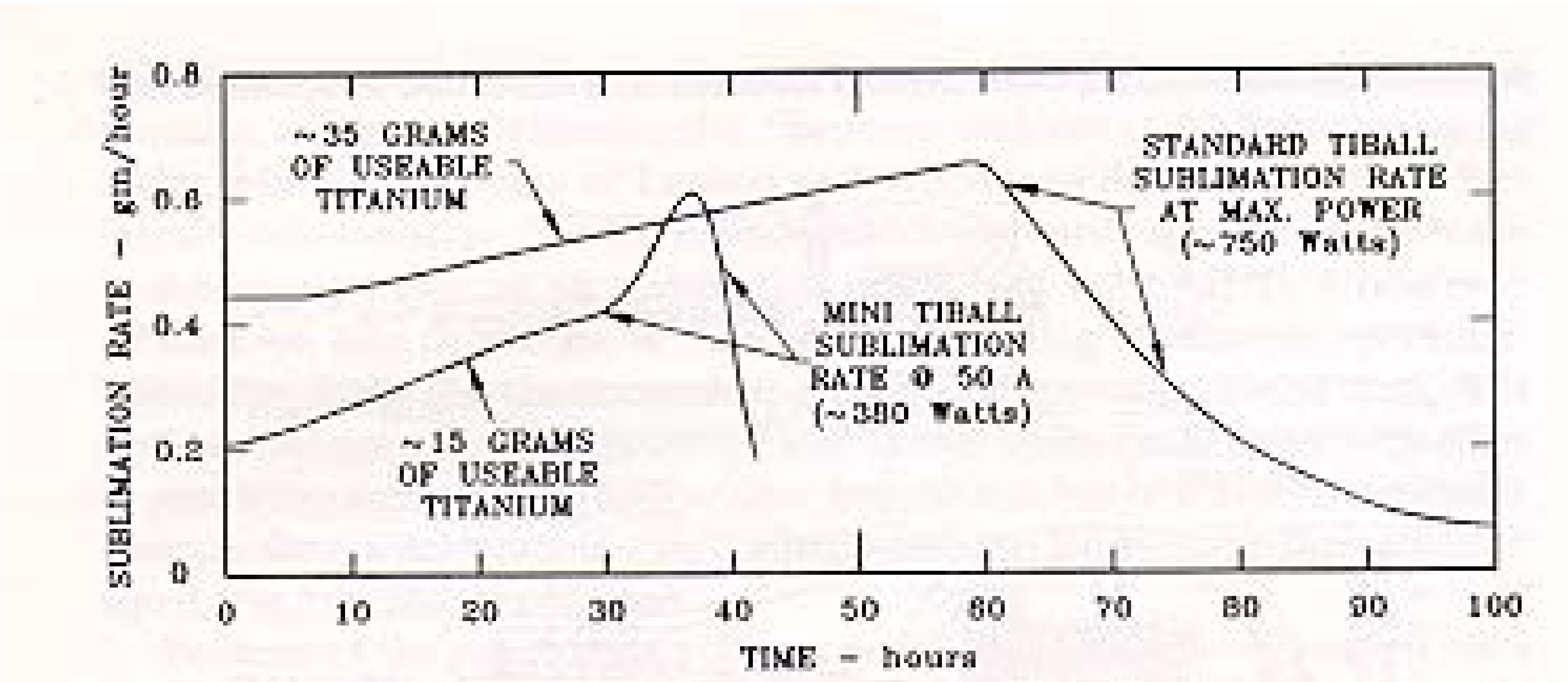
Radiantly Heated Titanium Sources

- Titanium heating occurs primarily through radiation from a secondary Tungsten (W) filament.
- The Titanium sphere surrounds the filament and provides the return current path.
- Titanium source assembly is mounted as a removable flange with an electrical feedthrough.
- Functional life ends when a "hole" opens up in the Titanium sphere.



Ref. Varian Vacuum

Sublimation rates for Varian TiBall and "Mini" TiBall Sources



Ref."A Radiant Heated Titanium Sublimator," Proc. 5th Int. Vacuum Congress, 1971, JVST 9 (1), 552 (1972)

Disadvantage of Radiantly Heated Sources

- Sources require operation at some level of standby power to maintain Titanium temperature above 900°C.

- Temperature cycling through the crystalographic phase transformational temperature of 880°C eventually results in distortion.

- Two things can happen (both bad):

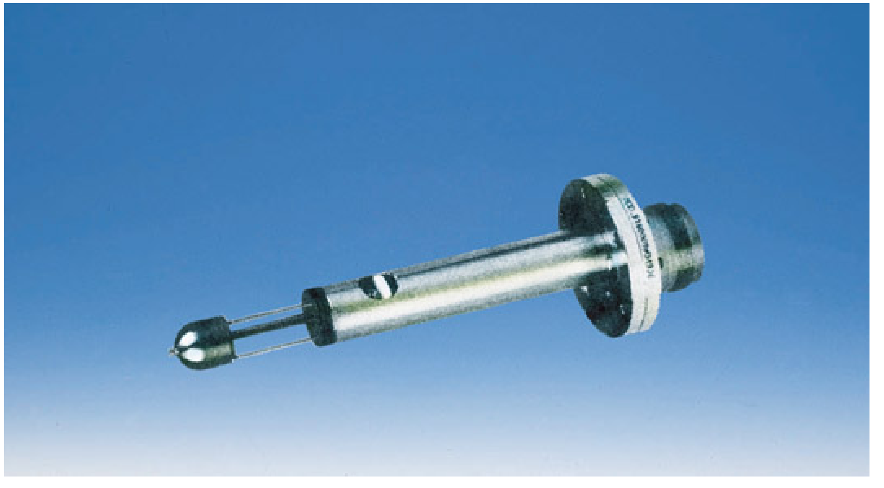
    1. Distortion leads to electrical shorting of W filament.
    2. Distortion leads to increased emissivity, lower temperatures, and reduced sublimation rates.

Summary of Radiantly Heated Titanium Sources

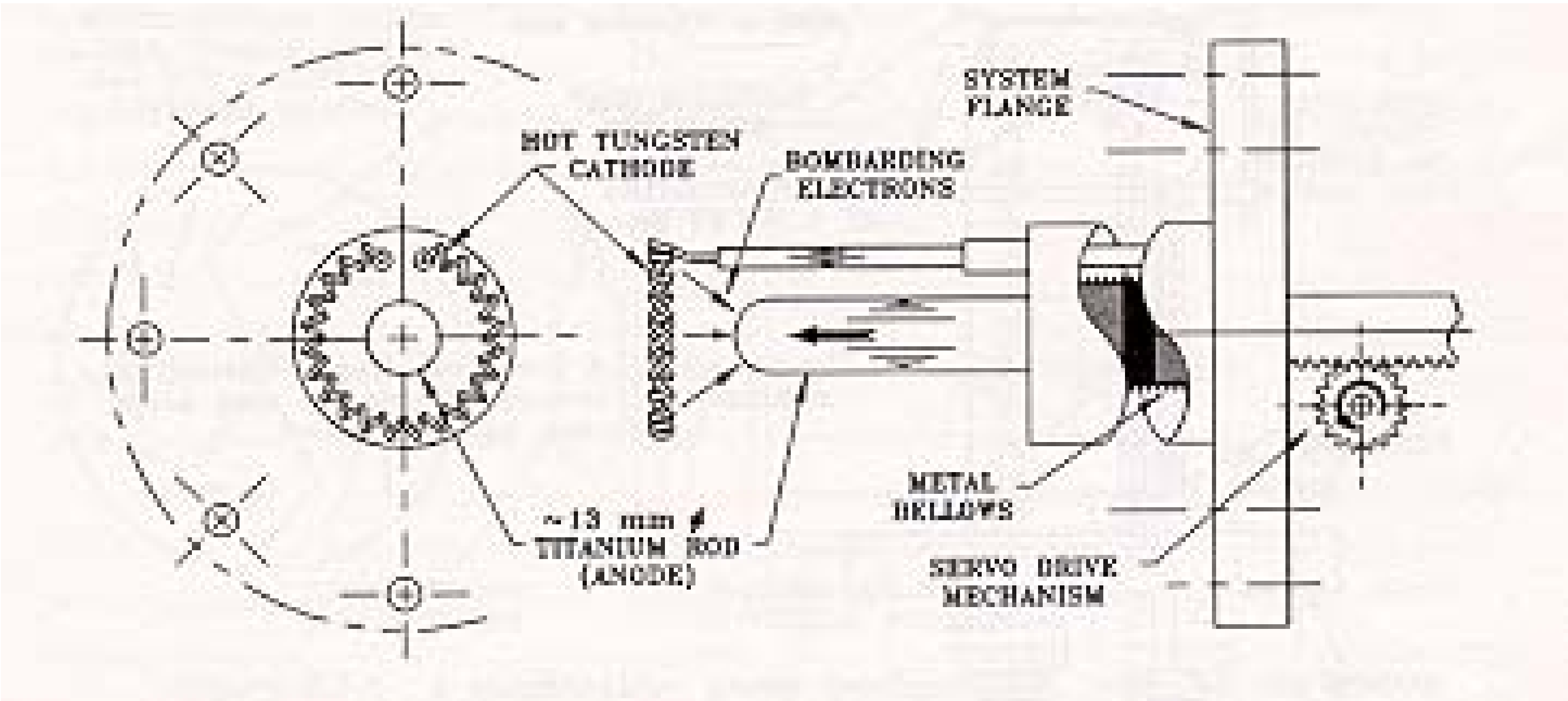
- Standby power (100-200 W) required to prolong source life.

- Heat from standby mode can increase gas load.

- In storage rings (operating at 10^{-10} Torr), Titanium quantity is less important than reliability.



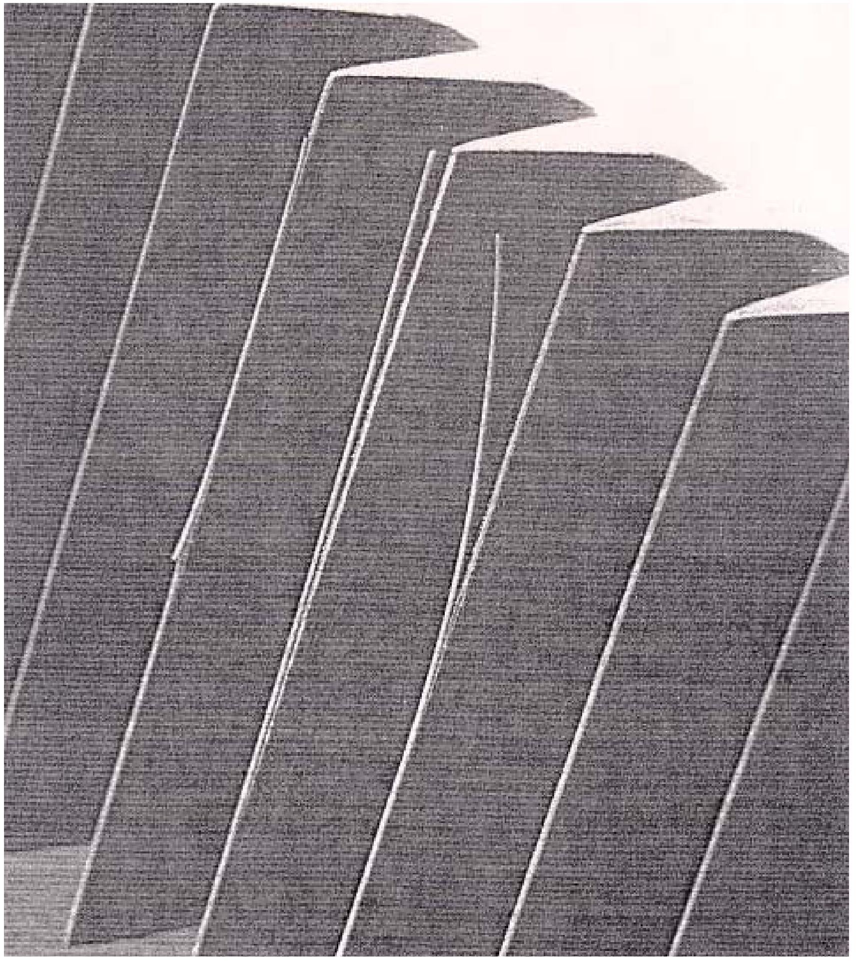
Electron-gun Titanium Sources



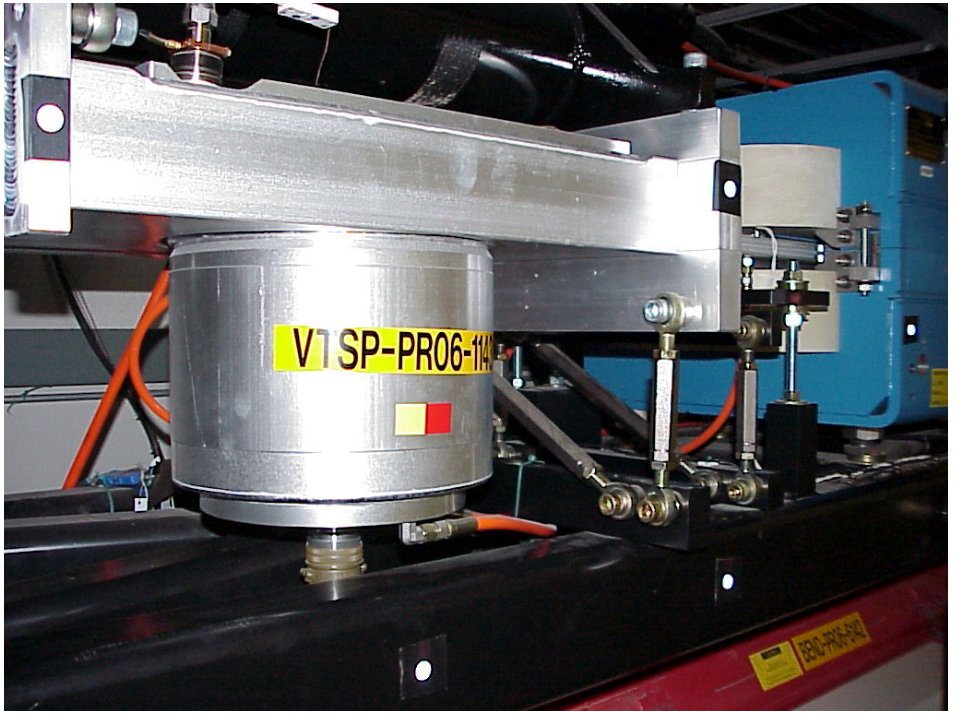
Ref. Perkin-Elmer Corporation

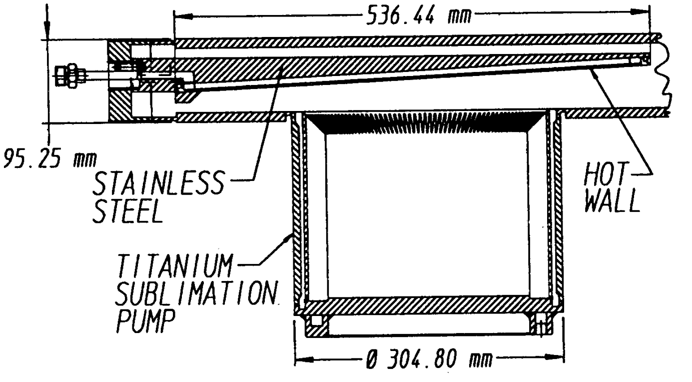
Peeling of Titanium Films

- As Titanium builds-up on a pumping surface, it will begin to peel.
- A typical thickness where peeling begins is 0.05 mm.
- Peeling produces dust particles and increases surface temperatures during sublimation.
- Because of peeling, pumping surfaces may require periodic cleaning (glass bead blasting and/or chemical cleaning).
- If peeling is a problem, a TSP was probably a bad choice or you are misusing the pumps.



PEP-II LER Arc TSP and Photon Stop





Pumping Speed as a Function of Gas for an Extended Surface 6" TSP PUMP

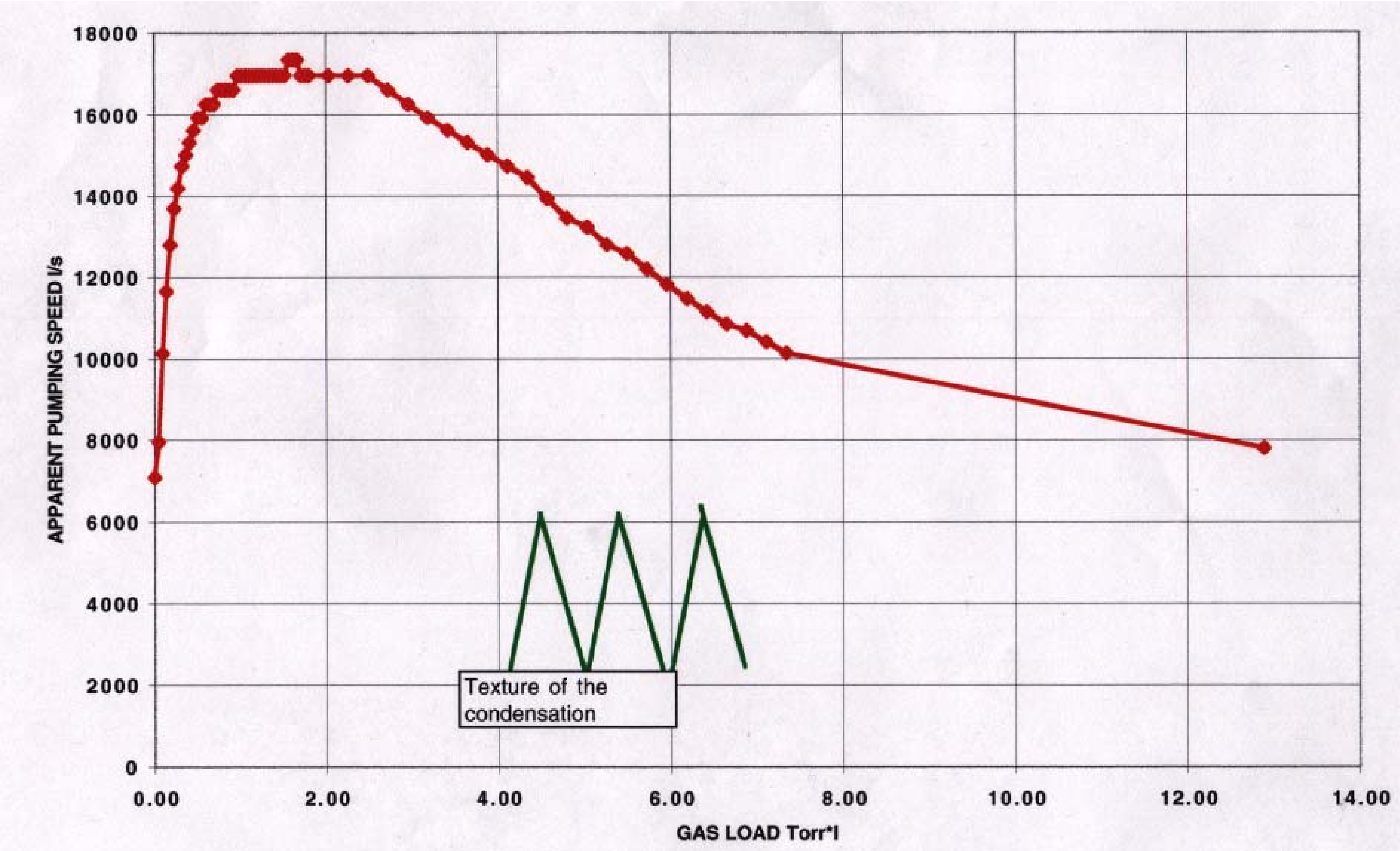
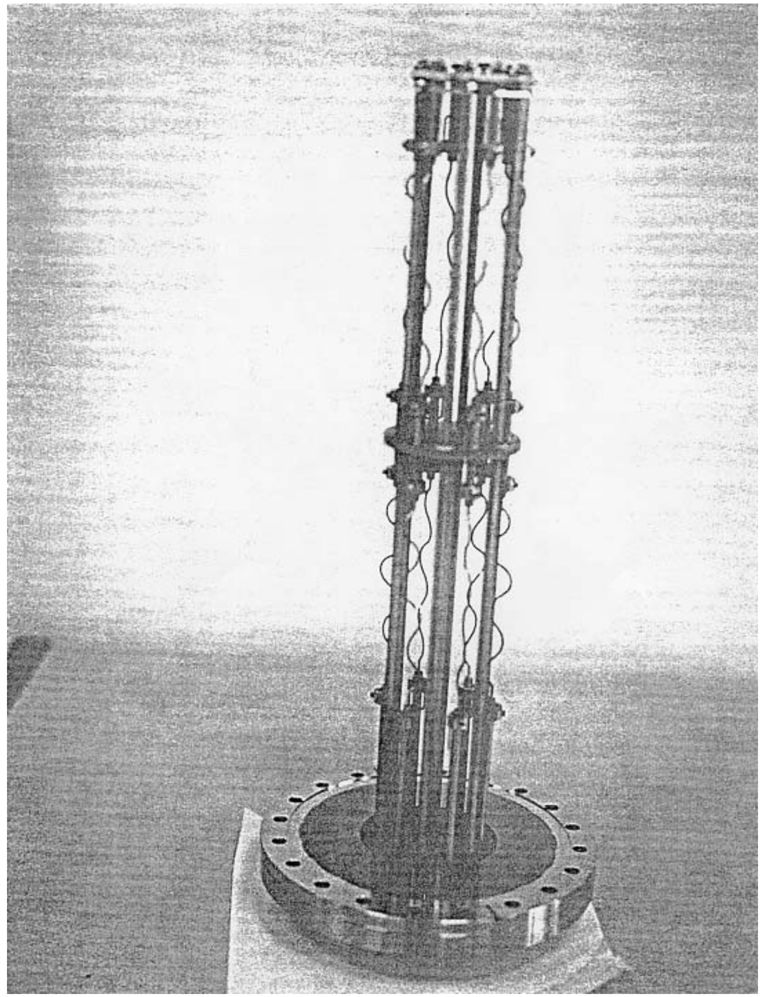
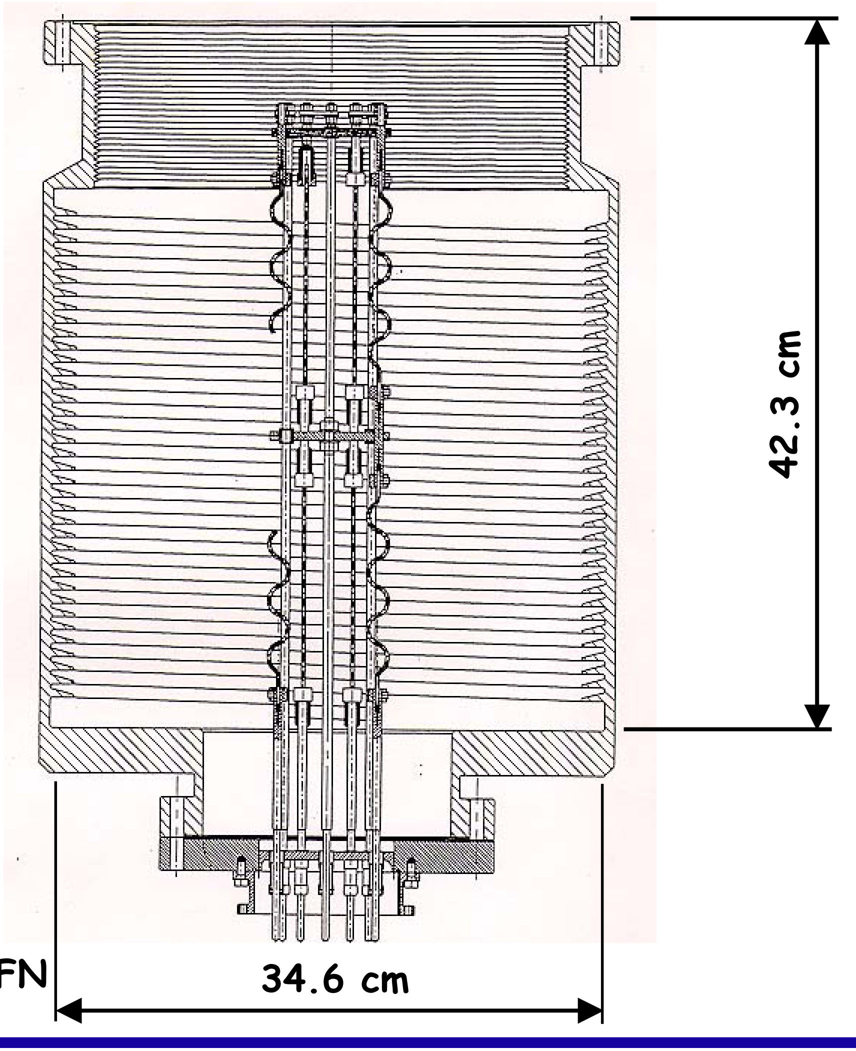


Photo of custom Varian TSP designed for ALS and DAFNE



DAFNE Collider TSP



Courtesy: C. Vaccarezza, INFN

Helium Compressors

- Helium Compressors provide a continuous source of clean high pressure helium to the cryopump cold head.
- Helium Compressors also provide conditioned electrical power to the cold head.
- A compressor consists of four main systems:
  - Pump
  - Cooling
  - Oil injection / separation
  - Cold head power

Helium Compressor Pumps

The pump is the "Heart" of the compressor. Compressors utilize two different types of positive displacement pumps:

- Rotary Pumps
- Piston Pumps

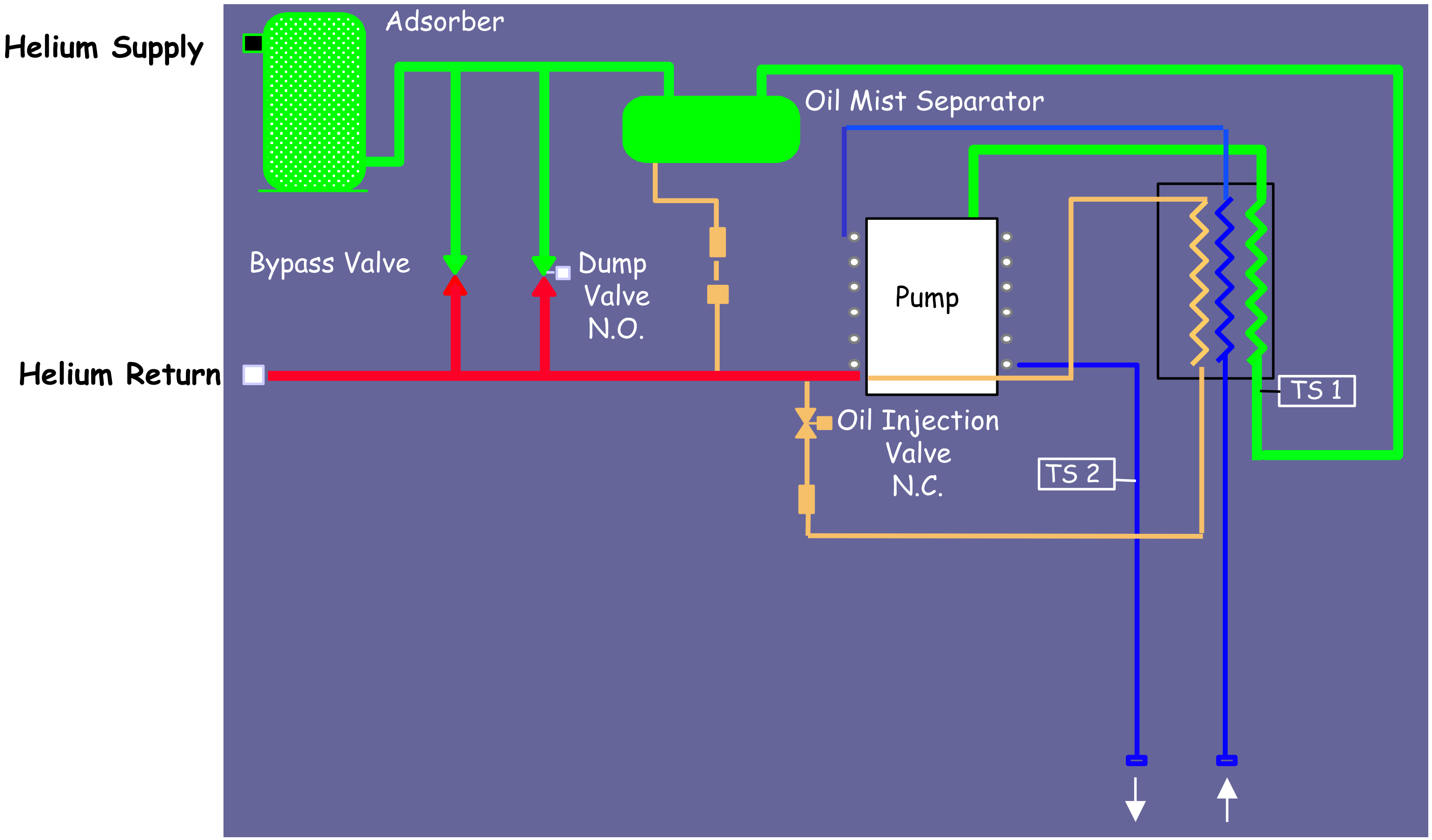
Helium Compressor Cooling System

Compressors use either water or air to cool the helium and the oil within the compressor. Cooling is critical to insure proper compressor operation. Without proper cooling:

- The compressor will overheat and shut off.
- The oil separation system will not operate and oil-contamination can reach the cold head.
- The helium will become overheated and the cold head will warm up.

Cooling is typically achieved by the use of counterflow heat exchangers.

A typical Helium Compressor Schematic



Helium Compressor Oil System

- The compression of helium generates heat within the compressor pump.
- Oil must be injected during compression to cool the pump and helium.
- The helium-oil mixture is cooled at the heat exchanger.
- The oil must be separated from the helium before the gas is pumped back to the cryopump(s). The oil will then be recirculated within the compressor.

Helium Compressor Oil System

The oil system consists of FOUR main elements:

- The Oil Heat Exchanger
- The Bulk Oil Separator
- The Oil Mist Separator
- The Adsorber

Helium Compressor Oil System:
Bulk Oil Separation

In compressors with rotary pumps, the pump acts as a bulk (oil stream) separator by slowing down the velocity of the helium and oil mixture. The oil stream then "rains" directly into the oil sump.

In compressors with piston pumps, a separate bulk separator is used and the oil is then returned to the pump.

Helium Compressor Oil System:
Oil Mist Separator

The oil mist (aerosol) separator utilizes very fine fibers to coalesce oil vapor into droplets and thus "clean" the helium gas. Oil from this separator is re-injected into the pump.

Helium Compressor Oil System: Adsorber

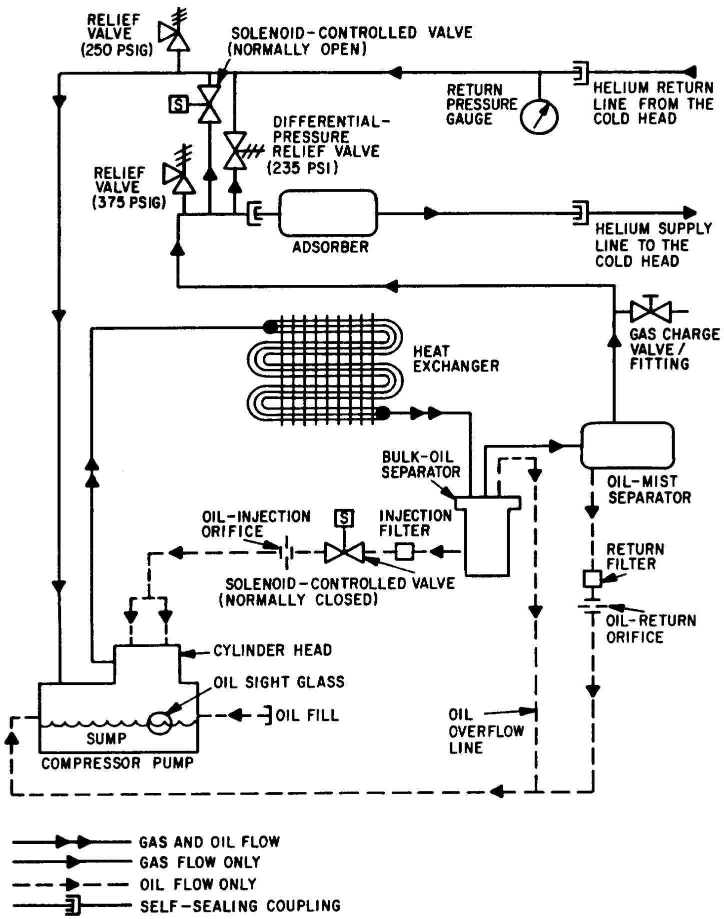
The adsorber contains activated charcoal to filter out the remaining oil in the helium by adsorption. As the adsorber gets filled up with oil and other contaminants it needs to be replaced (typically once a year).

Helium Compressor Operating Temperature

Most Compressors can operate in ambient temperatures from 50-100 °F.

Note: Starting a compressor that is colder than 50 °F can cause start up problems.

CTI-CRYOGENICS
Helium Compressor Schematic



Ref ©2000 Helix Technology Corporation

Typical Operating Parameters for CTI-CRYOGENICS Compressor Chart

Compressor	Static	Operating	Running
Type	Charge	Pressure	Current
SC	250 psig	275 psig	8 amps @ 208 V
8200	250 psig	275 psig	8 amps @ 208 V
1020R	185 psig	275/80 psig*	14.5 amps @ 208 V

The thermal switch on these compressors trips the main circuit breaker.

Compressor	Static	Operating	Running
Type	Charge	Pressure	Current
8300	250 psig	95 psig	8 amps @ 208 V
8500/8510	200 psig	60-90 psig*	14.5 amps @ 208 V
9600	250 psig	110 psig	15 amps @ 208 V

When running multiple cryopumps with these compressor, the return pressure will be about 110 psig.

The US Particle Accelerator School
Cryosorption Pumps

Lou Bertolini

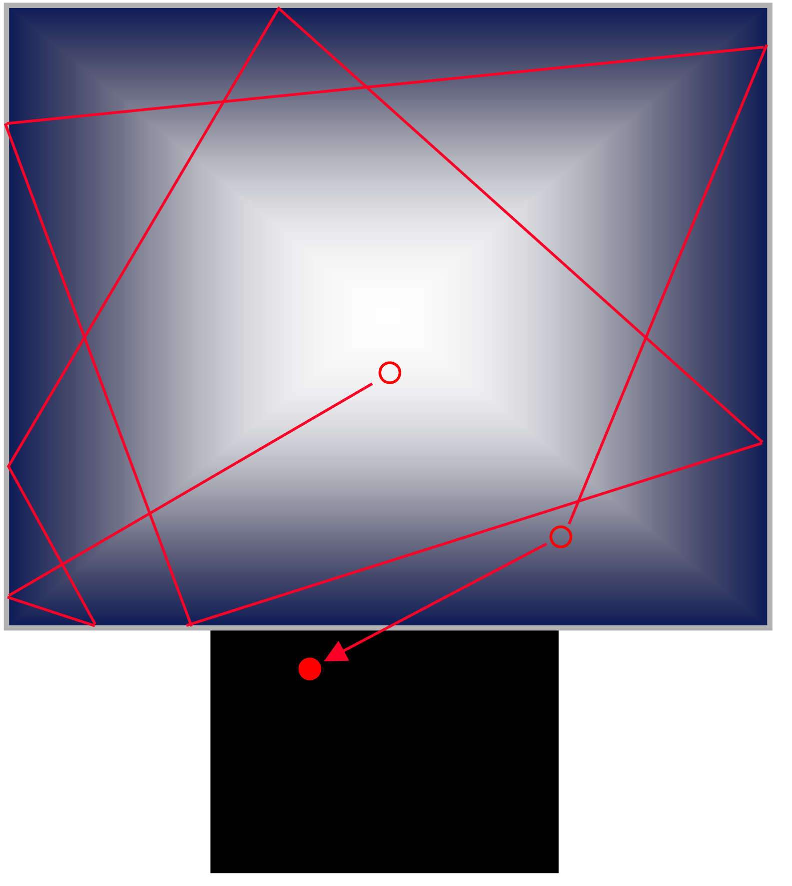
Lawrence Livermore National Laboratory

January 19-24, 2004

Cryopumping Basics . . . Cryocondensation

Cooling gases to the extent that gas molecules lose sufficient energy to form condensation layers.

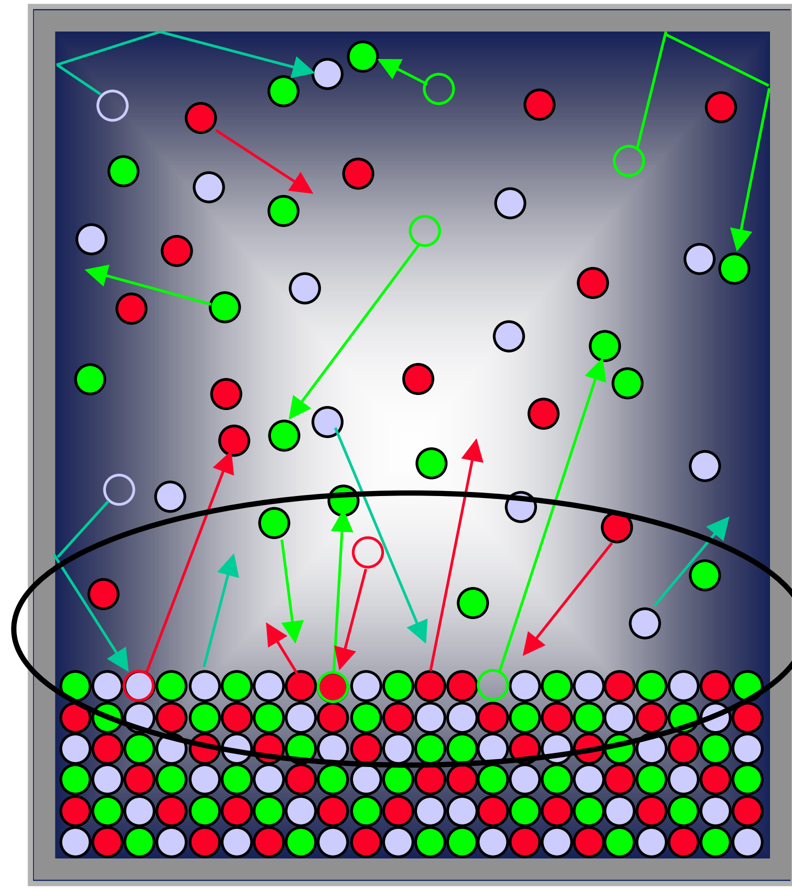
- A cryogenic surface will trap any molecule that contacts the surface if it is cold enough.



Cryopumping Basics . . .
Equilibrium Vapor Pressure

Equilibrium vapor pressure is the state where as many molecules are condensing as are vaporizing.

Equilibrium occurs when the rate of gas molecules returning to the liquid/solid (condensing) is equal to the rate of energetic molecules becoming gaseous (vaporizing).



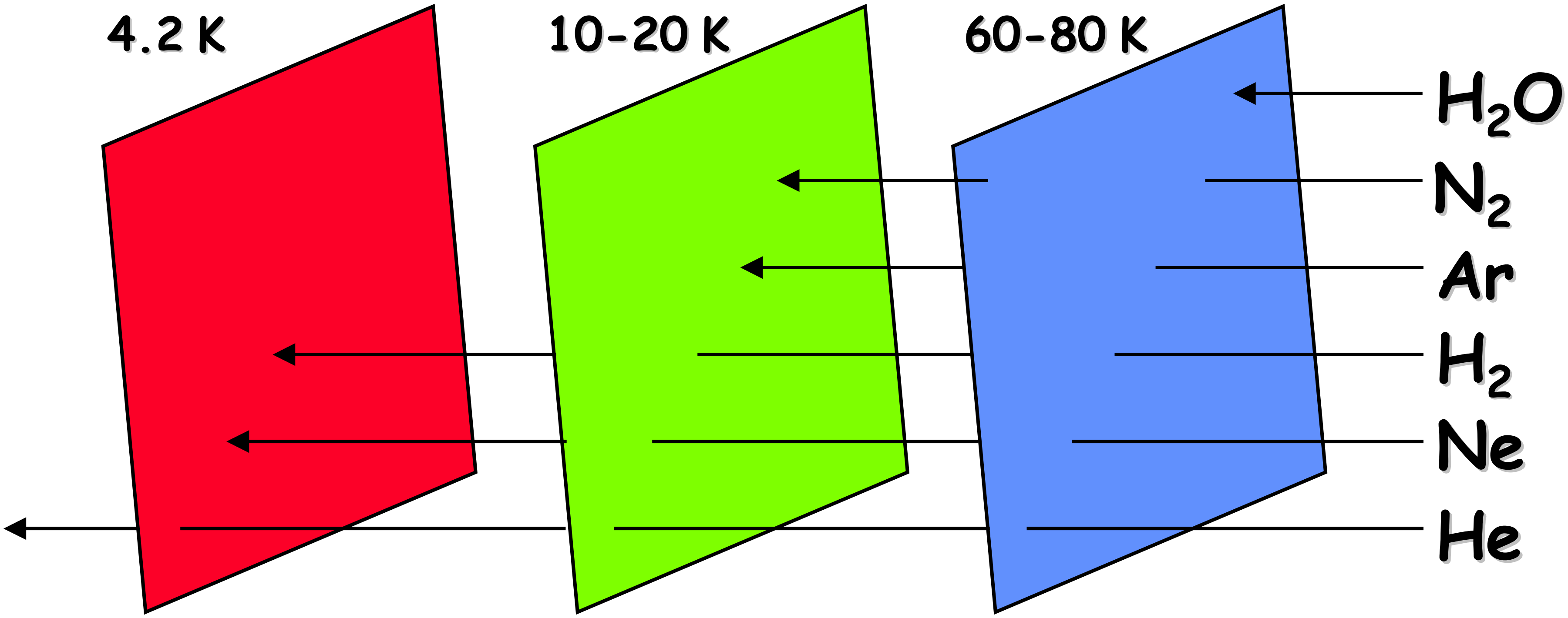
Cryopumping Basics . . .
Pressure within a Cryopump

What determines the Pressure inside a Cryopump?

Surface Temp.	at 16K	at 25K	at 31K
•Nitrogen	> 10^{-12} Torr	> 10^{-7} Torr	> 10^{-4} Torr
•Argon	> 10^{-12} Torr	> 10^{-9} Torr	> 10^{-4} Torr
•Oxygen	> 10^{-12} Torr	> 10^{-10}Torr	> 10^{-4} Torr
•Hydrogen	> 10^{+2} Torr		
•Helium	> Atm.		

Cryopumping Basics . . . Cryocondensation

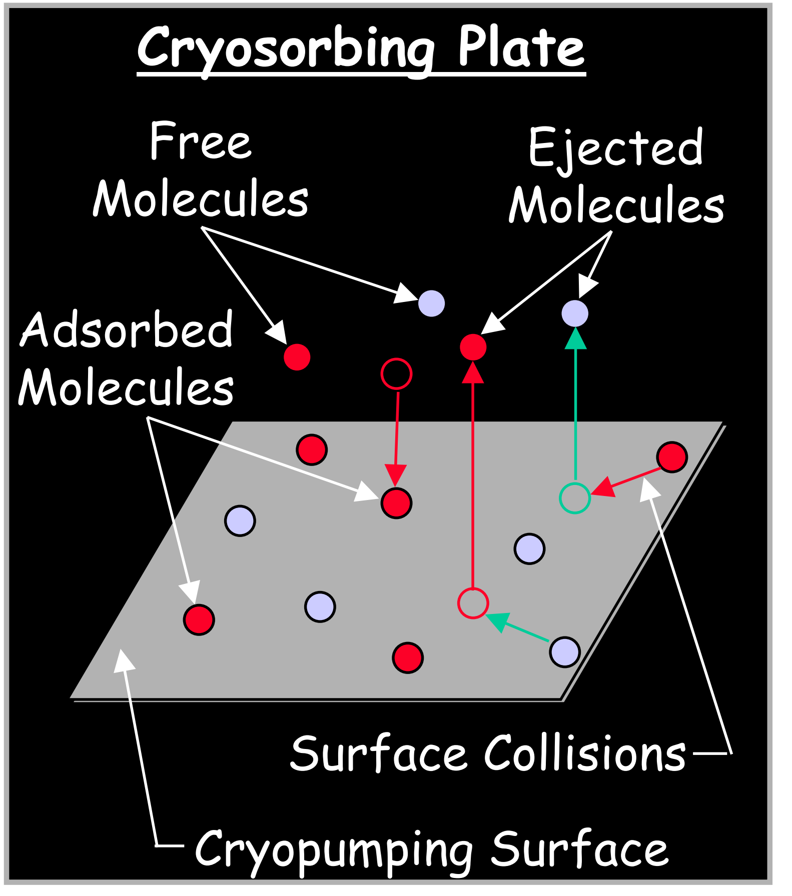
4.2 K is impractical as Helium still boils



Cryopumping Basics . . . Cryosorption

Cooling gas molecules to the extent that gas molecules, upon contacting a sufficiently cooled surface, lose enough energy to accumulate on the surface.

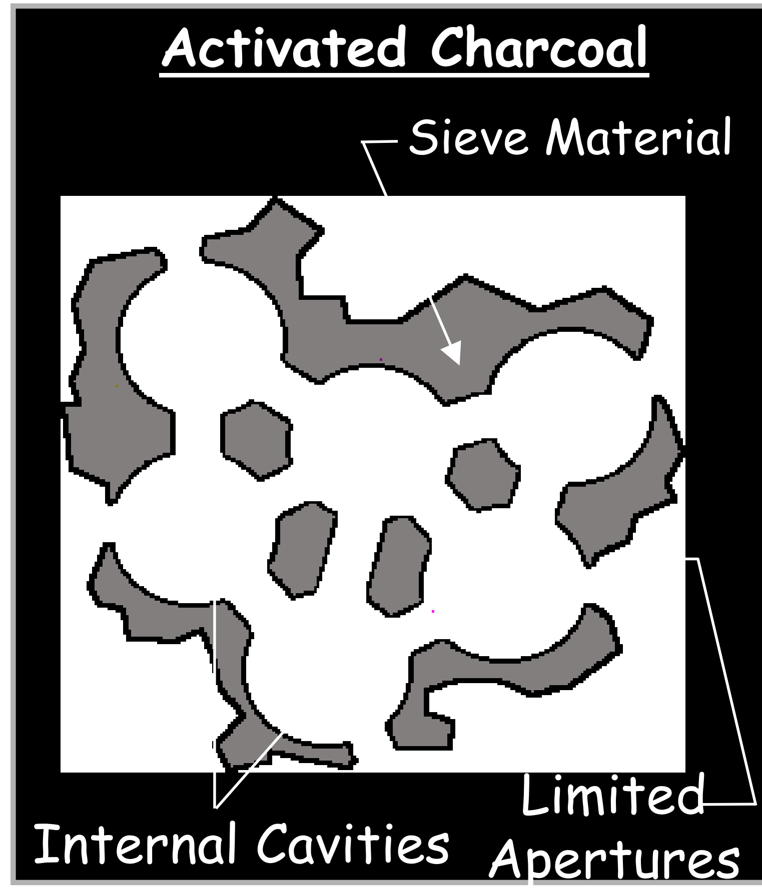
- A flat cryoadsorbing plate retains some molecules.
- Flat surface allows molecules to continue moving.



Cryopumping Basics . . . Cryosorption

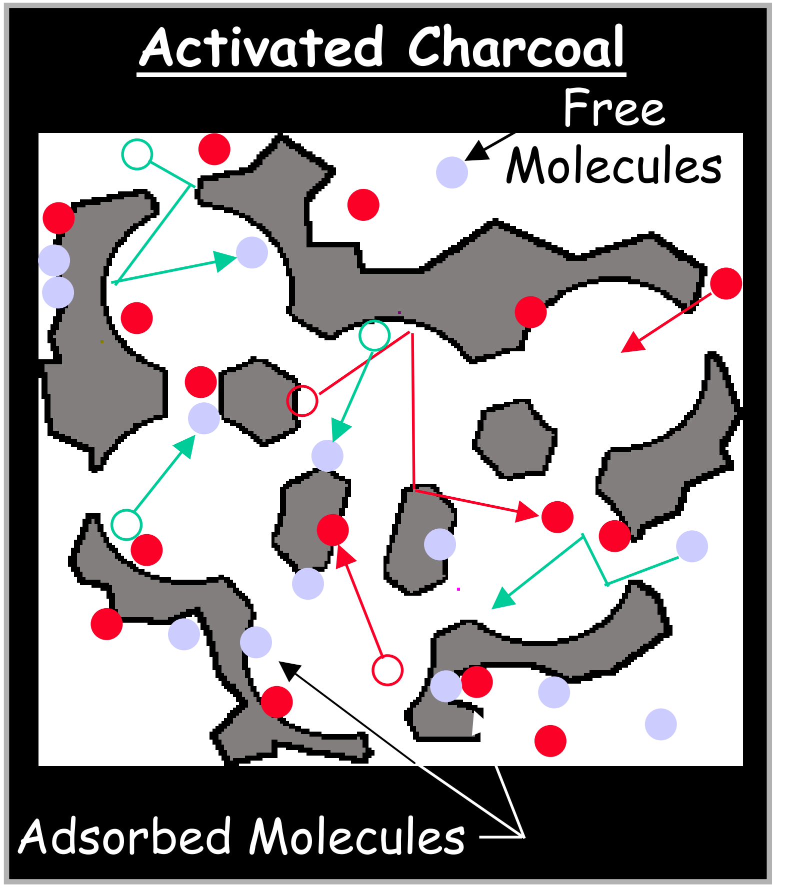
- Sieve material, such as charcoal, provides greater surface area and limited apertures.

- Large surface area capacity:
  1150-1250 m^2/gm



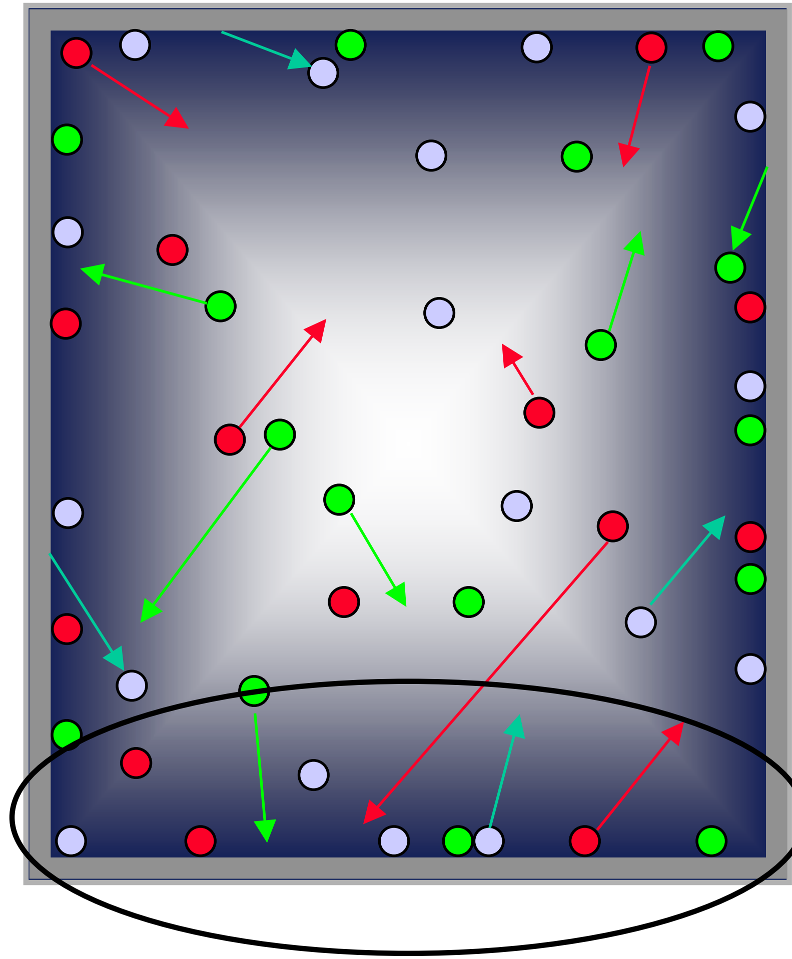
Cryopumping Basics . . . Cryosorption

- Increased surface area provides greater capacity.
- Released molecules remain confined.
- Irregular surface constricts motion.
- Cryosorption of hydrogen, neon, and helium accomplished.



Cryopumping Basics . . . Surface Equilibrium

When the number of molecules arriving on the chamber surface (adsorbing) equals the number leaving the surface (desorbing), then the system is in "Surface Equilibrium".



Equilibrium

Equilibrium Vapor Pressure:

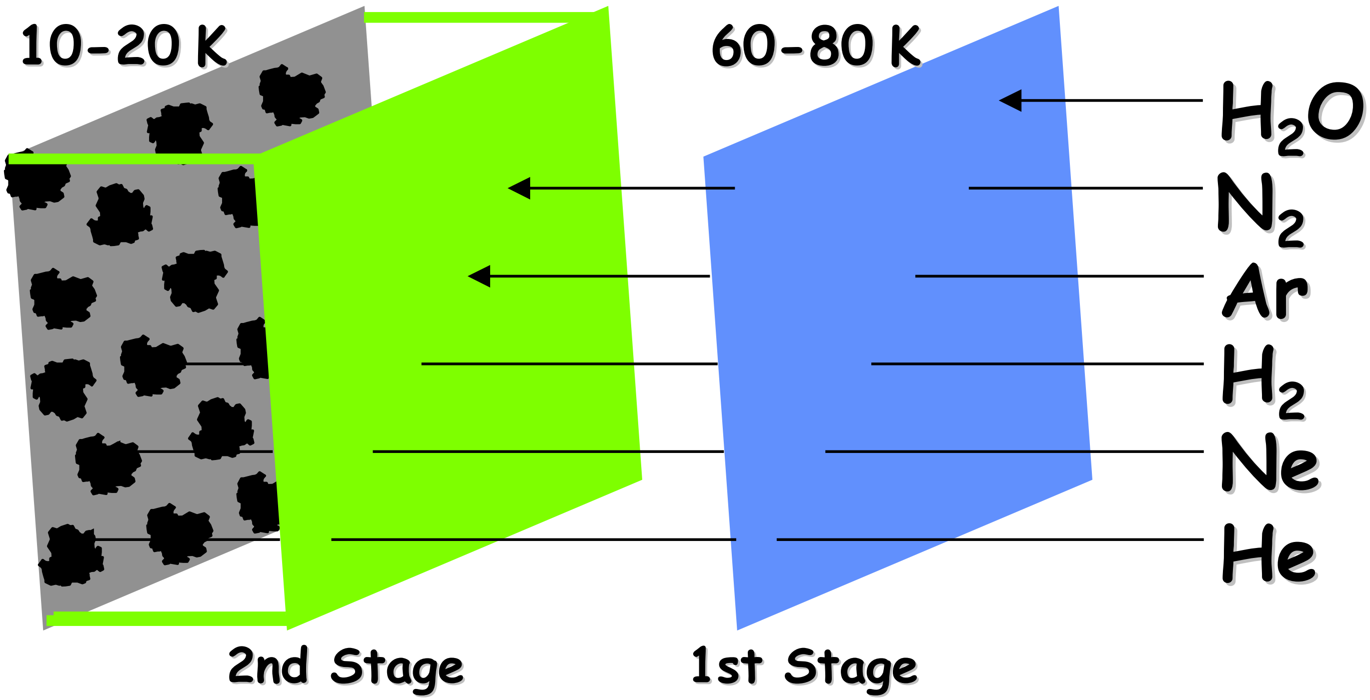
- CONDENSATION
- VAPORIZATION

Surface Equilibrium:

- ADSORPTION
- DESORPTION

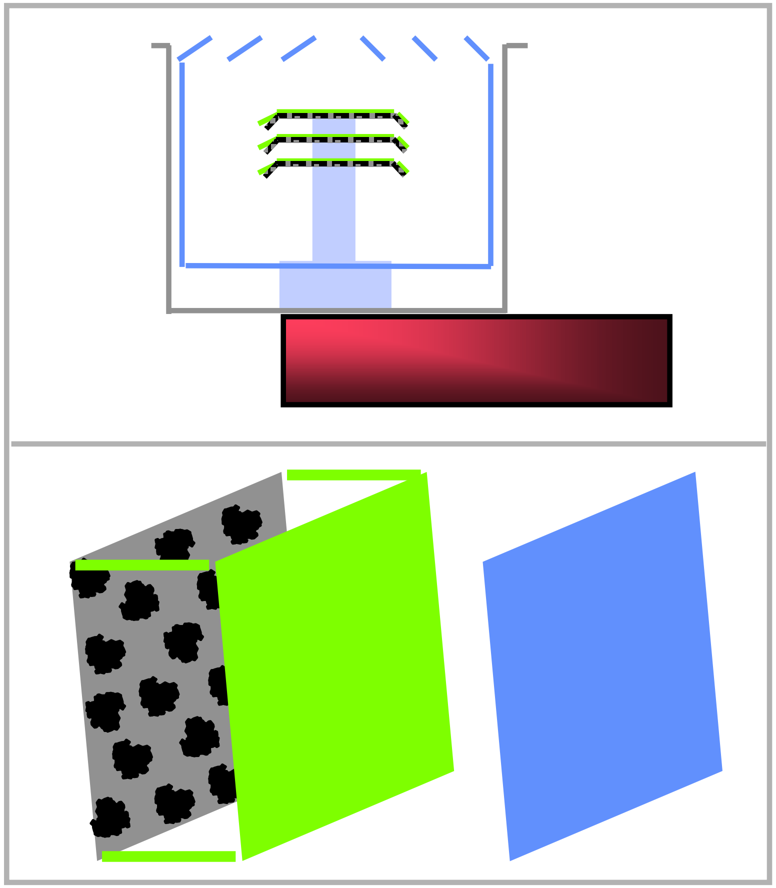
Cryopumping Basics . . . Cryosorption and Cryocondensation

Air gases and water vapor are condensed, noncondensible gases are captured.



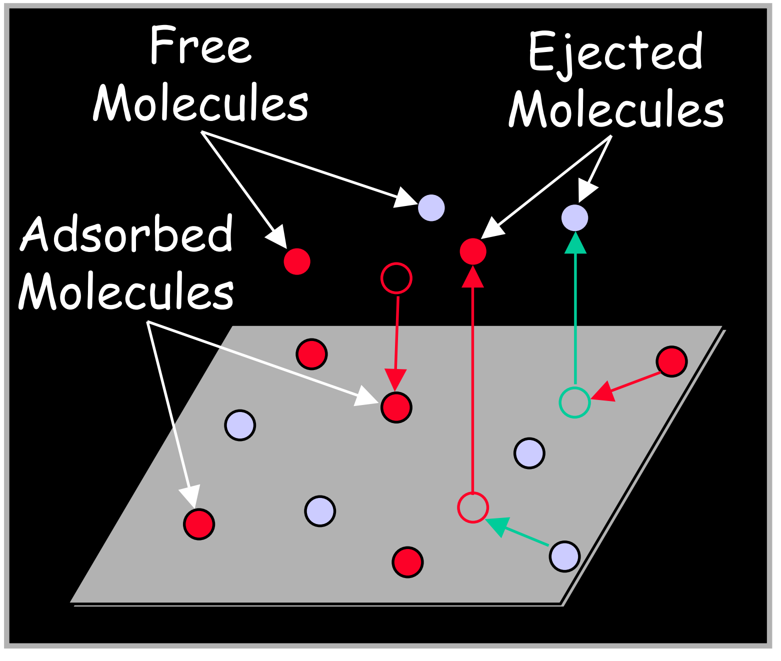
Cryopump Concept

- Cryopumps are designed to create these condensing and adsorbing surfaces.



Cryopumping Basics . . . Adsorption Isotherm

An adsorption isotherm is a measure of the surface population density of a gas at a constant temperature.



$$\sigma = f(P, T)$$

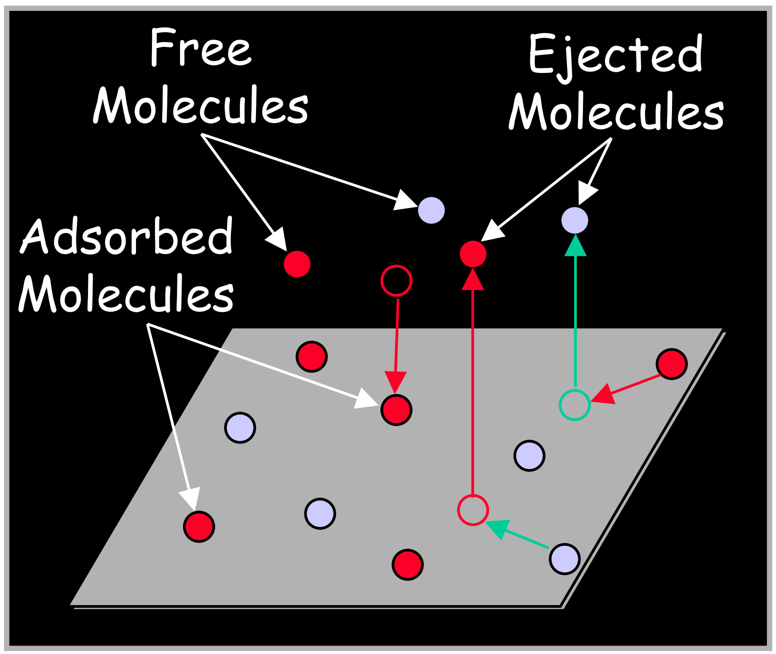
where σ = density of molecules of gas on a surface per cm^2

P = equilibrium pressure of system

T = system temperature

Cryopumping Basics . . . Adsorption Isotherm

Adsorption isotherms can be expressed several ways:



% Coverage

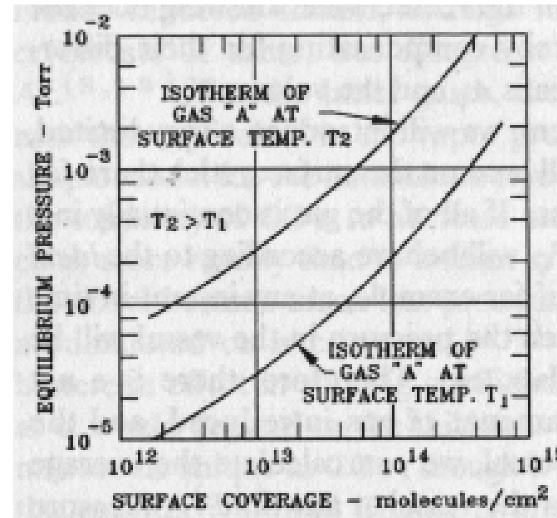
σ = 0.20 surface 20% covered
σ = 1 One monolayer (σ_m)
σ = 2 Two monolayers ($2\sigma_m$)

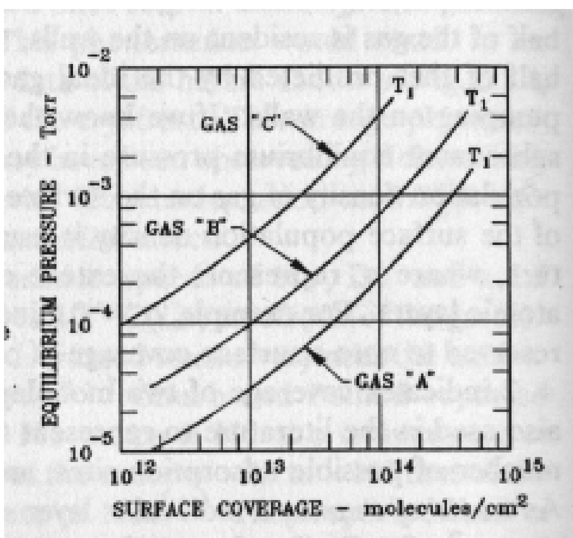
Molecules/cm²

$\sigma = 10^{15}$ molecules/cm²

Cryopumping Basics . . . Adsorption Isotherm

- Usually an adsorption isotherm represents pressure vs. coverage data for a specific temperature.
- As the temperature increases, the equilibrium pressure increases for a specific surface coverage.





- Each gas has its own unique adsorption isotherm for the same temperature.
- For all gases, the equilibrium pressure of an adsorption isotherm is less than the vapor pressure at that temperature.
- As surface coverage goes up (to several monolayers), the equilibrium pressure will approach the vapor pressure.

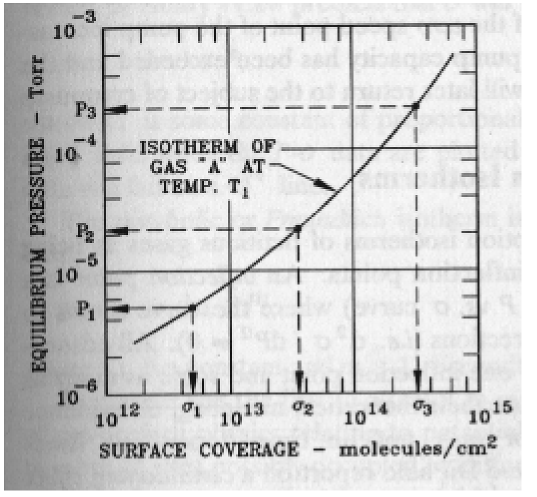
Cryopumping Basics . . . Pumping Speed

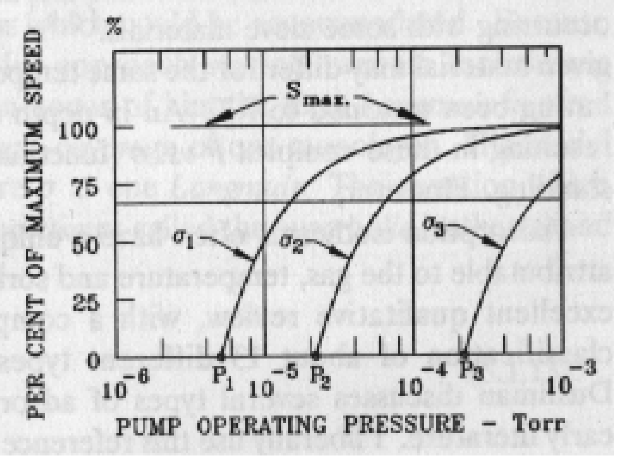
- A cold surface has a finite pumping speed for a gas as long as the pressure of the adsorption isotherm is less than the pressure of the gas.
- As the surface coverage increases, the equilibrium pressure increases.

$$S = S_{max}\left(1 - \frac{P_e}{P}\right)$$

- S_{max} is set by the surface conductance limitations of the cryopump.

In cryosorption pumping, speed is dependent on the quantity of gas already adsorbed and the pressure.



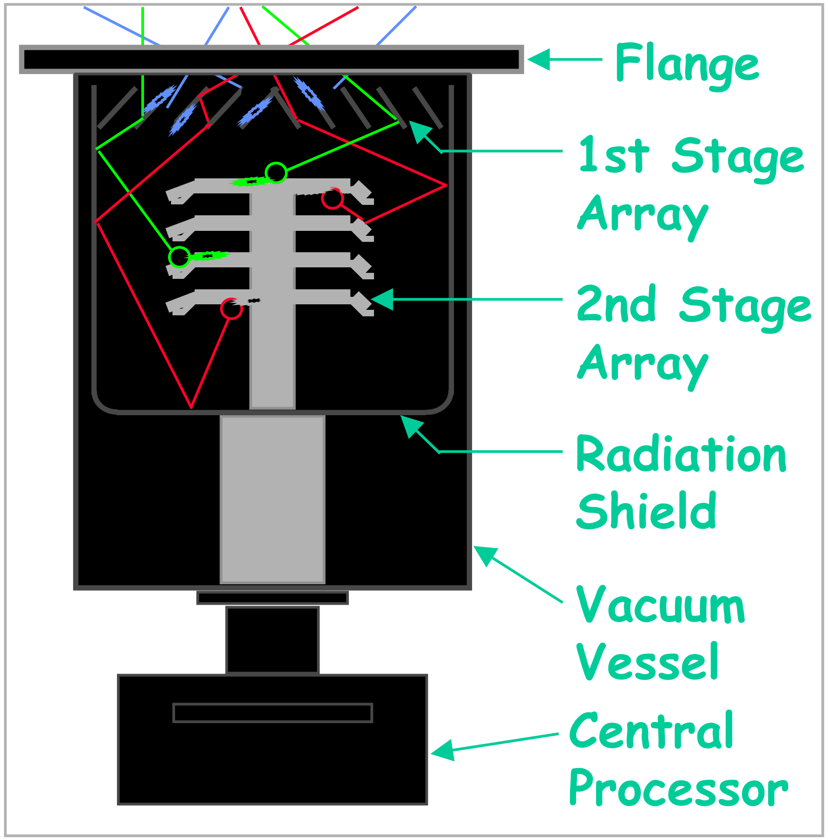


Cryopumping Basics . . . Sticking Coefficients

CryoSurface Temperature (K)	Gas and Gas Temperature									
	N_2		CO		O_2		Ar		CO_2	
	77 K	300 K	77 K	300 K	77 K	300 K	77 K	300 K	77 K	300 K
10	1.0	0.65	1.0	0.90			1.0	0.68	1.0	0.75
12.5	0.99	0.63	1.0	0.85			1.0	0.68	0.98	0.70
15	0.96	0.62	1.0	0.85			0.90	0.67	0.96	0.67
17.5	0.90	0.61	1.0	0.85	1.0	0.86	0.81	0.66	0.92	0.65
20	0.84	0.60	1.0	0.85			0.80	0.66	0.90	0.63
22.5	0.80	0.60	1.0	0.85			0.79	0.66	0.87	0.63
25	0.79	0.60	1.0	0.85			0.79	0.66	0.85	0.63
77									0.85	0.63

Ref. "Cryopumping", Dawson and Haygood, Cryogenics 5 (2), 57, (1965)

Cryopump



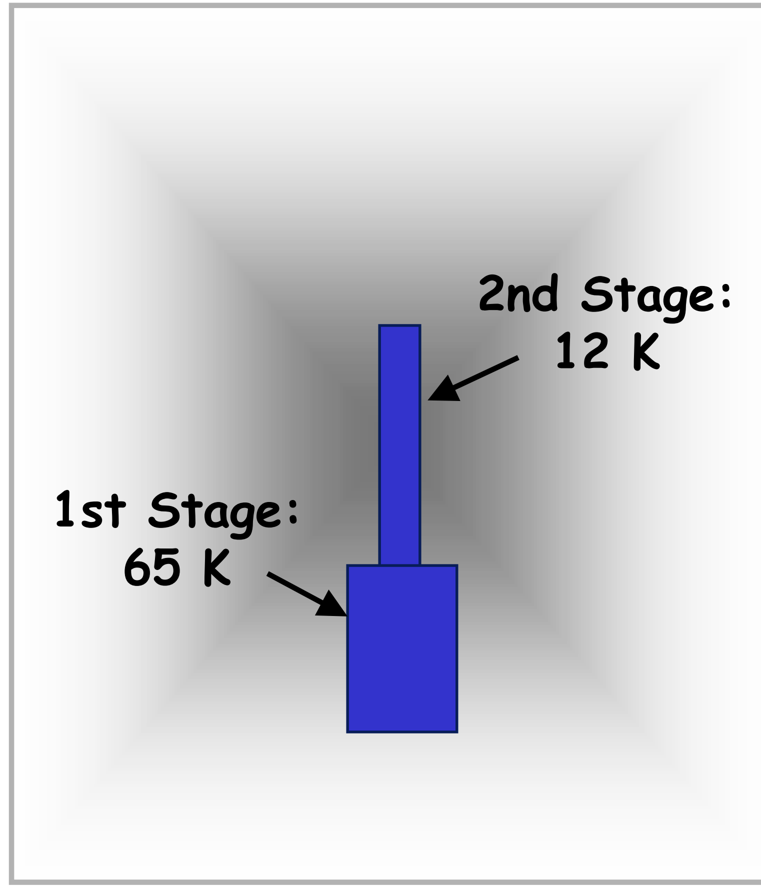
Capture Type Pump

Characteristics:

- No fluids, lubricants, or moving parts
- High crossover capability minimizes backstreaming
- High water pumping speed
- Tailorable pumping speeds
- Operate in all orientations
- Continuous backing not required

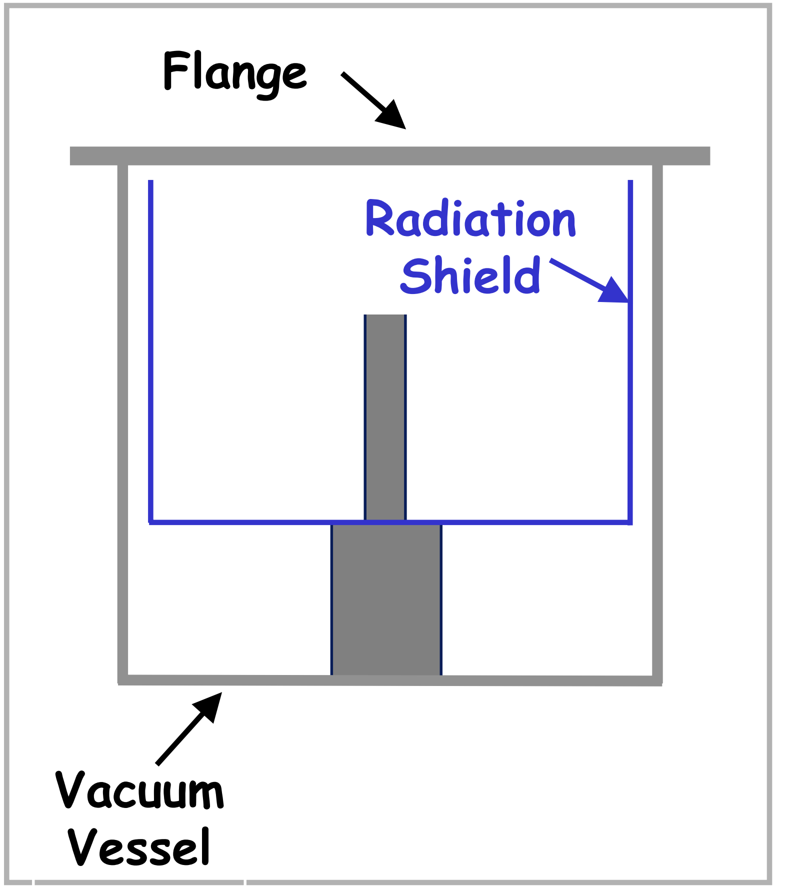
Cryopump Components . . . *The Cold-Head*

- A cryopump is built around the cold-head.
  - Creates the cold temperatures needed to condense and adsorb gases
  - Two stages, each at a different temperature
- Achieves these temperatures by the expansion of helium.



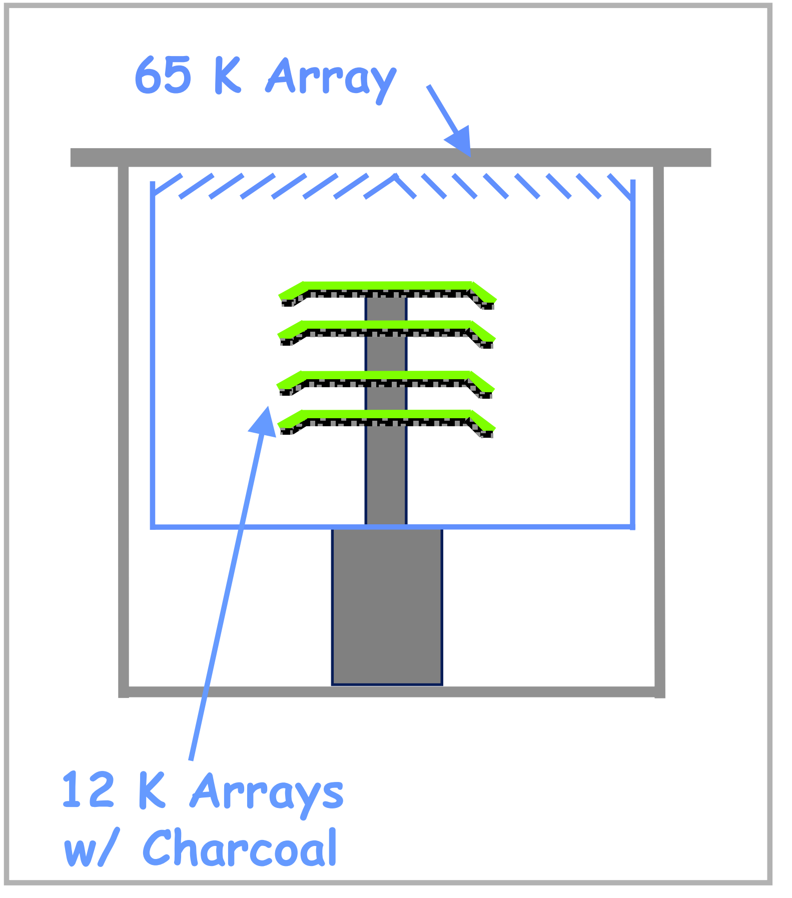
Cryopump Components . . .
shield, vacuum vessel, and flange

- A radiation shield is attached to the 1st stage of the cold-head.
  - Copper for conductivity
  - Nickel plating for protection
- The vacuum vessel isolates the cryopump.
- The inlet flange attaches to the chamber.

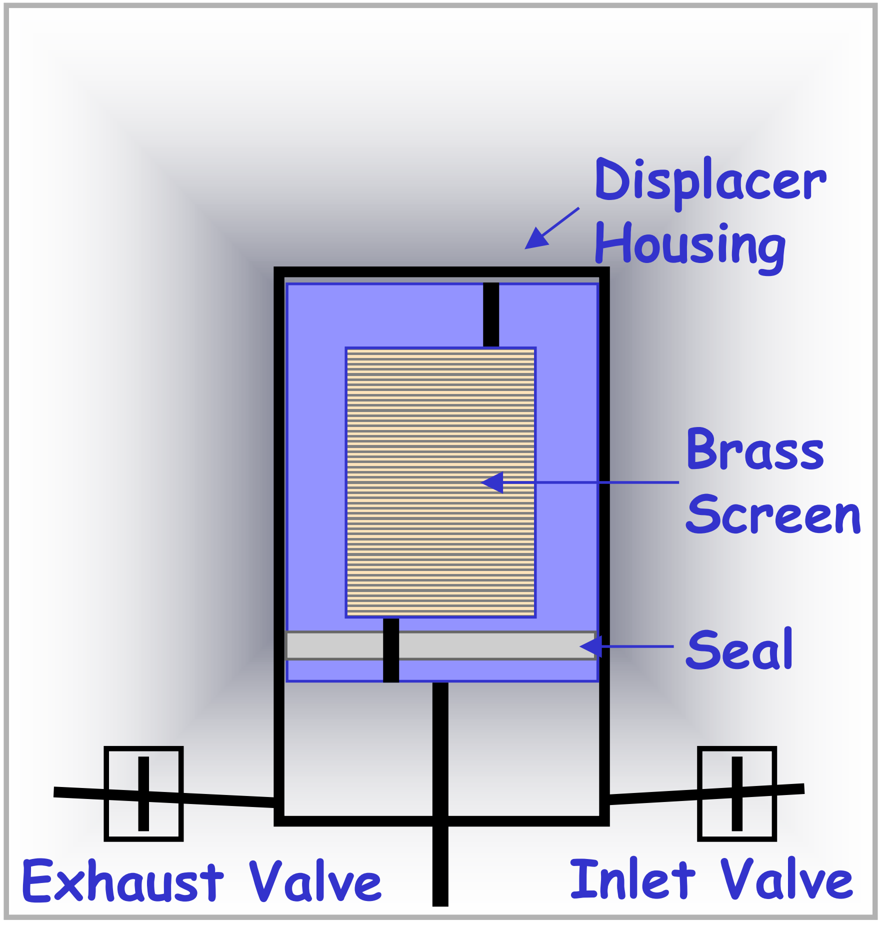


Cryopump Components . . .
1st and 2nd Stage Arrays

- The 1st stage (65 K) array is attached to the radiation shield.
  - Condenses water vapor
- A series of arrays with charcoal are attached to the 2nd stage (12 K) of the cold-head.
  - Condenses O_2, N_2, Ar
  - Adsorbs H_2, He, Ne



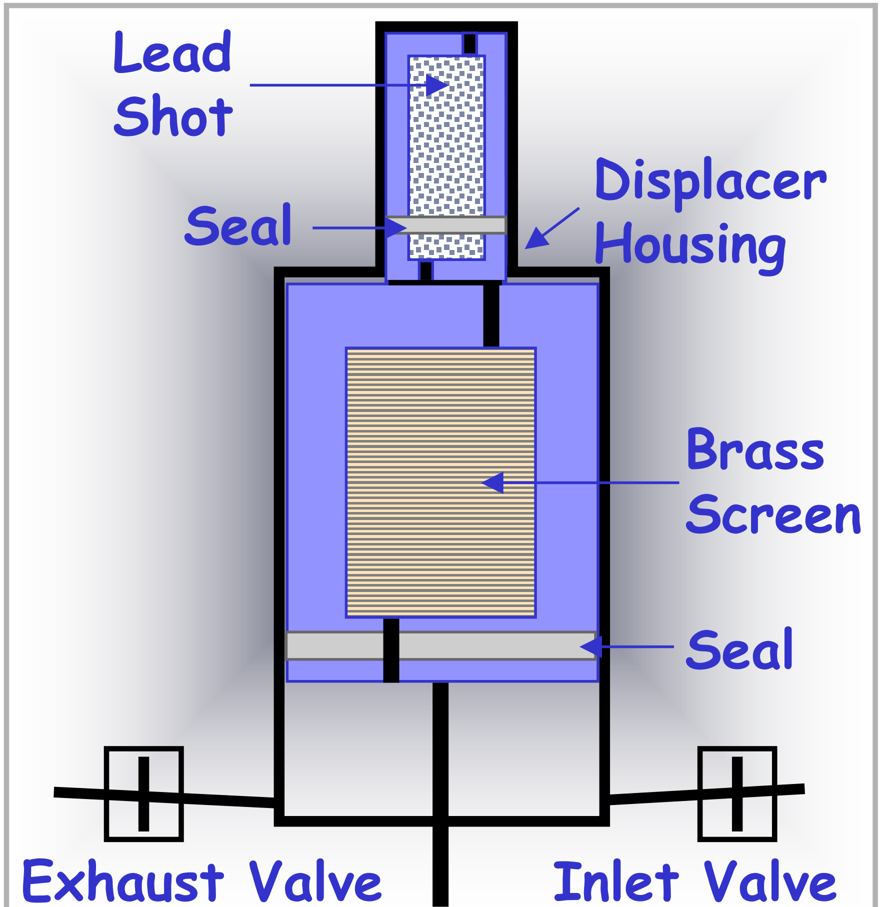
Cryopump System . . . *The Refrigerator*



Primary Displacer

- Stainless housing
- Brass screen for thermal mass
- Phenolic casing
- Helium inlet and exhaust

Cyropump System . . . *The Refrigerator*

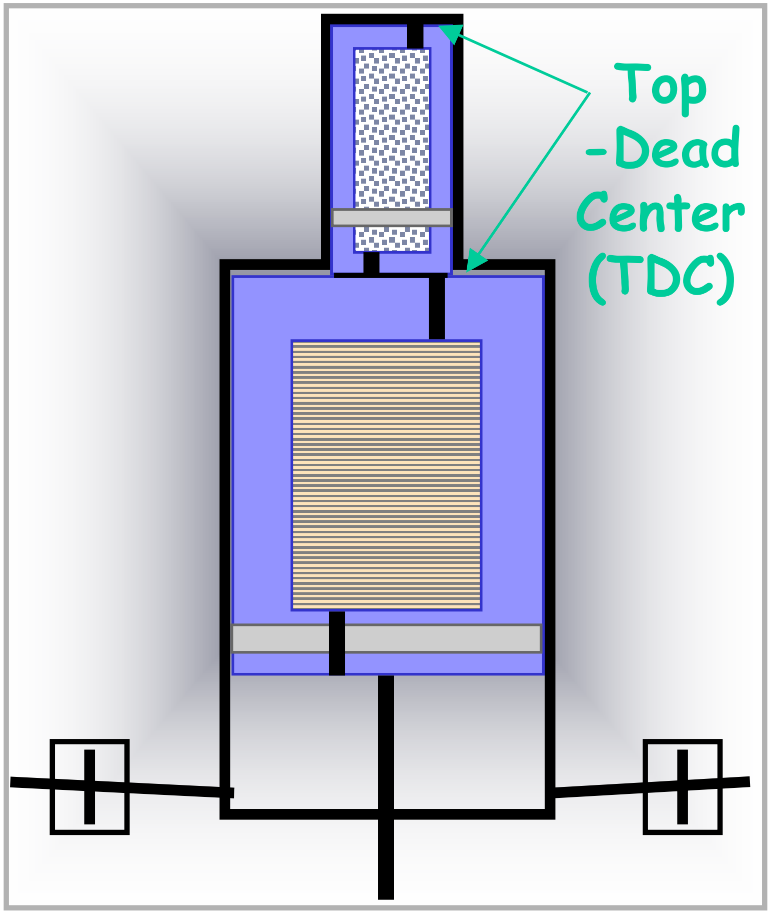


Secondary Displacer

- Second stage attached to top of primary displacer allows even lower temperatures.
- Lead shot for thermal mass.
- Phenolic casing.

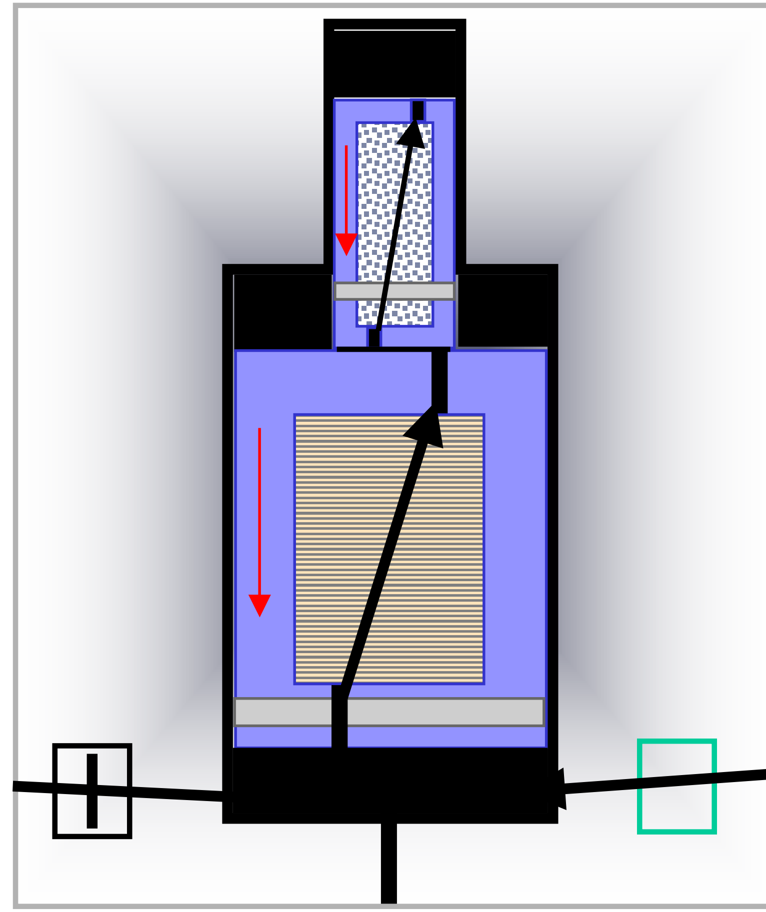
Cyopump System . . . *The Refrigerator*

- Cycle begins with both displacers at TDC.



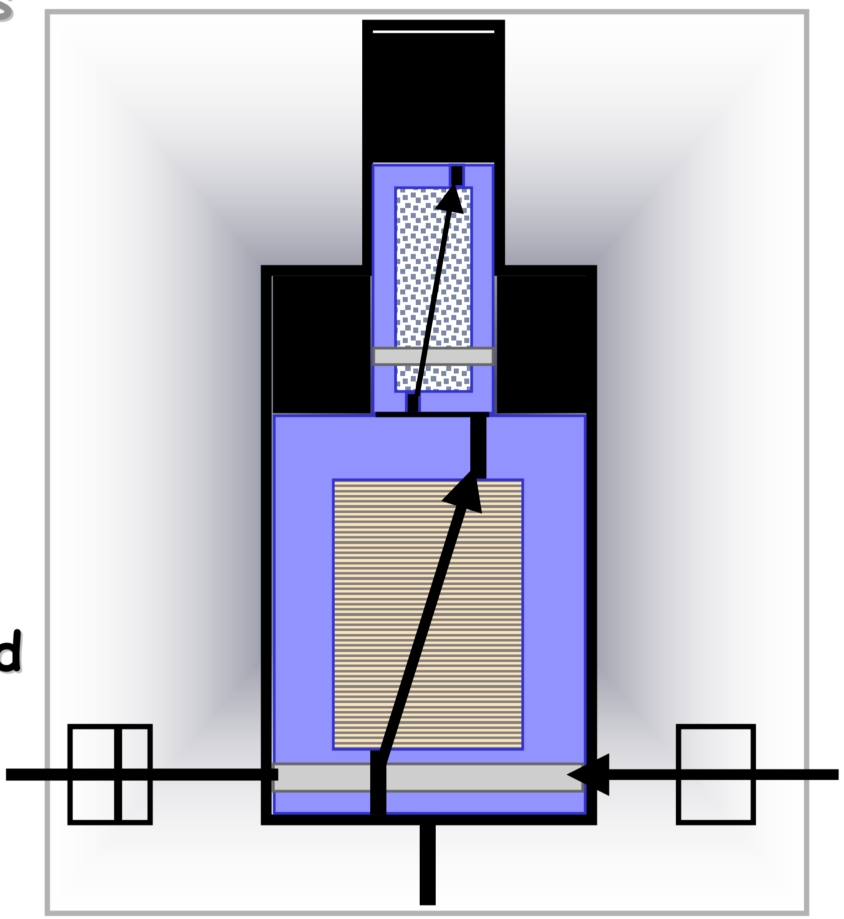
Cryopump System . . . *Refrigeration Cycle*

- Cycle begins with both displacers at TDC.
- Inlet valve opens.
- Displacers move downward.



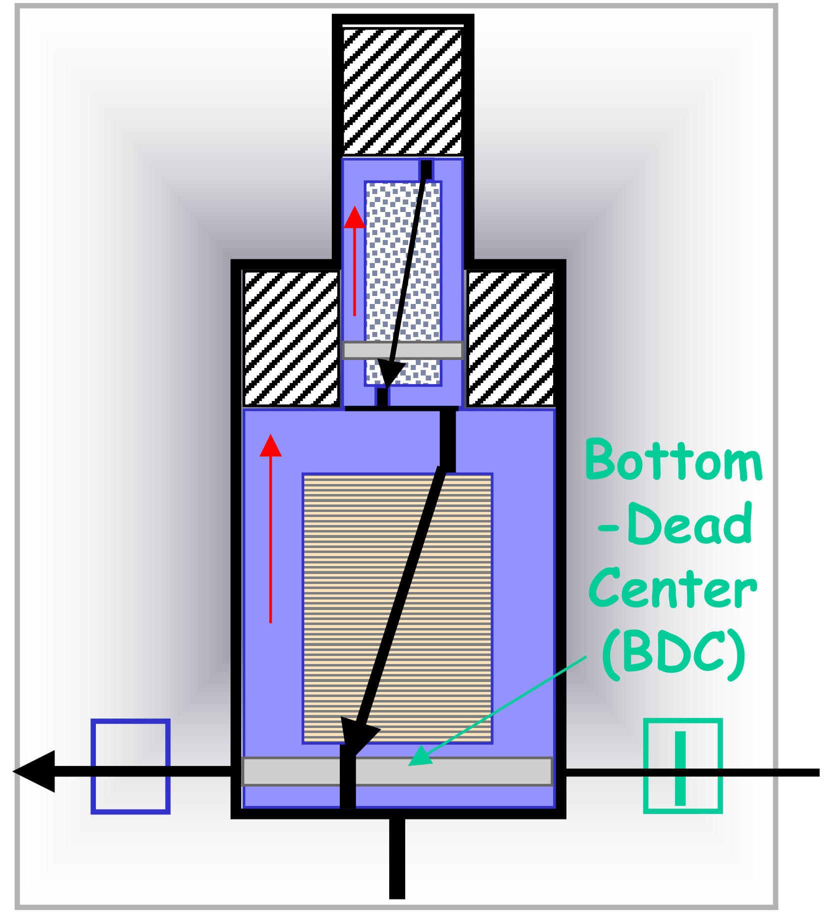
Cryopump System . . . *Refrigeration Cycle*

- Cycle begins with both displacers at TDC.
- Inlet valve opens.
- Displacers move downward.
- **Helium fills void above primary displacer and passes through secondary displacer to fill second void.**



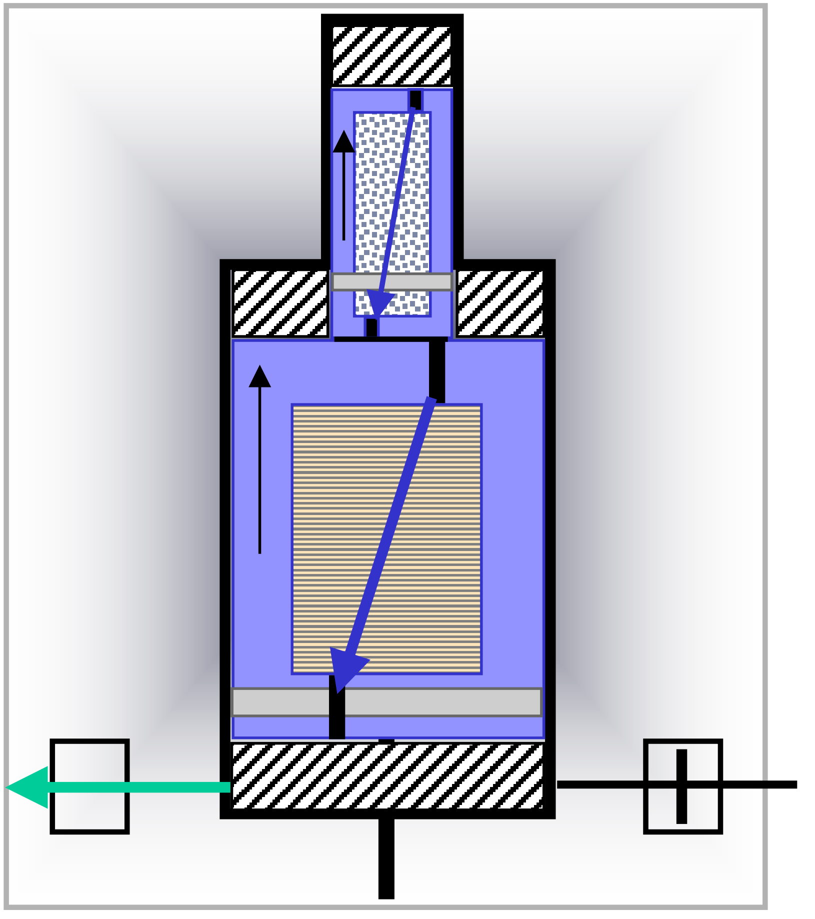
Cryopump System . . . *Refrigeration Cycle*

- At BDC, inlet valve closes.
- Exhaust valve opens.
- Gas has expanded in both voids and cools.
- Displacers move upward.



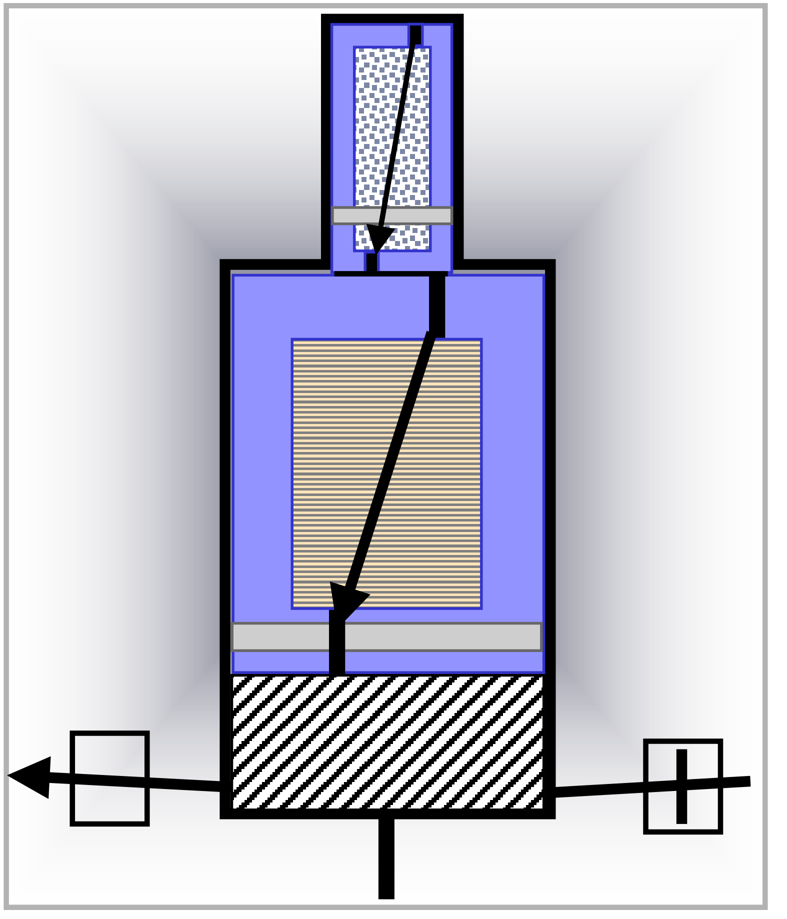
Cryopump System . . . *Refrigeration Cycle*

- Cooled gas flows down through both displacer matrices removing heat from thermal masses.
- Gas exits through exhaust valve.



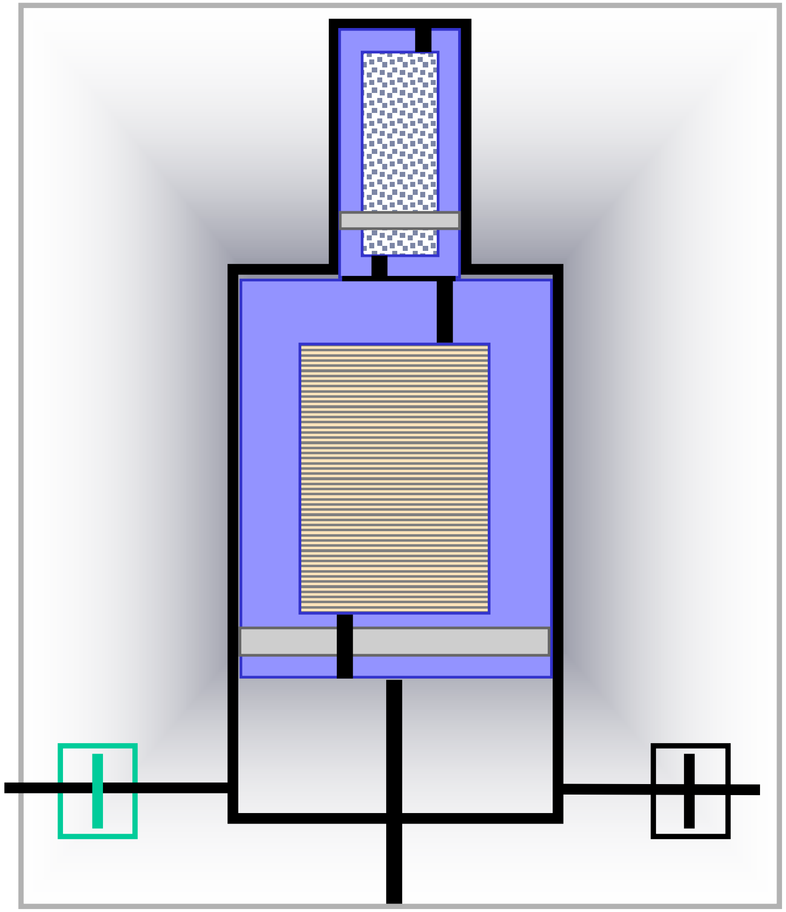
Cryopump System . . . Refrigeration Cycle

- Displacers again at TDC.



Cryopump System . . . *Refrigeration Cycle*

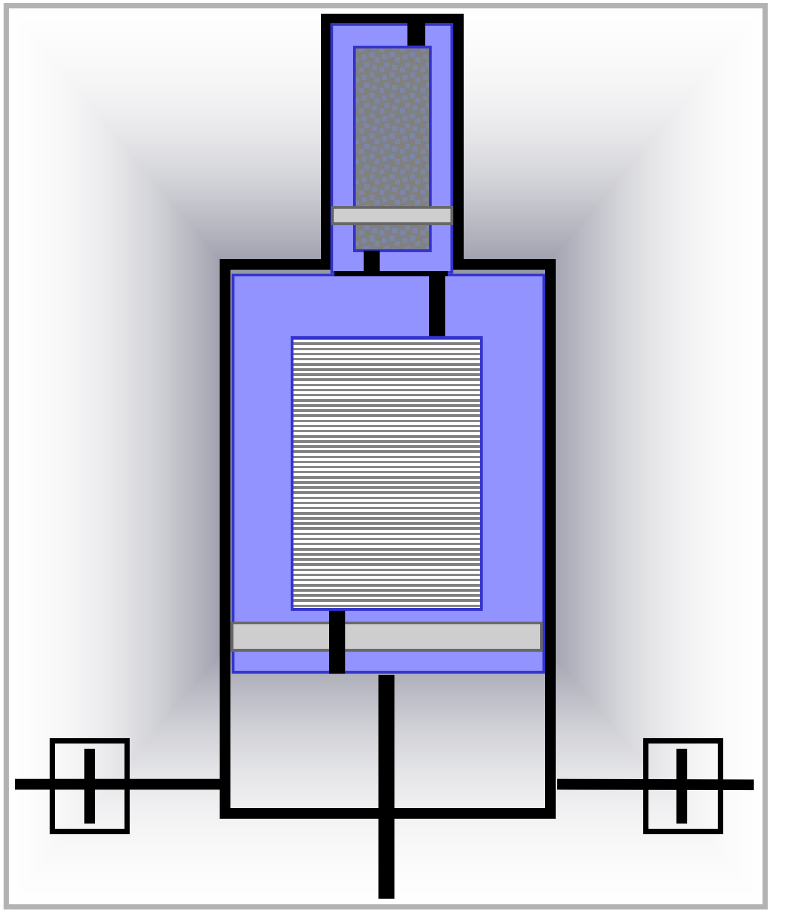
- Displacers again at TDC.
- Remaining gas exits.
- Exhaust valve closes.
- Cycle repeats at 72 rpm.



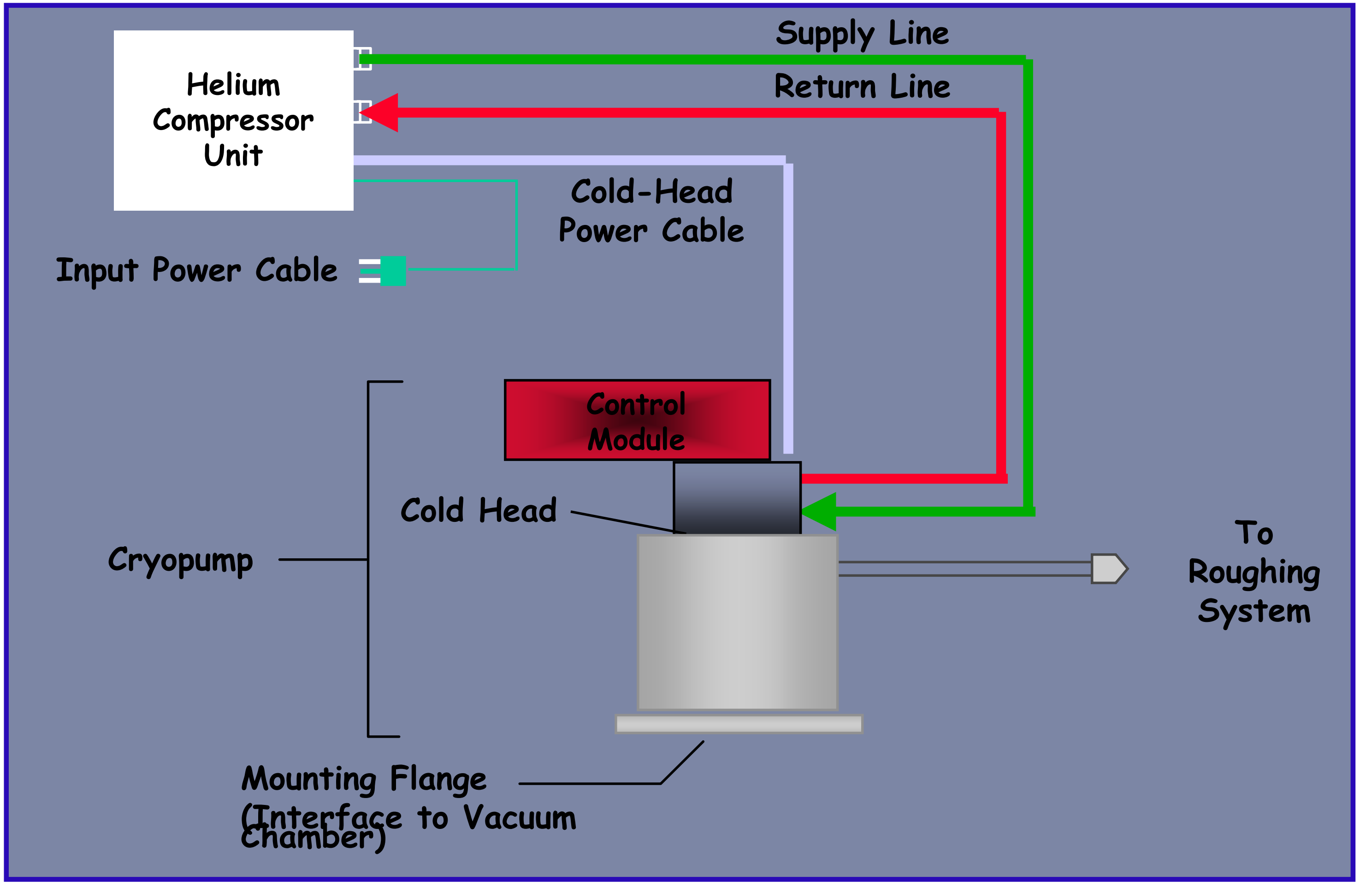
Cryopump System . . . *Refrigeration Cycle*

After each cycle both displacer matrices (thermal masses) are colder, with the secondary mass colder than the primary ...

... incoming helium is pre-cooled accordingly BEFORE expansion.



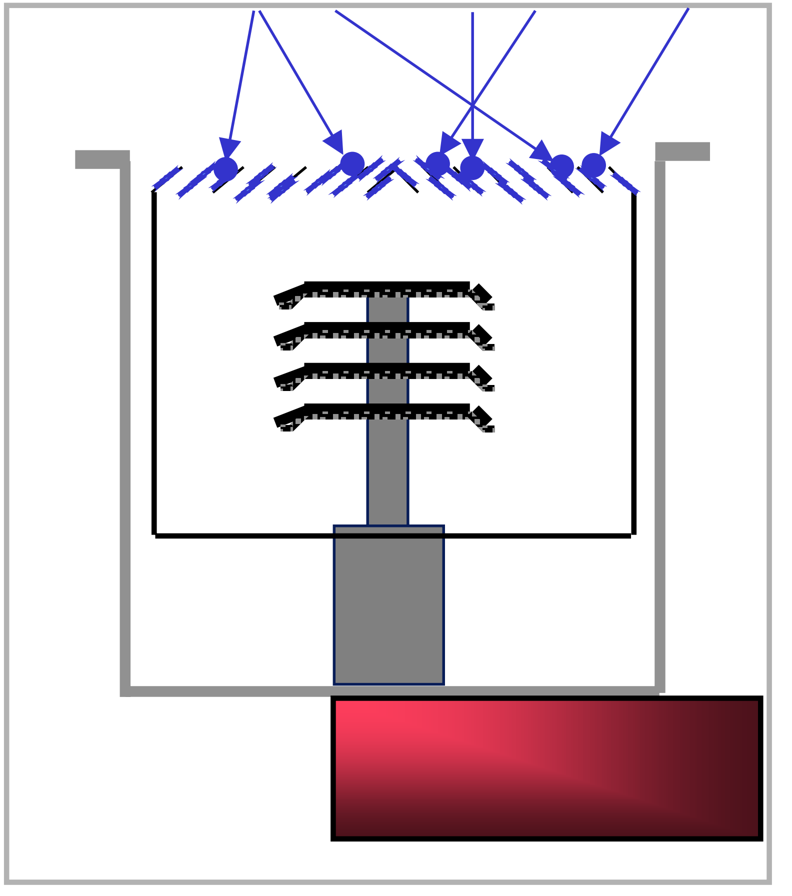
Cryopump System Overview



Cyropump Operation - *Cryocondensation*

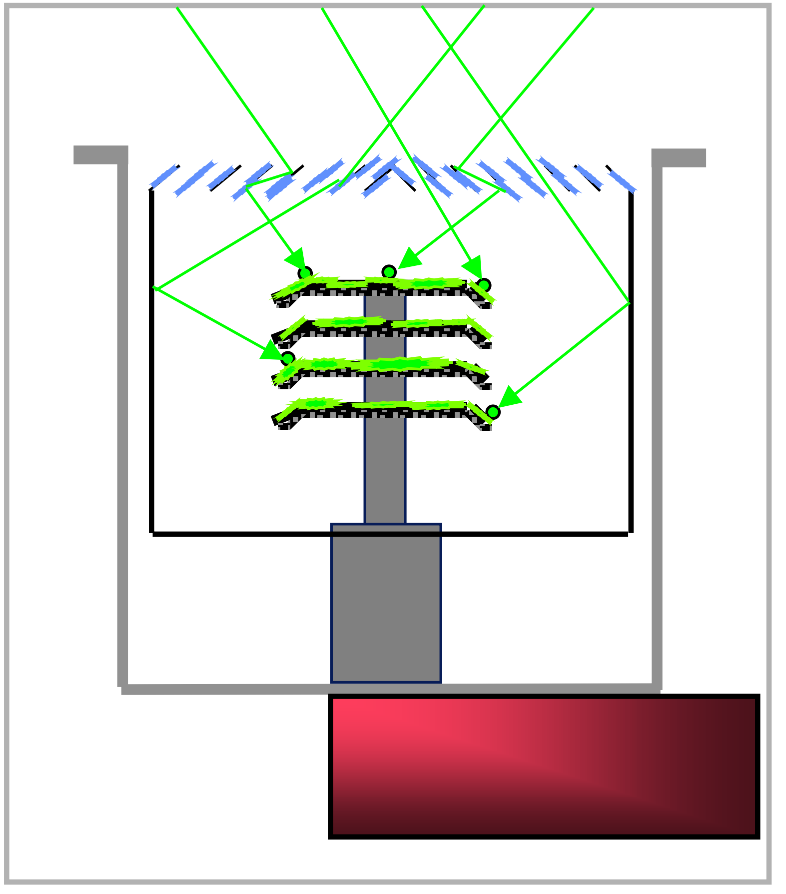
- Water molecules collide with the cooled surfaces of the 65 K first stage array.

- Condensation layers form as more of these molecules collect.



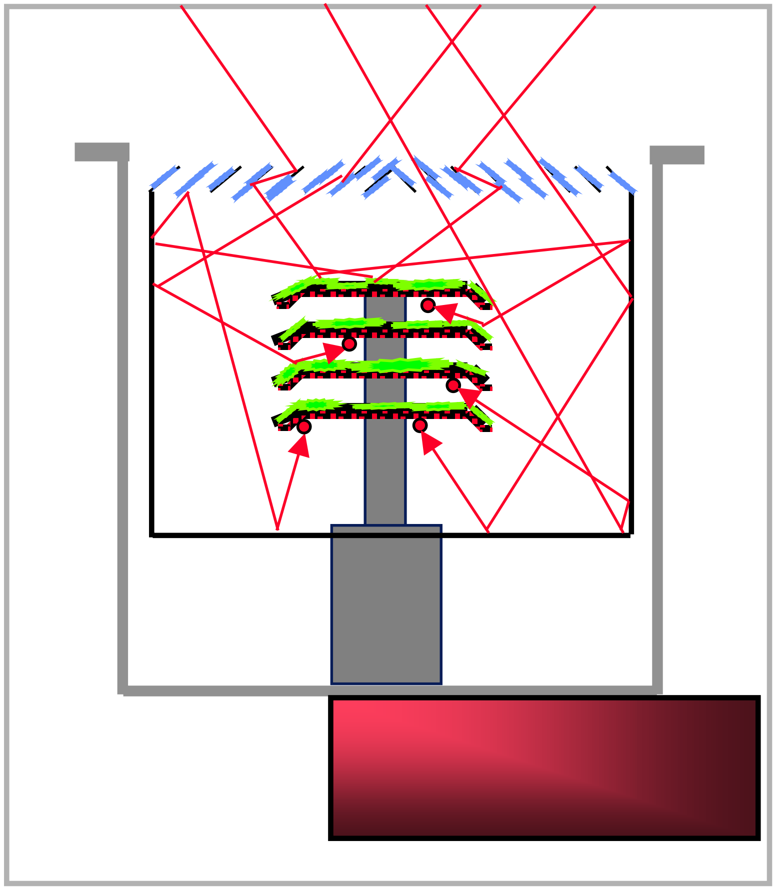
Cyropump Operation - *Cryocondensation*

- Other molecules such as oxygen, nitrogen, and argon pass between the first stage arrays.
- By colliding with the 12 K second stage arrays, these molecules also form condensation layers.



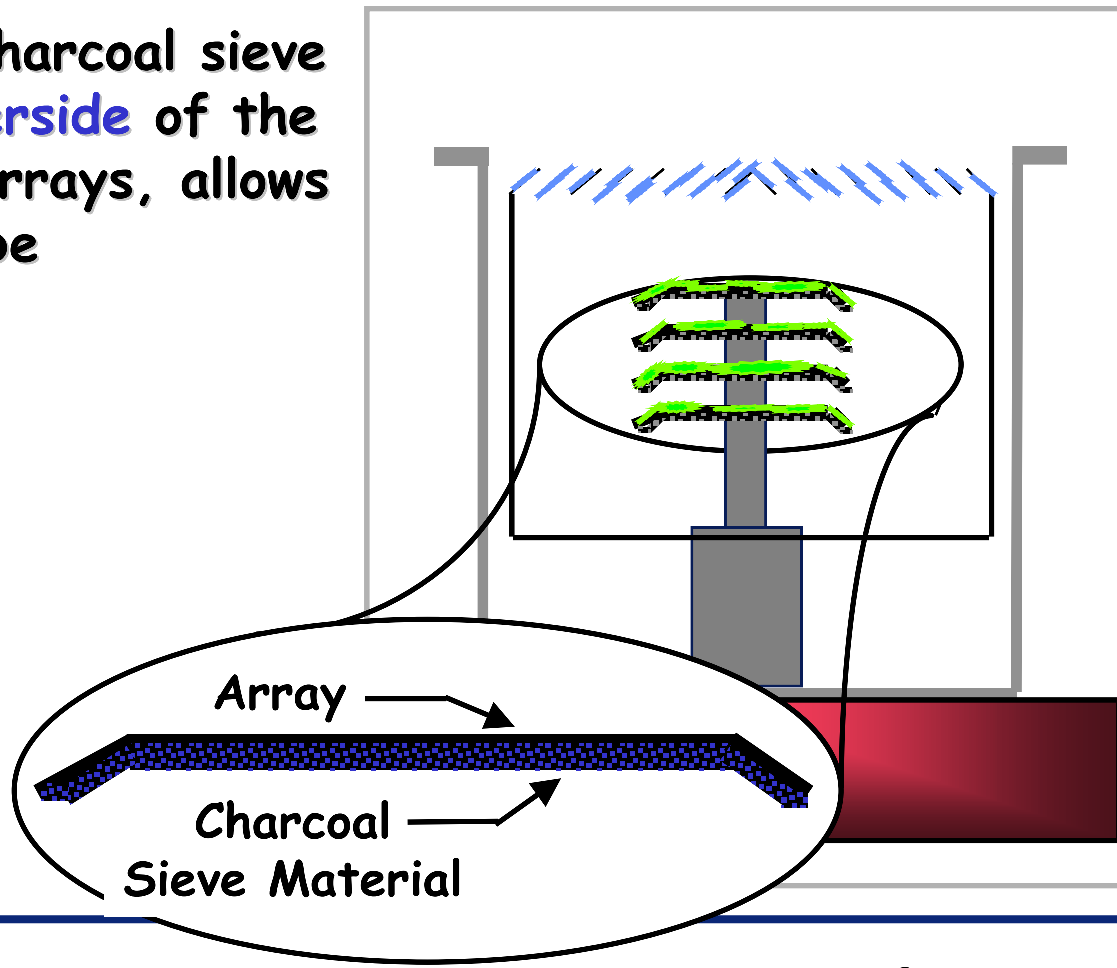
Cyropump Operation - *Cryoadsorption*

- The noncondensible H_2, He, and Ne molecules pass between the first stage arrays.
- Collide with walls and second stage arrays.
- Become adsorbed upon contacting the charcoal surfaces.



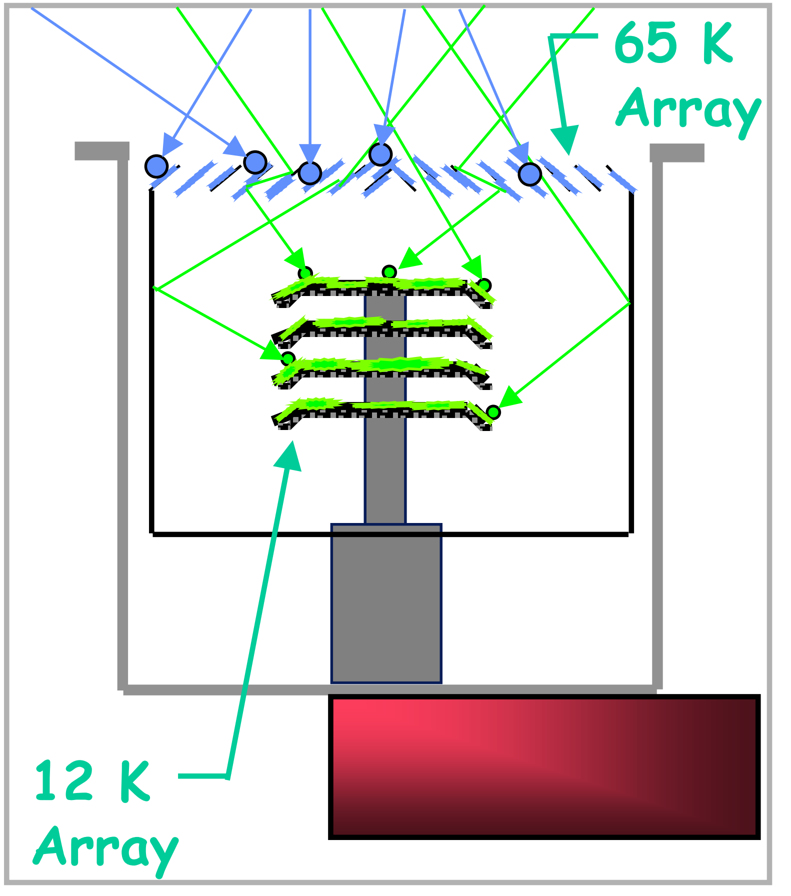
Cyropump Operation - *Cryoadsorption*

- Affixing activated charcoal sieve material to the underside of the 12 K second stage arrays, allows H_2, He, and Ne to be cryoadsorbed.



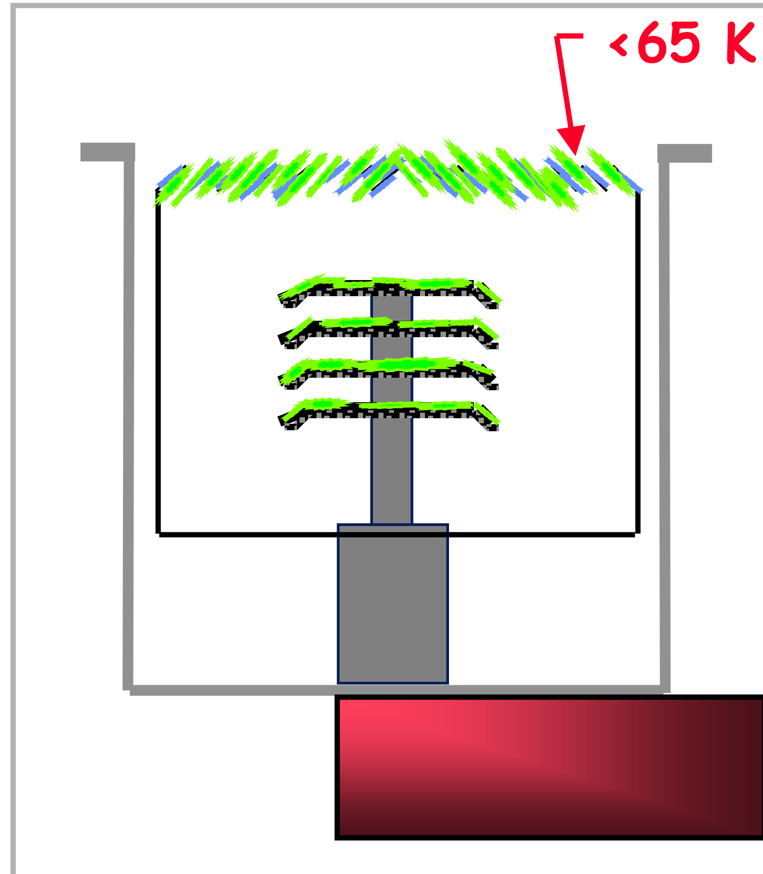
Cyropump Operation – *Argon Hang-Up*

During normal operation, water vapor is condensed on the 65 K first stage array while oxygen, nitrogen, and argon are condensed on the 12 K second stage array.



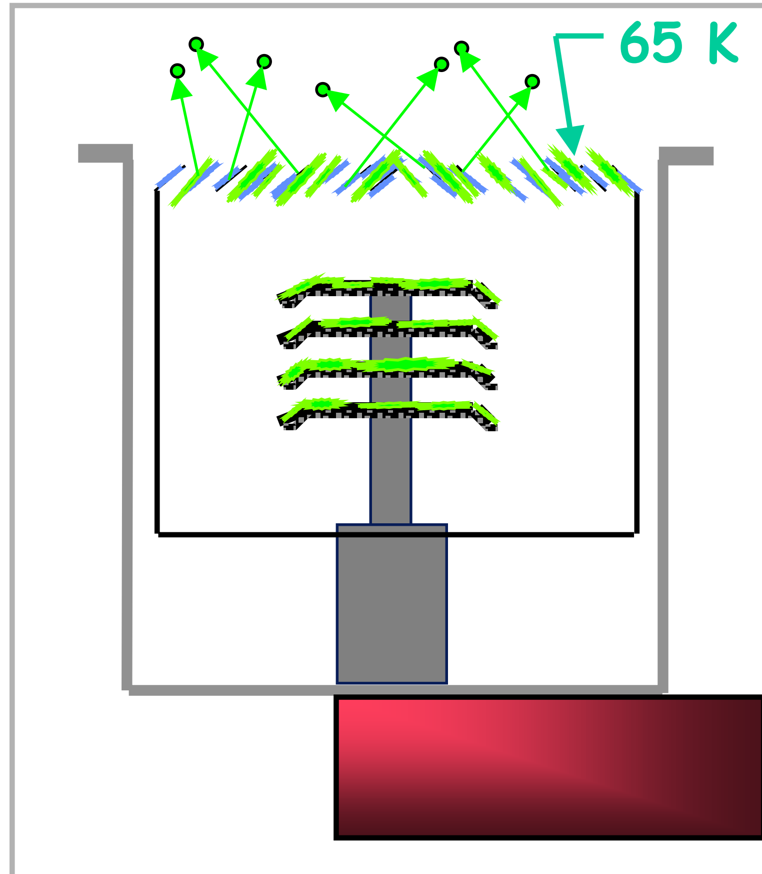
Cyropump Operation – *Argon Hang-Up*

- Argon Hang-Up can occur if the first stage gets too cold.
- Results in argon being condensed (pumped) on the first stage.
- Where it stays until lower partial pressures are reached.



Cyropump Operation – *Argon Hang-Up*

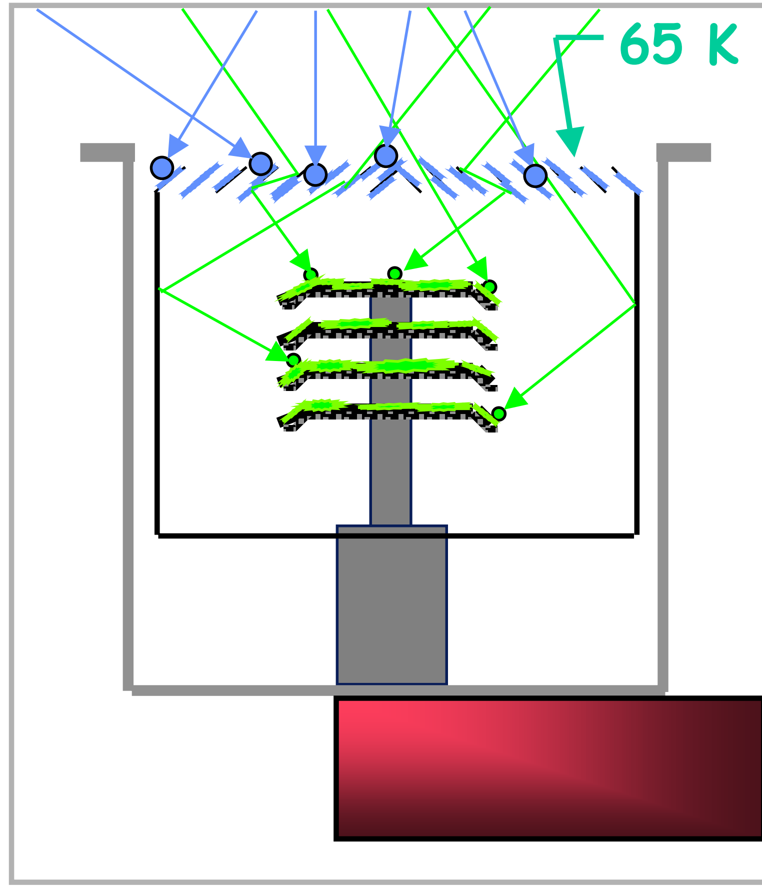
- When the equilibrium pressure is reached.
  - Argon liberates
  - Pumpdown slows
  - Causes "False Full" condition



EQUILIBRIUM VAPOR PRESSURE	10^{-10}	10^{-7}	10^{-4}	10^{-3}
Water	130K	153K	185K	198.5K
Argon	23.7K	28.6K	35.9K	39.2K

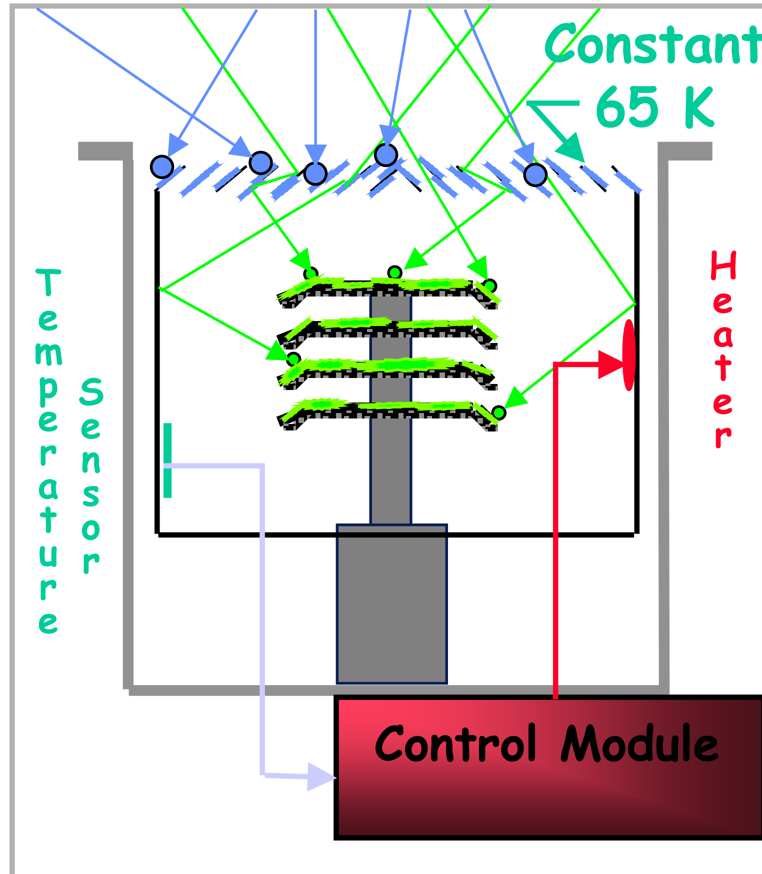
Cyropump Operation – *Argon Hang-Up*

- Argon liberates until it is repumped onto the second stage where it should have been pumped.



Cyropump Operation – *Argon Hang-Up*

- Argon Hang-Up can be avoided with modern controllers interfaced to the first stage sensor and heater.
  - Monitors and controls temperature
  - Prevents a "Too Cold" condition



Cyropump Design . . . *Capacities*

Typical Capacity - *8" Cryopump*

Gas Collected = Pressure x Speed x Time

Gas	Capacity (at STP)
Water Vapor	1000 liters (gas)
	1 liter (ice)
Nitrogen & Argon	1000 liters (gas)
	1 liter (ice)
Hydrogen	17 liters (gas)

Cyropump Operation . . . *Crossover*

During chamber evacuation,when should the high-vacuum valve be opened?

For cryopumps, the maximum crossover capability is specified as the impulsive mass input that causes the second stage to rise no higher than 20 K.

Cyropump Operation . . . *Crossover*

Example: Crossover Pressure Calculation

Crossover value for a CTI On-Board 8 = 150 Torr-liters

Crossover formula: $\frac{\text{Crossover value}}{\text{Chamber volume}}$ = P in Torr

$\frac{\text{150 Torr-liters}}{\text{300 liters}}$ = .5 Torr or 500 milliTorr

Understanding crossover can produce faster pumpdown times and cleaner vacuum too.

Cyropump Operation . . . *Regeneration*

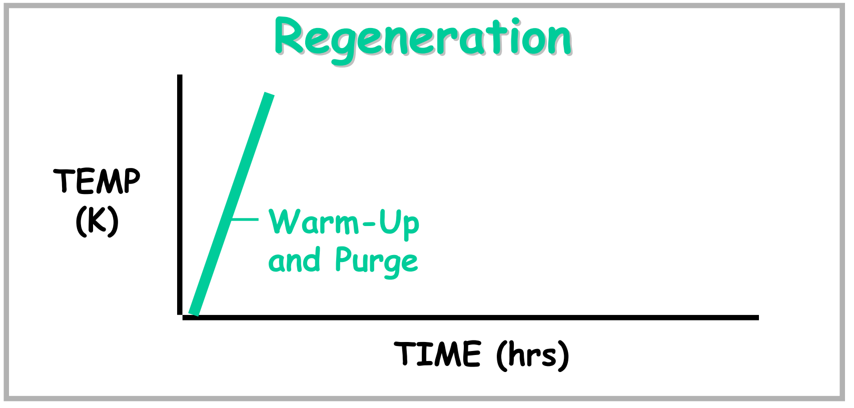
The objective of regenerating a cryopump is to remove the captured gases from the pump and restore its pumping capacity.

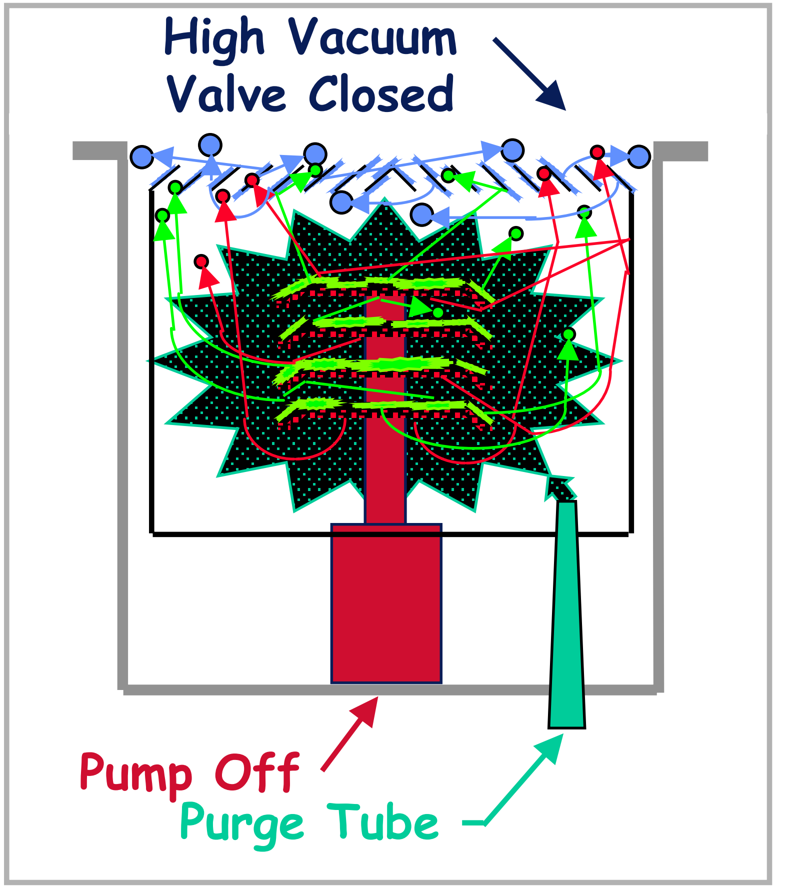
So . .. when should cryopumps be regenerated?

Whenever your system is down is a good opportunity to regenerate your cryopump without affecting your up-time.

Cyropump Operation . . . *Regeneration*

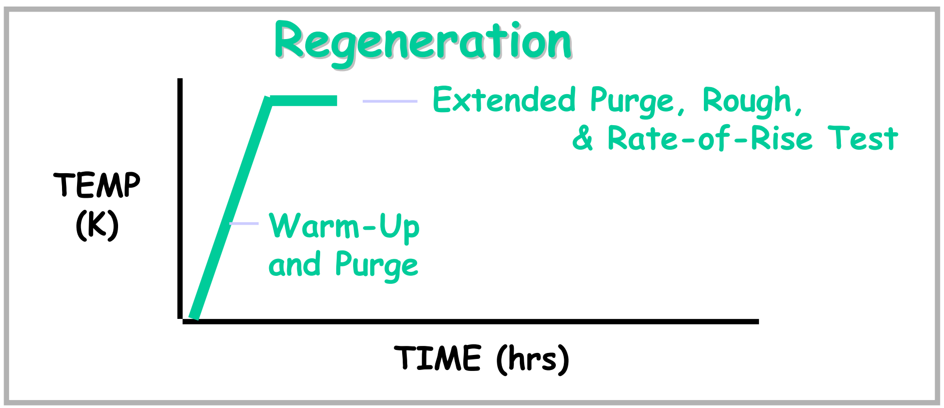
- Regeneration
  - Warm-Up and Purge

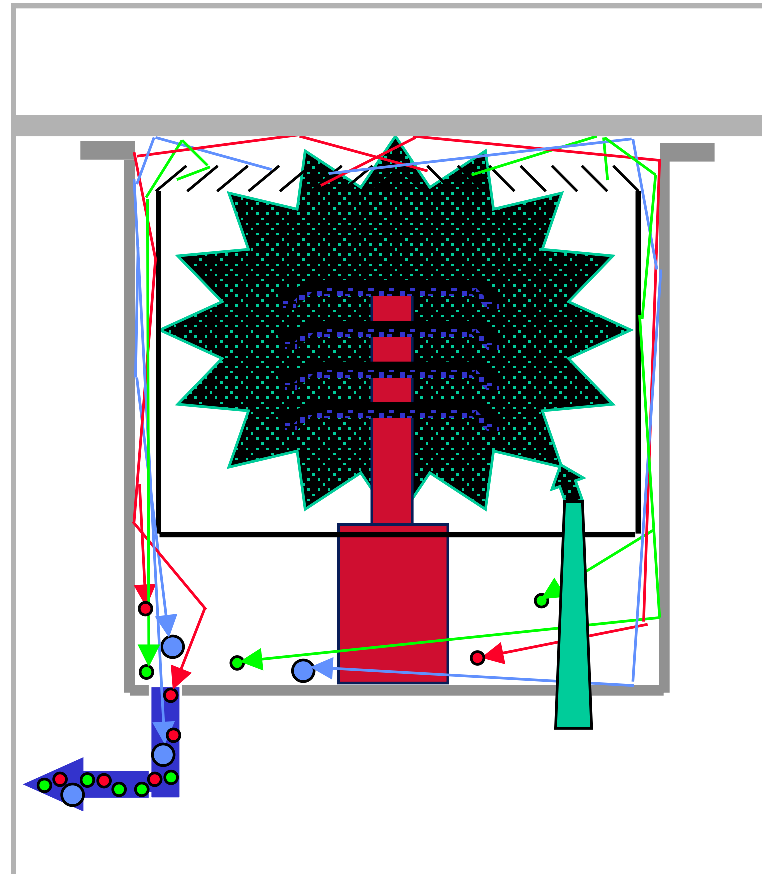




Cyropump Operation . . . *Regeneration*

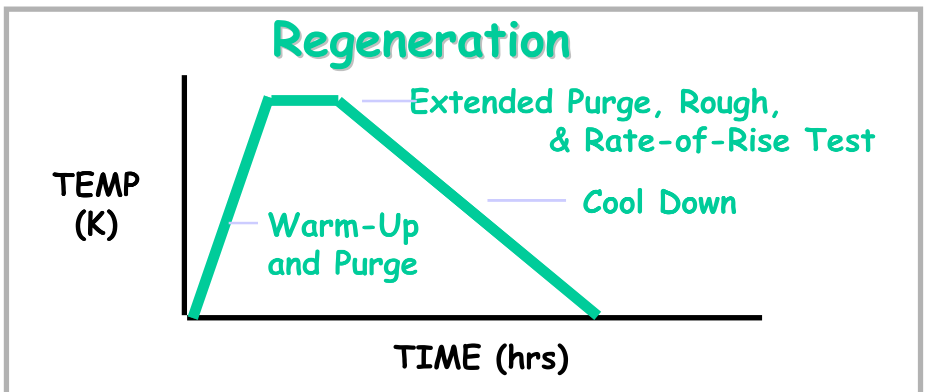
- Regeneration
  - Warm-Up and Purge
  - Extended Purge
  - Rough Out
  - Rate-of-Rise (ROR) Test

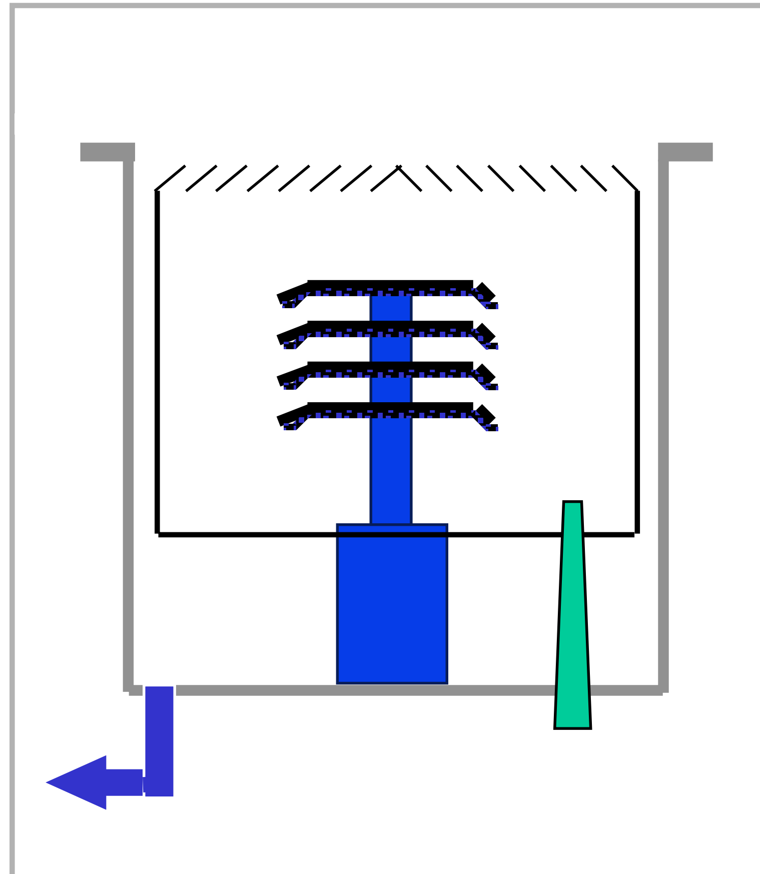




Cyropump Operation . . . *Regeneration*

- **Regeneration**
  - Warm-Up and Purge
  - Extended Purge
  - Rough Out
  - Rate-of-Rise (ROR) Test
  - Cool Down

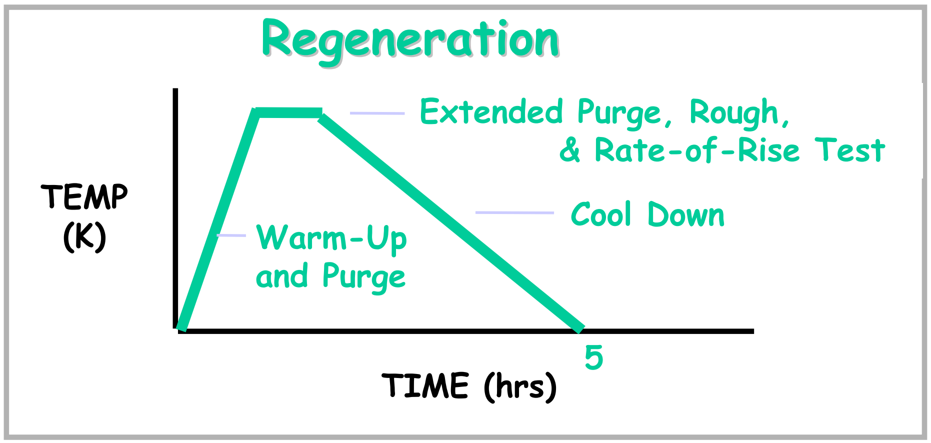


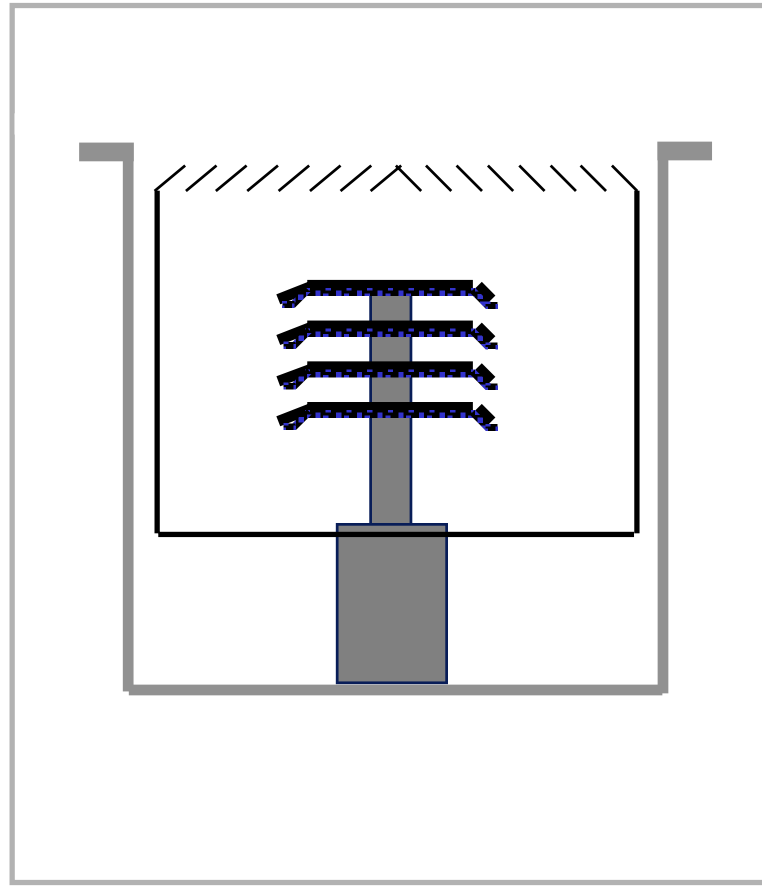


Cyropump Operation . . . *Regeneration*

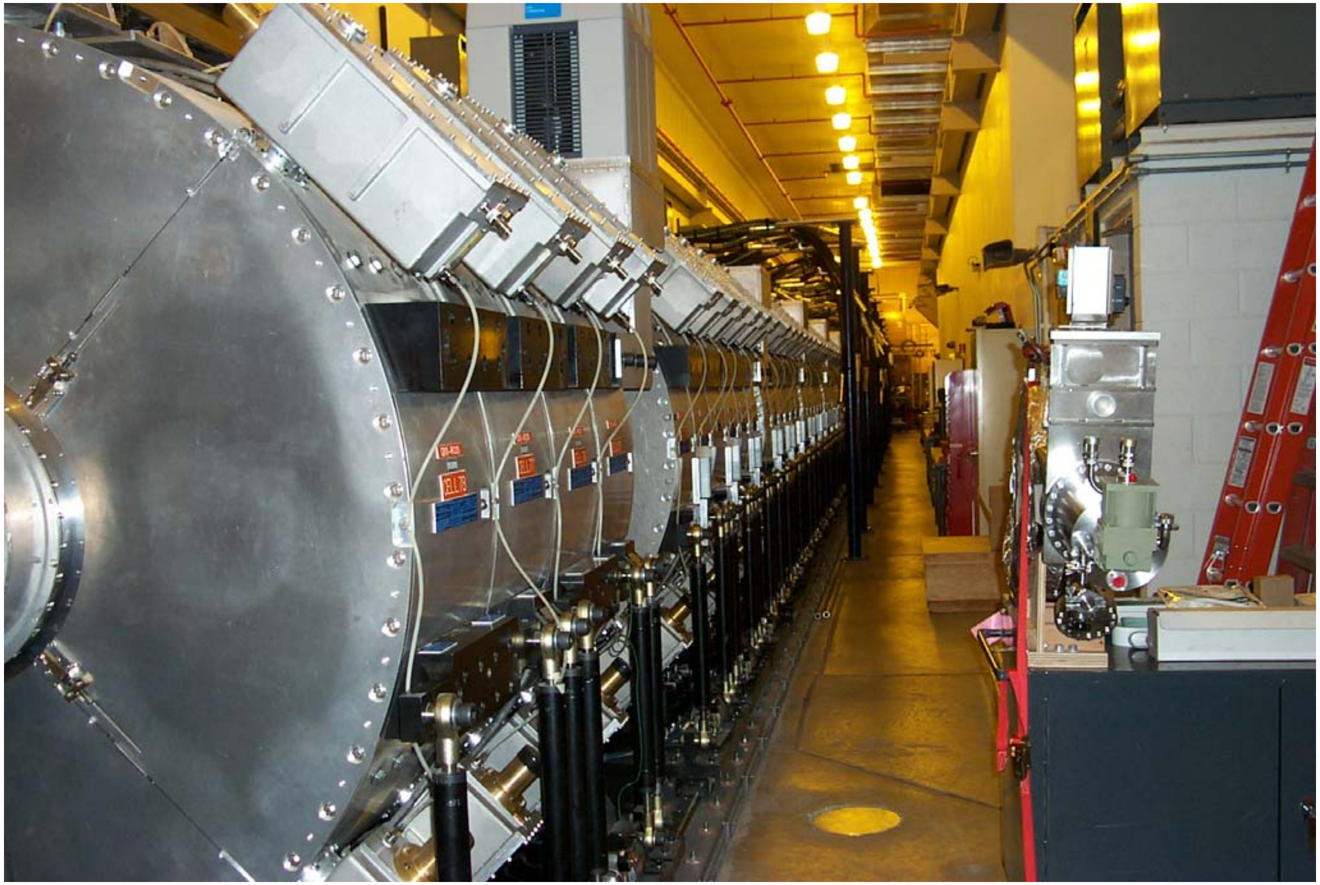
- Regeneration

Typically 5-6 hours cold-to-cold.



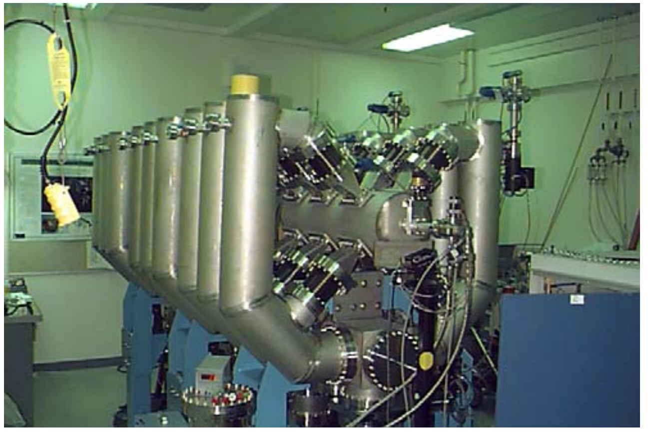


Example of Cryopumped Accelerator – DARHT II



Example of Cryopumped Accelerator – APT RFQ

- Cryogenic Pumping System for Cavity system, with H_2 Pumping Speed of 12,000 L/s
- This assembly was completed and successfully tested at LLNL Vacuum Lab. The whole system was then delivered and installed at the APT/LEDA facility.



Helium Compressors

- Helium Compressors provide a continuous source of clean high pressure helium to the cryopump cold head.

- Helium Compressors also provide conditioned electrical power to the cold head.

- A compressor consists of four main systems:
  - Pump
  - Cooling
  - Oil injection / separation
  - Cold head power

Helium Compressor Pumps

The pump is the "Heart" of the compressor. Compressors utilize two different types of positive displacement pumps:

- Rotary Pumps
- Piston Pumps

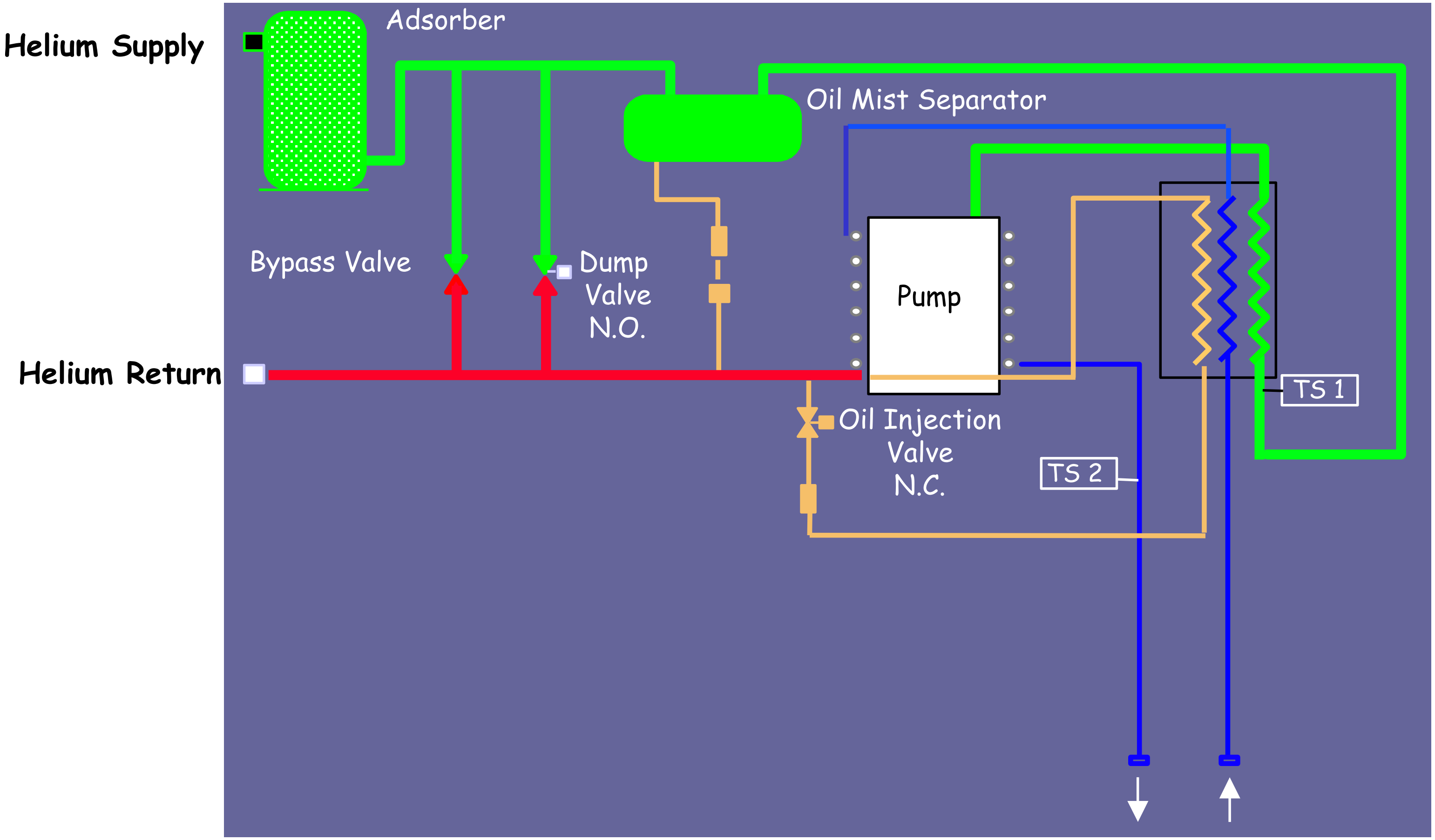
Helium Compressor Cooling System

Compressors use either water or air to cool the helium and the oil within the compressor. Cooling is critical to insure proper compressor operation. Without proper cooling:

- The compressor will overheat and shut off.
- The oil separation system will not operate and oil-contamination can reach the cold head.
- The helium will become overheated and the cold head will warm up.

Cooling is typically achieved by the use of counterflow heat exchangers.

A typical Helium Compressor Schematic



Helium Compressor Oil System

- The compression of helium generates heat within the compressor pump.
- Oil must be injected during compression to cool the pump and helium.
- The helium-oil mixture is cooled at the heat exchanger.
- The oil must be separated from the helium before the gas is pumped back to the cryopump(s). The oil will then be recirculated within the compressor.

Helium Compressor Oil System

The oil system consists of FOUR main elements:

- The Oil Heat Exchanger
- The Bulk Oil Separator
- The Oil Mist Separator
- The Adsorber

Helium Compressor Oil System:
Bulk Oil Separation

In compressors with rotary pumps, the pump acts as a bulk (oil stream) separator by slowing down the velocity of the helium and oil mixture. The oil stream then "rains" directly into the oil sump.

In compressors with piston pumps, a separate bulk separator is used and the oil is then returned to the pump.

Helium Compressor Oil System:
Oil Mist Separator

The oil mist (aerosol) separator utilizes very fine fibers to coalesce oil vapor into droplets and thus "clean" the helium gas. Oil from this separator is re-injected into the pump.

Helium Compressor Oil System: Adsorber

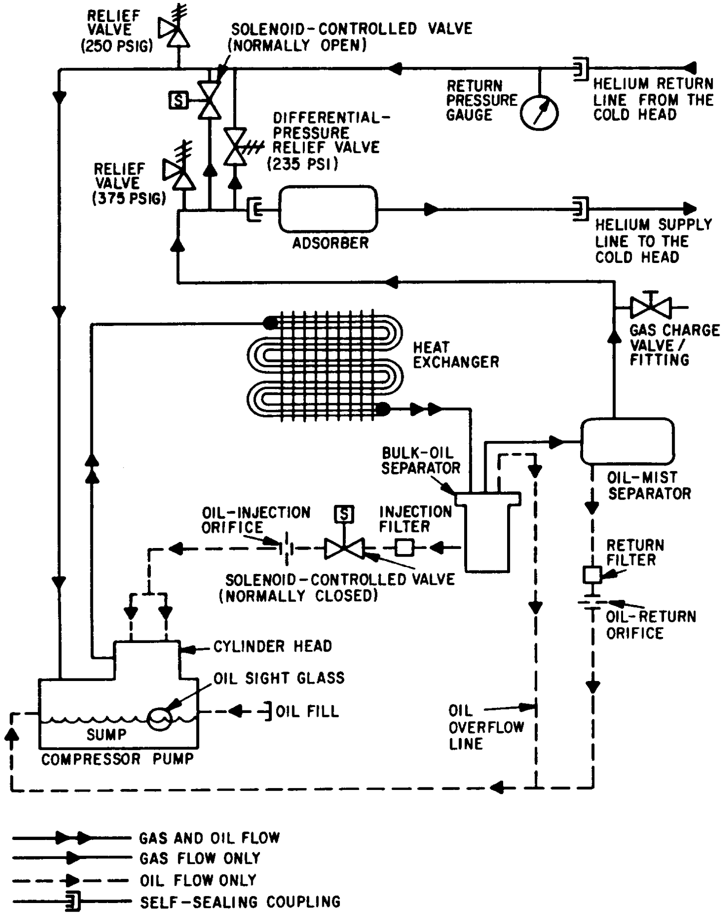
The adsorber contains activated charcoal to filter out the remaining oil in the helium by adsorption. As the adsorber gets filled up with oil and other contaminants it needs to be replaced (typically once a year).

Helium Compressor Operating Temperature

Most Compressors can operate in ambient temperatures from 50-100 ^{o}F.

Note: Starting a compressor that is colder than 50 ^{o}F can cause start up problems.

CTI-CRYOGENICS
Helium Compressor Schematic



Typical Operating Parameters for CTI-CRYOGENICS Compressor Chart

Compressor Type	Static Charge	Operating Pressure	Running Current
SC	250 psig	275 psig	8 amps @ 208 V
8200	250 psig	275 psig	8 amps @ 208 V
1020R	185 psig	275/80 psig*	14.5 amps @ 208 V

The thermal switch on these compressors trips the main circuit breaker.

Compressor Type	Static Charge	Operating Pressure	Running Current
8300	250 psig	95 psig	8 amps @ 208 V
8500/8510	200 psig	60-90 psig*	14.5 amps @ 208 V
9600	250 psig	110 psig	15 amps @ 208 V

When running multiple cryopumps with these compressor, the return pressure will be about 110 psig.

Ref ©2000 Helix Technology Corporation

The US Particle Accelerator School
Pressure Measuring Devices

Lou Bertolini

Lawrence Livermore National Laboratory

January 19-24, 2004

Vacuum Measurement Considerations

- Large measurement range: 760 - 10^{-13} Torr (16 orders of magnitude)
- Some gauges do not measure pressure directly
- Some gauges are gas species dependent
- Measured environment is usually a dynamic one
- Placement of gauge will influence it's response

Vacuum Measurement

- Total pressure gauges
  - *Direct measurement*
    - Liquid column level
    - Solid wall movement
  - *Indirect measurement*
    - Thermal conductivity
    - Viscosity
    - Ionization
- Partial pressure gauges
  - *Indirect* only: ionization & mass filtering

Vacuum Pressure Gauges

The pressure range measured in most vacuum systems is too broad to be measured with a single gauge!

1×10^{-10} Torr Base Vacuum Pressure	⟷	760 Torr Atmospheric Pressure

1 unit is ~11,000,000,000 [11 billion] times the other!

10 meters The dimension of a room.	⟷	10^9 km Distance between Earth and Saturn

It is not practical to measure both with the same device.

Units of Pressure Often Used in Vacuum Technology

Atmospheric Pressure (Standard) =	
760	Torr
760	mm of mercury (Hg)
29.9	inches of Hg
14.7	lbs. per square inch – abs. (psia)
0	psig (psi at gauge)
760,000	Millitorr or "microns" of Hg
101,000	Pascal (Newton/m^2)
1.01	Bar
1010	Millibar

Types of Vacuum Gauges

Direct Gauges (Displacement of a wall)

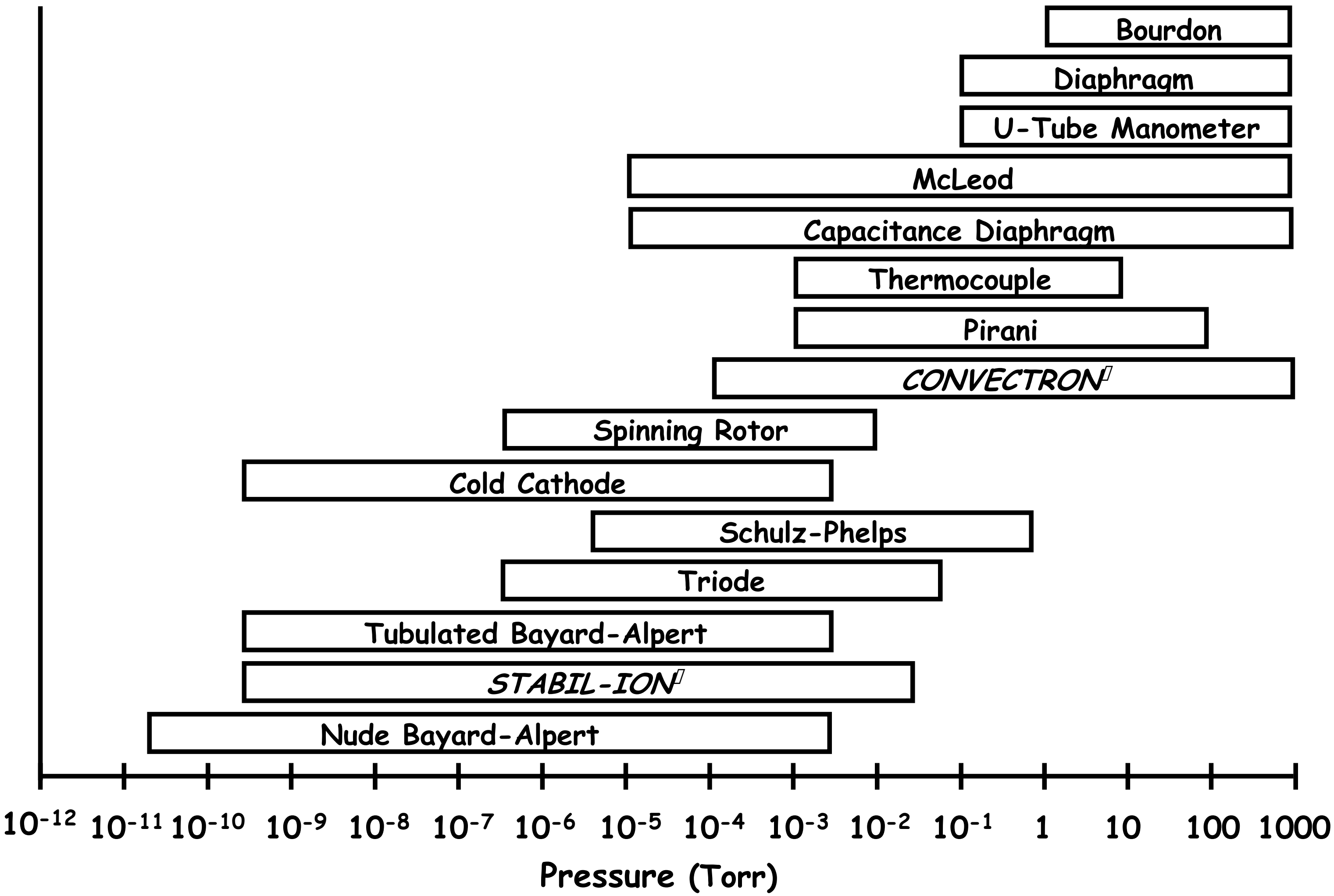
- **Solid Wall**
  - Diaphragm
  - Bourdon Type
  - Capacitance Diaphragm
- **Liquid Wall**
  - McLeod
  - U-Tube Manometer

Types of Vacuum Gauges

Indirect Gauges
(Measurement of a gas property)

- **Charge Generation (Ionization)**
  - **Cold Cathode**
    - Penning
    - Inverted Magnetron
  - **Hot Cathode**
    - Triode
    - Schulz-Phelps
    - Bayard-Alpert
    - *STABIL-ION*
- **Energy Transfer (Heat Loss)**
  - Thermocouple
  - Pirani
  - *CONVECTRON*
- **Momentum Transfer (Viscosity)**
  - Spinning Rotor

Range of Vacuum Gauges



Gauge Summary

Gauge	Measurement Mechanism	Operating range (Torr)	Accuracy
Bourdon tube/ diaphragm	solid wall movement	1000s-1	low
Capacitance manometer	solid wall movement	$10{,}000-10^{-6}$	high
Thermocouple	thermal conductivity	$1-10^{-3}$	medium
Pirani	thermal conductivity	$1-10^{-4}$	medium
Bayard-Alpert	ionization	$10^{-2}-10^{-11}$	medium
Penning	ionization	$10^{-2}-10^{-6}$	medium
Inverted magnetron	ionization	$10^{-3}-10^{-12}$	medium
Spinning rotor	momentum transfer	$760-10^{-7}$	high

Gauges Used on Commercial Vacuum Systems

Medium and Low Vacuum: 10^{-3} Torr to 1000 Torr

- Direct Gauges - Displacement of a Solid Wall
  - Capacitance Diaphragm Gauge
- Indirect Gauges - Heat-Loss Gauges
  - Thermocouple Gauge
  - Pirani Gauge
  - *CONVECTRON* Gauge (Convection-Enhanced Pirani)

Ultra-High and High Vacuum: 10^{-11} Torr to 10^{-3} Torr

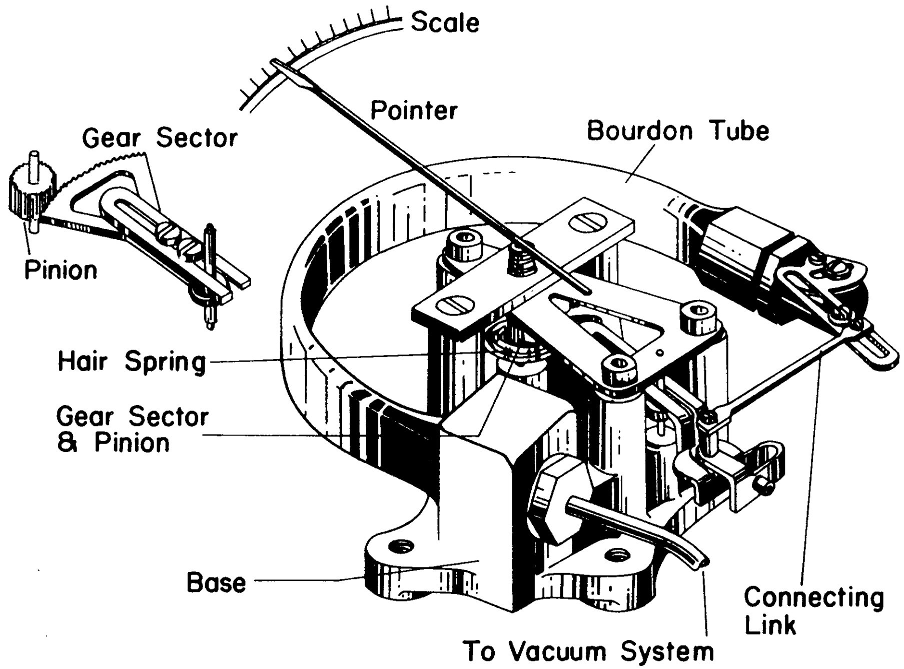
- Indirect Gauges - Ionization Gauges
  - Hot Cathode Gauge
  - Cold Cathode Gauge

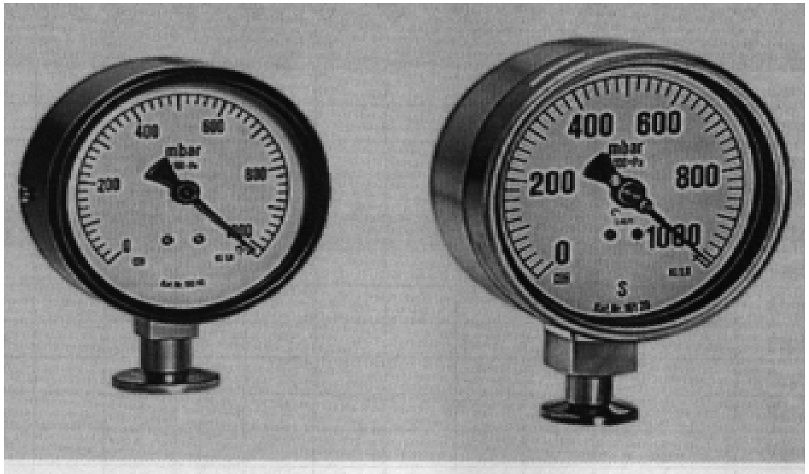
Bourdon Tube & Diaphragm Gauges

Distinguishing features & operating characteristics:

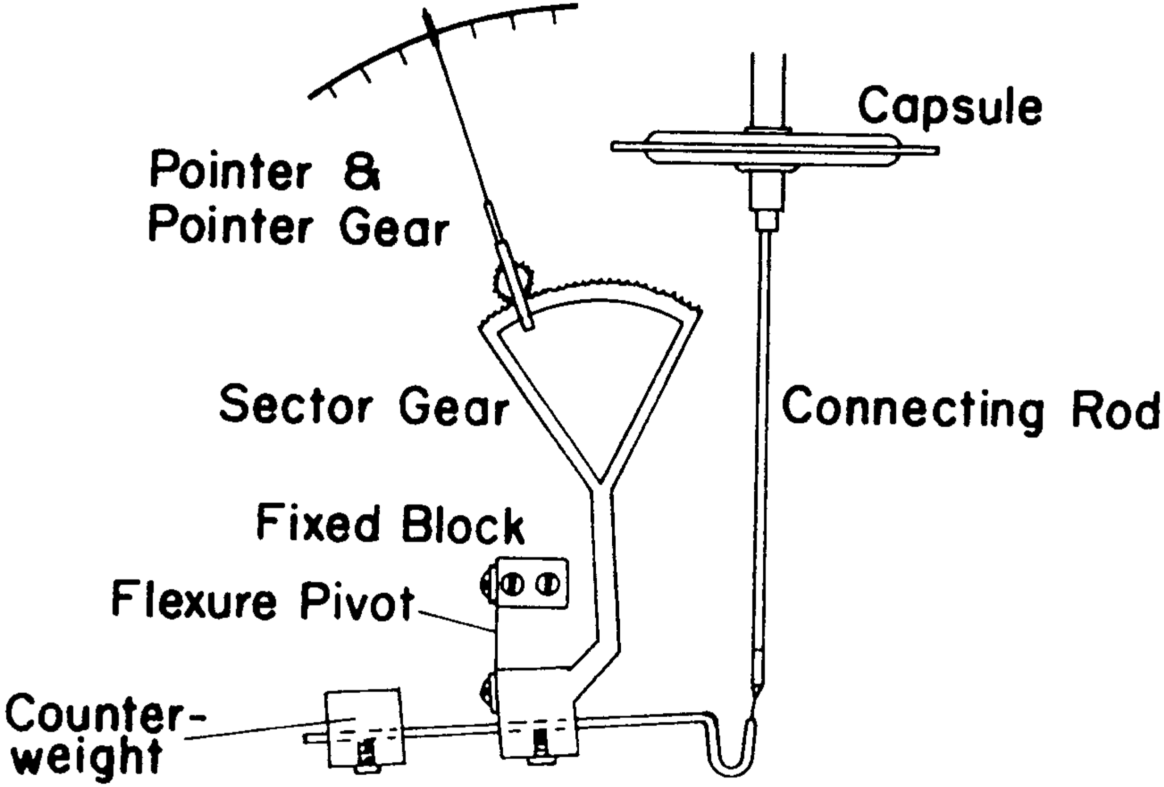
- Measures pressure directly
- Operating range above atm pressure to 1 Torr
- Indicated value is independent of gas specie being measured
- System of gears & levers transmit the movement of a small tube or wall to a pointer
- Can be constructed such that all parts exposed to vacuum are stainless steel
- Optionally configured as a compound gauge
- Bourdon tube often used as an indicator of system status
- For safety reasons: Bourdon tube recommended for most systems

Bourdon Tube Gauge Components



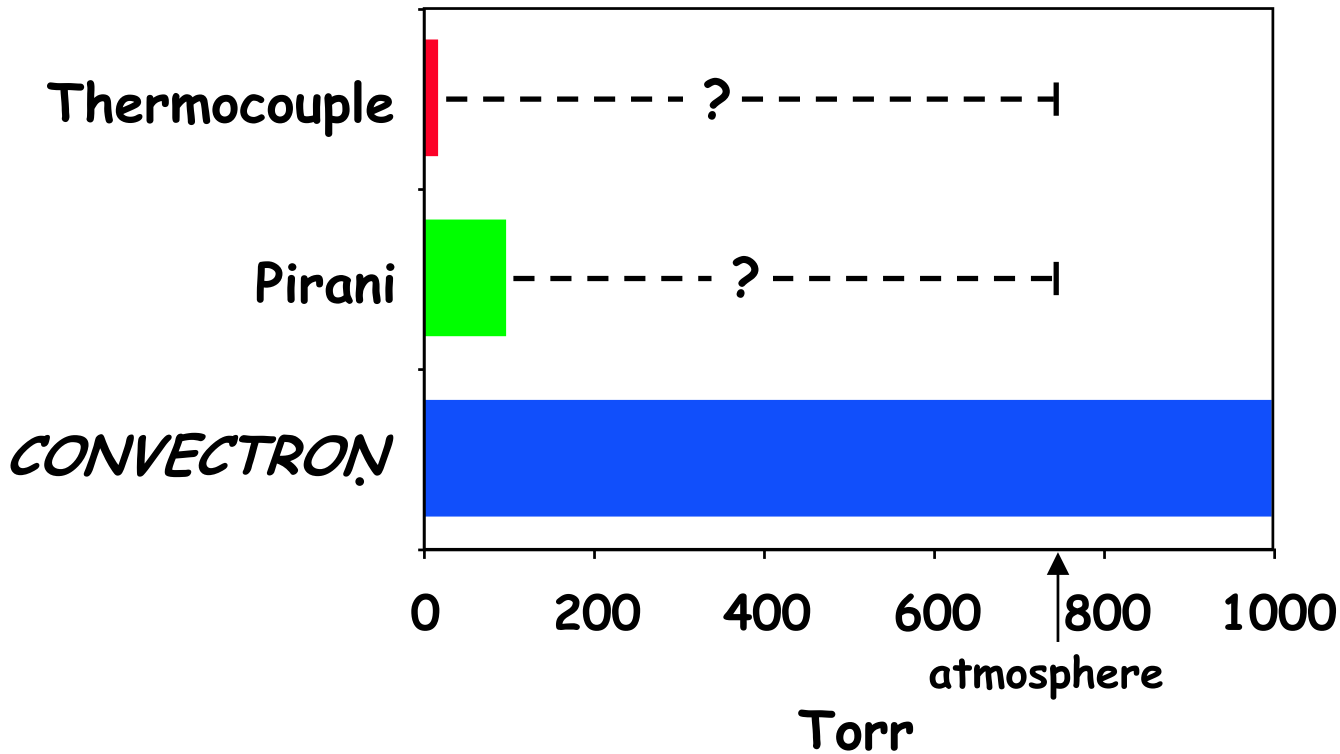


Diaphragm Gauge Components



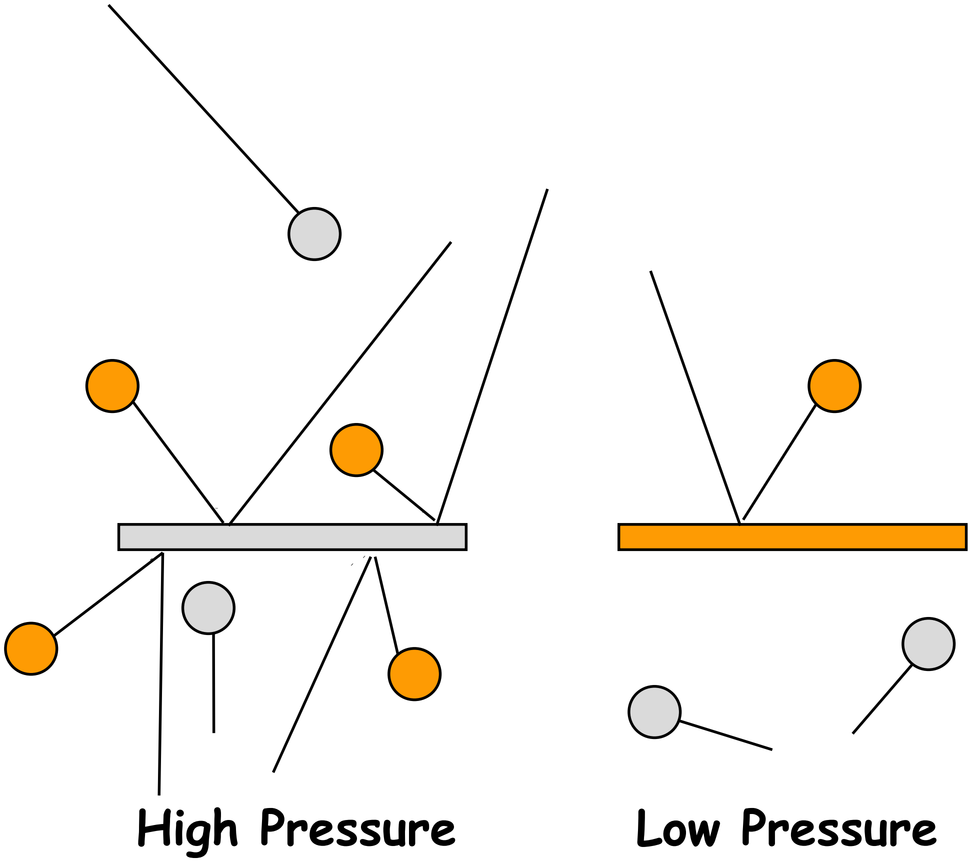
Operating Ranges for Heat-Loss Gauges

Pressure Range Comparison of Heat-Loss Sensors



Heat-Loss or Energy Transfer

- Heated element cools as molecules strike
- Higher pressure means increased cooling of sensor
- Gas species dependent



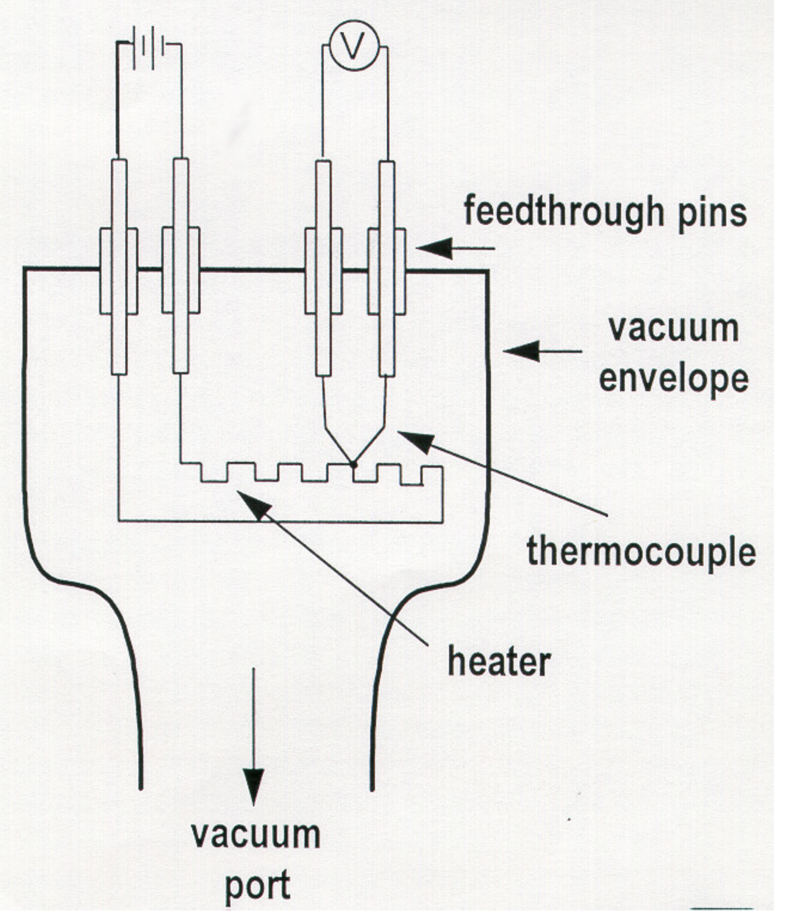
Thermocouple gauge

Distinguishing features & operating characteristics:

- Indirectly measures pressure via thermal conductivity of gases
- Operating range 1 Torr to 10^{-3} Torr
- Indicated value is gas dependent
- Constant current is delivered to a wire & it's temperature is measured by a thermocouple
- Thermocouple voltage is read on a pressure scale
- Not capable of good measurements above 1 Torr
- Rugged design, inexpensive, however somewhat inaccurate

Thermocouple Gauges

- Constant current through the heater (sensor).
- TC junction measures temperature changes.
- Slow response time.



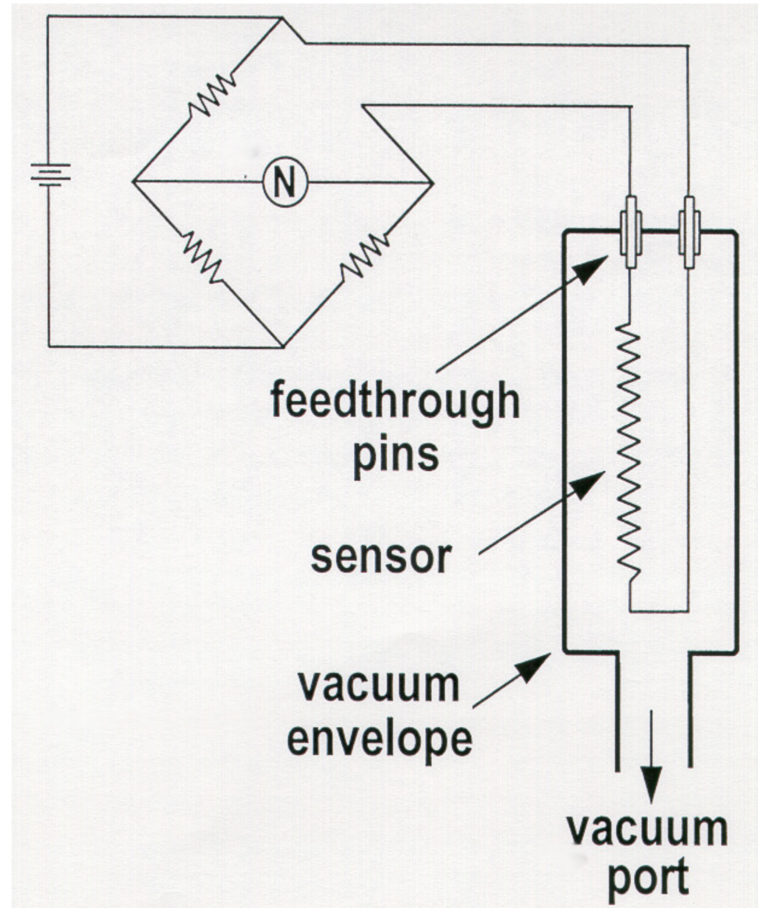
Pirani Gauges

Distinguishing features & operating characteristics:

- Indirectly measures pressure via thermal conductivity of gases
- Operating range 100 to 10^{-4} Torr
- Indicated value is gas dependent
- Resistance heated wire which is part of a Wheatstone bridge
- Pirani gauge that is sensitive to convection heat losses is available

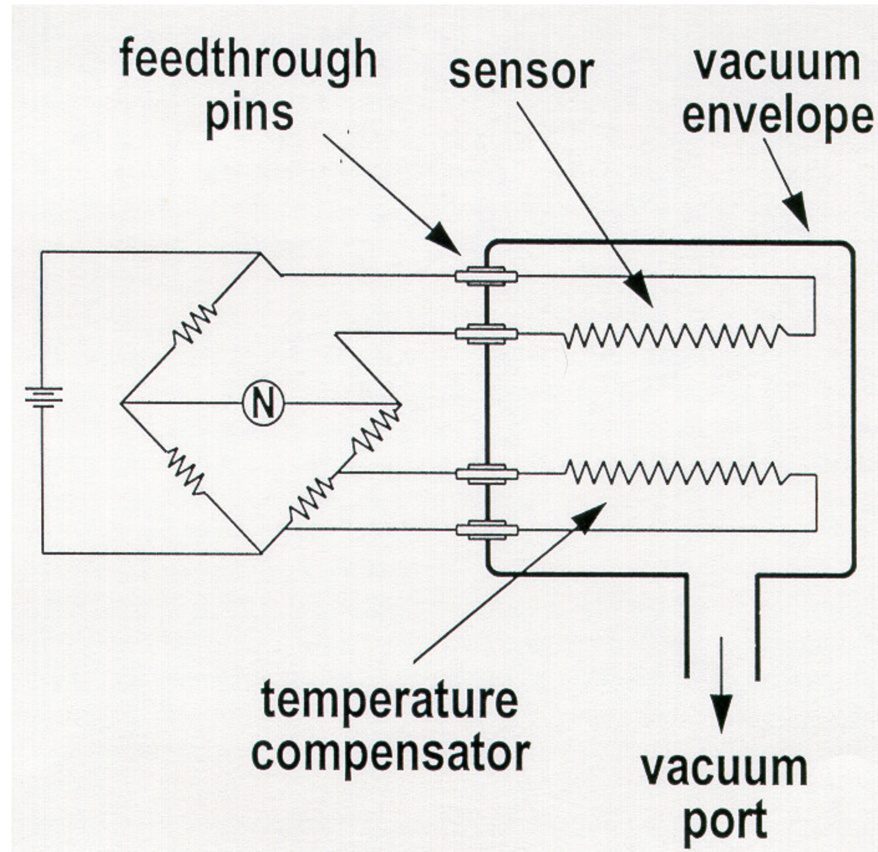
Pirani Gauge

- Wheatstone bridge with sensor as one leg of bridge.
- Current through sensor changes to maintain balance.
- Reads to ~100 Torr.



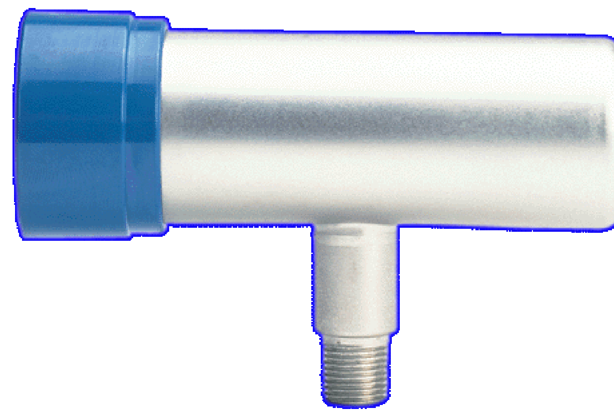
Convection Enhanced Pirani Gauge – *CONVECTRON*® Gauge

- Similar principle to pirani.
  - Conductive heat loss (10^{-3} Torr to ~100 Torr)
  - Adds convective heat loss (~100 Torr to 1000 Torr.)
- Improved temperature compensation.
- Gold plated tungsten sensor.



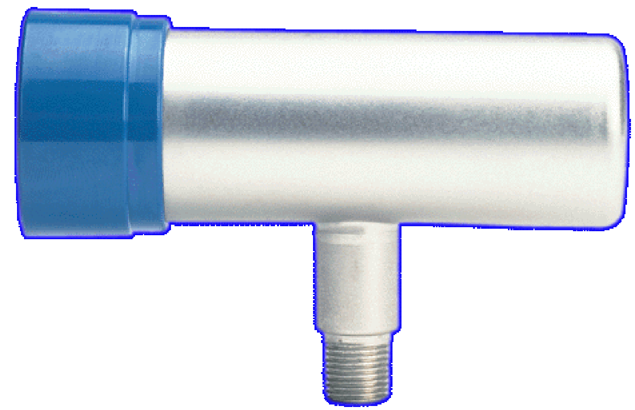
CONVECTRON ® Gauge Benefits

- Wide Measurement Range:
  10^{-3} Torr - 1000 Torr.
- Individual calibration.
- Accurate, fast measurement.
- Long term stability.
- Recalibrate for contaminated gauge or
- after cleaning gauge.
- Very reliable - industry standard.



CONVECTRON ® Gauges - Drawbacks

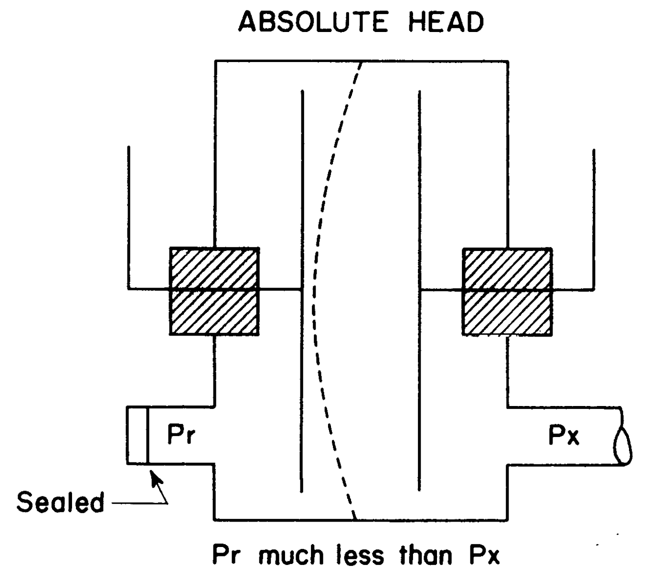
- Gas dependent
- Sensitive to orientation
- S-curve, analog output
- Fragile
- Corrosive gases - attacked by fluorine, chlorine, mercury



Capacitance Manometers

Distinguishing features & operating characteristics:

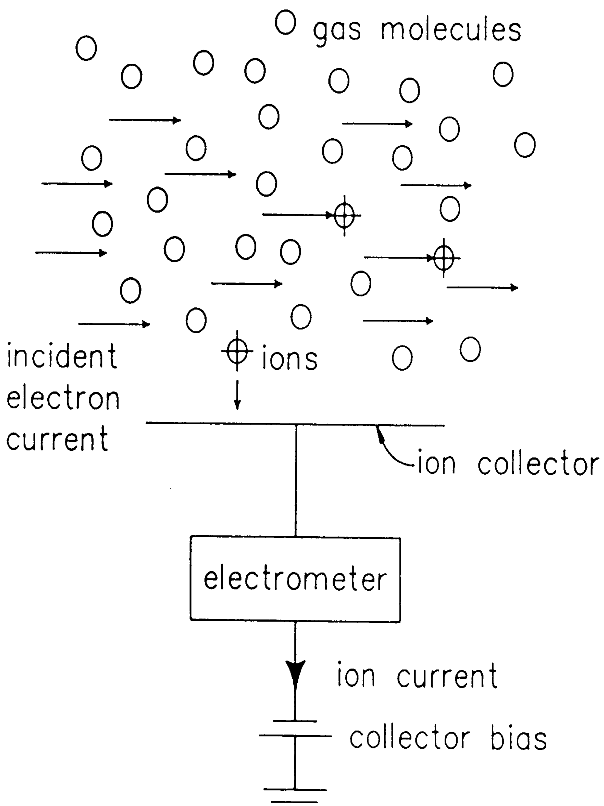
- Measures pressure directly
- Operating range 10,000 to 10^{-6} Torr, with different ranged sensors
- Indicated value is independent of gas being measured
- Diaphragm gauge that senses the change in capacitance of a circuit which contains the diaphragm wall as an active element
- Deflections of the diaphragm as small as one Å can be sensed
- Available in several ranges with differing resolution
- Measurements requiring a high degree of accuracy use heated sensors
- High precision work requires frequent "zeroing"



Ionization Gauges

- At pressures below 10^{-5} Torr (high vacuum) direct measurement of pressure is very difficult
- Thermal conductivity gauges have exceeded their operational limits
- Primary method for pressure measurement from 10^{-4} to 10^{-12} Torr is gas ionization & ion collection/measurement
- These gauges can be divided into hot & cold cathode types
- Most common high vacuum gauge today is the Bayard-Alpert

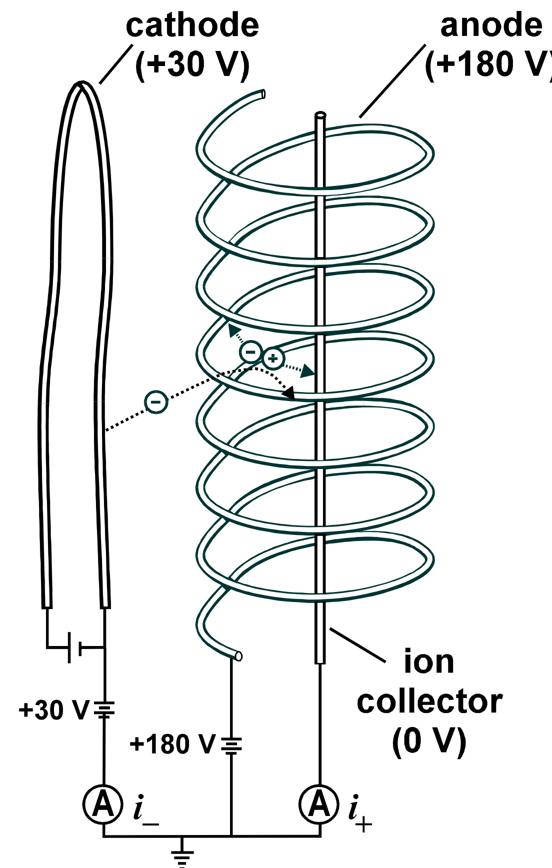
Ionization Gauge Principle of Operation



- Gas atoms and molecules are normally without charge or "neutral", they have equal numbers of protons and electrons
- If one or more electrons are removed from an atom it becomes positively charged and we call it an ion
- Numerous processes in vacuum technology utilize energetic free electrons to strip atoms of some of their electrons, thus creating ions
- Ions, being positively charged, can be manipulated by magnetic and electrical fields
- An atom has a probability of being ionized that is dependent on the atom itself and the energy of the colliding electron. The ionization cross section quantifies the probability of ionization

Hot Cathode Ionization Gauge, Basics

- Hot filament (cathode) emits electrons.
- Molecules are ionized and collected.
- Pressure reading is determined by the electronics from the collector current.



Gauge Sensitivity

Gauge Sensitivity: A constant that indicates how well a gauge creates ions.

- Ion gauge equation:

$$P = \frac{i_+}{i_e \cdot S}$$

where:
i_+ = ion current
i_e = emission current
S = sensitivity

- Sensitivities of B-A Gauges
  - Glass Gauge and Standard Nude Gauge ~10/Torr
  - UHV Nude Gauge ~25/Torr

Emission Current

- Emission current = Electron Current ≈ No. of electrons

- A variable controlled by the electronics

$$P = \frac{i_+}{i_e \cdot S}$$

Typical Gauge Sensitivities

Gas	Sensitivity
Ar	1.2
CO	1.0-1.1
H_2	0.40-0.55
He	0.16
H_2O	0.9-1.0
N_2	1.0
Ne	0.25
O_2	0.8-0.9
Organic Solvents	>>1

What Emission Current Should Be Used?

- Selected, based on measurement range

- Typical emission settings for B-A gauges:
  - High pressure: i_e = 0.1 mA
  - Widest pressure range: i_e = 1 mA (default)
  - UHV range: i_e = 10 mA

- Typical problems:
  - High emission + high pressure = gauge off
  - Low emission + low pressure = "nervous" display

X-Ray Limit

- Lower limit of the gauge
- Low accuracy readings near the x-ray limit
- Select gauge with x-ray limit 5 to 10 times lower than lowest pressure
- Only an issue for UHV measurement at $P < 1 \times 10^{-9}$ Torr

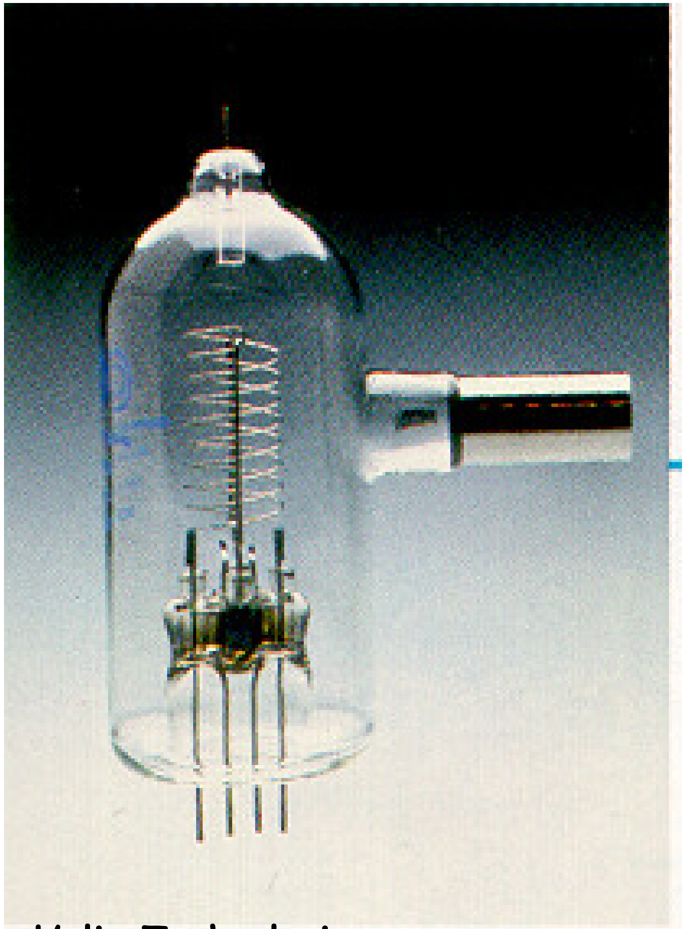
Filament Selection

- Thoria-coated Iridium
  General purpose
  Operates cooler (~900° C)
  Burn-out resistant

- Tungsten
  Special purpose
  Operates hotter (~1200° C)
  Burns out easily and oxidizes when exposed to atmosphere

Granville-Phillips Series 274: Glass B-A Gauge

- Filaments: single thoria-coated
- iridium, or dual tungsten
- Sensitivity: 10/Torr.
- Helical grid: EB or I^2R degas.
- X-ray limit: < 3 x 10^{-10} Torr
- Port diameter: 3/4 in. or 1 in.
- Vacuum connections: straight tube,
  NW25, 1.33 in. ConFlat-type (16CF),
  2.75 in. ConFlat-type (35CF)



Ref. Helix Technologies

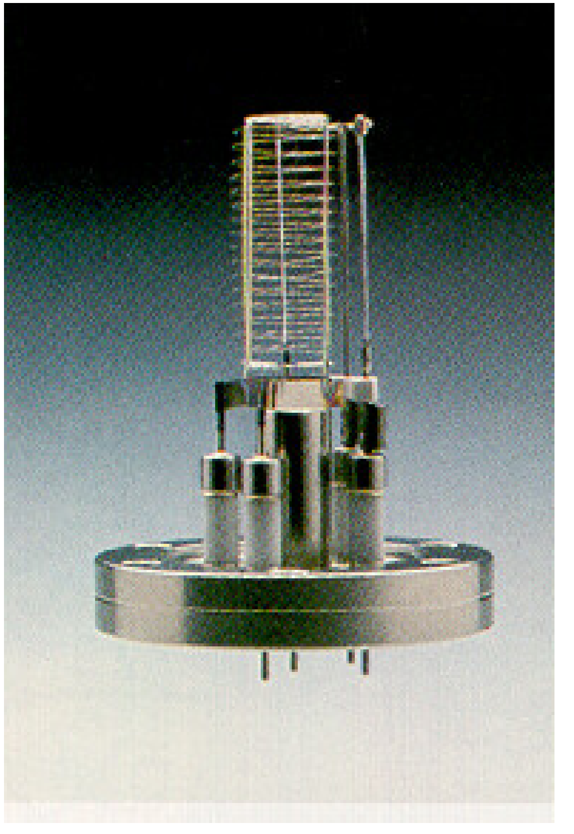
Granville-Phillips Series 274: Nude B-A Gauge

- Filaments: single thoria-coated iridium, replaceable
- Sensitivity: 10/Torr
- Helical grid: EB or resistive degas
- X-ray limit: about 4×10^{-10} Torr
- Flanges: NW40, 2.75 in. ConFlat-type (35CF)
- Available with pin-guard

Ref. Helix Technologies

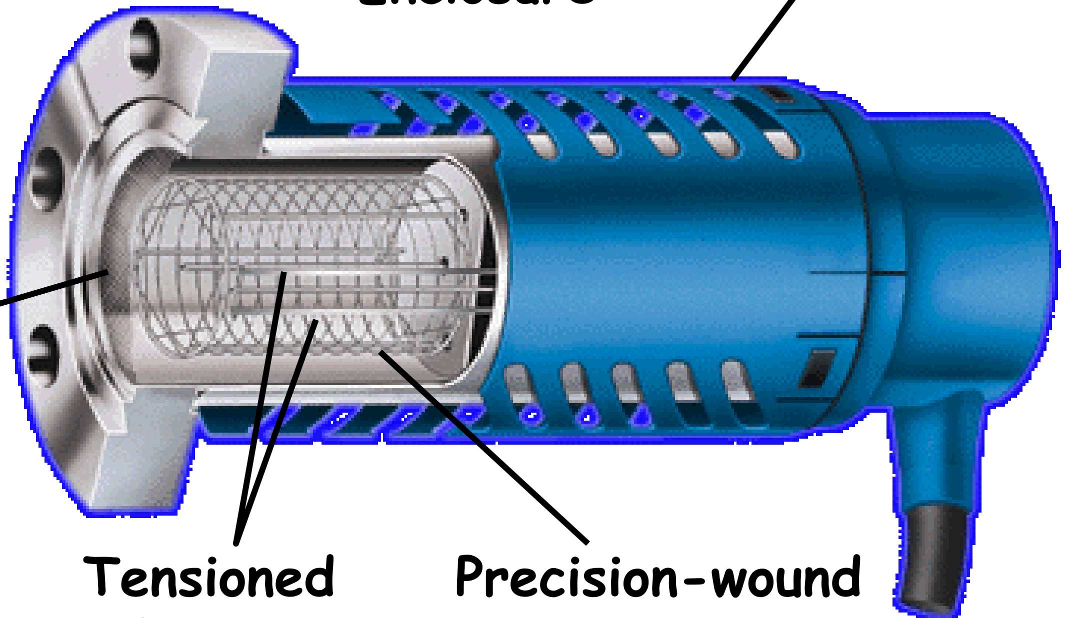
Granville-Phillips Series 274:
UHV Nude B-A Gauge

- Filaments: dual thoria-coated iridium, or dual tungsten, replaceable.
- Sensitivity: 25/Torr.
- Enclosed grid: EB degas only
- X-ray limit: about 2 x 10^{-11} Torr
- Flanges: NW40, 2.75 in. ConFlat-type (35CF)
- Available with pin-guard



Ref. Helix Technologies

STABIL-ION® Gauge Design



Ref. Helix Technologies

STABIL-ION ® Gauge Types

- Extended Range Gauge
  - 1×10^{-9} to 2×10^{-2} Torr
  - x ray limit: < 2×10^{-10} Torr
  - Highest accuracy & stability
  - Sensitivity: 50/Torr
- UHV Gauge
  - 10^{-11} to 10^{-3} Torr
  - x ray limit: <2×10^{-11} Torr
  - Less accurate & stable than Extended Range Gauge
  - Sensitivity: 20/Torr

Only design difference is collector diameter

- Extended Range: 0.040 inches
- UHV: 0.005 inches

Ref. Helix Technologies

Advertised Accuracy of *STABIL-ION* ® Gauge

- 370120 with 370 controller = +/-4% of reading
- 360120 with 360 controller = +/-6% of reading [mid-scale pressures]
- 360120 with other controllers such as 347 module or older style Series 303, 307, or 350 = ~+/-15% of reading
- Independent Labs [Sandia & PTB] report better accuracy levels than the manufacturer

Ref. Helix Technologies

MICRO-ION™ Gauge Design

Electrode Assembly

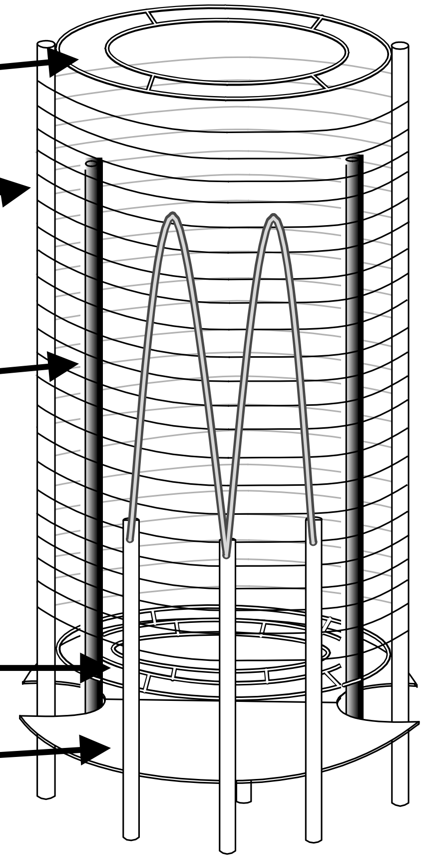
Grid Top End Cap

Grid Supports (2)

Ion Collectors (2)

Grid Bottom End Cap

Collector Shield



Ref. Helix Technologies

MICRO-ION™ Gauge: Wide Measurement Range

- X-ray limit: < 3×10^{-10} Torr (< 4×10^{-10} mbar).
- Upper pressure limit: 5×10^{-2} Torr/mbar.
- Stable behavior at pressures > 1×10^{-3} Torr/mbar.
- Useable in place of glass and nude B-A gauges.
- Good overlap with low vacuum (> 1×10^{-3} Torr/mbar) gauges such as *CONVECTRON*®.

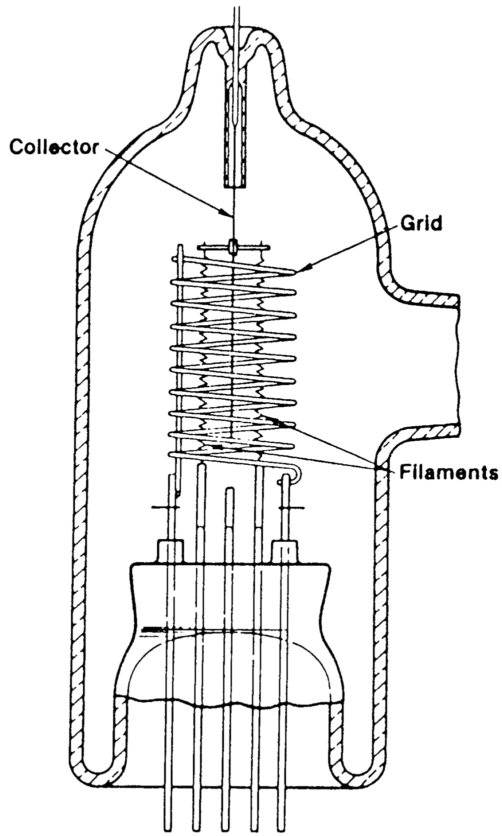
Ref. Helix Technologies

Bayard-Alpert Ionization gauge

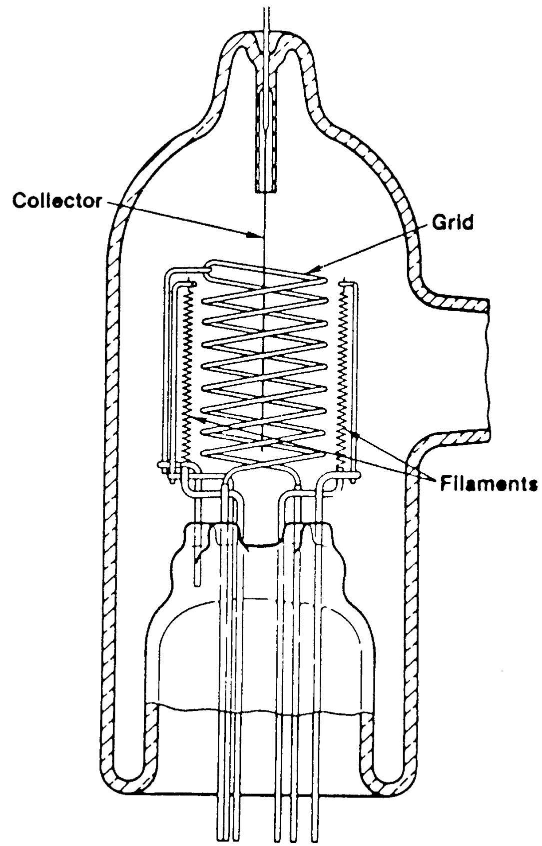
Distinguishing features & operating characteristics:

- Measures pressure indirectly
- Operating range is 10^{-3} to 10^{-11} Torr
- Indicated value is gas dependent
- Gas ionization from electron impact & then ion collection
- Three electrode geometry
- Hot cathode (filament)
- Two configurations available, tubulated & nude

Bayard-Alpert gauge components



Bayard-Alpert Gage
Side-By-Side Filaments



Bayard-Alpert Gage
Opposed Filaments

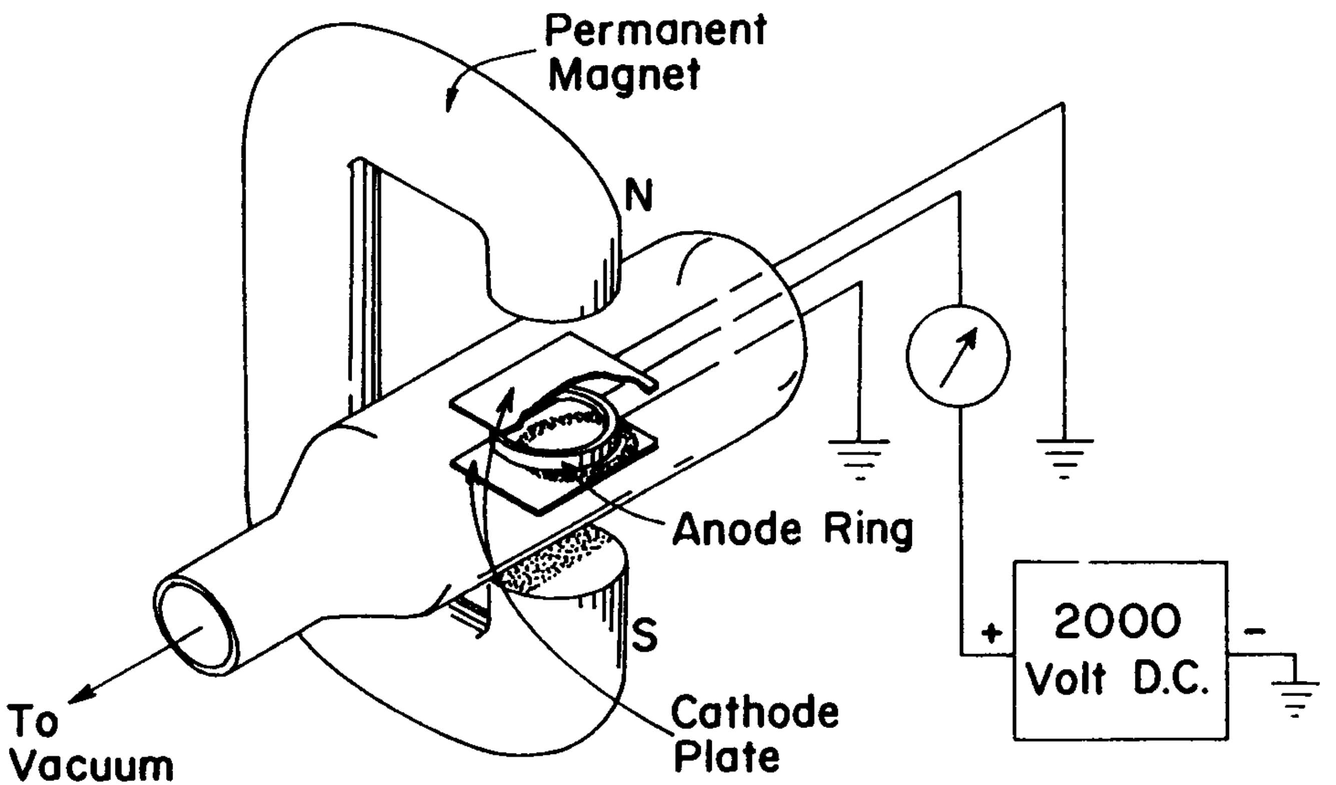
Ionization Gauges

- Glass tubulated
  - Pumping capacity can mask true pressure
  - About one third the price of a nude gauge
- Nude
  - More robust
  - Placed directly into environment, pumping is minimized
  - Filaments are replaceable
  - Higher sensitivities & can measure lower pressures (UHV)
  - Larger variation in sensitivity

Penning gauge

- Measures pressure indirectly
- Operating range 10^{-2} to 10^{-7} Torr
- Indicated value is gas dependent
- Cold cathode (no hot filament)
- Penning discharge: crossed electrical & magnetic fields to enhance ionization efficiency
- Discharge current is used as a measure of pressure
- $S = I_c/P^n$ $1.1 < n < 1.4$ pressure-current relationship is nonlinear
- Does not produce gases like a hot filament gauge
- Difficult to start & maintain discharge at pressures $<10^{-6}$ Torr
- Discharge mode "hopping" may confuse pressure indication
- Less accurate and less stable than a B-A gauge

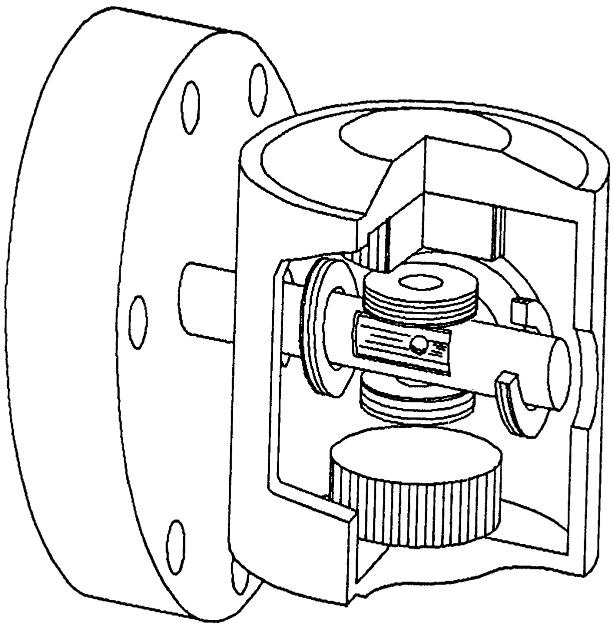
Penning gauge (cutaway and circuit)

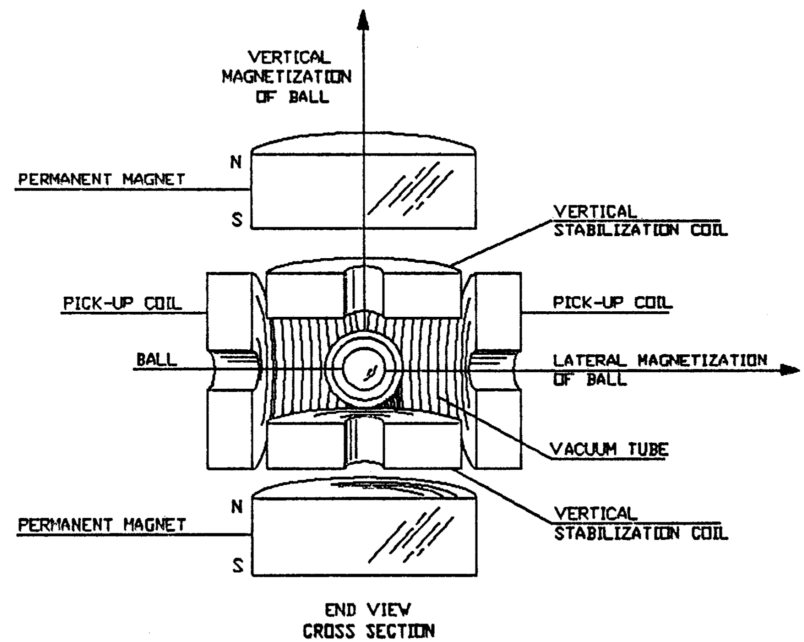


Spinning Rotor Gauge (SRG)

- Also called the molecular drag gauge (MDG)
- Measures pressure indirectly
- Operating range 10^{-2} to 10^{-7} Torr
- Indicated value is gas dependent (viscosity)
- Works by the principle of momentum transfer
- Utilizes a magnetically levitated, spinning, steel 4mm ball
- Ball rotation is slowed by gas collisions & measured
- Vibration sensitive
- Requires 30 seconds to 5 minutes to make a measurement
- Very good accuracy and linearity
- Often used in laboratories for calibration transfer standard

Spinning Rotor Gauge (SRG)



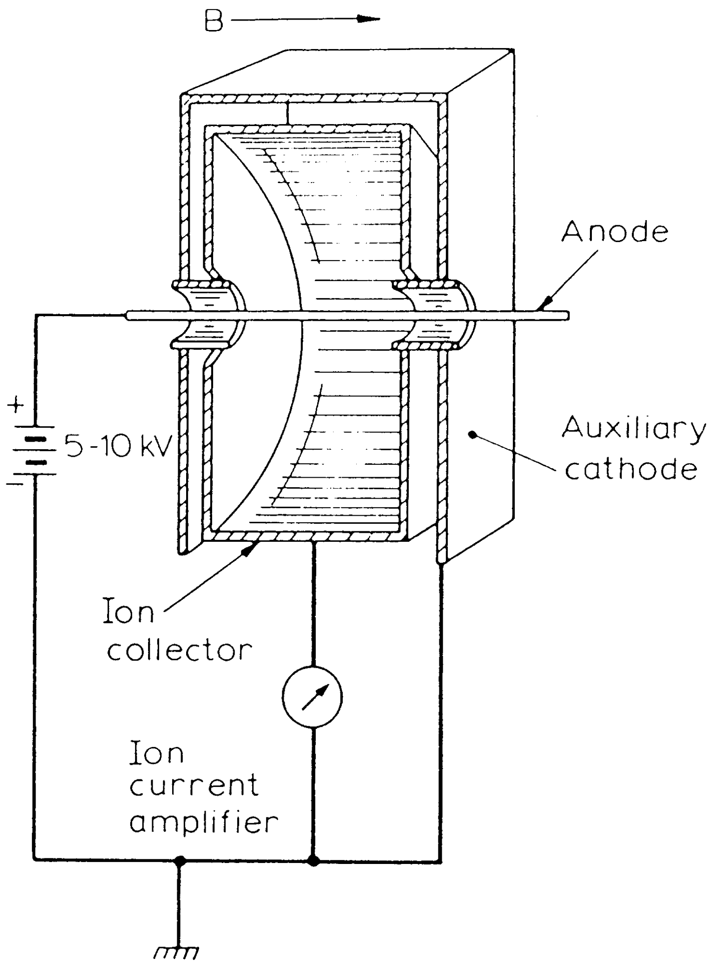


From *Handbook of Vacuum Science and Technology*, Hoffman

Inverted Magnetron Gauge

- Measures pressure indirectly
- Operating range 10^{-3} to 10^{-12} Torr (note low pressure)
- Indicated value is gas dependent
- Cold cathode (no hot filament)
- Ion current & pressure are not linearly related
- Same advantages as Penning, improvement on drawbacks
- Electrode geometry evolved from Penning configuration
- Anode changed to a rod and auxiliary (shield) cathode added
- Less accurate & reproducible than Bayard-Alpert

Inverted Magnetron Cut-away with Circuitry



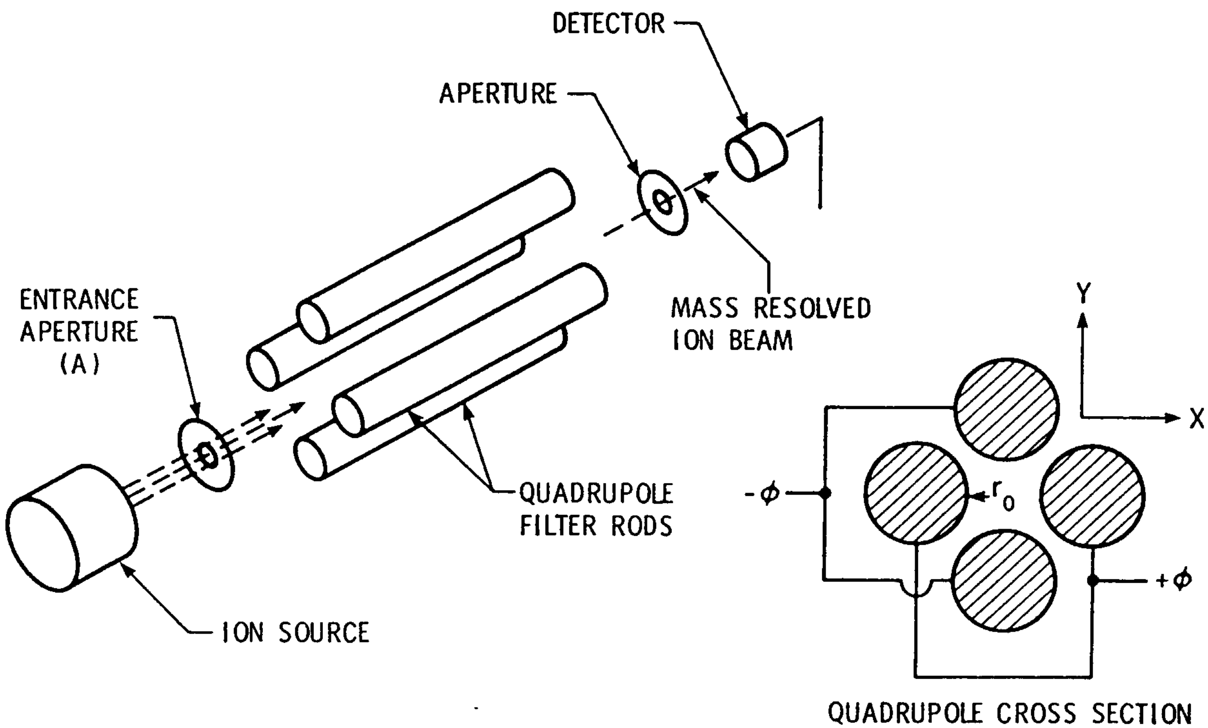
Partial Pressure Gauges

- Determine the composition of gases in a vacuum environment
- Usually qualitatively, sometimes quantitatively
- Mass spectrometer
- Amount of ions vs. mass/charge ratio (m/e or m/q)
- AMU - atomic mass unit C_{12} is exactly 12 AMU
- PPA & RGA
- Analytical mass spectrometer
- N_2^+ m/e = 28.0061 CO^+ m/e = 27.9949

Partial Pressure Gauges (continued)

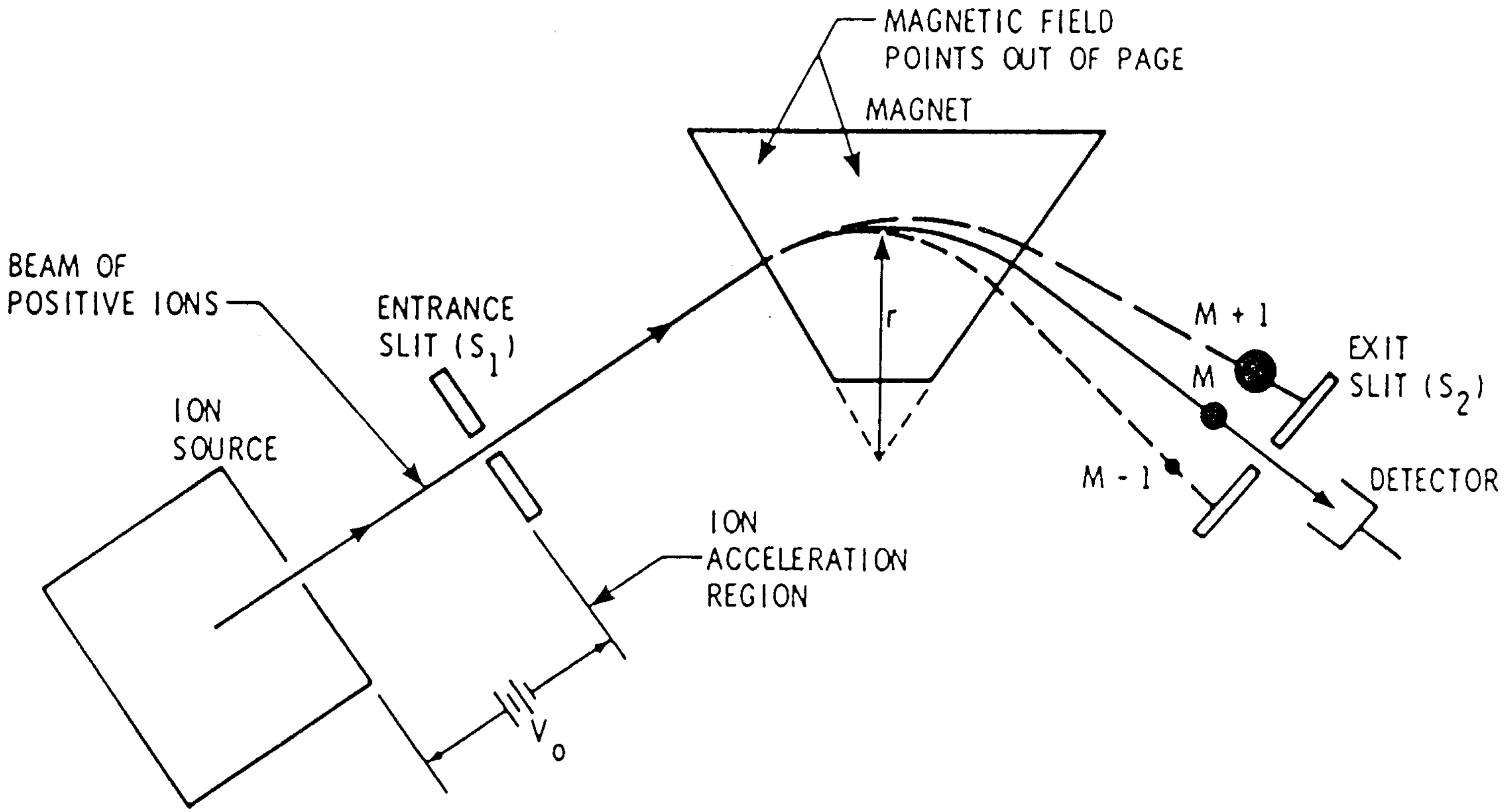
- PPA components
  - Ionizer
  - Mass filter
  - Detector
- Common types of PPAs
  - Quadrupole
  - Magnetic sector
  - Time of flight

Quadrupole Analyzer, Exploded View



Quadrupole mass filter.

Magnetic Sector Analyzer, Block Diagram



Analysis of Mass Spectra

- Fragmentation or cracking patterns
  - Dissociative ionization
  - Isotopes
  - Multiple ionization
  - Combined effects
- Cracking patterns are dependent on instrumental parameters
- Be careful with tabulated patterns
- Beware of instruments that convert ion currents to partial pressures

The US Particle Accelerator School
Materials, Fabrication Techniques, and Joint Designs

Lou Bertolini

Lawrence Livermore National Laboratory

January 19-24, 2004

Stainless Steel

- High strength, moderate formability, excellent weldability.
- Can be extruded in simple shapes
- 304 SS, least expensive

  304L SS, most commonly used in vacuum, a little more expensive

  316 SS, most expensive, resistant to chemical attack, welds are non-magnetic
- Wide variety of circular tubes and pipes available (seamless & welded)
- Outgassing rates can be decreased by employing good machining techniques, chemical cleaning and baking (up to 900°C)
- Thermal and electrical conductivity is poor

Typical Mechanical Properties for Stainless Steels

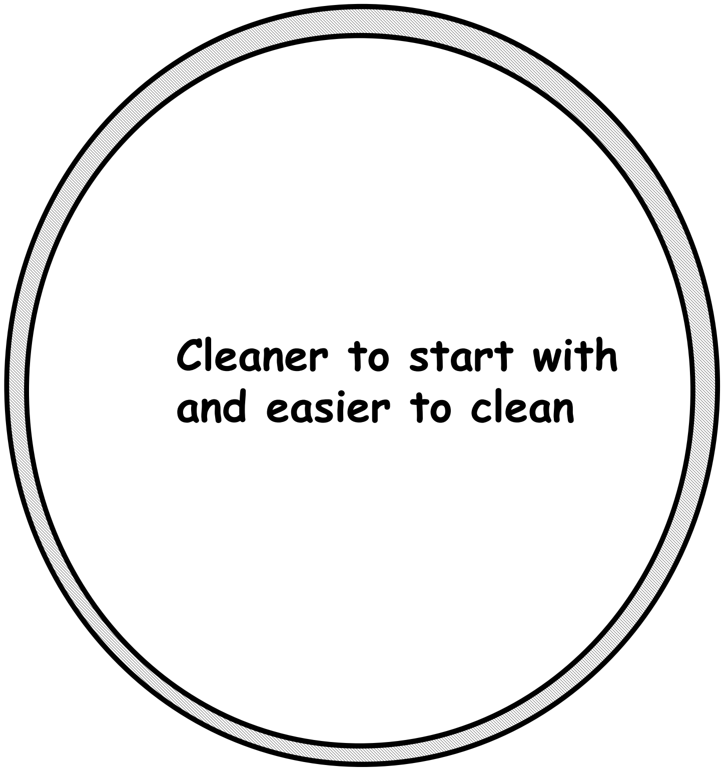
Property	304	304L	316	OFE Cu
Tensile Strength (MPa)	505	564	565	338
Tensile Strength (ksi)	73.2	81.8	81.9	49.0
Yield Strength (Mpa)	215	210	250	217
Yield Strength (ksi)	31.2	30.5	36.3	31.5
Elongation (%)	70	58	55	55
Modulus of Elasticity (Mpa)	197	197	193	115
Modulus of Elasticity (ksi)	28.6	28.6	28.0	16.7

Ref. www.matls.com

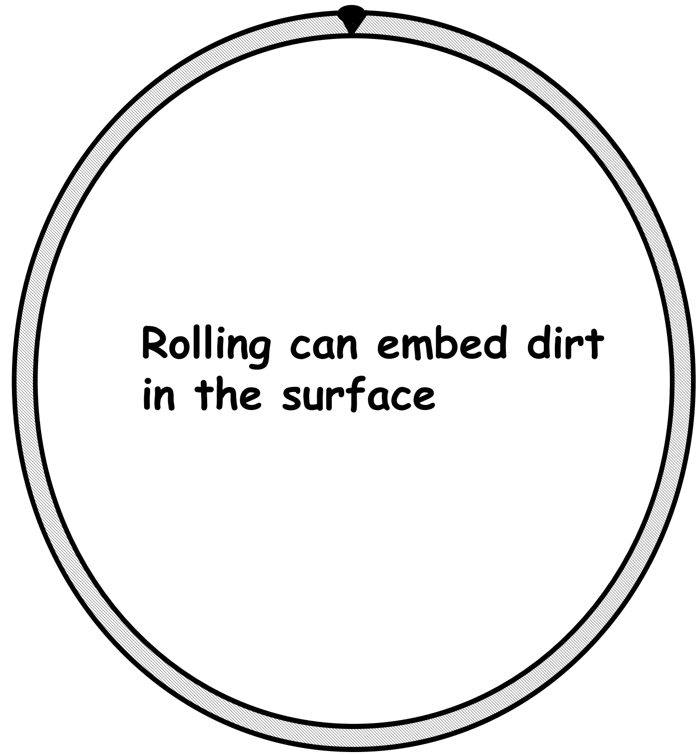
Typical Physical Properties for Stainless Steels

Property	304	304L	316	OFE Cu
Composition:	C 0.08% Cr 18-20% Mn 2% Fe 66-74% Ni 8-10.5% P 0.045% S 0.03% Si 1%	C 0.03% Cr 18-20% Mn 2% Fe 66-74% Ni 8-12% P 0.045% S 0.03% Si 1%	C 0.08% Cr 17% Mn 2% Mo 2.5% Fe 65% Ni 12% P 0.045% S 0.03% Si 1%	Cu 100%
Melting Point (°C)	1427	1425	1385	1083
Density (g/cc)	8.0	8.0	8.0	8.92
Electrical Resistivity (W-cm)	7.2×10^{-5}	7.2×10^{-5}	7.4×10^{-5}	1.71×10^{-6}
Elect. Conduct. (% IACS*)				101
Therm. Conduct. (W/m-K)	16.2	16.2	16.3	391
Coeff. Of Therm. Exp. ($^{o}C^{-1}$)	17.2×10^{-6}	17.2×10^{-6}	16.0×10^{-6}	17.5×10^{-6}
Mod. Of Elasticity (psi)	28.6×10^{6}	28.5×10^{6}	28×10^{6}	17×10^{6}

Tubing - Seamless and Welded

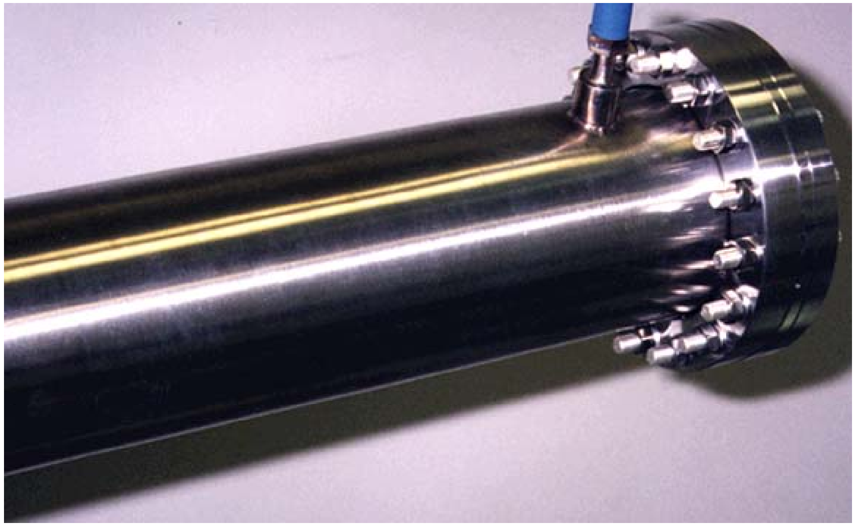


Seamless (extruded)



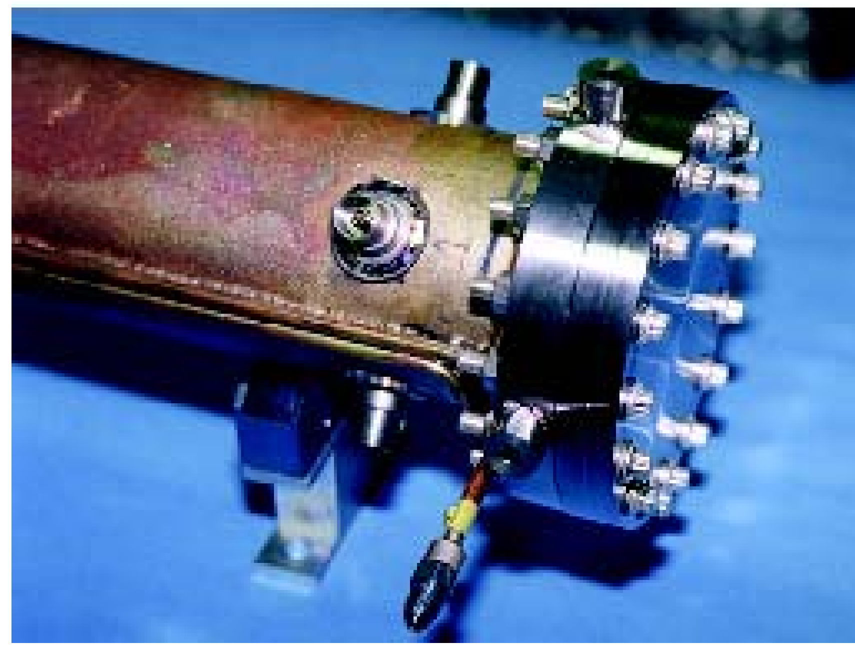
Welded (rolled & welded)

PEP-II Straight Section Stainless Steel Beampipes



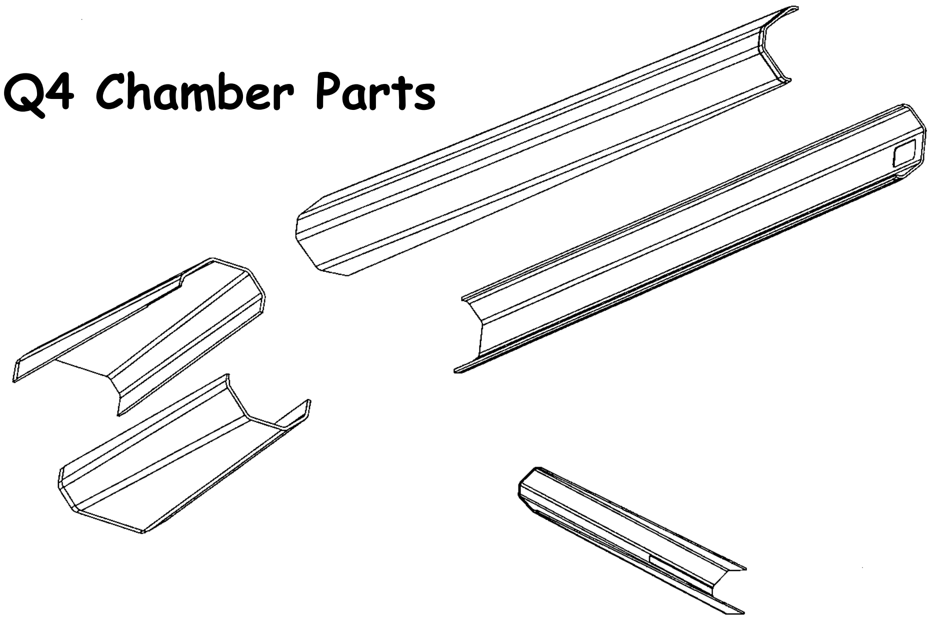
Stainless Steel Double-wall Tube

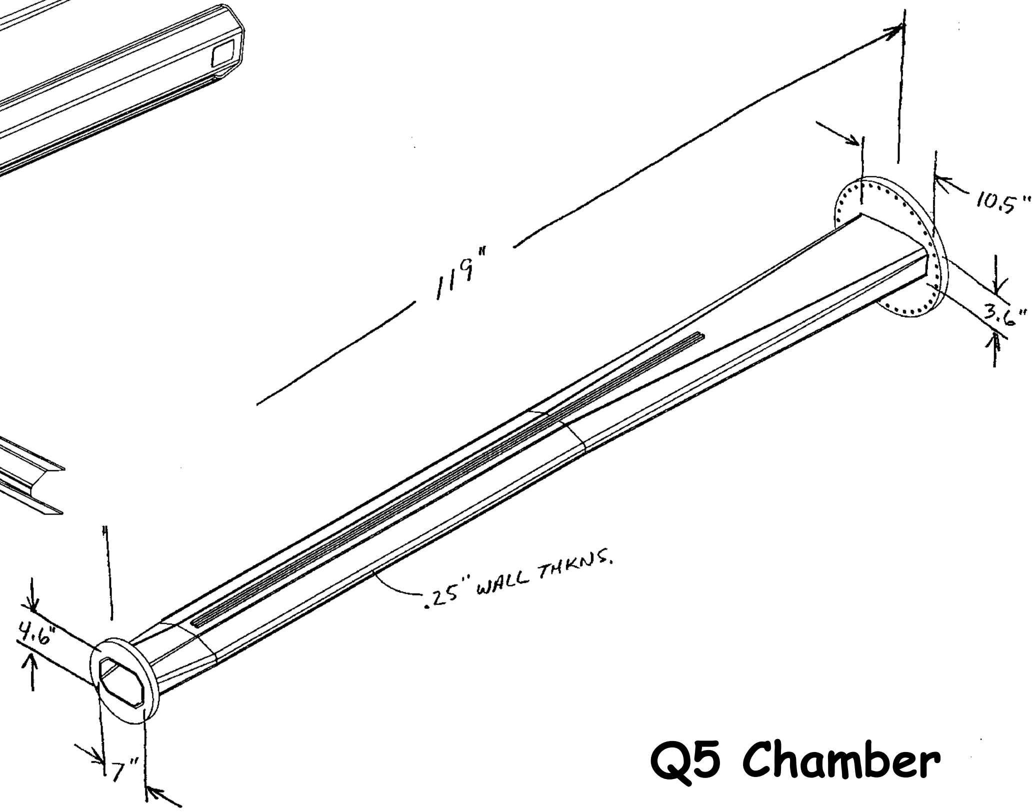
Copper-plated Seamless Stainless Steel Tube



Formed and Welded Stainless Steel Chamber - Manpower Intensive

Q4 Chamber Parts





Q5 Chamber

Aluminum

- Moderate strength, good formability, easy to machine
- Can be extruded in complicated shapes
- 6061-T6 is the most common aluminum alloy for vacuum components
- 5083 is a good alloy for welding
- Aluminum is much cheaper to machine than stainless steel
  (2x to 3x cheaper)
- Special care must be taken in the design of welds and the techniques used due to higher thermal conductivity and thermal expansion (30% > SS)
- Surface anodizing degrades outgassing characteristics, but improves chemical resistance

Typical Mechanical Properties for Aluminum

Property	1100-0	5083-H34	6061-T6	OFE Cu
Tensile Strength (MPa)	165	345	310	338
Tensile Strength (ksi)	23.9	50.0	45.0	49.0
Yield Strength (Mpa)	150	280	275	217
Yield Strength (ksi)	21.8	40.6	39.9	31.5
Elongation (%)	5	9	12	55
Modulus of Elasticity (Mpa)	69	70.3	69	115
Modulus of Elasticity (ksi)	10.0	10.2	10.0	16.7

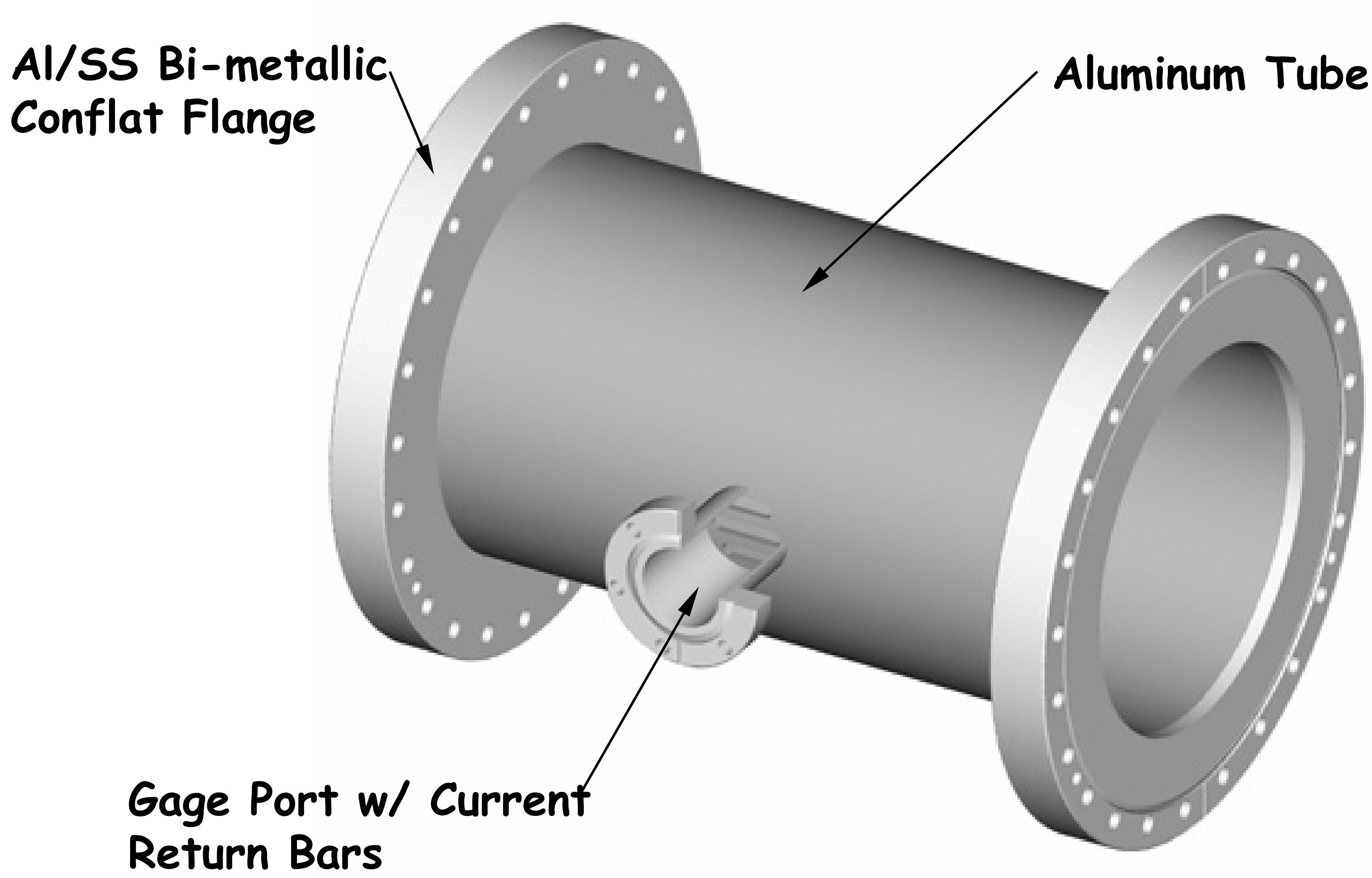
Ref. www.matls.com

Typical Physical Properties for Aluminum

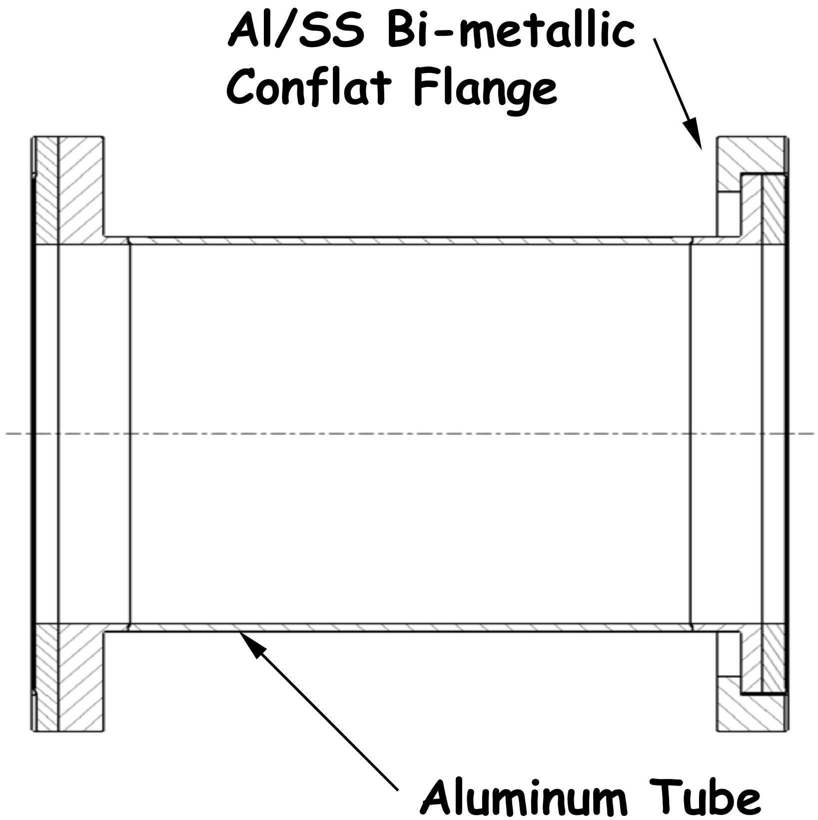
Property	1100-0	5083-H34	6061-T6	OFE Cu
Composition:	Al 99% Cu 0.05-0.2% Mn 0.05% Si+Fe 0.95% Zn 0.1%	Al 94.8% Cu 0.1% Cr 0.05-0.25% Mg 4-4.9% Mn 0.4-1% Fe 0.4% Si 0.4% Ti 0.15% Zn 0.25%	Al 98% Cu 0.15-0.4% Cr 0.04-0.35% Mg 0.8-1.2% Mn 0.15% Fe 0.7% Si 0.4-0.8% Ti 0.15% Zn 0.25%	Cu 100%
Melting Point (°C)	643	591	582	1083
Density (g/cc)	2.71	2.66	2.7	8.92
Electrical Resistivity (W-cm)	$3x10^{-6}$	$5.9x10^{-6}$	$3x10^{-6}$	$1.7x10^{-6}$
Heat Capacity (J/g-°C)	0.904	0.9	0.896	0.385
Therm. Conduct. (W/m-K)	218	117	167	391
Coeff. Of Therm. Exp. ($°C^{-1}$)	$25.5x10^{-6}$	$26x10^{-6}$	$25.2x10^{-6}$	$17.5x10^{-6}$

Ref. www.matls.com

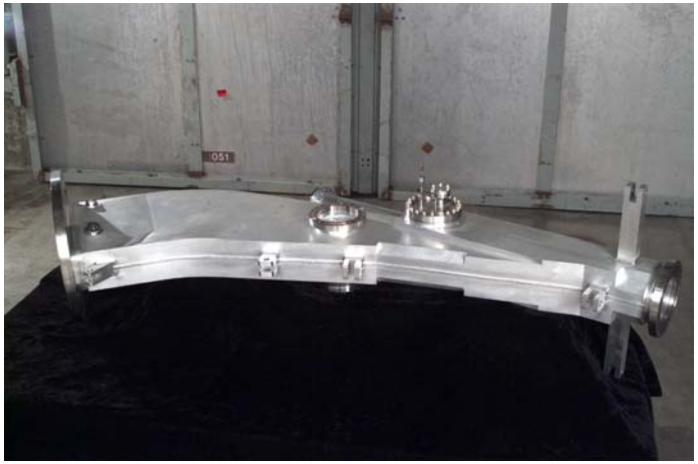
Aluminum Beam Pipe Spool

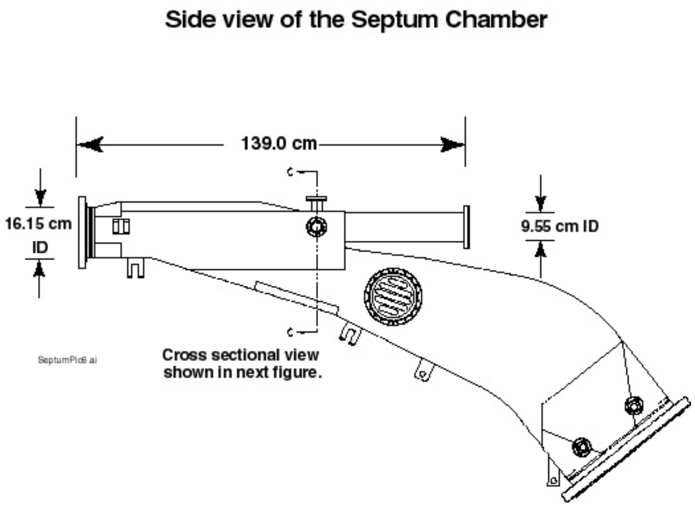


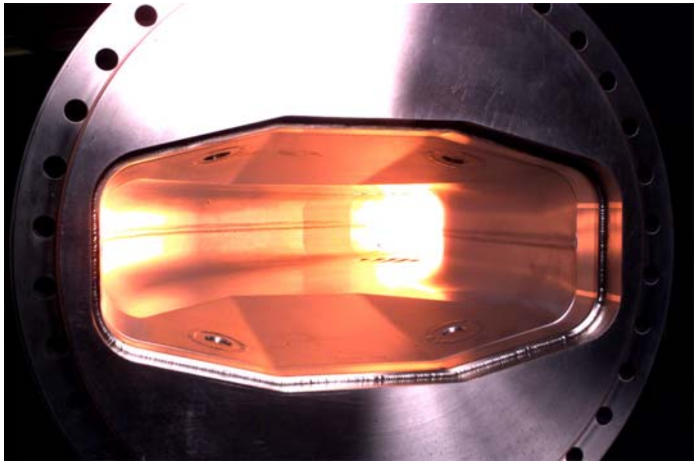
Aluminum Beam Pipe Spool

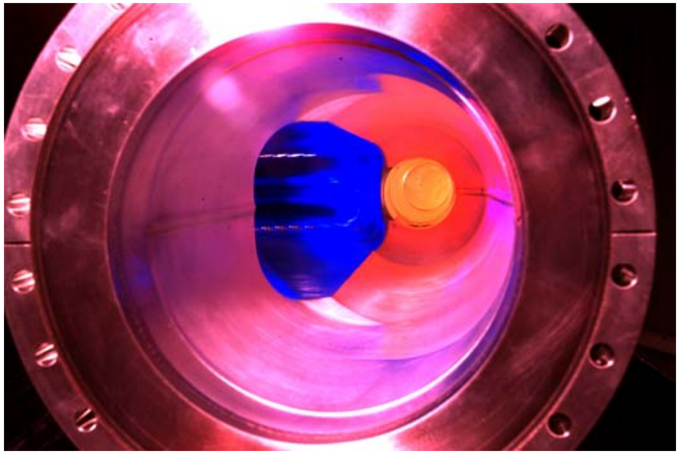


Machined Aluminum Vacuum Chamber

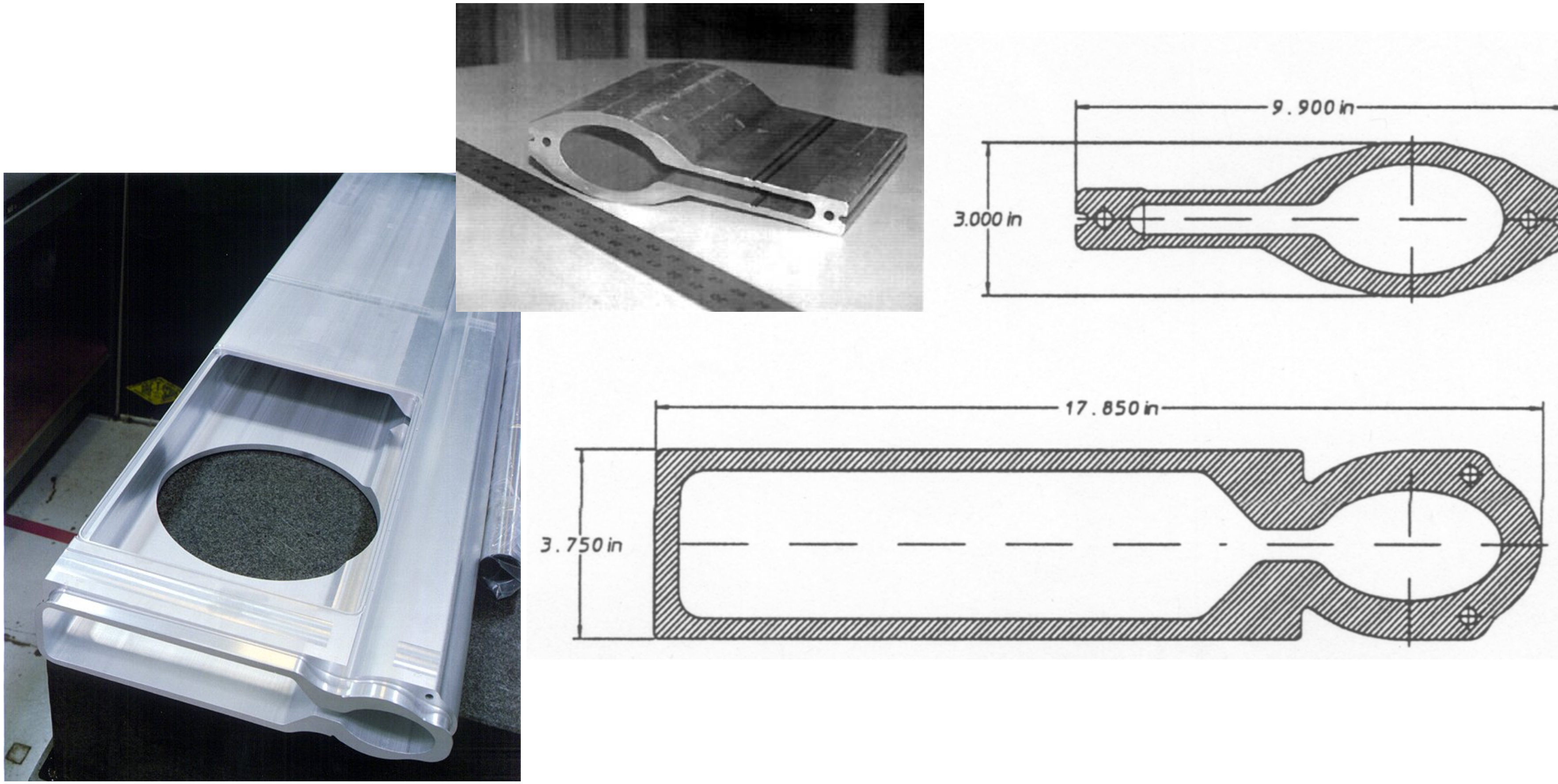








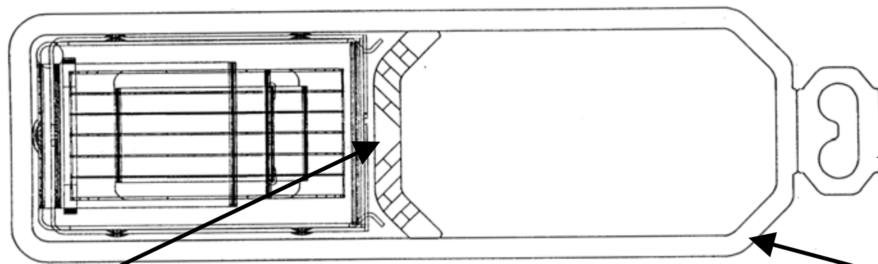
Aluminum Extrusions



Copper

- Typical copper alloys are C10100, C26800, C61400, C17200
- Low-to-moderate strength, good formability
- Excellent electrical and thermal characteristics
- Difficult to weld (e-beam welding is best)
- May be joined by welding, brazing, and soldering
- Good outgassing characteristics, rates can be decreased by following good machining techniques, chemical and baking (~200°C)

Copper Extrusions

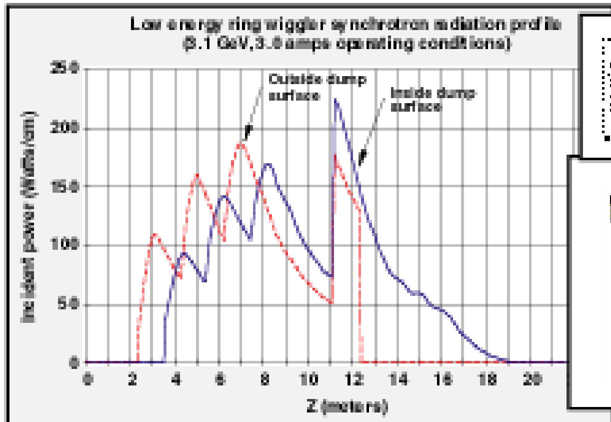


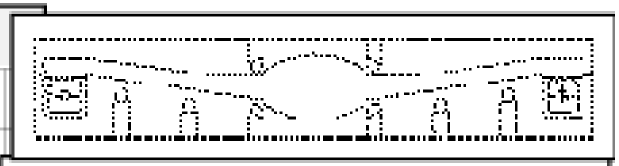
Cooling Bar Extrusion

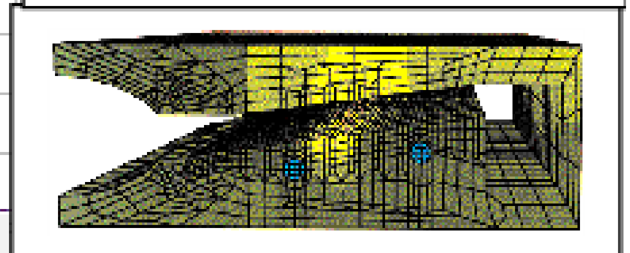
Screen Extrusion

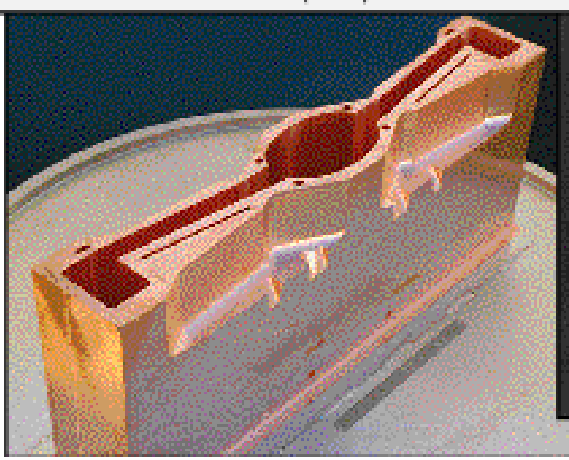
"Dipole" Chamber Extrusion

Machined Copper Chamber (PEP-II Wiggler Vacuum Chamber)



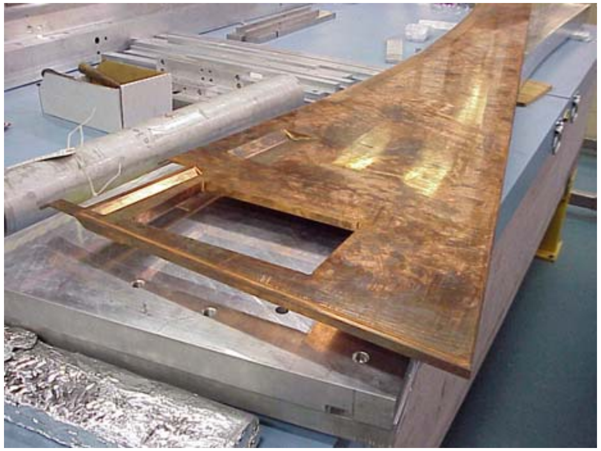




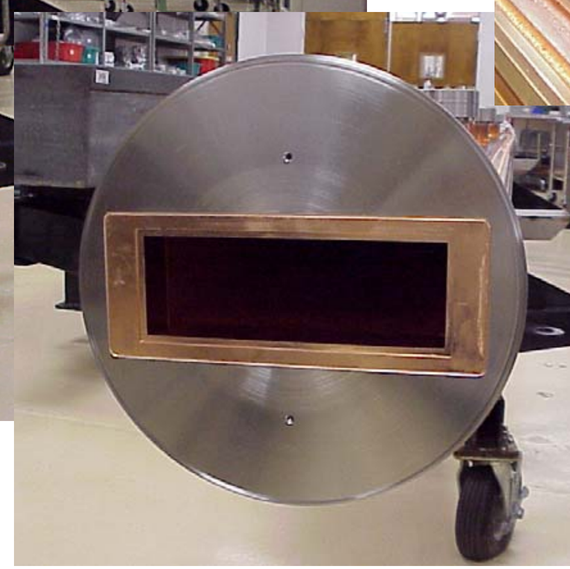


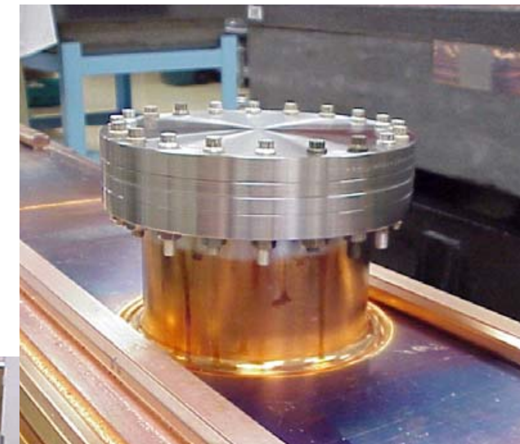
- 25 meters of machined copper chamber (5 – 5 meter sections)
- 410 kWatts of synchrotron radiation power absorbed
- Water cooling passages are externally machined and e-beam welded closed
- 1-1/2 years to fabricate

Machined Copper Chamber (SPEAR3)

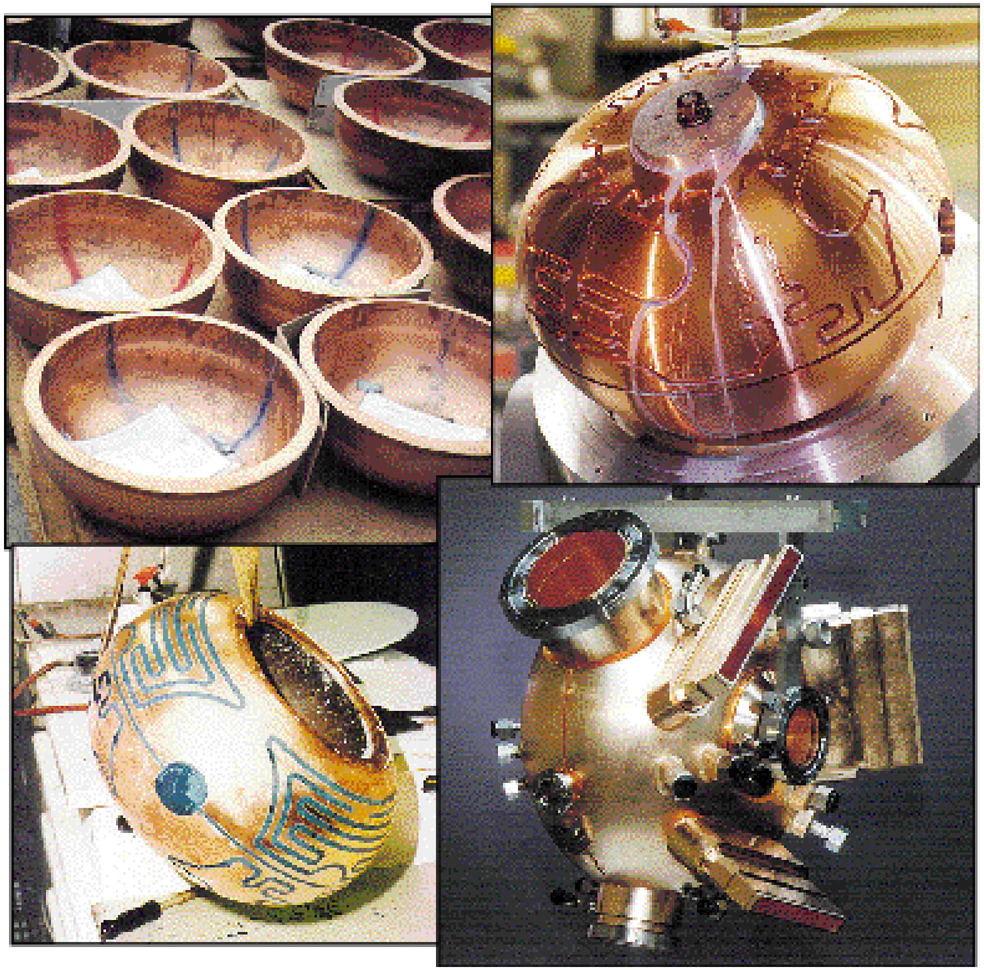


PEP-II HER High Power Synchrotron Radiation Dump Chamber





Machined Copper Chamber (PEP-II RF Cavities)



- 26 cavities
- $4M total fabrication cost
- Integral cooling channels with electroformed cover
- 5 axis machining
- e-beam welded
- 17 separate manufacturing steps

Glidcop ™

Glidcop is pure copper with Al_2O_3 dispersed throughout.

- High strength, moderate formability, poor weldability.
- Available in sheets, plate, wire, and extruded rounds.
- Maintains good mechanical strength after brazing.
- Outgassng rates are similar to pure copper.
- Thermal and electrical properties are good.

Grade Designations		Copper		Al_2O_3	
UNS	SCM Metal Prod.	Wt %	Vol %	Wt %	Vol %
C15715	Glidcop AL-15	99.7	99.3	0.3	0.7
C15725	Glidcop AL-25	9.5	98.8	0.5	1.2
C15760	Glidcop AL-60	98.9	97.3	1.1	2.7

Ref. SCM Metal Products

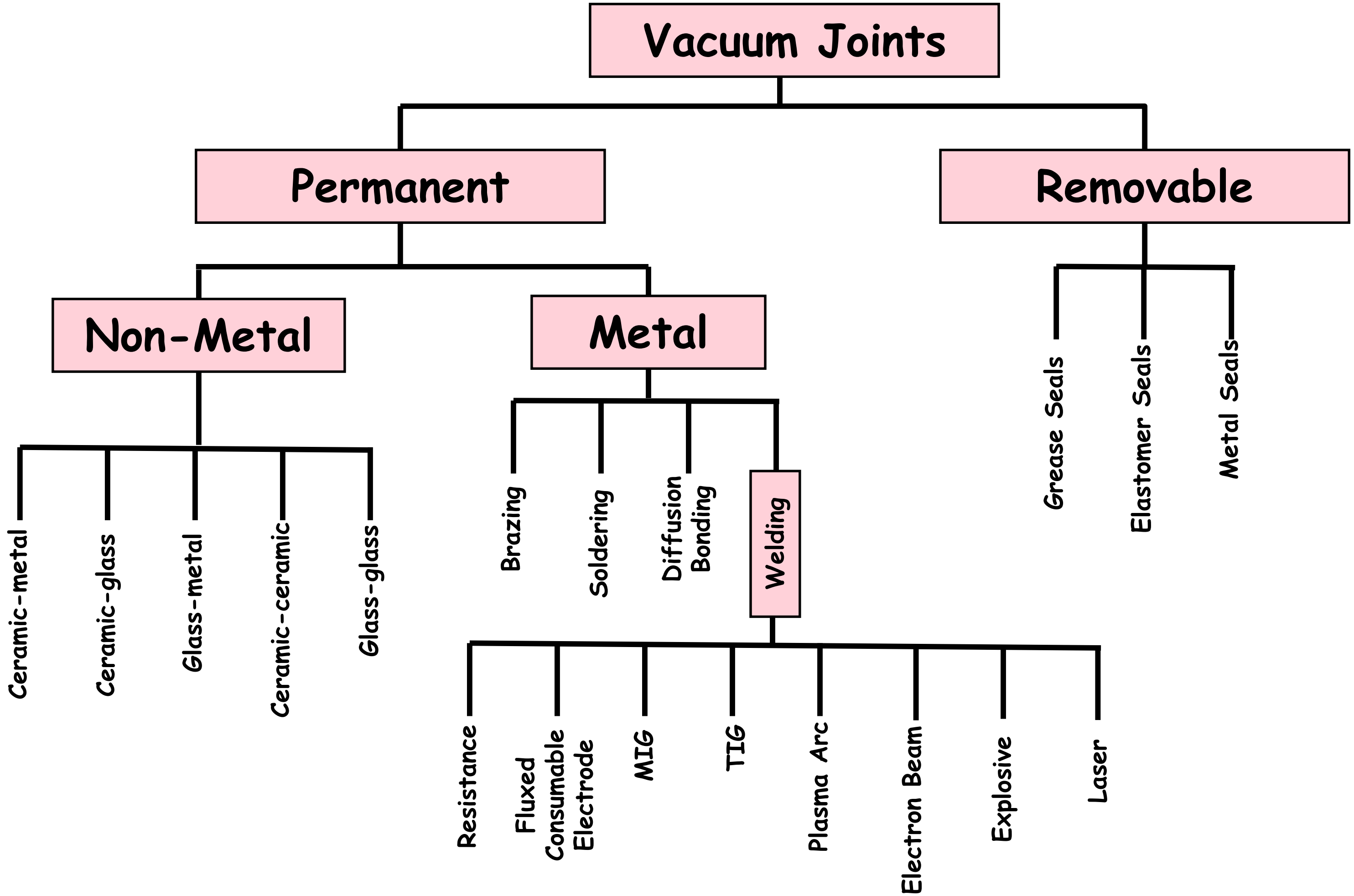
Glidcop™ Physical Properties

Property	C15715	C15725	C15760	OFE Cu
Melting Point (°C)	1083	1083	1083	1083
Density (lb/in^3)	0.321	0.320	0.318	0.323
Electrical Resistivity (W)	11.19	11.91	13.29	10.20
Elect. Conduct. (% IACS*)	92	87	78	101
Therm. Conduct. (W/m-K)	365	344	322	391
Coeff. Of Therm. Exp. (°C^{-1})	16.6×10^{-6}	16.6×10^{-6}	16.6×10^{-6}	17.7×10^{-6}
Mod. Of Elasticity (psi)	19×10^6	19×10^6	19×10^6	19×10^6

* International Annealed copper Standard

Ref. SCM Metal Products

Methods of making Vacuum Joints



Welding

Welding is the process where two materials are joined by fusion

- Welding is the most common method for joining metals in vacuum systems.
- Inert gas welding is the most common type of welding (TIG, MIG).
- Joint design is critical from vacuum, metallurgical and distortion standpoints.
- Cleanliness is essential.
- Other welding processes to consider are electron beam and laser welding.

Welding Aluminum

- Low melting point, relatively high thermal conductivity, and high rate of thermal expansion make welding aluminum more problematic than stainless steel.

- Aluminum requires:
  1. High welding speeds (higher current densities)
  2. Good material purity and cleanliness
  3. Good joint design

- Aluminum welds have a tendency to crack from excessive shrinkage stresses due to their high rate of thermal contraction.

Welding Copper

- The high thermal conductivity of copper makes welding difficult. Heating causes the copper to recrystalize forming large grain size and annealing. Distortion is also a big problem.

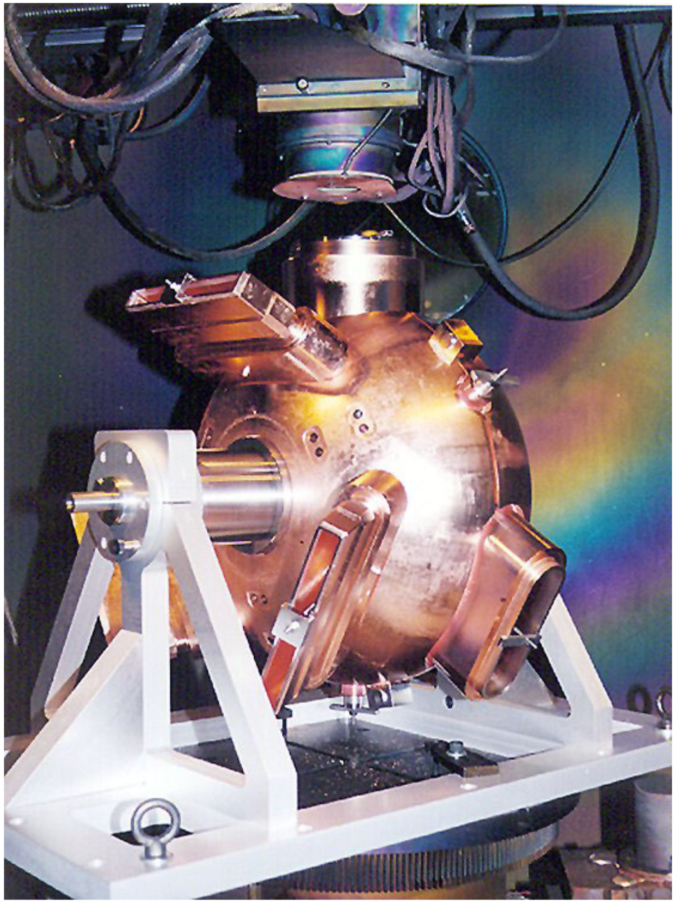
- Copper requires:
  1. Very high welding speeds
  2. Excellent material purity (OFE copper) and cleanliness.
  3. Good joint design

- Electron beam welding is an excellent process for welding copper.

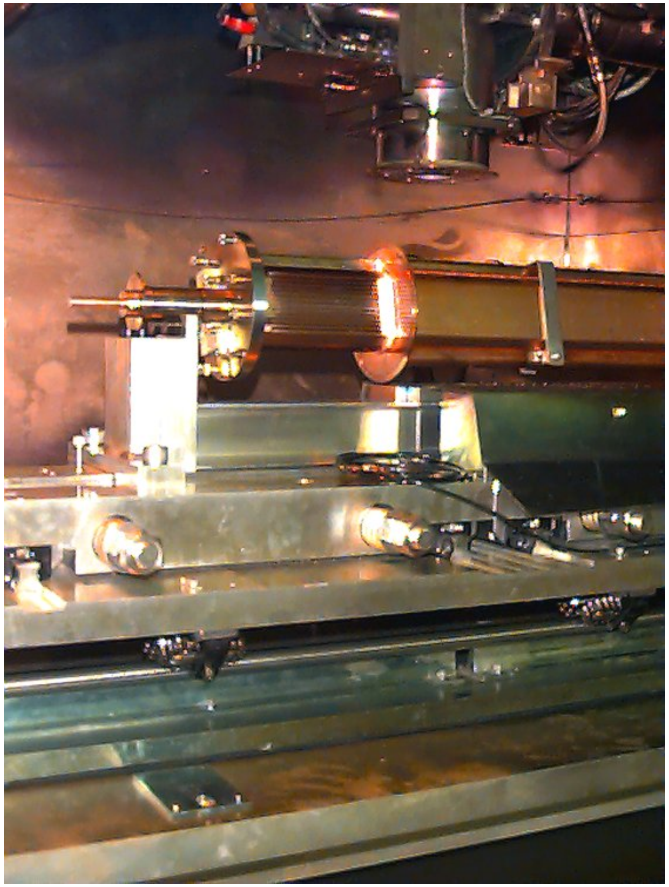
Electron Beam Welding (EBW)

- EBW provides extremely high energy density in its focused beam producing deep, narrow welds.
- This rapid welding process minimizes distortion and the heat affected zone.
- A disadvantage of EBW is that the process takes place under vacuum ($P = 10^{-4}$ Torr):
  - Extensive fixturing required
  - High cost
  - Complexity
  - Welds are not cleanable

Copper chambers ready for electron beam welding



RF Cavity



HER Quadrupole Chamber

SLAC Electron Beam Welder

Soldering

Soldering is the process where materials are joined together by the flow of a "filler metal" through capillary action.

- Soldering is differentiated from brazing primarily by the melting temperature of the filler metals. Solder alloys melt below 450°C.
- All soft solders are unacceptable for UHV systems because:
  - They contain Pb, Sn, Bi, Zn (vapor pressures are too high)
  - System bake-out temperatures typically exceed alloy melting points.
- Most silver solders are unacceptable.

Brazing

Brazing is the process where two dissimilar materials are joined together by the flow of a "filler metal" through capillary action.

- There are several different brazing processes:
  1. Torch
  2. Furnace
  3. Induction
  4. Dip
  5. Resistance
- Brazing can be used to join many dissimilar metals. The notable exceptions are aluminum and magnesium.
- Cleanliness is important in brazing. Cleanliness is maintained by use of a flux or by controlling the atmosphere (vacuum or H_2).

Brazing (cont.)

- Filler metals come in the form of wire, foils, or paste.
- Filler metals are selected to have melting points below that of the base metal.
- Multiple braze steps are possible by choosing alloys of differing melting points and proceeding sequentially from highest to lowest temperature.
- Braze joints require tight tolerances for a good fit (0.002” to 0.004”).

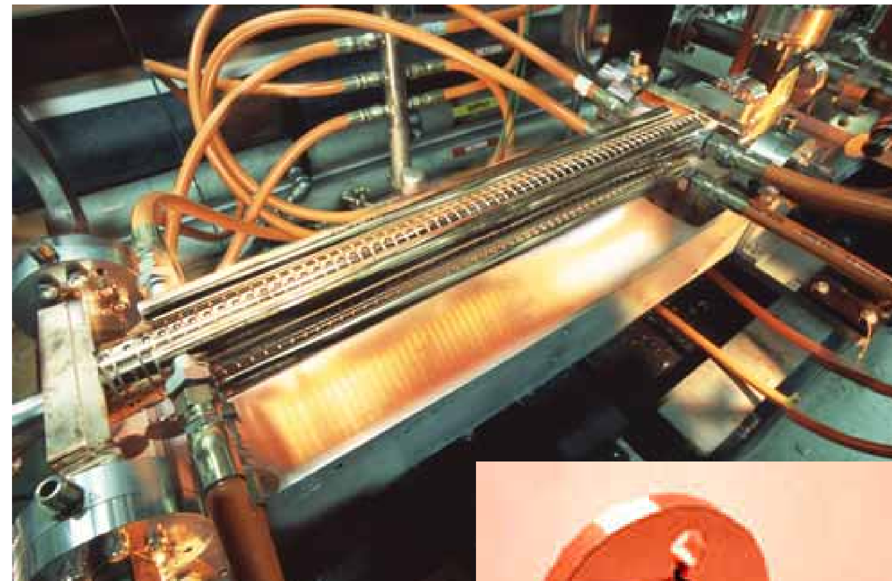
Typical Braze Alloys for UHV Components

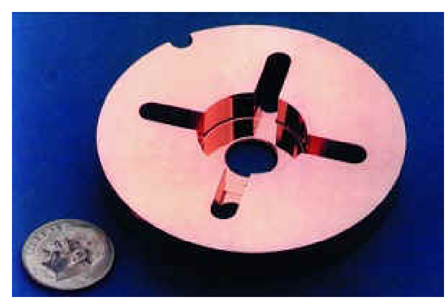
Alloy	Brazing Temperature	Composition
BAu -2	890°C	80% Au, 20% Cu
Au-Cu-Ni	925°C	81.5% Au, 16.5% Cu, 2% Ni
BAu -4	950°C	82% Au, 18% Ni
50/50 Au-Cu	970°C	50% Au, 50% Cu
35/65 Au-Cu	1010°C	35% Au, 65% Cu

Time @ Temperature: 2-20 minutes

Diffusion Bonding

- Diffusion bonding is a joining techniques where pre-machined components are held together under modest loads at elevated temperatures.
  - The loads are usually well below those producing deformation.
  - Bonding temperatures typically range from 50-80% of melting temperatures of the metals.
  - Processing times vary from 1 minute to over an hour.
  - Most diffusion bonding operations are conducted in vacuum or in an inert gas atmosphere
- Diffusion bonding requires very clean components with excellent surface finishes.



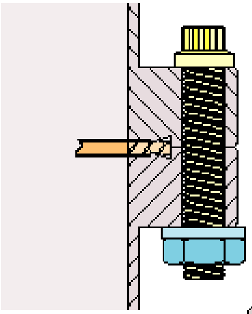


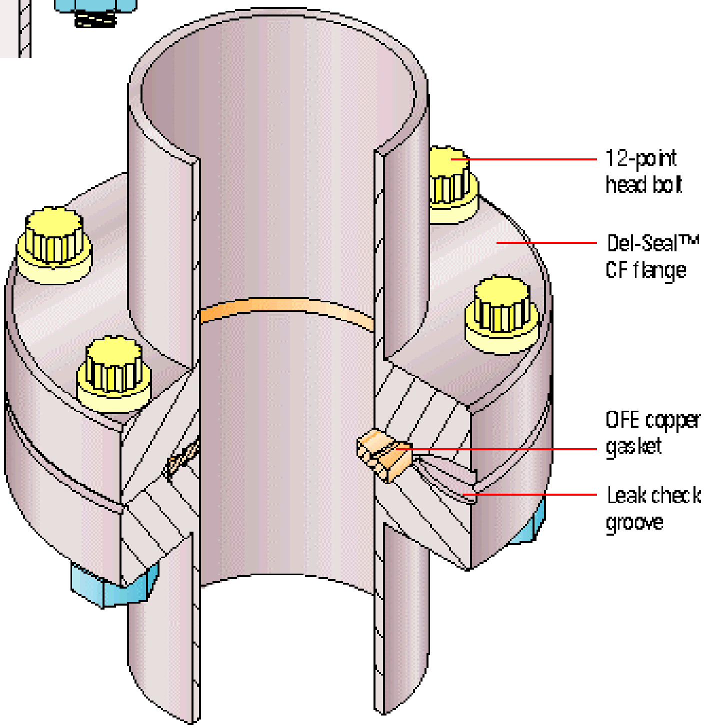
There are a variety of metal seals available for vacuum systems

- Copper (Conflats, wire, VATSEALS)
- Indium Foil or Wire
- Aluminum Wire
- Tin Wire or Foil
- Gold/Silver Wire

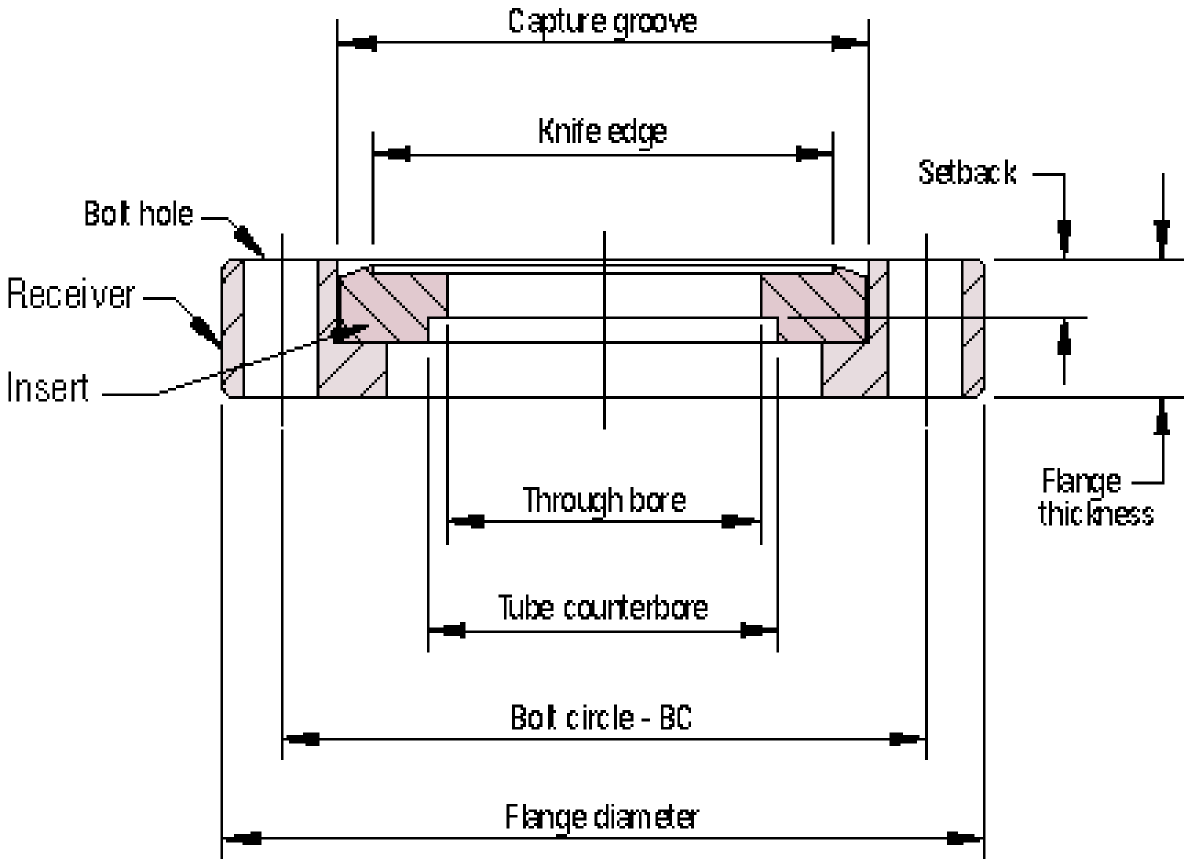
Conflat® Flanges

- Vacuum rated to 1 x 10^{-13} Torr
- Temperature rated to 450°C
- Typical size range: 1-1/3”-16-1/2” od (conflats designs have been applied to very large diameters & rectangular shapes with poor results)
- Flanges come in a variety of configurations
  - rotatable
  - non-rotatable
  - tapped or clearance bolt holes
  - double-sided
- Flanges are genderless
- Aluminum conflats have been constructed from A2219-T87 with TiN coated knife-edges.





Conflat® Flange Designations

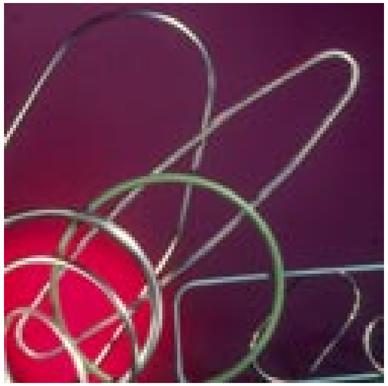


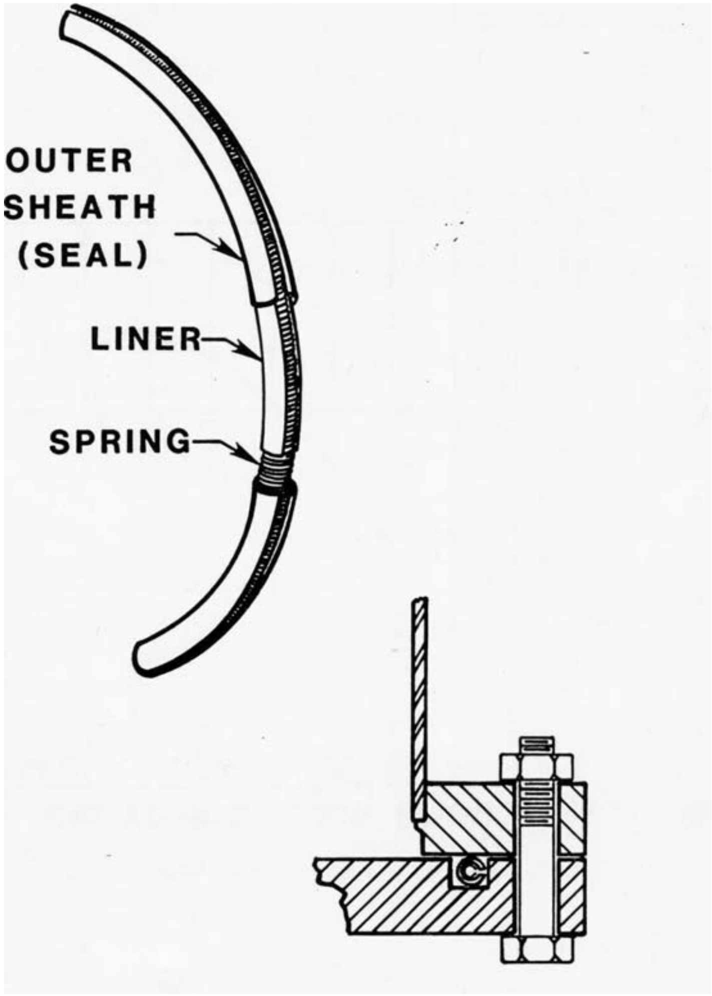
Gold and Silver Seals

- Gold and silver are ideal sealing metals.
  - Both are soft metals requiring low sealing forces
  - Chemically passive, resistant to oxidation during bake-out
- Gold and silver are often used as plating materials for metal o-rings and gaskets.
- Gold is a good material to consider for very large joints or odd shapes.
- Can be expensive

Helicoflex® Flanges

- Metal o-ring using an internal spring to maintain the seal force
- Vacuum rated to 1 x 10^{-13} Torr
- Temperature rated to 450°C
- Typical size range: 10" - 20" od

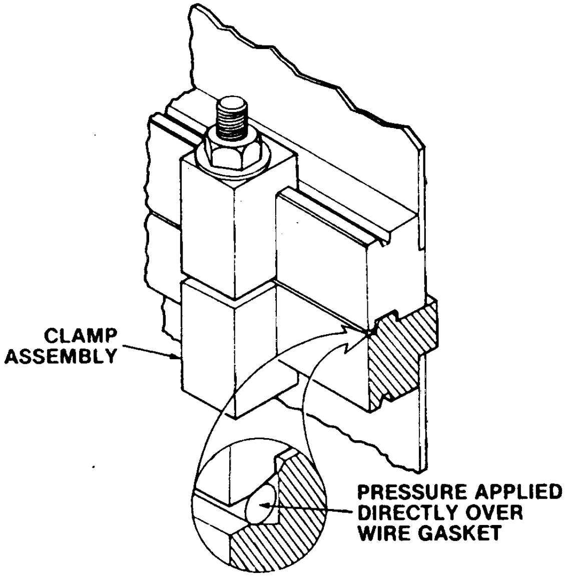


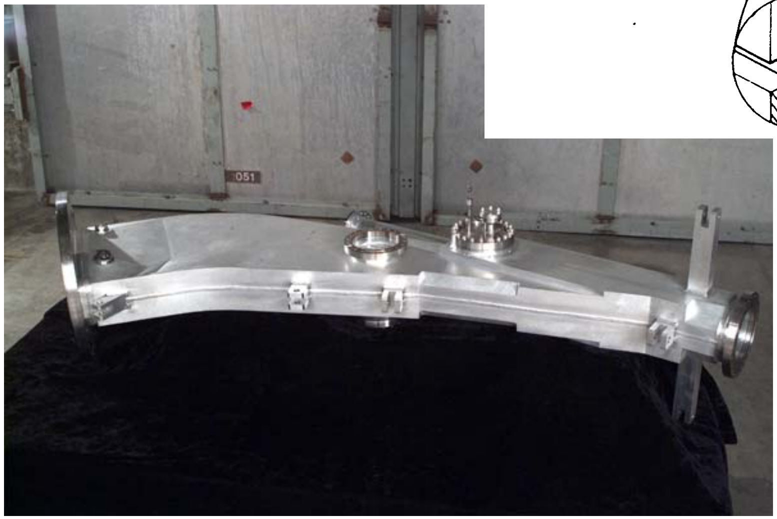


Ref: Helicoflex Cefilac

Commercial Wire Seal Flanges

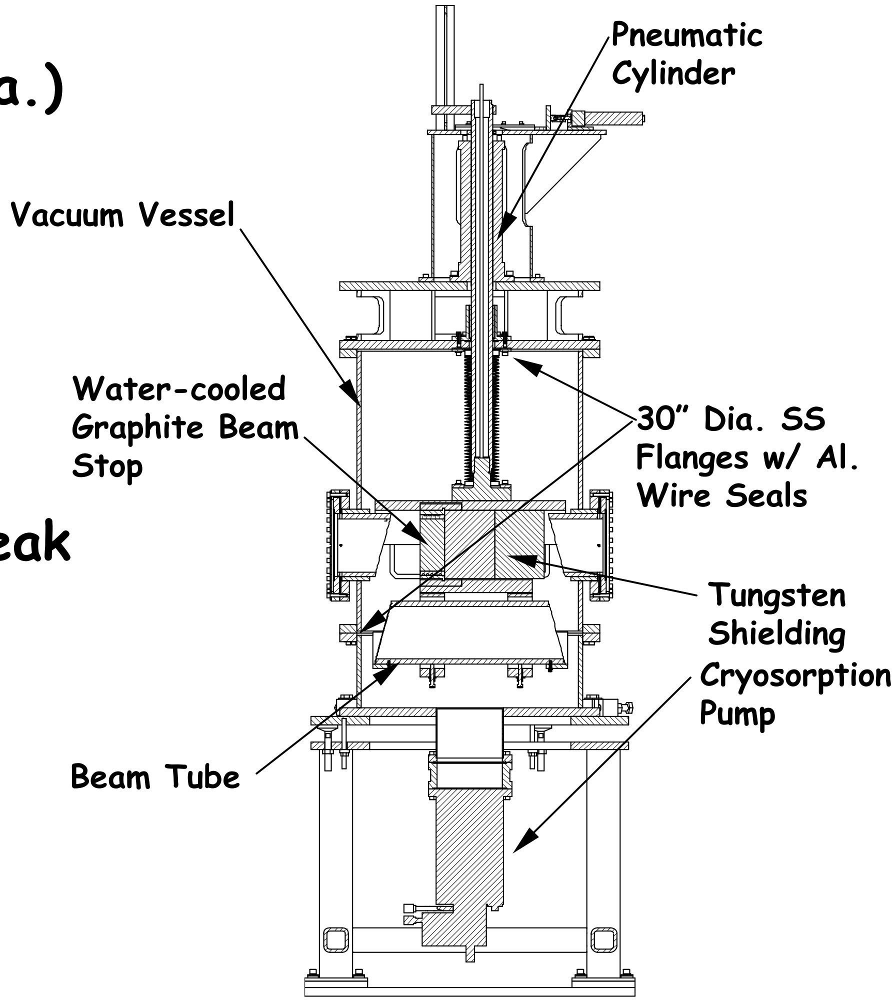
- Vacuum rated to 1 x 10^{-13} Torr
- Temperature rated to 450°C
- Typical size range: 10" - 20" od
- Warning – male and female flanges



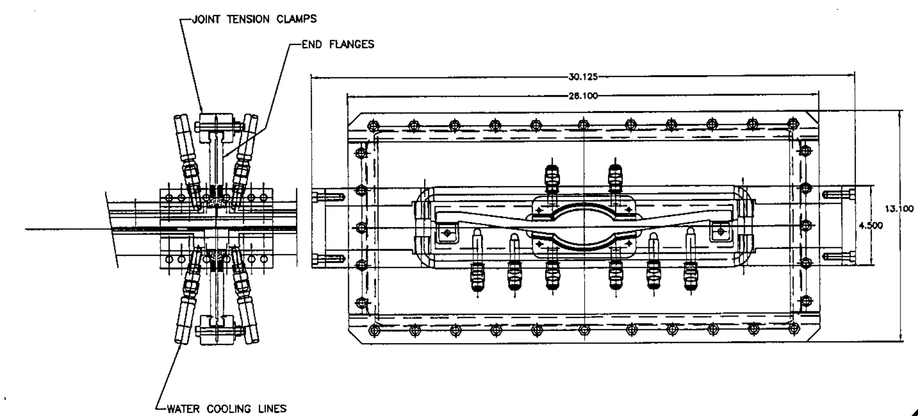


"LANL" Wire Seal Flange Design

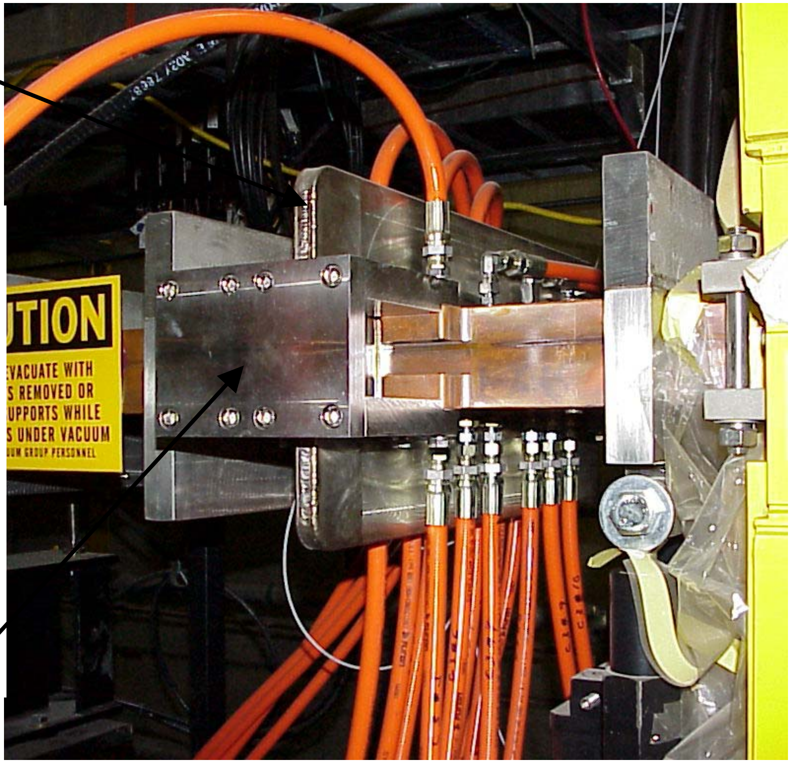
- Aluminum wire (0.040-0.063" dia.) either welded at the ends or simply lapped.
- Vacuum rated to 1 x 10^{-8} Torr
- Temperature rated to 200°C
  - Above 250°C seals begin to leak
  - Cold welding of Al wire to SS flanges becomes a problem
- Typical size range: 6" - 30" od
- Flat Face Flanges



PEP-II Wiggler Vacuum Chamber Welded Flanges

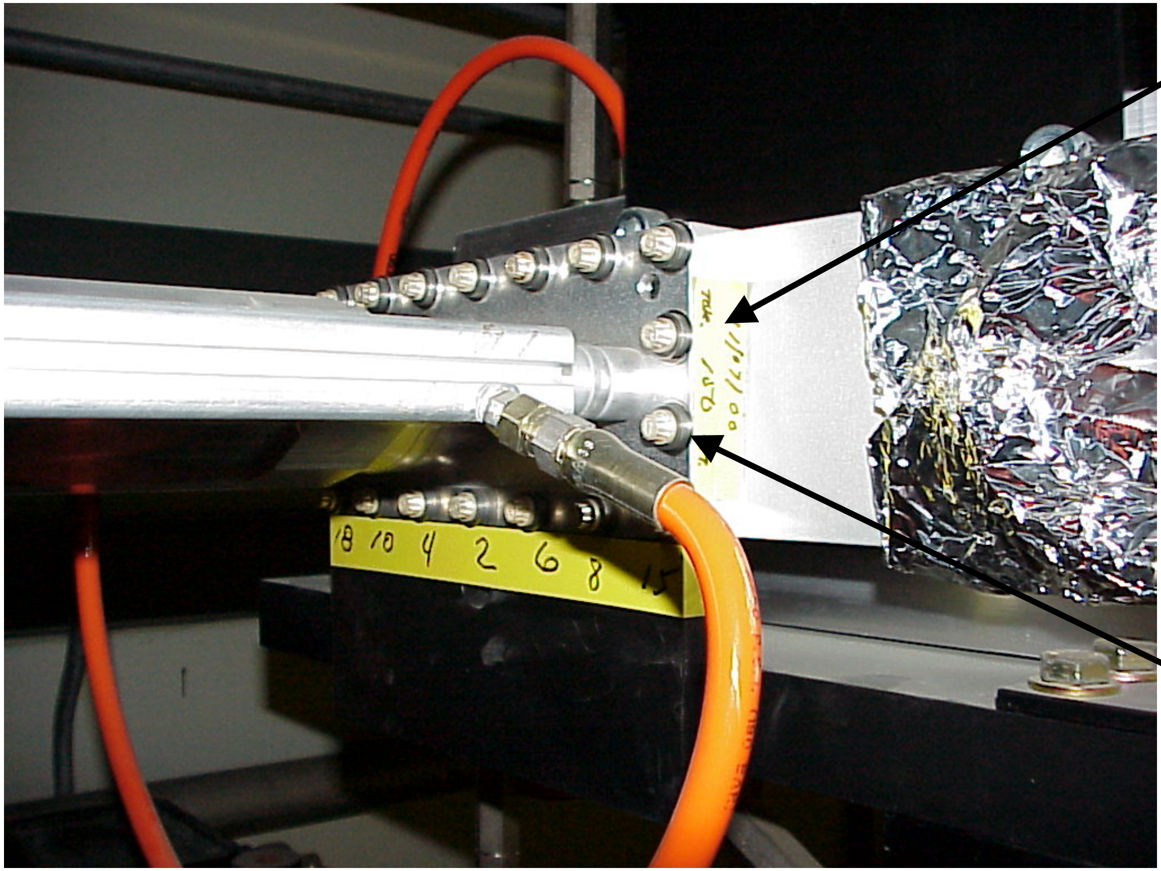


Weld Joint



Structural Joint

PEP-II LER Arc Magnet Chamber Tin-Seal Flanges



Aluminum Raised-Face Flange with 0.010" thick Tin-Seal

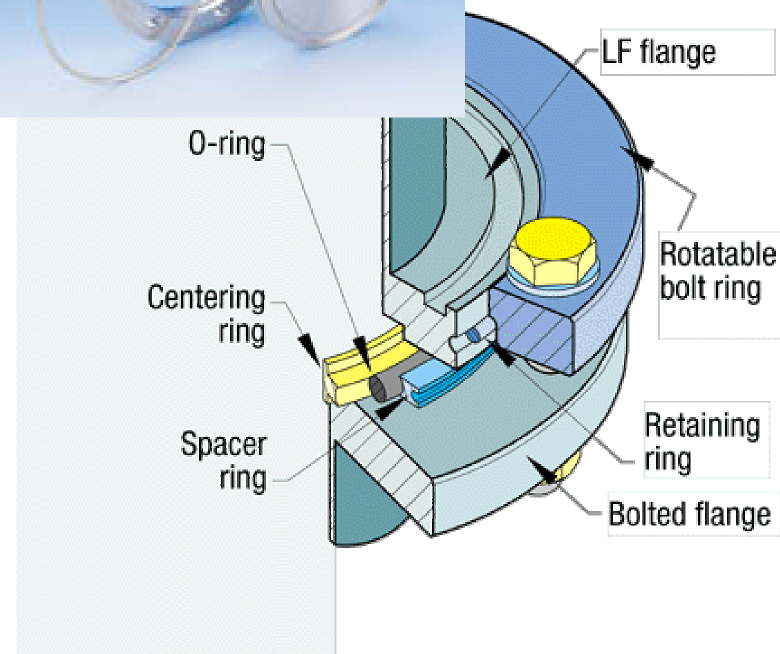
Bellville Washers

ANSI ASA Flanges

- Flanges come with either a flat-face or with an o-ring groove.
- Vacuum rated to 1×10^{-8} Torr (better suited to 1×10^{-6} Torr)
- Temperature rating is dependent on which elastomer o-ring is used (usually 150°C)
- Typical size range: 1" to 12" dia.

ISO Flanges

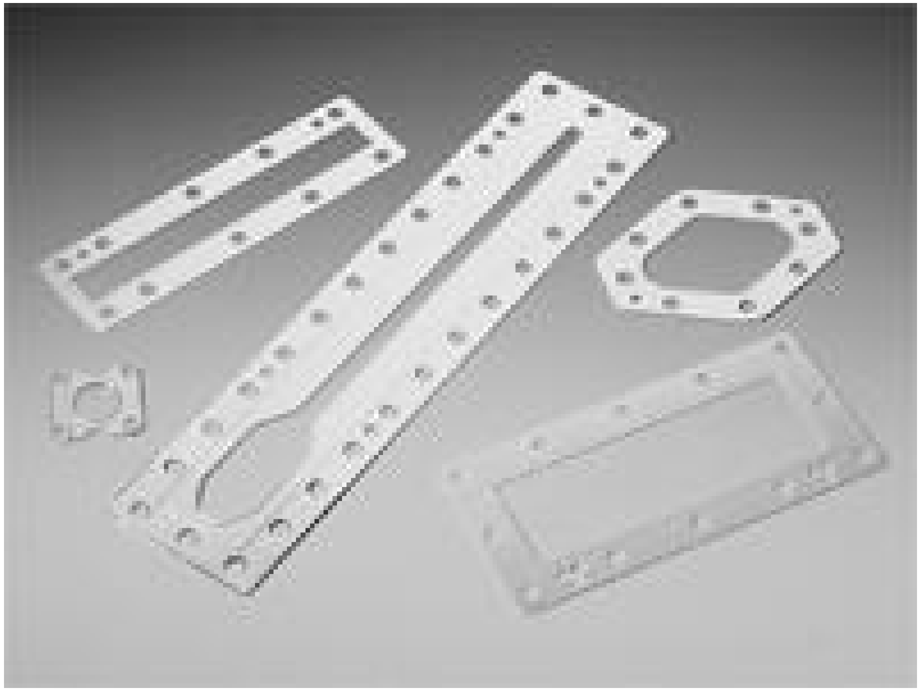
- Vacuum rated to 1 x 10^{-8} Torr (better suited to 1 x 10^{-6} Torr)
- Economical, re-usable flanges
- Elastomer gasket seal
- Temperature rated to 150°C
- Flanges come in a variety of fastening styles:
  - Kwik-flange
  - Rotatable
  - Non-rotatable
  - Double claw clamp
  - Banded clamps



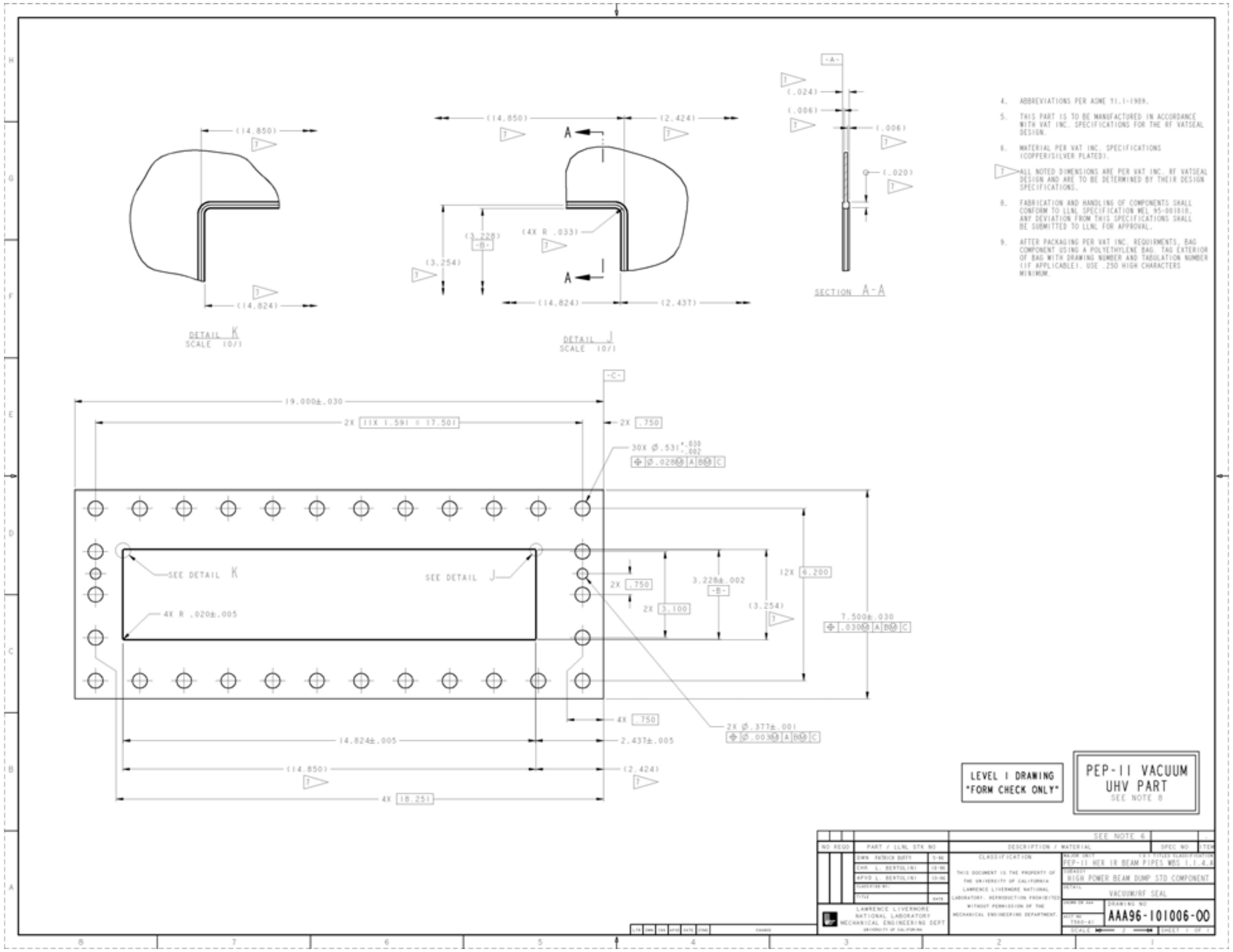
VATSEAL® Flanges

Silverplated copper

- Metal seal, bakeable to 300°C
- Custom sizes and shapes
- Radiation resistant
- UHV compatible
- Accelerator option - RF contact between flanges

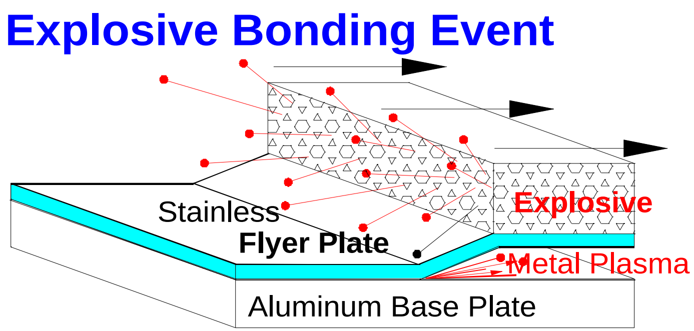


Example of a VATSEAL Flange Gasket



Explosion Bonding allows for joining a variety of metals

- Plates Are Spaced Above Each Other with Ammonium Nitrate Explosives Above
- A Point Source Progressive Charge is Detonated and the Plates Accelerated to Contact
- An Ion Plasma Jet is Formed at the Contact Point Stripping Oxides and Contaminates from the Metal Surfaces
- Extreme pressures at Impact and Ultra Clean Surfaces



- Dissimilar Atoms Bonded Together
- Metallurgical Bond is made

Ref: Atlas Technologies

Explosion Bonding Materials Matrix

Atlas Technologies Bonding Matrix		Aluminum 1	AL. Alloy 2	Chromium 3	Copper 4	CU Alloy 5	GlidCop 6	Gold 7	Hafnium 8	Indium 9	Iron 10	Lead 11	Magnesium 12	Molydbenum 13	Moly. Alloy 14	Nickel, (Invar) 15	Niobium 16	Platinum 17	Rhenium 18	Silver 19	Steel, & Alloys 20	Steel, Mild 21	Stainless Steel 22	Tantalum 23	Tin 24	Titanium 25	Tungsten 26	Vanadium 27	Zinc 28	Zirconium 29
Aluminum	1																													
AL. Alloy	2																													
Chromium	3																													
Copper	4																													
CU Alloy	5																													
Gold	6																													
GlidCop	7																													
Hafnium	8																													
Indium	9																													
Iron	10																													
Lead	11																													
Magnesium	12																													
Molydbenum	13																													
Moly. Alloy	14																													
Nickel, (Invar)	15																													
Niobium	16																													
Platinum	17																													
Rhenium	18																													
Silver	19																													
Steel, & Alloys	20																													
Steel, Mild	21																													
Stainless Steel	22																													
Tantalum	23																													
Tin	24																													
Titanium	25																													
Tungsten	26																													
Vanadium	27																													
Zinc	28																													
Zirconium	29																													

Bonding Capability

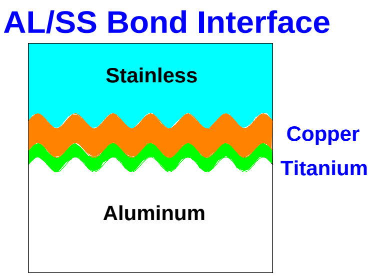
Flange Metal Standards

Beam Stop, Absorber Materials

Super-conducting Flange Materials

Ref: Atlas Technologies

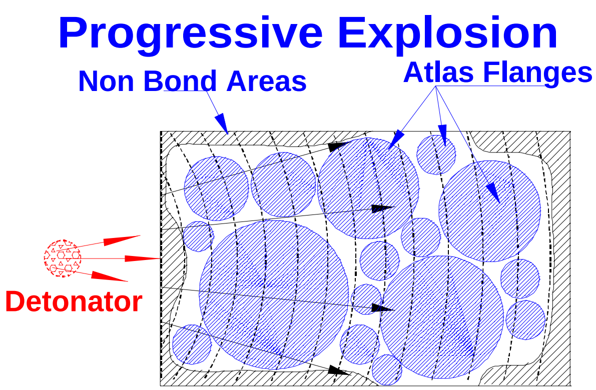
SS/AL Bond Interface
Patent# 5836623

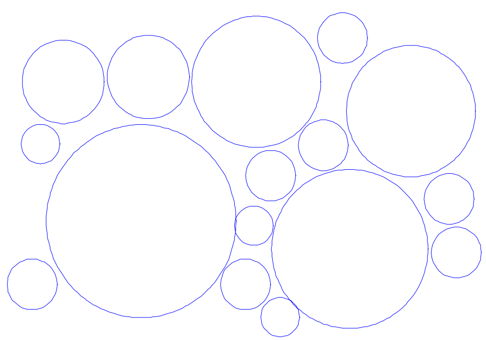


- Diffusion Inhibiting Layers
  - Copper and Titanium Interlayer
  - Enables Bonding AL/SS
- Vacuum:
  - $<1 \times 10^{-10}$cc He/Sec
- Thermal:
  - Peak 500C at weld up
  - 0-250C Operational
- Mechanical
  - Tensile 38,000 Psi,
  - Shear 30,000 Psi

Ref: Atlas Technologies

Flange Production Recipe
Patent # 5836623

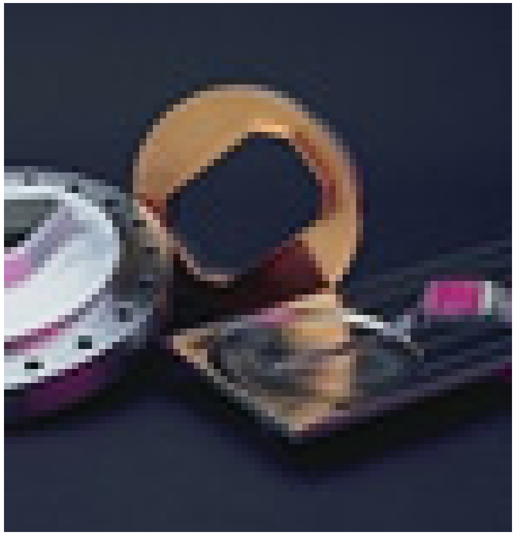




1. Bond AL Plate to Ti Sheet
   Bond SS Plate to Cu Sheet
2. Bond AL/Ti Plate to SS/Cu Plate
3. Determine Non-Bond Areas of the SS/Cu/Ti/Al Plate
4. Water Cut Discs From the Plate
5. Machine Flanges from Discs

Ref: Atlas Technologies

Different applications for bi-metallic joints



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atlas@olympus.net www.atlasbimetal.com

Ref: Atlas Technologies

The US Particle Accelerator School
Vacuum Testing and Leak Detection

Lou Bertolini

Lawrence Livermore National Laboratory

January 19-24, 2004

Measuring the speed of a pump

There are four common methods of measuring the speed of pumps:

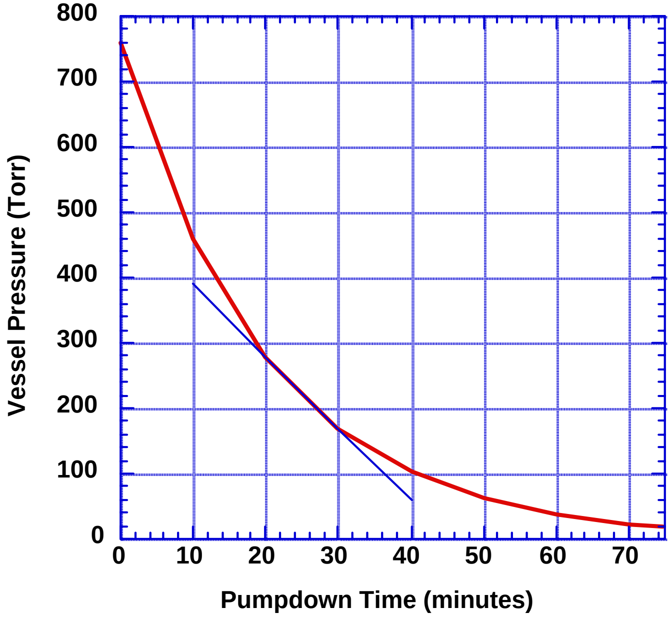
1. Rate of Pumpdown method
2. Single Gauge Dome method
3. Three Gauge Dome method
4. Fischer - Mommsen Dome method

Rate of Pumpdown Method

- Measure the rate in which a pump evacuates a vessel
- This method is normally used to measure the speed of roughing pumps

$$Q = \frac{d(VP)}{dt} = P\frac{dV}{dt} = V\frac{dP(t)}{dt}$$

$$Q = V\frac{dP(t)}{dt}$$



Rate of Pumpdown Method (continued)

$$C_t \text{ should be} >> S,\ P \sim P_{pump}:$$

$$Q_v \sim SP(t)$$

$$S = S_{max}\left(1 - \frac{P_B}{P}\right)$$

$$S_{max}\left(1 - \frac{P_B}{P}\right)P(t) = V\frac{dP(t)}{dt}$$

Solving for P(t),

$$P(t) = P_B + P_o e^{-\left(\frac{S}{V}\right)t}$$

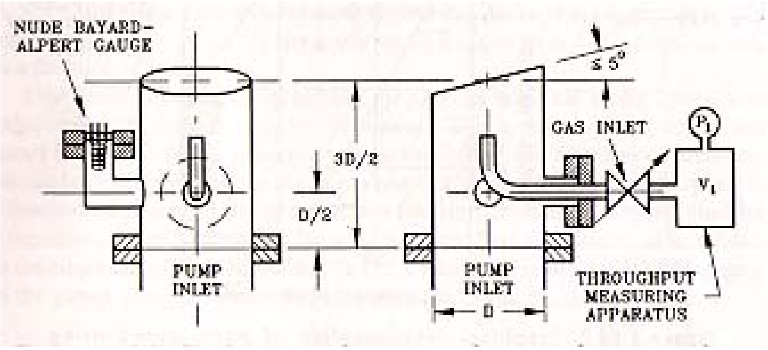
Single Gauge Dome Method

- Used for many years to measure diffusion pump speeds
- Pump throughput is determined by measuring dP/ dt of a known volume

$$Q_d = \left(\frac{dP}{dt}\right)V$$

- Pump speed is determined by assuming the chamber pressure is the same as the pump pressure

$$S = \frac{V_d}{P_d} \times \frac{dP}{dt}$$



- Requirements for this test method
  - —gauges calibrated for test gas
  - —known volume

Three Gage Method

- Pump throughput is determined by measuring the pressure difference along a tube of known conductance

$$Q_p = C_1 (P_1 - P_2)$$

- We can either assume that the pressure of the pump is equal to P_3 or we can calculate the conductance between the pump and P_3

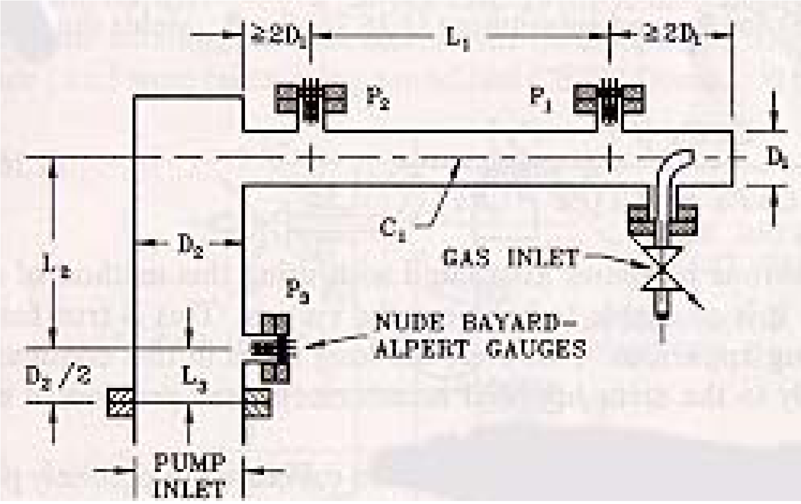
$$C_3 = 12.1 \frac{(D_2)^3}{L_3}$$

$$Q_p = C_3(P_3 - P_p) = C_1(P_1 - P_2)$$

$$P_p = P_3 - \frac{C_1}{C_3}(P_1 - P_2)$$

- The pump speed is ultimately determine by the equation:

$$S_p = \frac{C_3 C_1 (P_1 - P_2)}{C_3 P_3 - C_1 (P_1 - P_2)}$$



Problems with the Three Gage Method

- Calculated conductances introduce errors
- The three pressure gages must be "normalized" with respect to each other

Typically,

$$P_{abs} \neq P_{1i} + P_{2i} + P_{3i}$$

Normalized,

$$P_{1i} = k_2 P_{2i} + k_3 P_{3i}$$

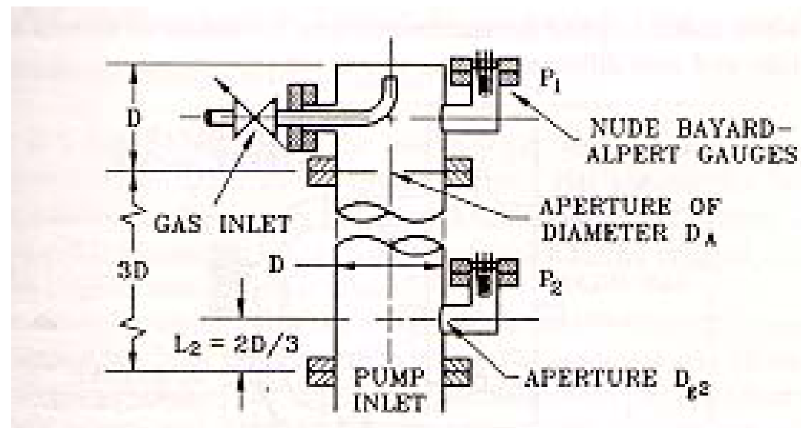
Fischer - Mommsen Dome Method

- Also known as the CERN method
- The aperture diameter is sized to maintain a minimum pressure differential. This requires some knowledge of the pump speed.

$$Q_p = C_a(P_1 - P_2)$$

$$P_p \sim P_2$$

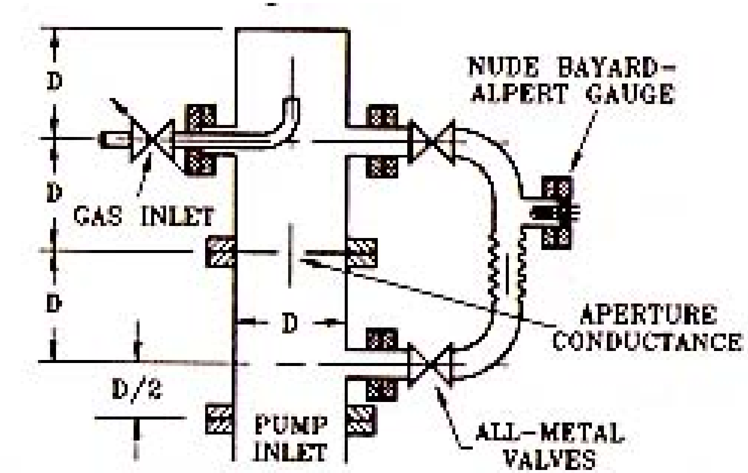
$$S_p = C_a \frac{(P_1 - P_2)}{P_2}$$



- Pressure gages need to be "normalized" to each other.

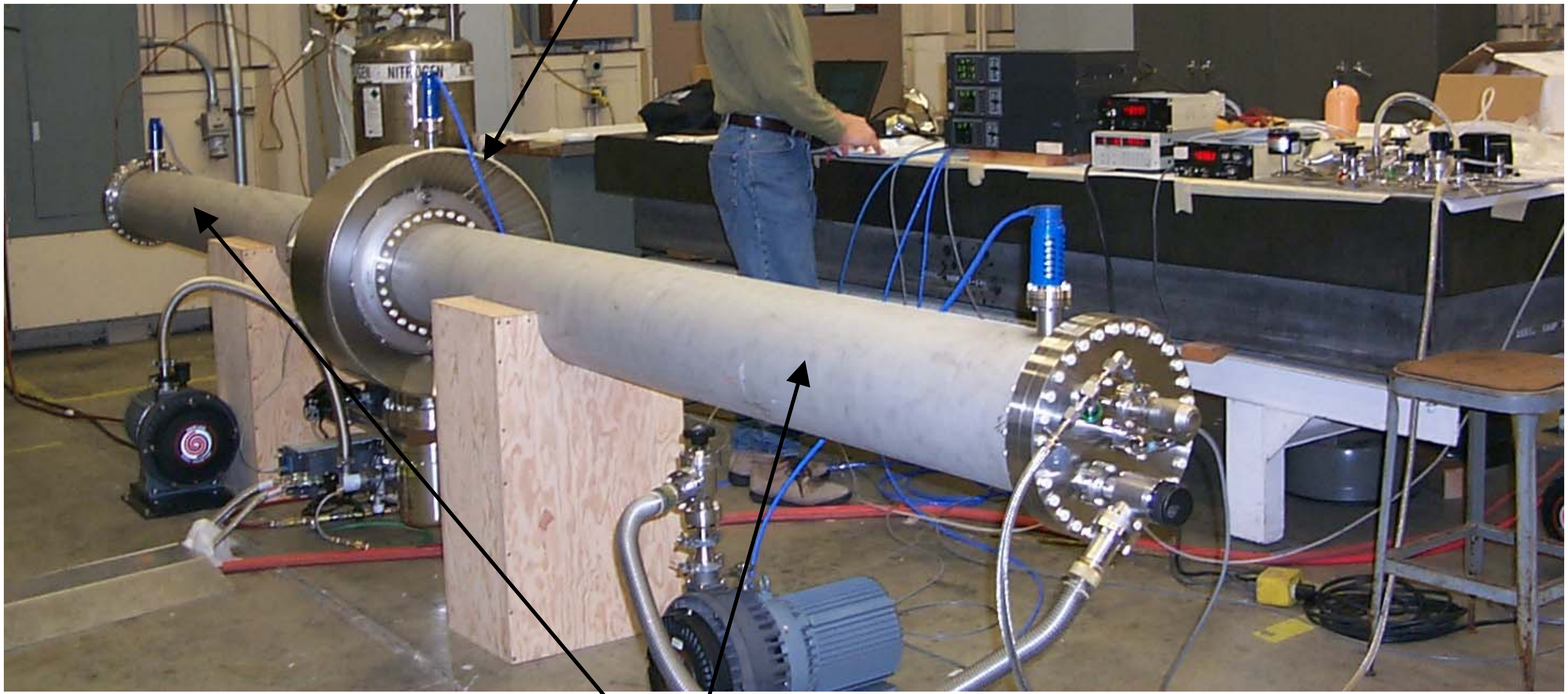
Modified CERN Method

- Utilizes a single gauge.
- By opening and closing the isolation valves, both P_1 and P_2 can be determined with the single gauge.
- Gauge normalization is eliminated (assuming gauge linearity with pressure).



DARHT II Accelerator Intercell Pump Speed Test

Intercell Pump Station



Tubes mock-up the Accelerator Bore

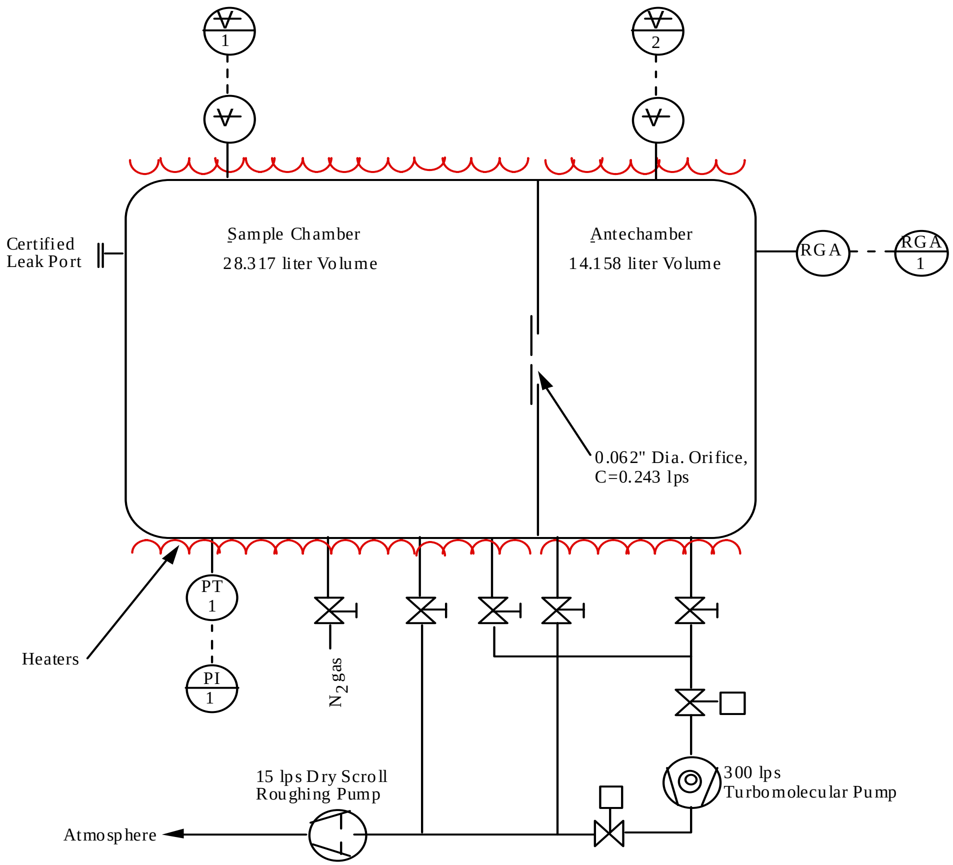
Desorption (outgassing) Tests

There are two approaches to conducting outgassing tests:

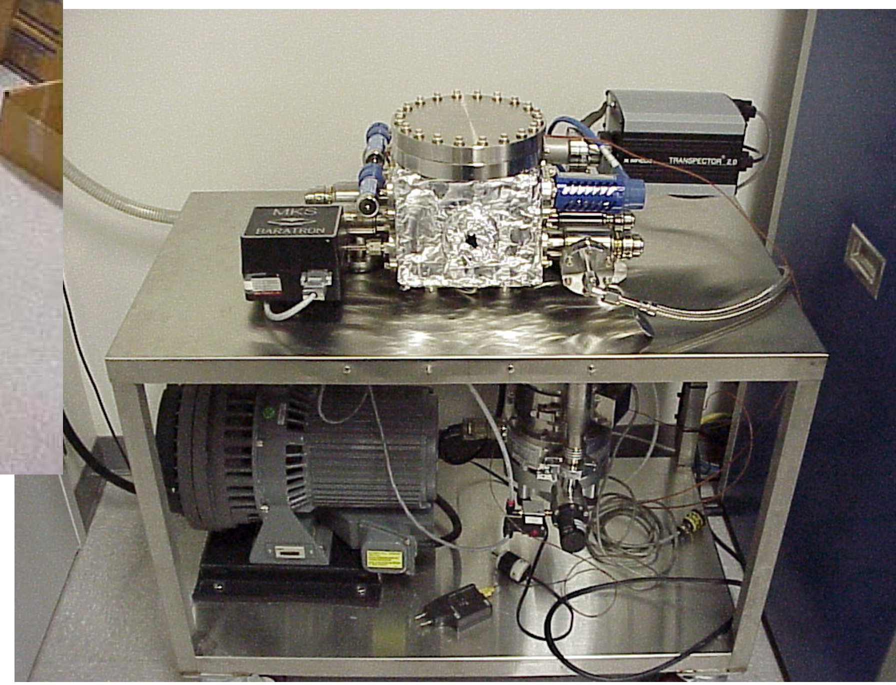
1. Measure rates of representative material samples within a test stand (such as an AVS dome).

2. Measure rates of actual vacuum system components (such as whole beam pipes, collimators, beam dumps, etc.).

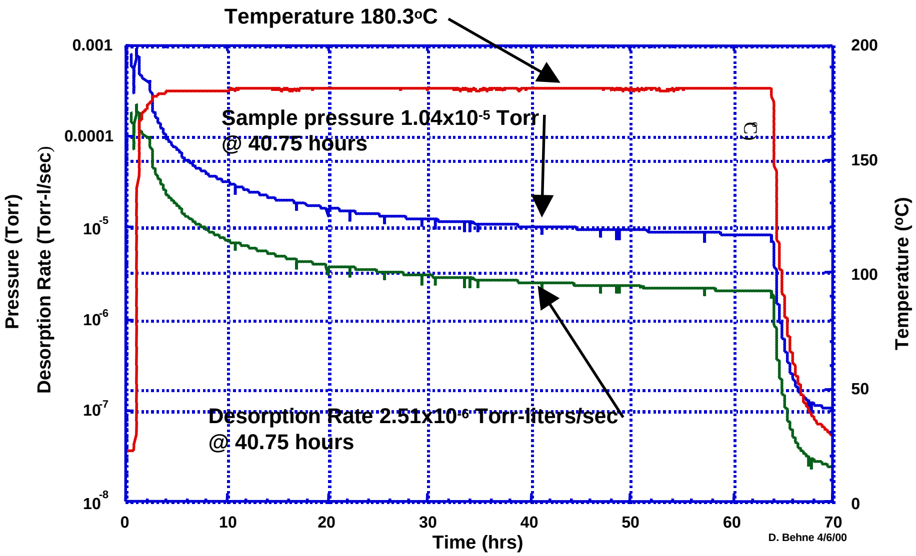
LLNL Outgassing Station Schematic

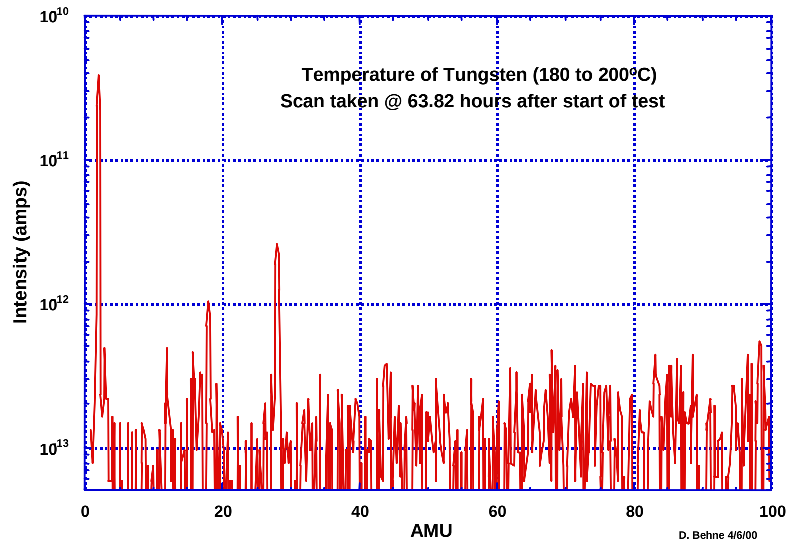


Photos of LLNL Outgassing Stations

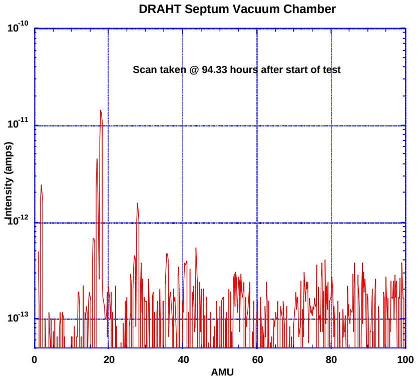


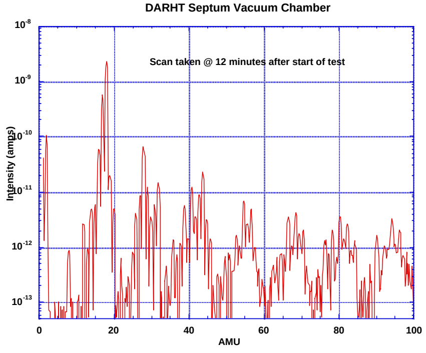
Sample Results from an Outgassing Test

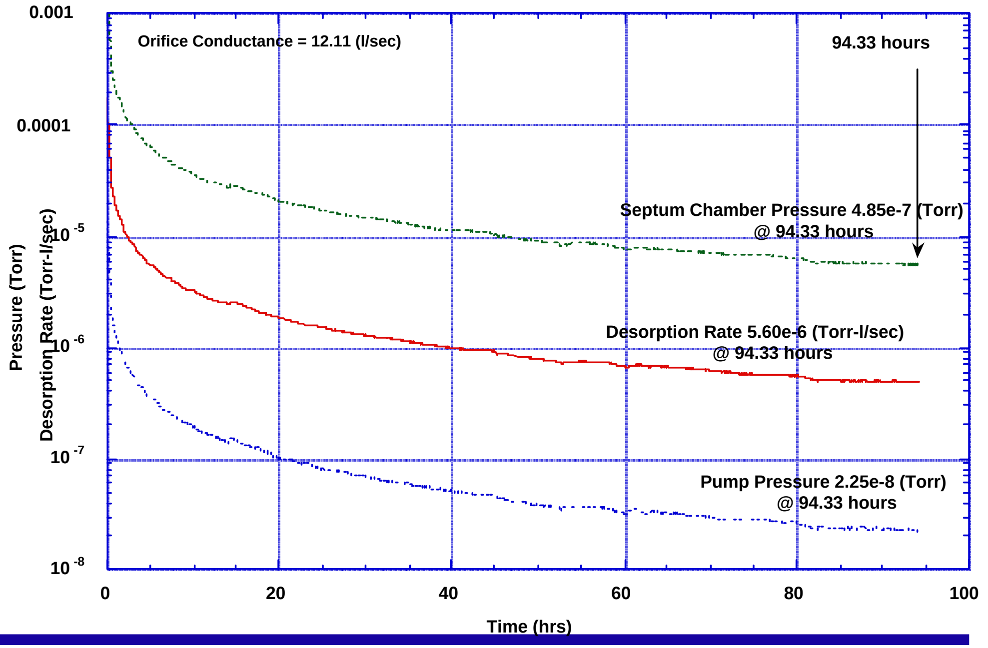




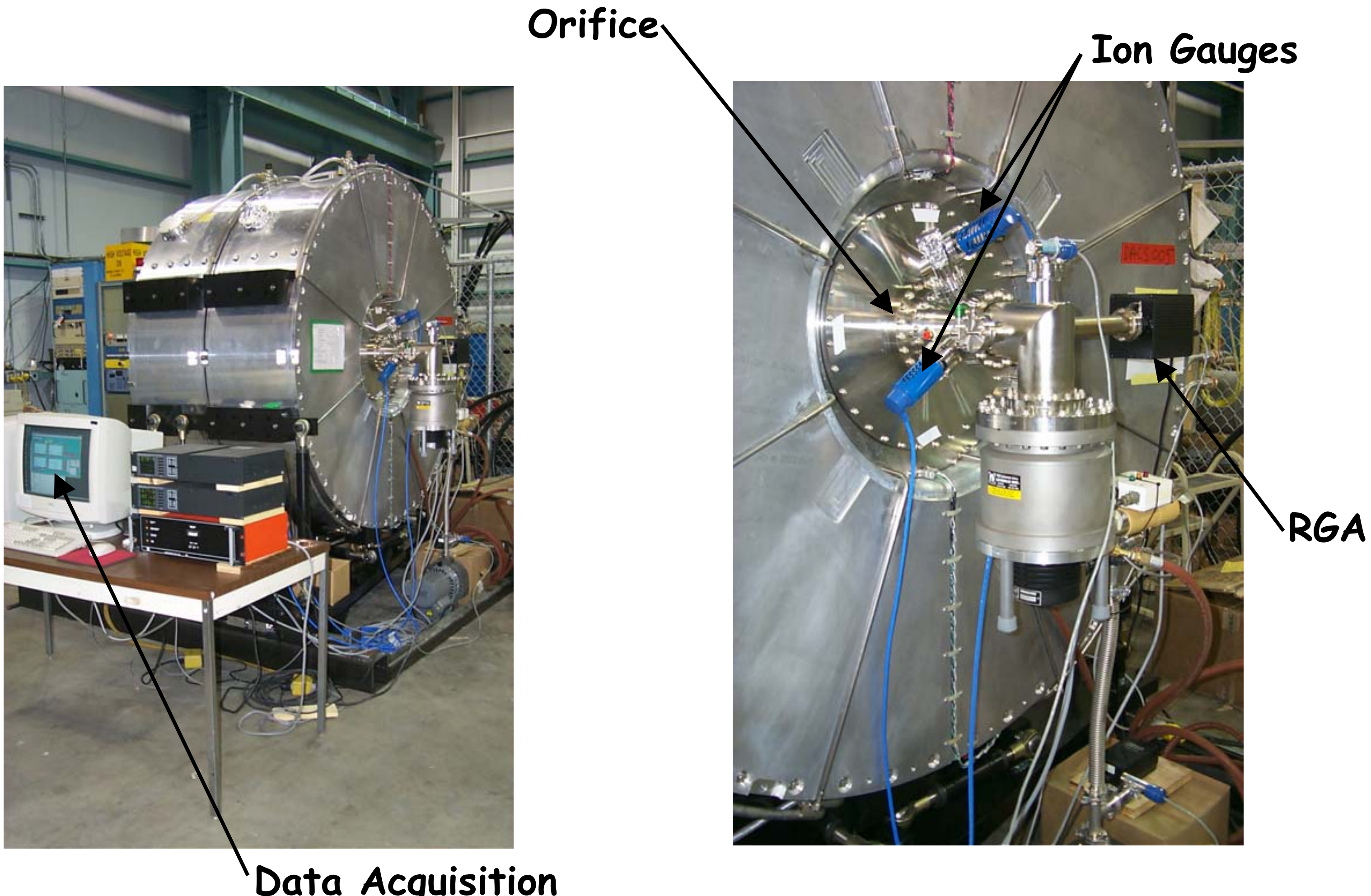
DARHT II Septum Chamber Test Results



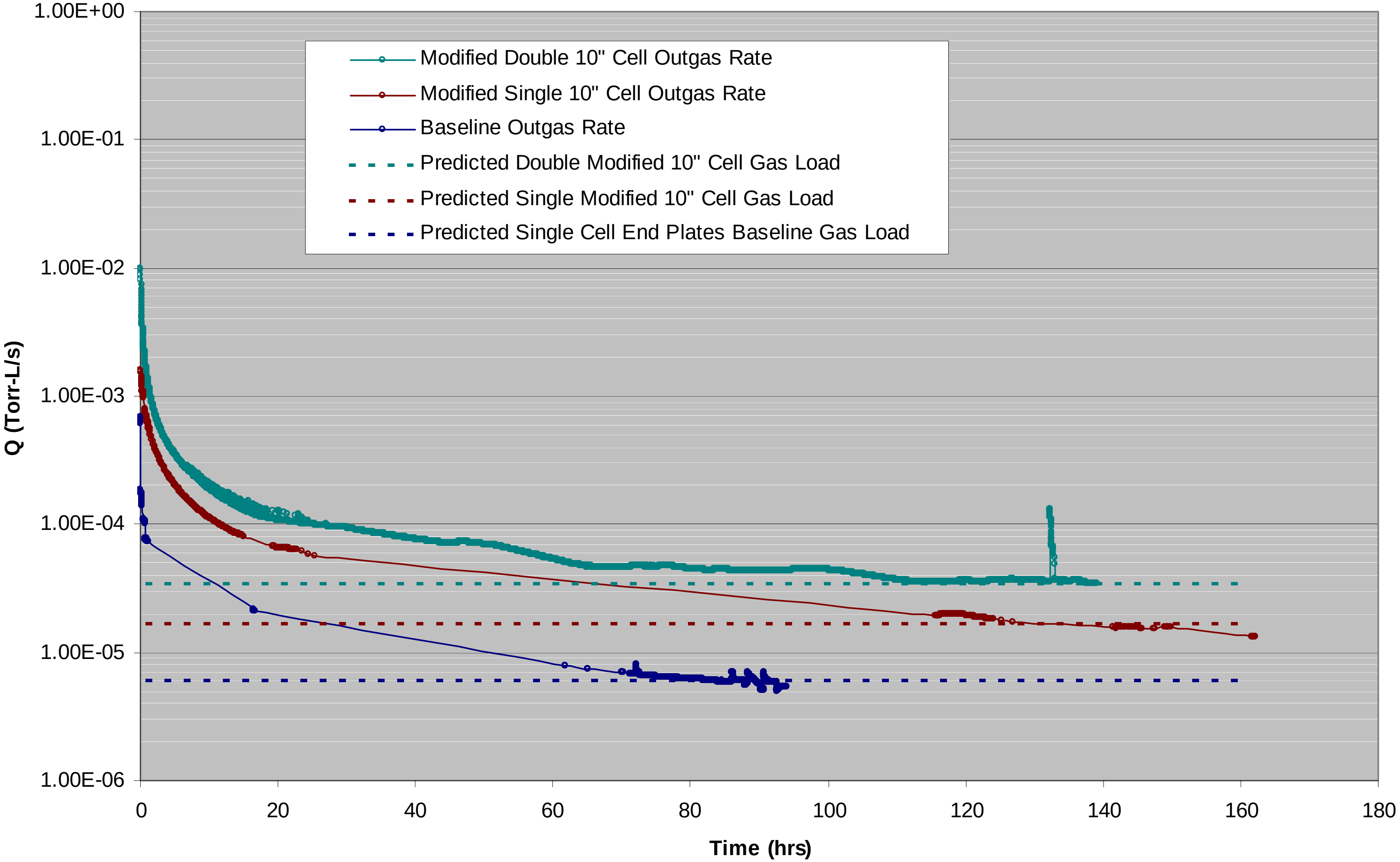




DARHT II Accelerator Cell Outgassing Tests



Data from DARHT II Accelerator Cell Outgassing Tests



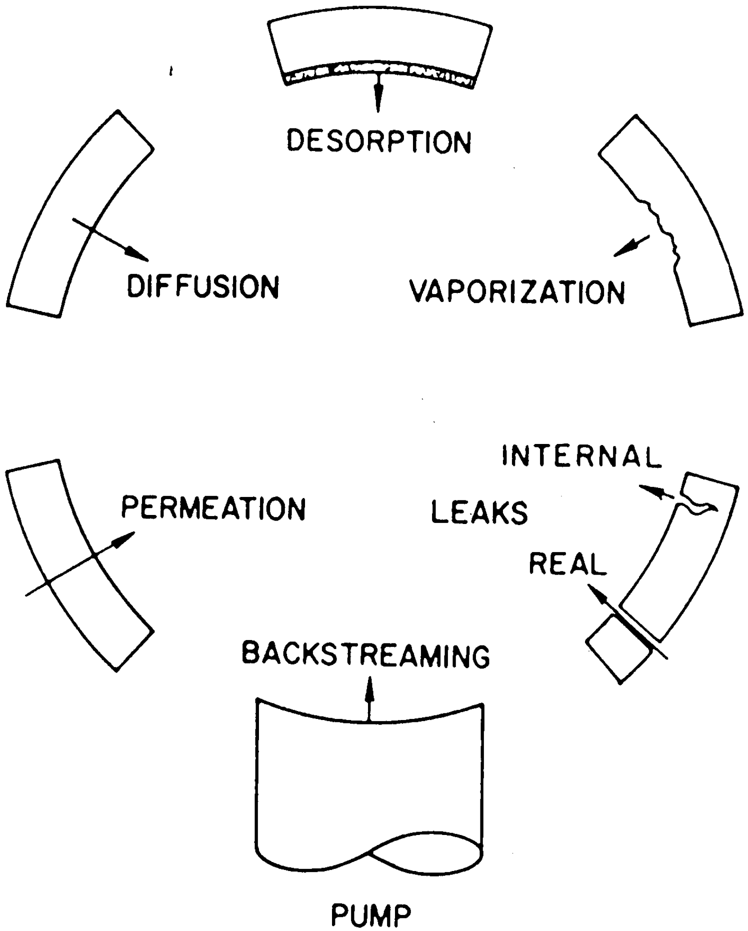
Fundamentals of Vacuum Leak Detection

- The Mike Benapfl "motherhood" statement. "Leak Detection is an art. Not everyone is an artist!"

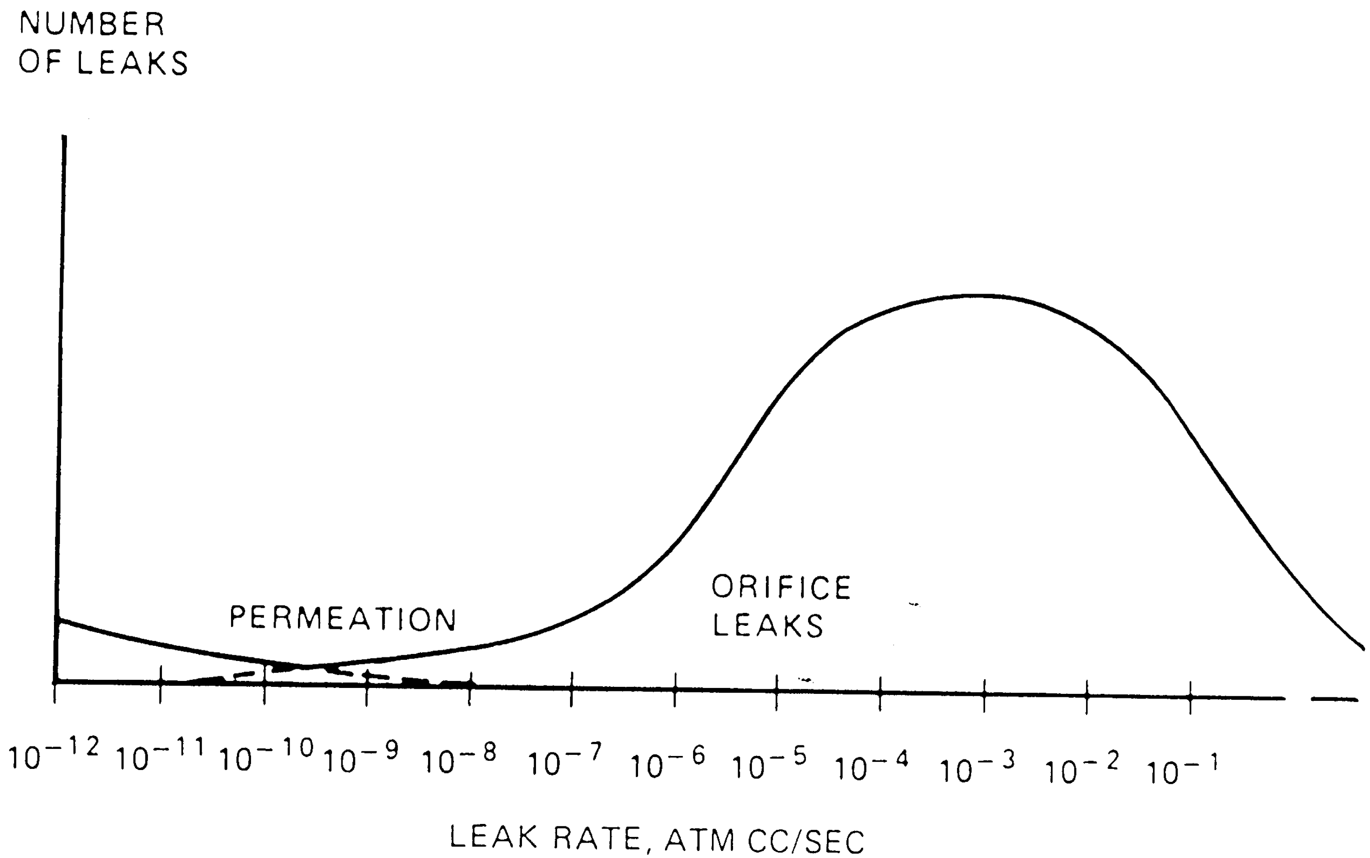
- Leak Detection should be performed in accordance with some ASTM Standard.
  - ASTM E493-94
  - ASTM E498-94
  - ASTM E499-97

- Leak Detection should be performed in a series of logical steps.

Sources of Gases in a Vacuum System



Distribution of Leaks



How do leaks adversely affect us?

- Is your machine or process being compromised by the current vacuum system performance?
  - poor beam lifetime
  - unacceptable detector backgrounds
- Leaks determine the base system pressure.
- Choosing the appropriate method of leak detection will help you quickly find the leaks.
  - pressure gauges, mass spectrometers, *Snoop*, *acoustical*

What is the Significance of a Leak?

Change in chemical composition within the vacuum vessel
Change in the process
Increase in pump speed required to maintain the desired pressure

EXAMPLE:

A 1000-division leak will require a calculatable pumping speed to maintain a pressure (assuming the pump can handle the gas species).

Using the relationship Q = S x P and the calibration data, we can determine the speed required.

$$Q = 2 \times 10^{-10} \frac{\text{atm - cm}^3}{\text{sec - division}} \times 1000 \text{ divisions} = 2 \times 10^{-7} \frac{\text{Torr - liters}}{\text{sec}}$$

$$S = \frac{Q}{P} = \frac{2 \times 10^{-7} \frac{\text{Torr - liters}}{\text{sec}}}{1 \times 10^{-7} \text{ Torr}} = 2 \frac{\text{liters}}{\text{sec}}$$

Different Methods of Leak Detection

- Acoustical (sonic and ultrasonic)
- Bubble testing
- Dye penetrant
- Vacuum decay ("rate of rise" test)
- Pressure decay
- Thermocouple gauges
- Ion gauges and ion pumps
- Halogen leak detectors
- Partial pressure analyzer (PPA)
- He Mass Spectrometer Leak Detector (HMSLD)

The Rate of Pressure Rise in a Vacuum Vessel is a Useful Inspection Technique

- This procedure integrates the accumulation of gases in the vessel from all sources; outgassing, permeation, inleakage, etc.

- The procedure is to evacuate the vessel to a pre-determined pressure, isolate it from the pump(s) and measure the rate of pressure increase.

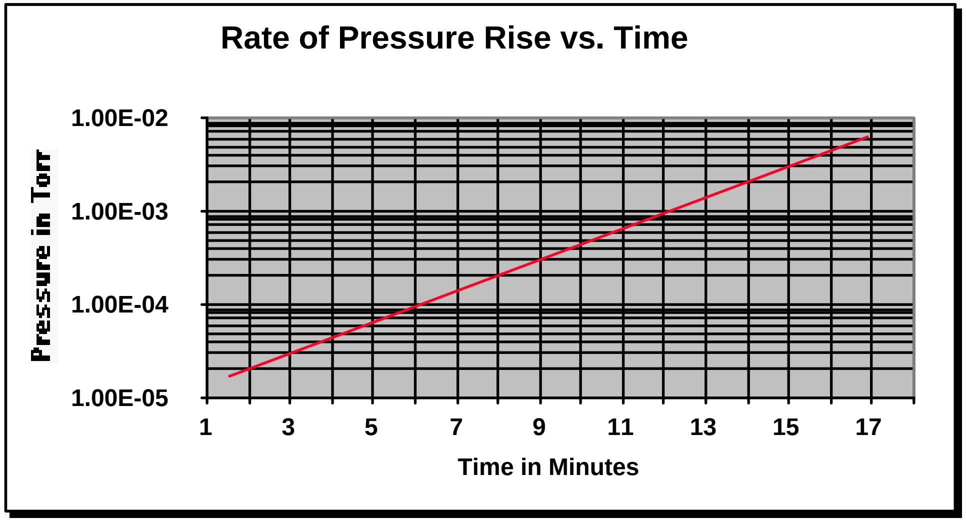
$$Q = V \frac{P_2 - P_1}{t_2 - t_1}$$

- What is measured is "Q", gas load in Torr-liters/sec, assuming the vessel volume is known or approximated.

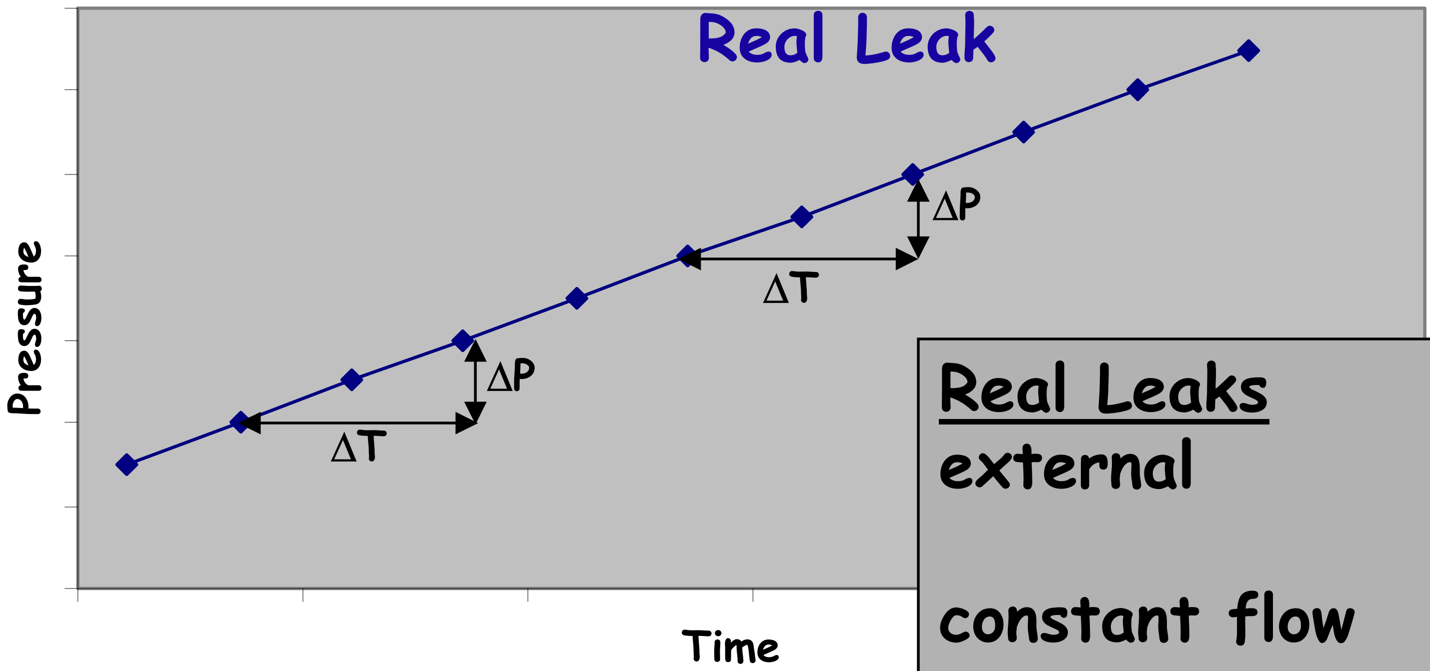
- The slope of the resulting curve can be used to determine the integrity of the vessel regarding leaks and surface cleanliness, and as a proof-test to verify that the vessel will achieve the desired pressure when placed in operation.

A Rate of Pressure Rise Test can be used to Your Advantage in Several Ways

- The rate of pressure rise can be used to determine in-leakage, permeation, and outgassing in a system or vessel.
- As an aid to the designing of new systems, rate of pressure rise data can be used to "model" the gas loads of existing systems or process.
- The pumping speed delivered to the vessel can be determined by using the rate of pressure rise data and the known pressure at the start of the test.



Rate of Pressure Rise (Real Leak)



Real Leaks

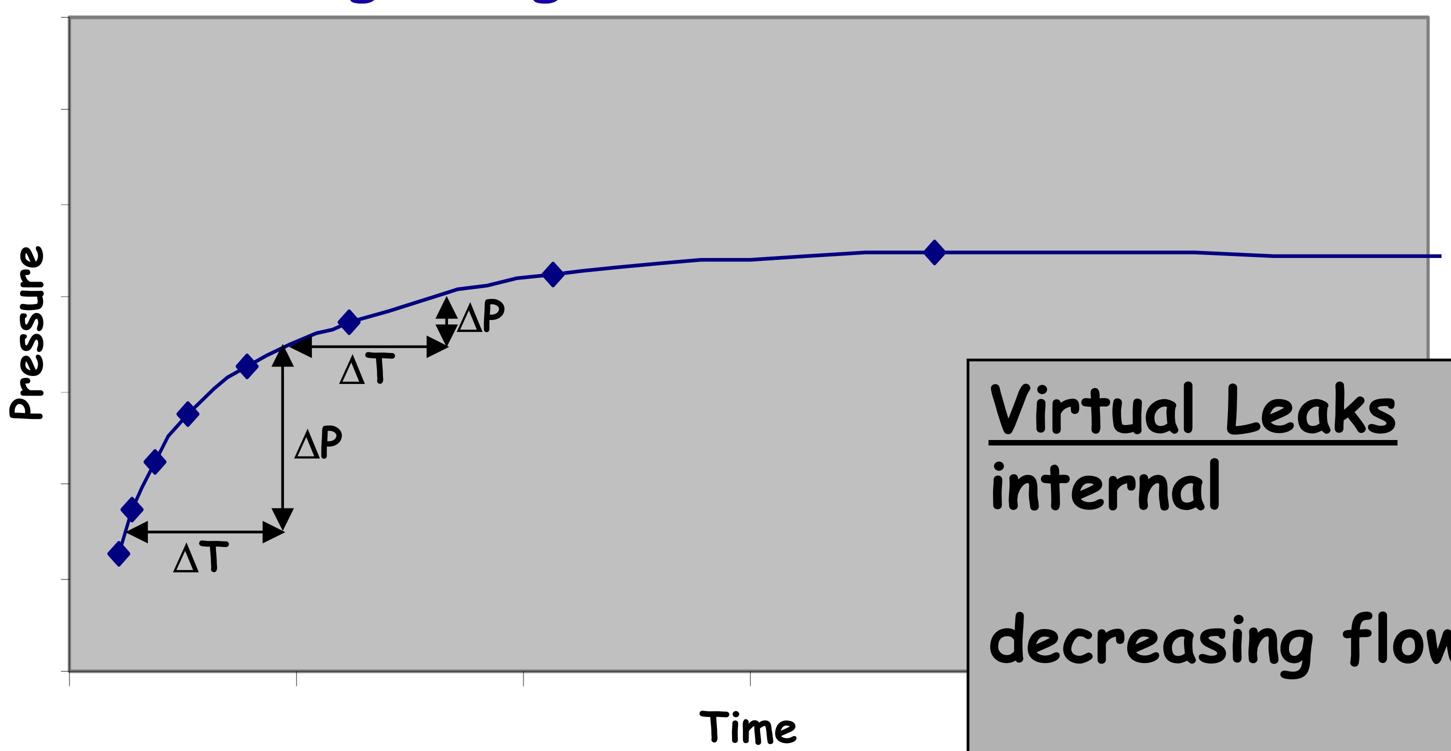
external

constant flow

constant pressure rise

Rate of Pressure Rise

Outgassing or a Virtual Leak



<u>Virtual Leaks</u>

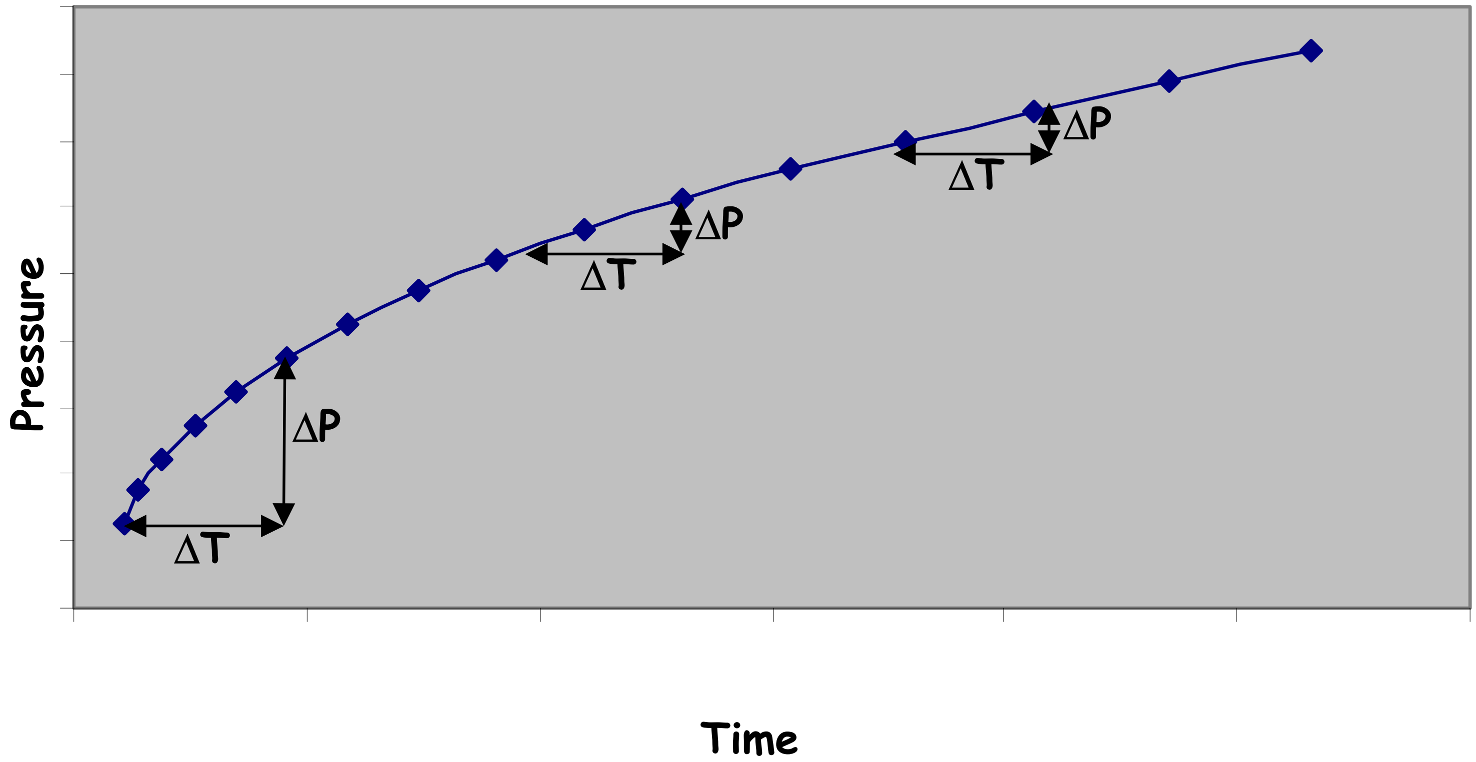
internal

decreasing flow

decreasing pressure rise

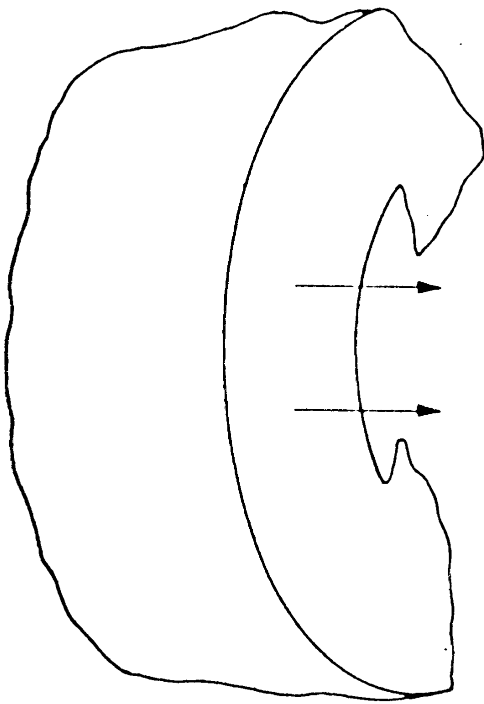
Rate of Pressure Rise

Outgassing + Real Leak



Vacuum Leak Detection

For Hole With Diameter At Least 10 X Length

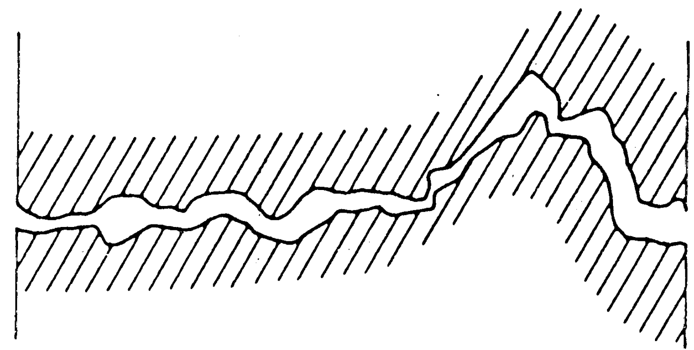


Void

Molecular Flow Through Circular Aperture:

Helium Rate = 2.7 x Air Rate

Kinetic Theory



Tortuous Path Whose Length is Greater Than Cross-Section:

Helium Rate May be Equal to Air Rate for Large Leak or Many Times Larger for Small Leak

Most Leaks

Types of Leakage

Gas passes through holes or cracks in the vessel wall. Flow is a function of the size of the flaw.

Permeative gas diffuses through a material having no holes large enough to allow passage of more than a few molecules of gas per unit time.
(polymeric materials such as rubber gaskets, O-rings diaphragms, etc.)

Vacuum Leak Detection

Leakage and Outgassing

In general, unless leaks are large, the effects of outgassing will overwhelm the effects of the leaks.

Technique:

1. Pump from ~100 mtorr to 1 mTorr, and record time.
2. Isolate pumps, allow the pressure to rise to 100 mTorr.
3. Repeat step 1 and compare pumping times.

If $T_1 = T_2$, then a leak is suspected.
If $T_2 < T_1$, then outgassing may be the culprit.

Average Composition of Dry Air

Knowing the composition of air can help determine whether you have a true leak or not.

Gas	Partial Pressure (Torr)	Volume %
Nitrogen	593	78.1
Oxygen	159	20.9
Argon	7.1	0.934
Carbon dioxide	0.25	0.033
Neon	1.4×10^{-2}	0.0018
Helium	4.0×10^{-3}	0.00053
Methane	1.5×10^{-3}	0.0002
Krypton	8.6×10^{-4}	0.00013
Hydrogen	3.8×10^{-4}	0.00005
Nitrous Oxide	3.8×10^{-4}	0.00005
Xenon	6.6×10^{-5}	0.0000087

Average Molecular Size of Some Gas Molecules

Gas molecules must "fit" through real leaks to be a problem. Molecules are not discrete spherical particles, however….molecular diameter can be calculated from gas viscosity.

Hydrogen	2.75 Angstroms
Helium	2.18
Argon	3.67
Oxygen	3.64
Nitrogen	3.64
"Air"	3.74
Carbon Dioxide	4.65
Xenon	4.91

A 10^{-10} atm-cc/sec air leak @ 20° C in a 0.25" plate will have a diameter of 10^{-5} cm, or 10^{3} Angstroms, or about 300 times the size of an air molecule.

Helium is the most common gas used as a "tracer" in locating leaks

When compared to other gases, helium has certain advantages as a tracer:

- Low molecular weight
- High intrinsic velocity
- Small molecular size
- Chemically inert
- Non-flammable
- Readily available
- Inexpensive
- Low partial pressure in the atmosphere

Some disadvantages are:

- Is not well pumped by ion or chemical combination pumps
- Is not well pumped by cryogenic pumps

Molecular Velocities

Molecules in the gas phase have a distribution of velocities, the average velocity (v):

$$v = 14{,}551 \left(\frac{T}{M}\right)^{1/2} \quad \text{cm/s}$$

M = molecular weight

For N_2 at room temperature (20 °C) :

$$v = 14{,}551\left(\frac{293}{28}\right)^{1/2} = 4.71x10^4 = 1054 \quad \text{mph}$$

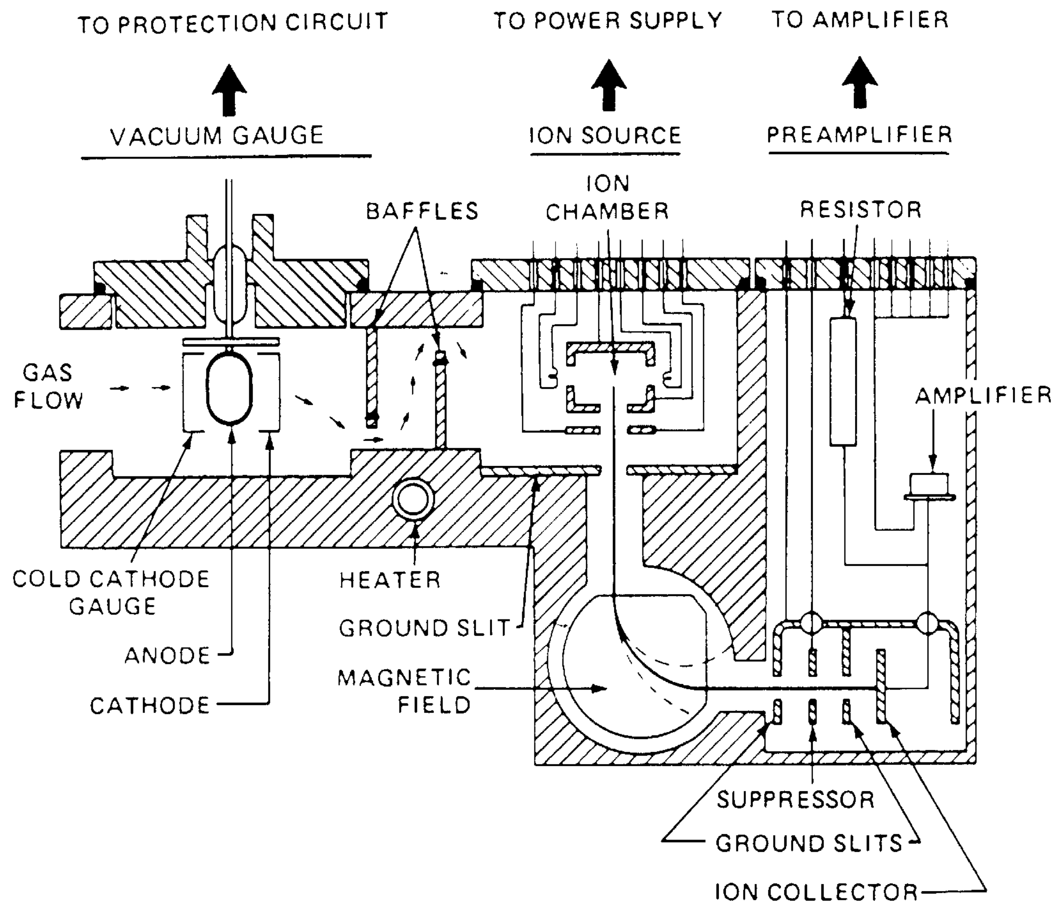
Note that v is independent of pressure

What is a Helium Mass Spectrometer Leak Detector?

- **It is a Helium-specific partial pressure analyzer**
- **It detects Helium applied as a tracer or probe gas**
- **It consists of:**

    the mass spectrometer tube
    it's own vacuum system capable of 10^{-5} Torr in the spectrometer tube
    a sensitive and stable amplifier
    valves, and auxiliary pumps for interfacing to vacuum system
    a display for monitoring leak rate
    normal-flow vs. contra-flow configurations

Cross-section of a Typical Spectrometer Tube



Calibration calculation

Calibration of a leak detector is accomplished by attaching the leak standard, allowing the leak to flow into the detector, and reading the output from the spectrometer tube on the leak rate meter. A straight forward calculation is made and the calibration of the meter is understood. It must be noted that variations in temperature, detector pumping speed, electronic "drift" and background noise can influence the stability of the calibration.

$$\text{Calibration} = \frac{\text{Standard Leak Rate}}{\text{Change in Leak Rate Meter}}$$

$$\textit{Calibration} = \frac{\text{atm - cm}^3}{\text{sec - division}} = \frac{2 \times 10^{-7}}{1000} = 2 \times 10^{-10}\ \frac{atm - cm^3}{sec - division}$$

Vacuum Method of Leak Detection

Most common (and desirable method): The HMSLD is connected to the system, and a helium tracer gas is applied to the exterior of the system under test in a controlled manner. ASTM E-498-94

Connection configurations:

1. Directly to the component or system

2. In parallel with other pumps on the system

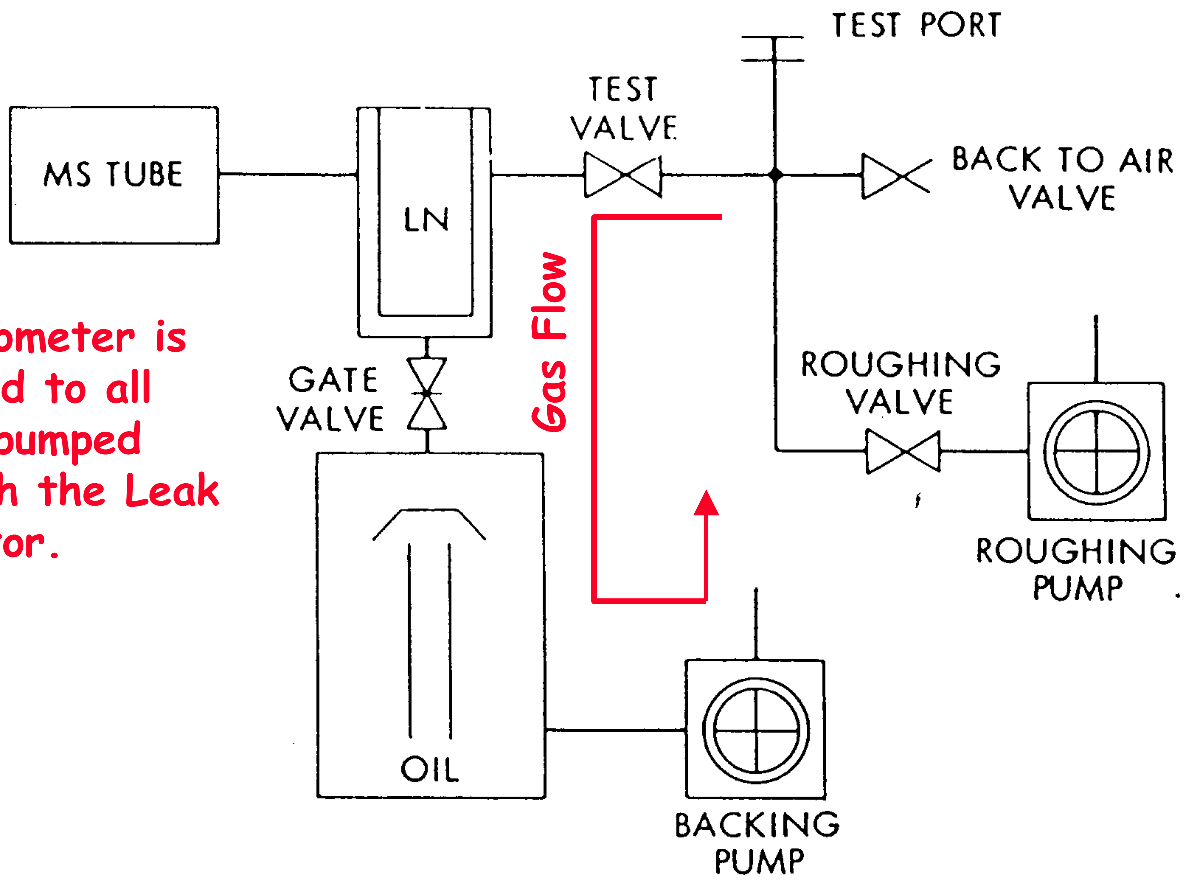
3. In series, backing another pump connected to the system

Vacuum Method of Leak Detection

Most helium leak detectors have two test modes; normal-flow and contra-flow. You, as the operator, can decide which mode you should be operating in.

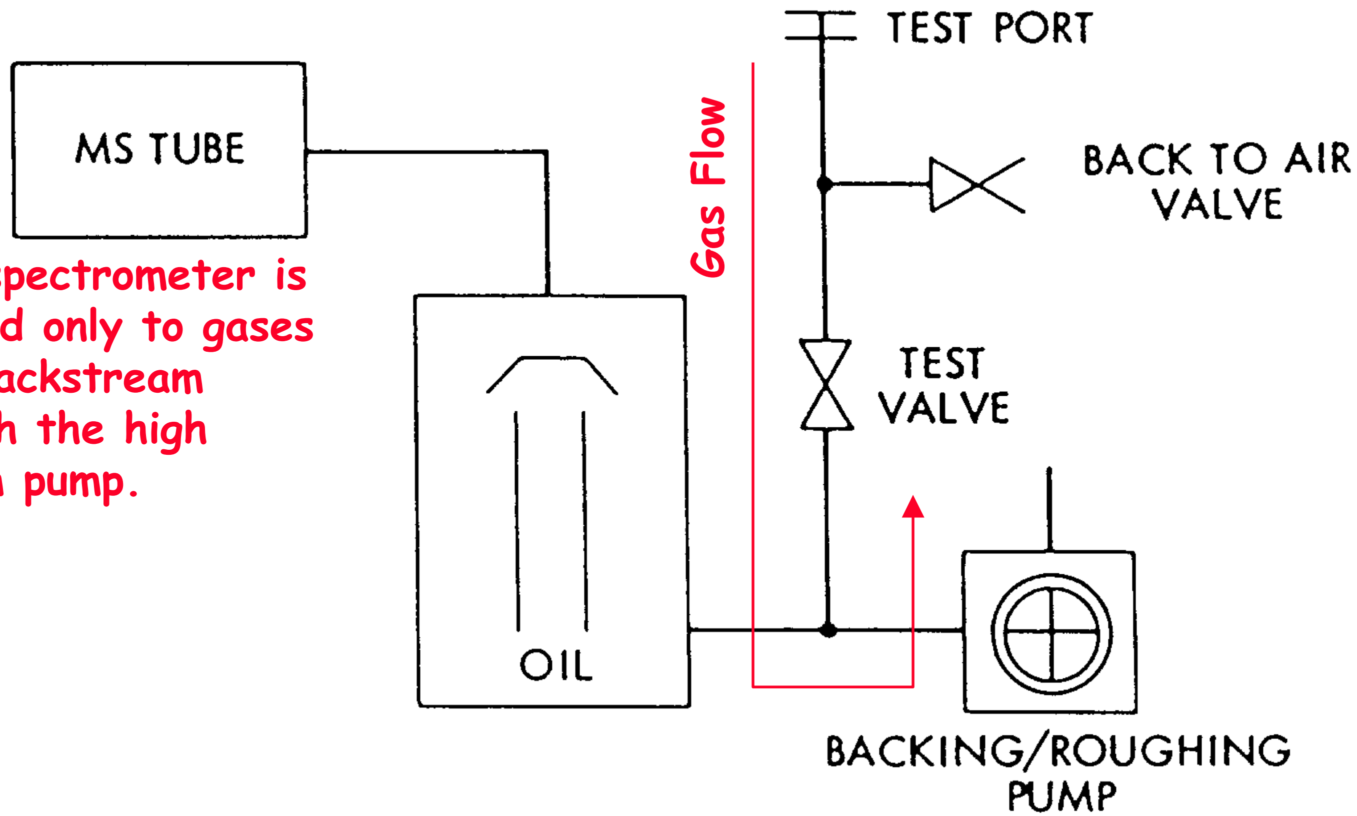
Either mode has distinct advantages and disadvantages!

Schematic of "Normal Flow" Configuration



Mass spectrometer is exposed to all gases pumped through the Leak Detector.

Schematic of Contra-flow Configuration



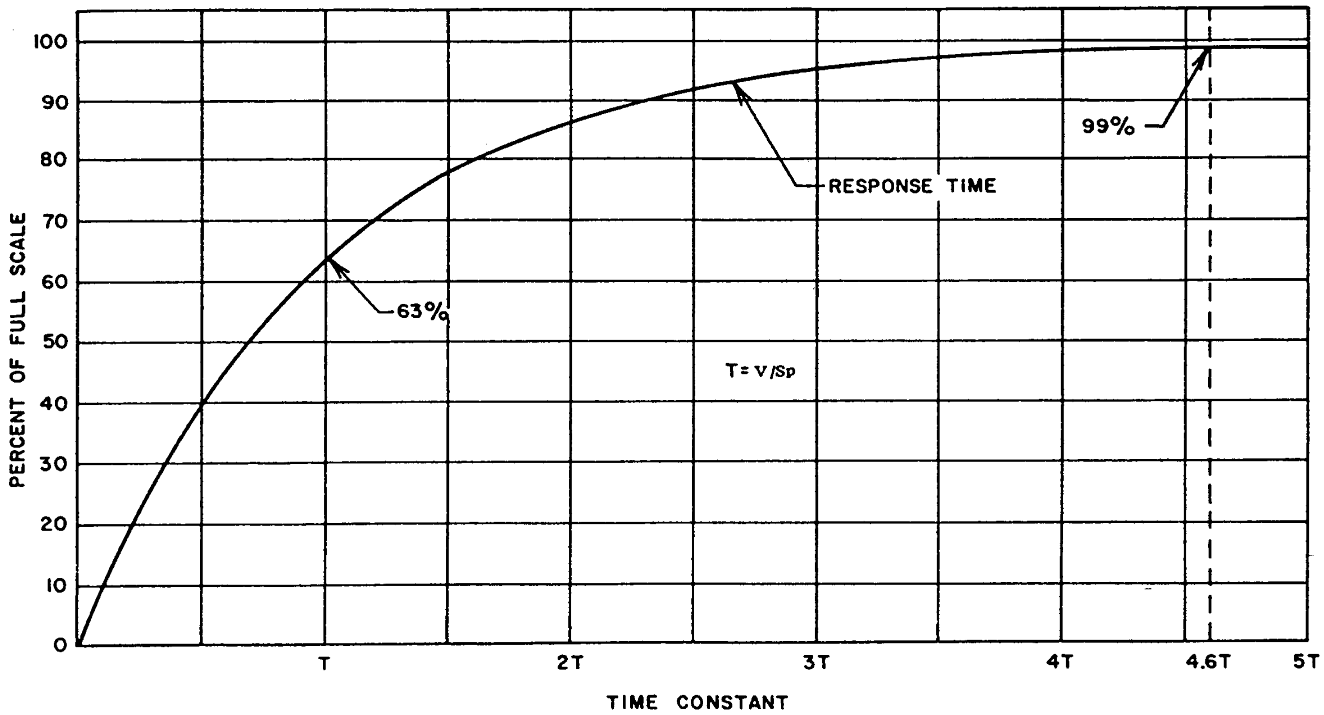
Mass spectrometer is exposed only to gases that backstream through the high vacuum pump.

HMSLD Response Time

Response time is often defined as the time it takes a HMSLD to indicate a rise in signal (63%) after the application of a tracer gas. Response time is dependent on:

- Sensitivity of the instrument
- Tracer gas leak rate
- Volume of the system under test
- Pumping speed for helium of the HMSLD
- Pumping speed of any additional pumps

Time Constant and Response Time



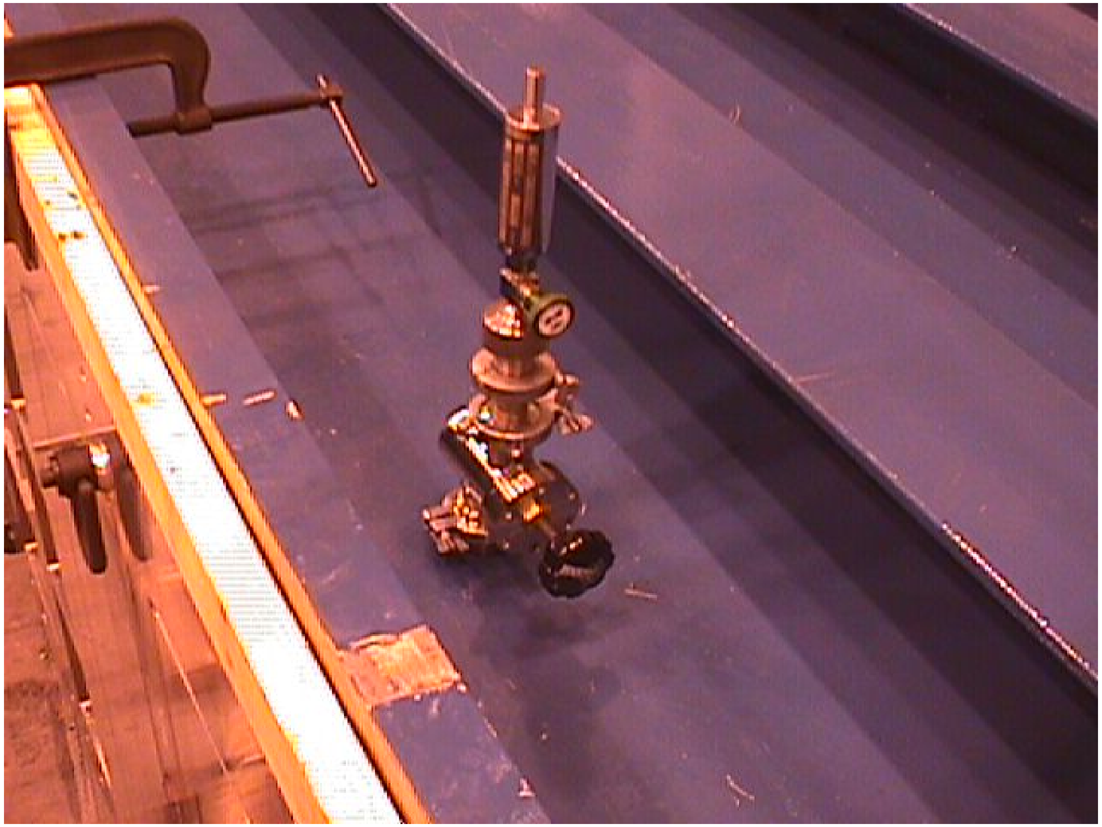
Manifolding Cells Together for Leak Testing of the NIF Spatial Filter Vacuum Vessel (Ranor)

10" vacuum lines connect to 2000 l/s turbo pump

Calibrated Leak Mounted to 100,000 liter Vessel

Leak was attached at the most remote port on the vessel.

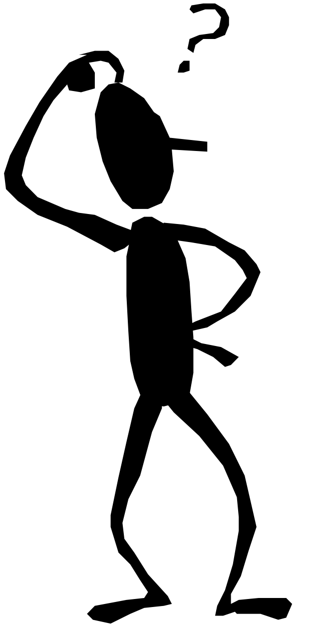
Response time was incredibly rapid, about 8 seconds!



NIF Spatial Filter Being "Bagged" for Total Integrated Helium Leak Test

Major Leak Testing Problems

- Background (outgassing)
- Large Volumes, slow pumping speed for Helium
- Helium permeation
- Leak "plugging"
- Detector maintenance
- Operator training



Leak Detection, Tips & Tricks

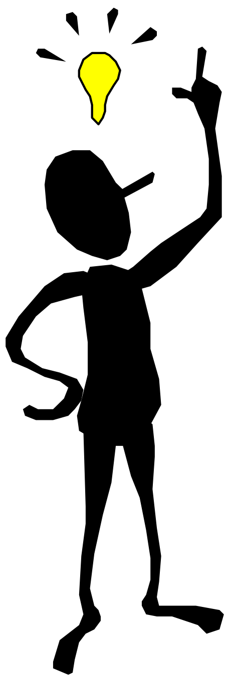
- Pipe threads (and the use of *Teflon* tape)
- Use of "Accu-pucky", vacuum sealants and sprays
- Helium dissolves in most vacuum greases
- Isolate O-rings to prevent permeative "masking" of real leaks
- Always test the connecting lines first!
- When introducing helium, start at top and work down (Tracer probe)

Tips & Tricks, Cont'd.

- Mount a calibrated leak to the system under test (response time)
- Calibrate the HMSLD before, and after, each use
- Minimal use of the tracer gas (adjust in water or solvent)
- Operate diffusion-pumped systems properly, especially at start-up and shutdown
- Don't use your leak detector as a portable pumping station!

Techniques for Detecting Small Leaks

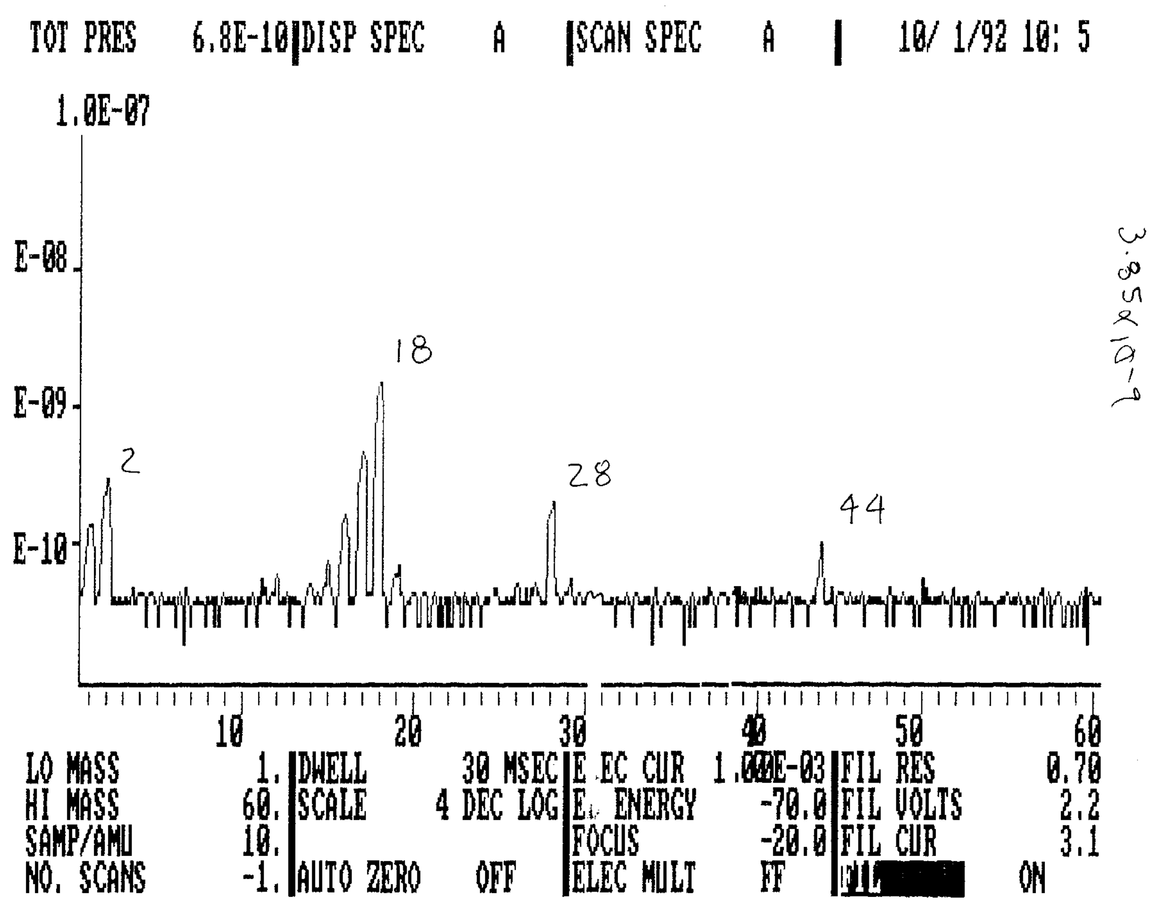
- Check the sensitivity of the leak detector
- Calibrate the HMSLD using an external standard
- Flow all pumped gases through the HMSLD, if possible
- Use low-flow tracer probe technique
- Keep Helium away from permeable materials (elastomers)
- Make use of "bagging" and "taping" techniques



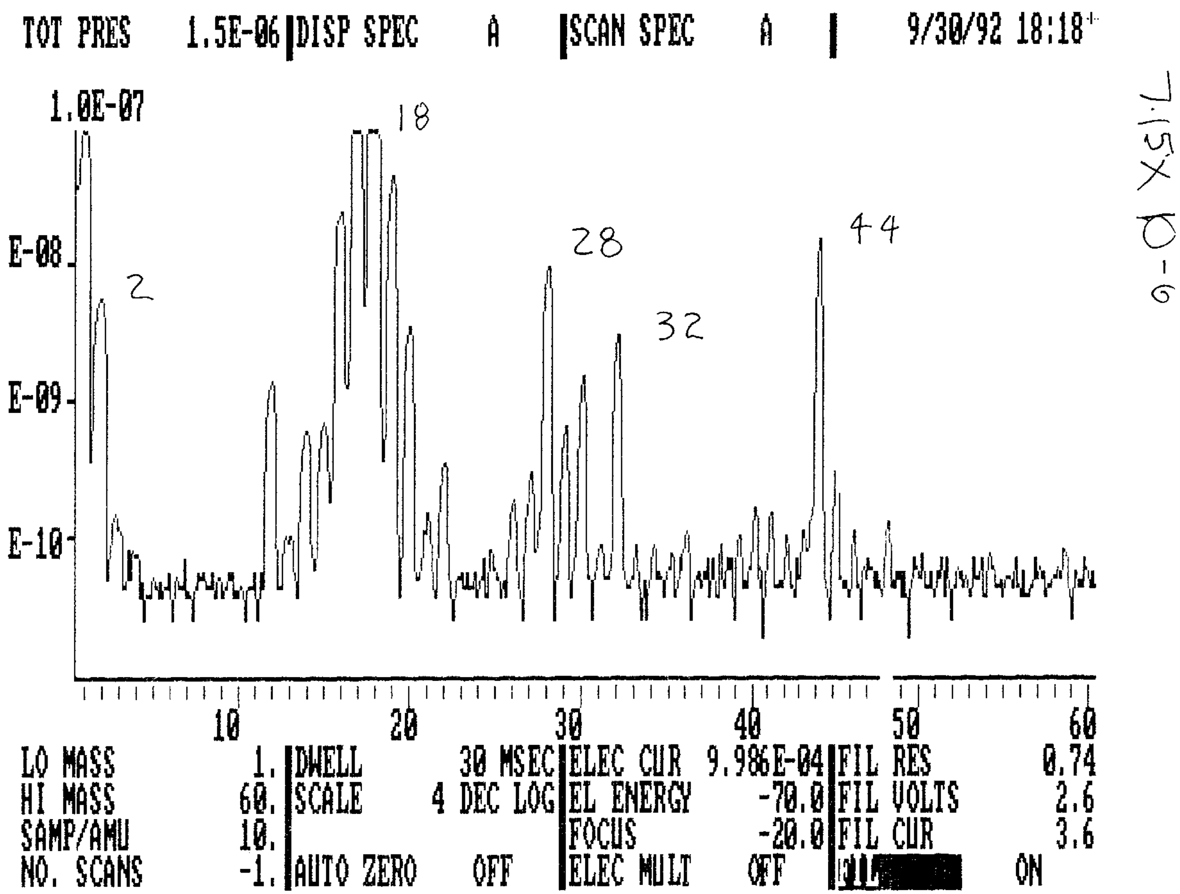
Partial Pressure Analyzers (RGA's) are often used in the leak testing of vacuum systems

- When calibrated, they can provide quantitative as well as qualitative data regarding the vacuum environment.
- RGA's have the ability to measure real-time environment changes.
- Gas Analyzers can be calibrated for various gas species.
- Gas Analyzers are often mounted permanently on a vacuum vessel or process equipment, utilizing the equipment's own pumping system.

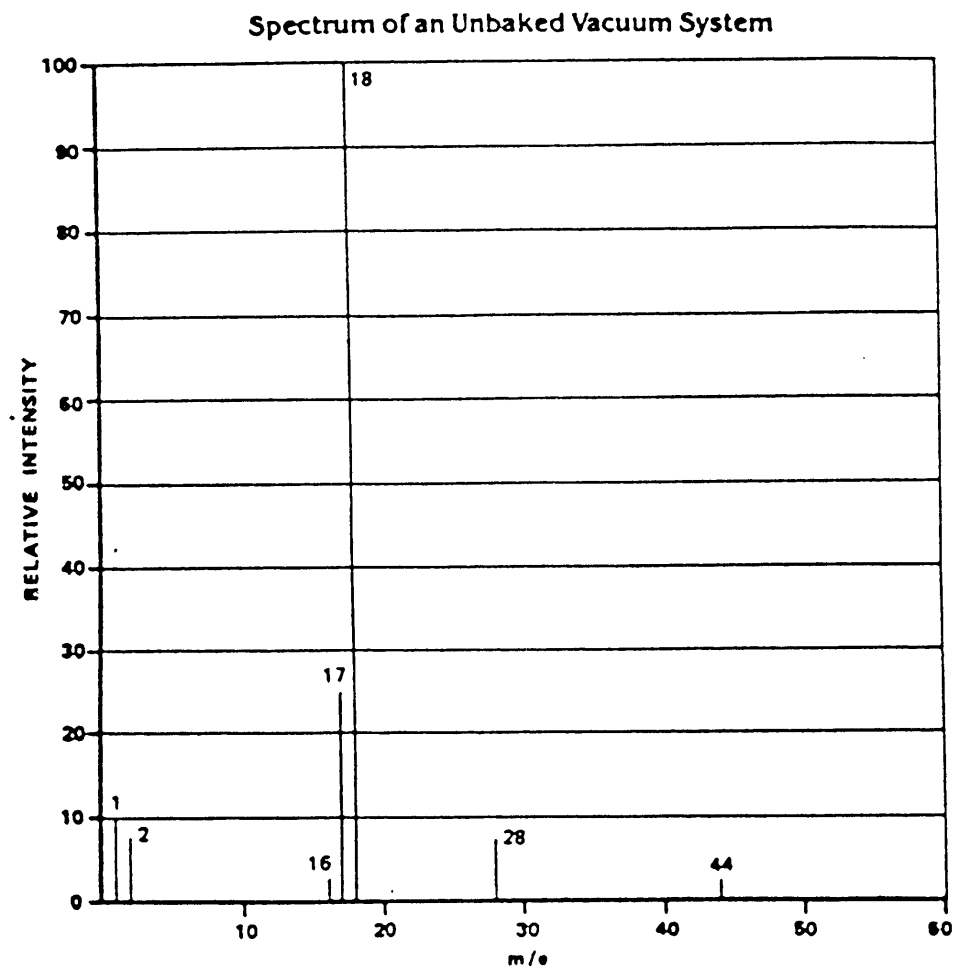
Clean System Spectrum



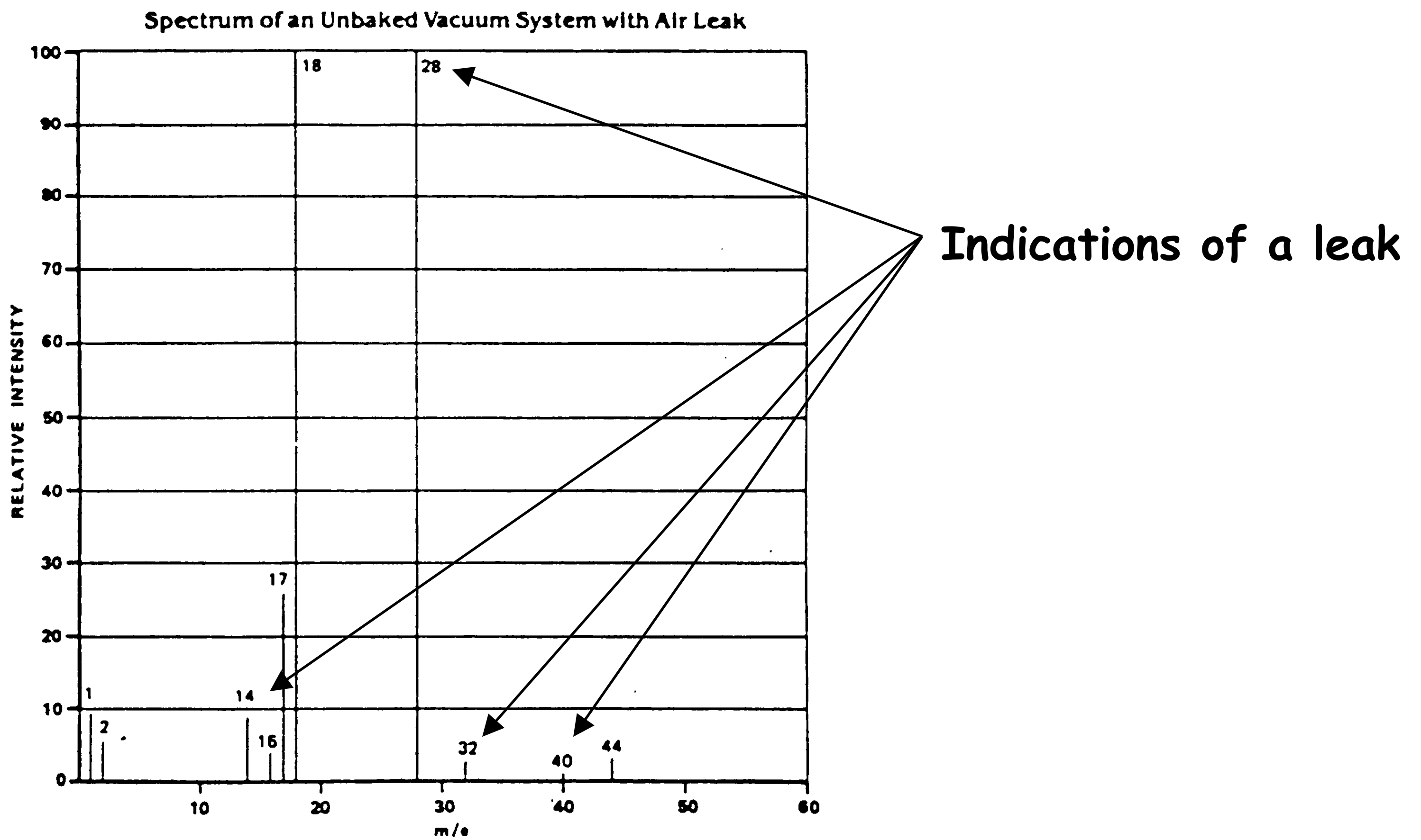
Less-than-clean System Spectrum



Spectrum of an Unbaked Vacuum System



Spectrum of a System With an Air Leak



Equipment-related Factors that Influence Residual Gases in the Vacuum Environment

Backstreaming
(system design)

Desorption
(surface condition of vessel walls)

Selection of pumping action
(capture vs. momentum transfer)

Permeation
(elastomers)

Vaporization of materials
(low vapor pressure materials)

Leakage
(real leaks)
(virtual leaks)

Operator-related Factors that Influence Residual Gases in the Vacuum Environment

- Handling procedures
  - grease, oil, salt
- Cleaning procedures
  - solvents (alcohol, acetone, MEK)
- Fabrication Techniques
  - machining coolants and lubricants
  - voids and occlusions
- Operation Procedures
  - use of traps
  - venting system to room air
  - backstreaming

Specifying Leak Rate and Detection Procedures

- Specification can include:
  1. Maximum allowable leak size
  2. Total maximum leakage rate (infers bagging)
  3. Component pressure during leak detection
  4. Type and sensitivity of the leak detector (e.g. MSLD with a sensitivity of 2×10^{-10} atm-cc of He/s
  5. Use of certified standard leak immediately before and after testing
- ASTM standards E432, E479, E493, E498, E499, and F97
- If application is critical, witness the testing, or do it yourself
- Avoid phrases like; leak tight, vacuum tight, good to 10^{-8} Torr, good for ultrahigh vacuum, etc.

The US Particle Accelerator School
Vacuum Hardware

Lou Bertolini

Lawrence Livermore National Laboratory

January 19-24, 2004

Bellows serve several functions within an accelerator vacuum system

- Make up for transverse offsets in beamline hardware
- Provide installation personnel with sufficient flexibility to install hardware.
- Reduce stresses on adjacent vacuum joints.
- Provide adequate expansion and/or contraction ability during thermal cycles.

When working with a bellows manufacturer, you will need to provide him the following information:

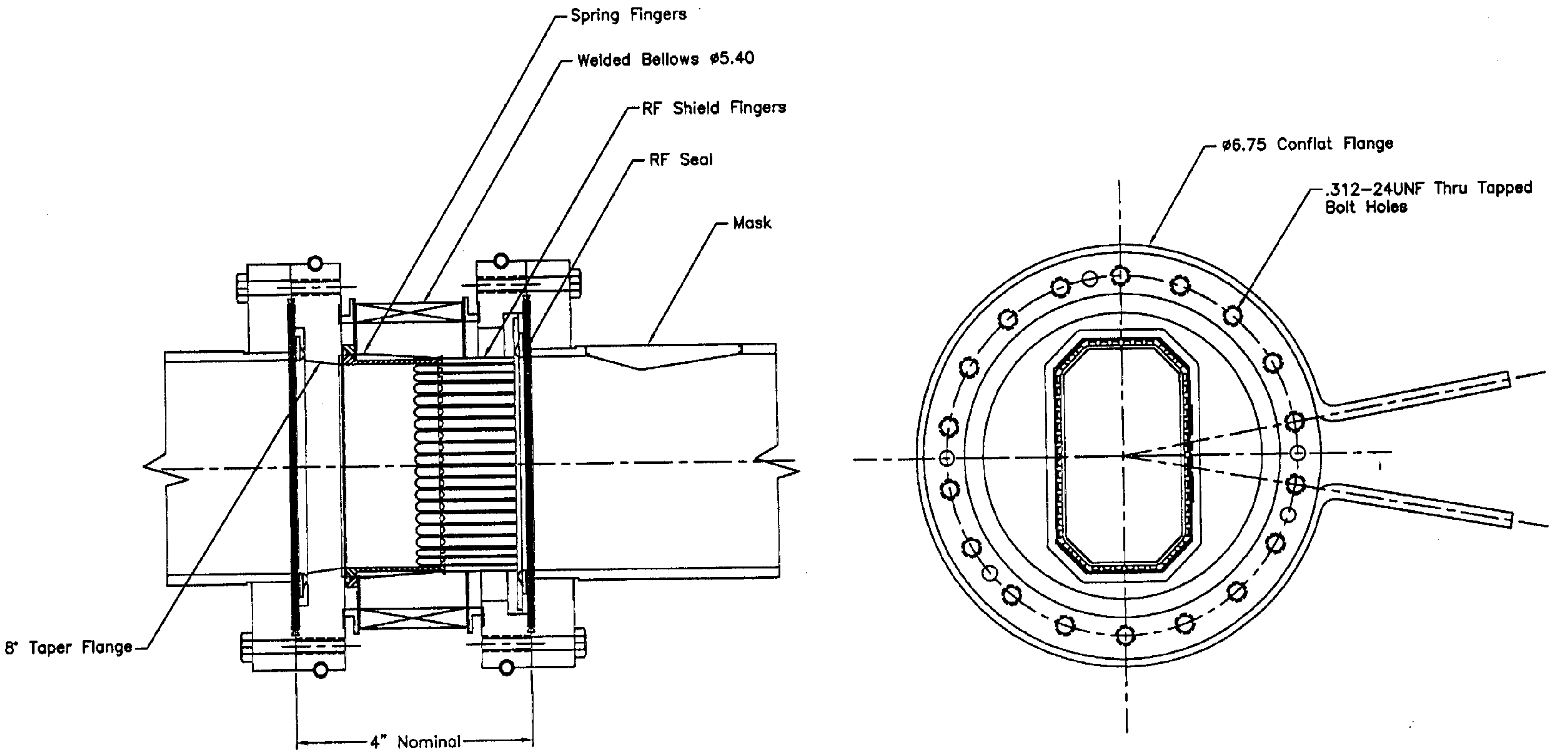
- Bellows free length
- Bellows maximum extended length
- Bellows minimum compressed length
- Bellows maximum transverse offset
- Maximum number of cycles

Types of Flexible Bellows

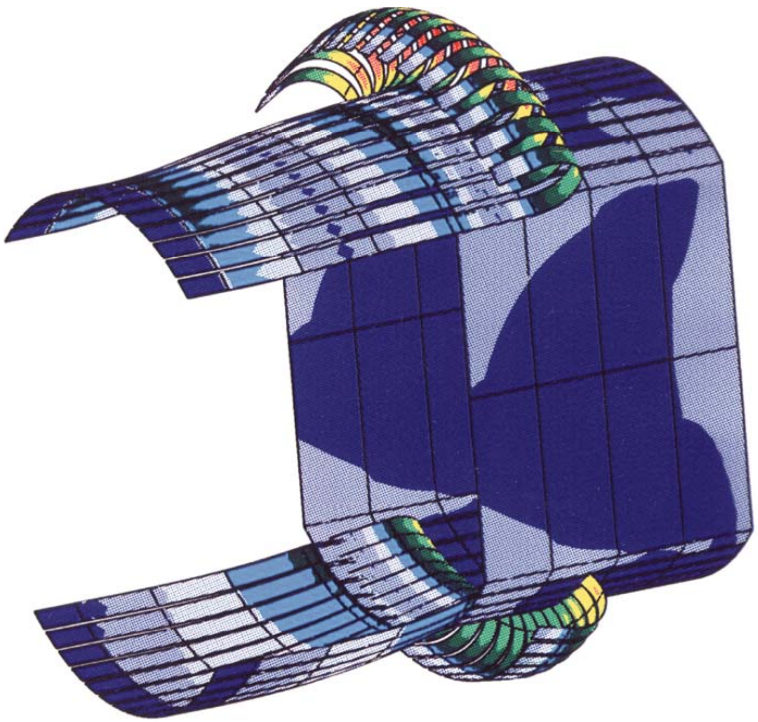
Welded

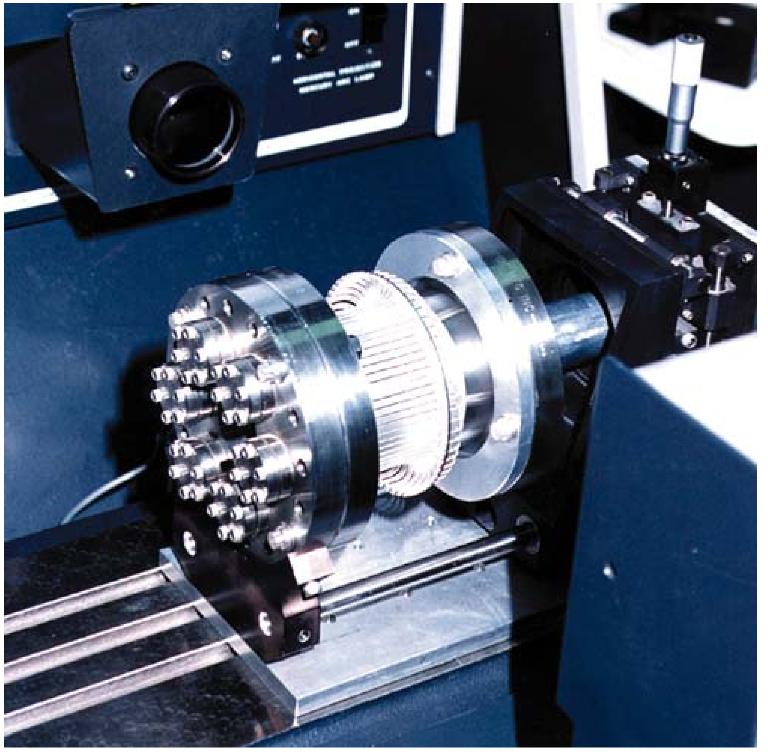
Formed

Bellows in Storage Rings Require RF Fingers



Another Example of an RF Shielded Bellows





Vacuum Valves for Accelerators

- All-metal Gate Valves
- All-metal Angle Valves
- RF All-metal Gate Valves
- Fast Closing Valves

RF All-metal Gate Valve

- Used as beamline isolation valves
- Pneumatic actuated only
- 316L stainless steel body
- Elastically deformed metal seals
- Max. operating temperature 200°C
- Bellows sealed

UHV Gate Valves

- Used as pump isolation valves
- Manual or pneumatic actuators
- 304L stainless steel construction
- Bellows sealed
- Viton seals
- Max. operating temperature 200°C

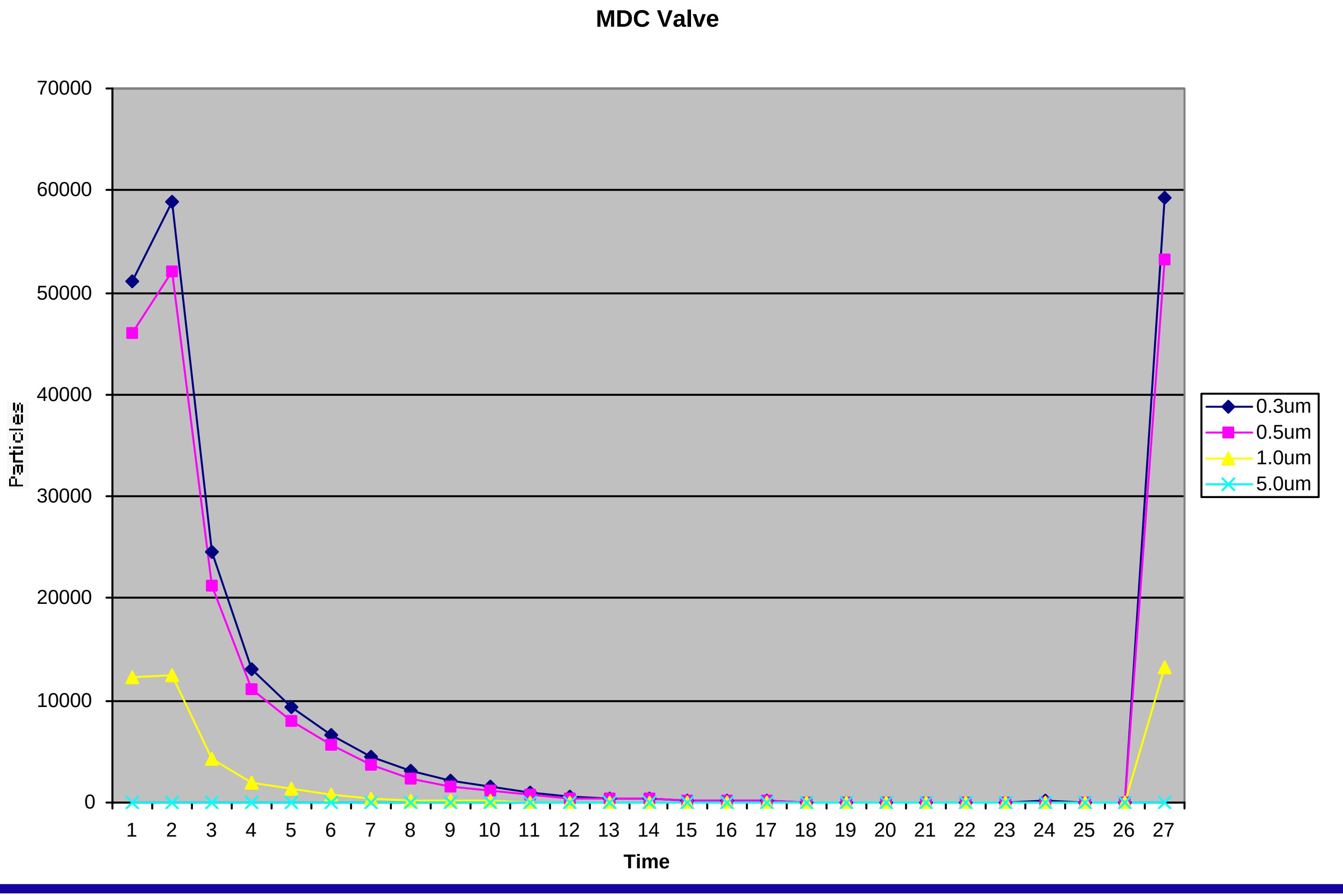
All-metal Angle Valves

- Used as roughing, purge, or vent valves
- Manual or pneumatic actuators
- 304L stainless steel construction
- Elastically deformed metal seals
- Max. operating temperature 300°C
- Bellows sealed

Fast Closing Valve

- **Designed to provide vacuum safety for accelerator systems.**
- **Detects pressure rise in milliseconds**
- **Closes leak tight in milliseconds**

Particle Generation Should be a Concern When Operating Vacuum Gate Valves!



Vacuum Feedthroughs

Electrical Power

Instrumentation

Rotary Motion

Linear Motion

Electrical Feedthroughs

- Coaxial
- Power
- High Current
- High Voltage
- Breaks
- RF Power

Instrumentation Feedthroughs

- Multi-pin (10 or 20 pin configuration)

- Type-D Subminiature Connectors

Rotary Motion Feedthroughs

- Manual or motorized actuation.
- UHV compatible
- Torque to 50 oz-in
- Speeds to 50 rpm

Linear Motion & Multi-motion Feedthroughs

- The class of feedthroughs span from simple "push-pull" to precision units.
- Manual, motorized, and pneumatic action.
- UHV compatible
- Linear travel ranges from ½" to 6"

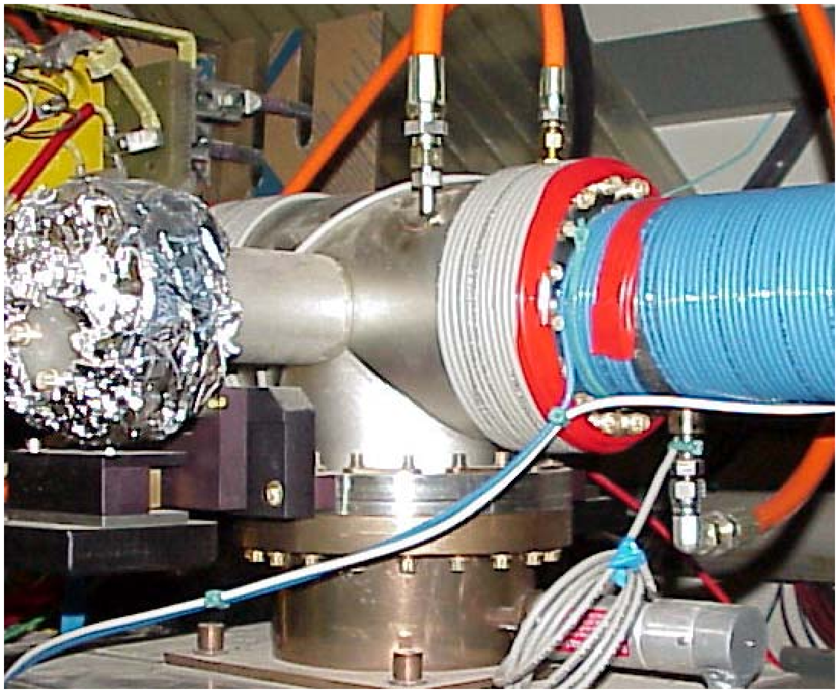
Pump Crosses and Pump Tees

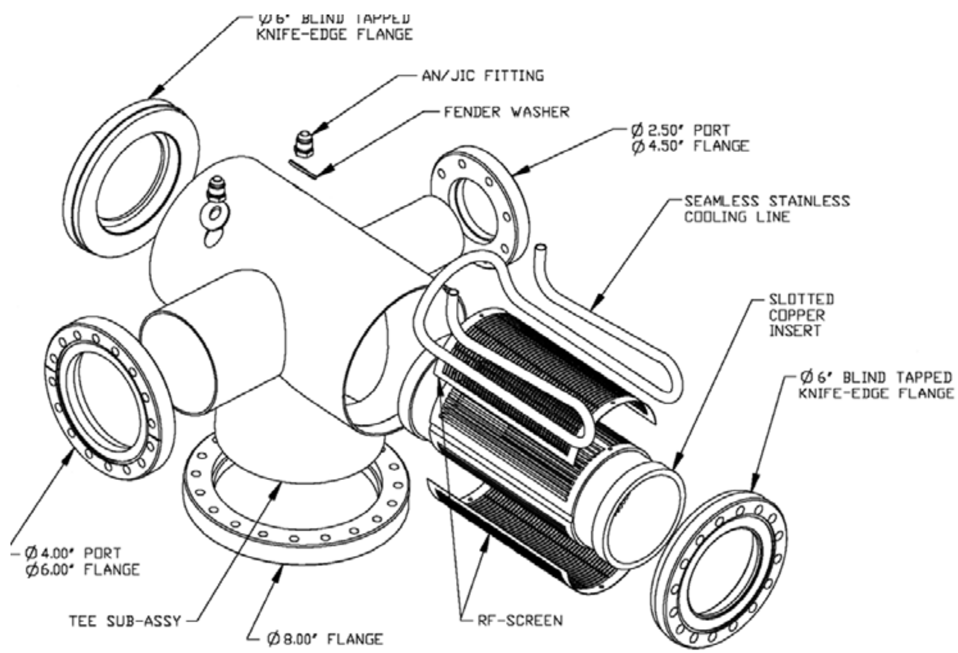
These components must maximize conductance to the pump, while minimizing detrimental effects on the beam.

- Pump crosses must provide current return bars for image currents.
- Minimize disturbing wakefields.
- Minimize conduction losses to the vacuum pump.

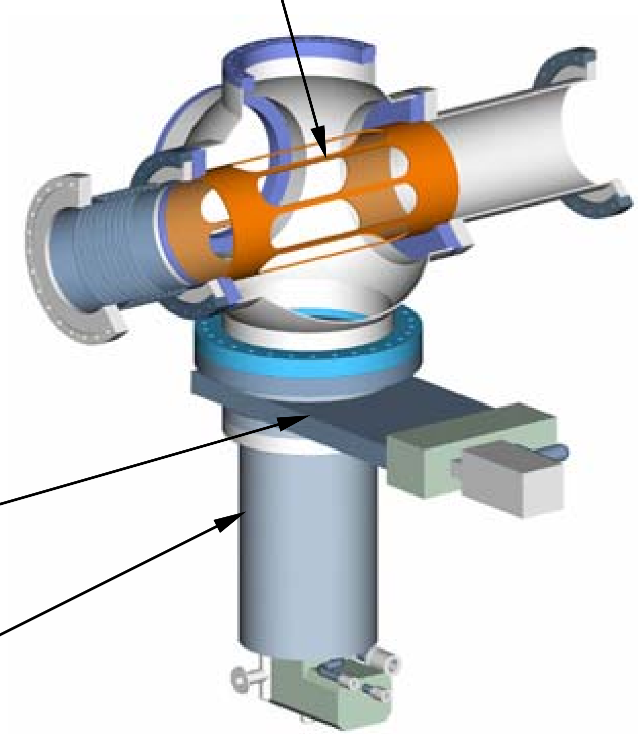
$$\frac{1}{S_{net}} = \frac{1}{C_{cross}} + \frac{1}{S_{pump}}$$

PEP-II Pump Tee





DARHT II Pump Cross



RF Seals

RF Seals provide current return capability and a smooth bore along the beamline.

There are several approaches to providing RF seals across flange joints:

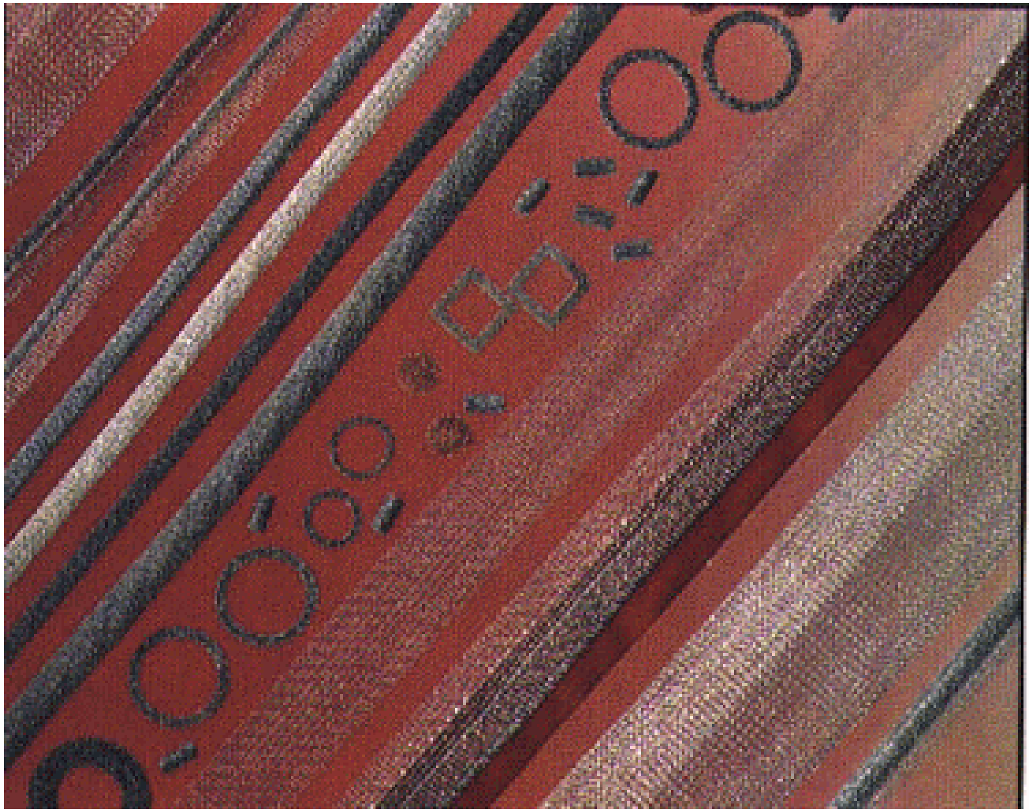
- "Omega" Seals
- Tecknit Gaskets
- "Gap" Rings
- Flange designs that provide RF sealing capability (VAT Seals, Helicoflex)

“Omega” Seals

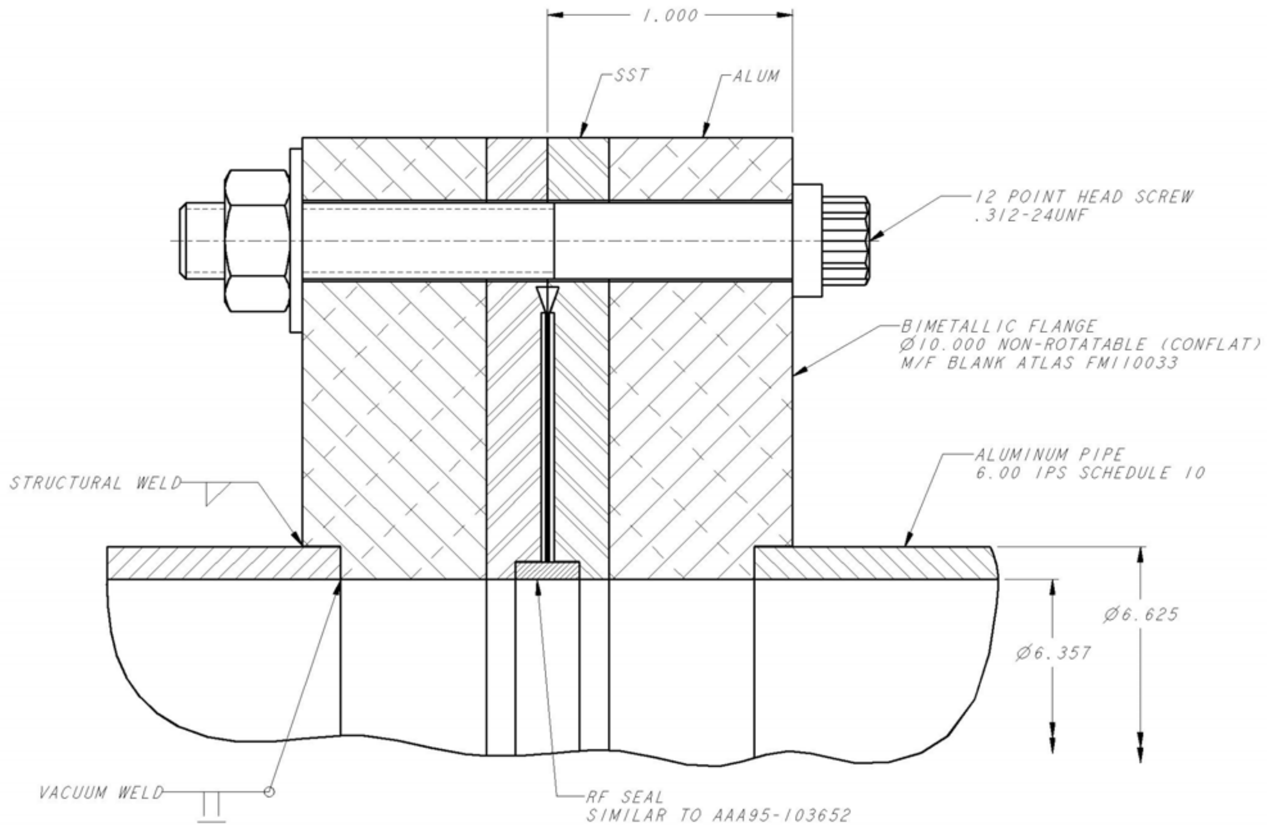
Tecknit Gaskets

- Materials are monel Sn/Cu/Fe, Copper, Aluminum, Phopher Bronze, and Silver-plated Brass wire

- Available in round, double round, round with a fin, and square sections



“Gap” Rings


1.000
SST
ALUM
12 POINT HEAD SCREW
.312-24UNF
BIMETALLIC FLANGE
Ø10.000 NON-ROTATABLE (CONFLAT)
M/F BLANK ATLAS FM110033
ALUMINUM PIPE
6.00 IPS SCHEDULE 10
STRUCTURAL WELD
Ø6.625
Ø6.357
VACUUM WELD
RF SEAL
SIMILAR TO AAA95-103652

The US Particle Accelerator School
Material Preparation, Cleaning, and Processing

Lou Bertolini

Lawrence Livermore National Laboratory

January 19-24, 2004

Material Preparation Techniques

- Vacuum materials may be prepared for finish machining by the following techniques:
    1. Rough Machining
    2. Metal Stamping
    3. Water-jet cutting
    4. Laser cutting
    5. Plasma arc cutting
    6. Bead/sand blasting

- When plasma arc cutting, make sure that sufficient material allowance is made for complete removal of the heat affected zone (HAZ) during final machining.

- Bead/sand blasting should only be permitted on material with large amounts of mill scale or heavy inclusions from contact with metallic or organic material.

Material Finishing Techniques

- The preferred technique for finishing vacuum materials is machining.

- The following techniques should be avoided or at least approved on a case-by-case basis:
  1. Grinding
  2. Honing
  3. Electric Discharge Machining (EDM)
  4. Chemical milling
  5. Glass/bead blasting

- Glass bead blasting may be permitted with new clean beads when an optically dispersive surface is required.

Material Finishing Techniques (cont.)

- When machining will not produce the required surface finish, polishing may be permitted. When polishing, care should be taken to avoid excessive rubbing or contact pressure.

- The following abrasives are acceptable for UHV components.
  - 3M Scotch - Type S, Silicon Carbide (color: gray), 500 grit
  - Brite - Type A, Aluminum Oxide (color: maroon), 240 grit
  - 3M Wet or Dry Fabricut Cloth - Aluminum oxide or silicon carbide, 600 grit

Acceptable Cutting Fluids for Final Machining

Relton A-9
Tap Magic
Tapmatic #1 or #2
"Pearl" Kerosene by Chevron Chem CO
"Tool Saver" by Do All Corp.
Cutzol EDM 220-30
Sunnen Man-852 Honing Oil
Vytron Concentrate
Rust-Lick G-25-J
Wheelmate #203
Aqua Syn 55 by G-C Lubricants CO
Cold Stream Coolant by Johnson Wax CO
"Acculube" by Lubricating Systems Inc.
Micro Drop "Advanced System Lubricant" by Trico
Micro Drop "New Vegetable Based" by Trico

Rapid Tap
Trim Tap
RD2-195
Dip Kool 868
DIP Kool 862
Dip Kut 819H
No Sul #6871
Kool Mist #88
Cimcool 5 Star 40
Cimperial # 1011
Haloform CW-40
Trim Sol
Trim9106CS
CINDOL 3102
PenWalt #DP 1131

Suggested UHV Handling and Assembly Guidelines

- No food, drink, or smoking allowed in CLEAN AREA.
- Limit entry and exit into CLEAN AREA.
- Hydrocarbons (oils, grease) and dust-collecting materials (cardboard) must be minimized.
- Equipment brought into CLEAN AREA must be clean. Carts, chambers, stands, and tools must be free of oils and dust.
- Wood must be minimized.
- A special set of tools expressly for use on vacuum components should be kept in the CLEAN AREA.

Suggested UHV Handling and Assembly Guidelines (cont.)

- Metal tools must be degreased. After degreasing, tools should be kept in clean trays and handled with clean gloves.
- No cadmium plated, lead, or painted tools should be permitted. Chrome and nickel plated tools are permitted.
- Aluminum foil shall be in accordance with ASTM B479, type designated as DRY ANNEAL A, (oil free). Each piece of foil should be used only once and then discarded.
- Aluminum foil and lint-free tissue should be stored in clean boxes with lids.
- Only use pens for writing in CLEAN AREA, do not use pencils. Minimize the use of paper.

Suggested UHV Handling and Assembly Guidelines (cont.)

- Clean vacuum parts and open chambers should be covered with foil at all times when work is not being performed.
- Do not wear wooly sweaters in CLEAN AREA.
- No sandpaper or abrasives allowed.
- Hands should be kept out of pockets (this produces lint).
- Clean parts should be handled with new polyethylene gloves used inside 100% stretch nylon gloves.
- Gloved hands which touch cleaned parts and tools should touch nothing else (this includes your face, hair, etc.). Gloves which touch unclean surfaces should be replaced immediately.

Suggested UHV Handling and Assembly Guidelines (cont.)

- Replace gloves with a new, clean pair at the beginning of each shift and following breaks.
- Hands should be washed before wearing clean gloves.
- Clean-room quality protective clothing (lab coats, hats, hair nets, face masks) should be worn when working on vacuum components in CLEAN AREA.

Generic Cleaning Procedures for Vacuum Components

Mechanical Cleaning

↓

Degreasing or Solvent Cleaning*

↓

Detergent Cleaning*

↓

Chemical Etch*

↓

Electrolytic Polishing*

↓

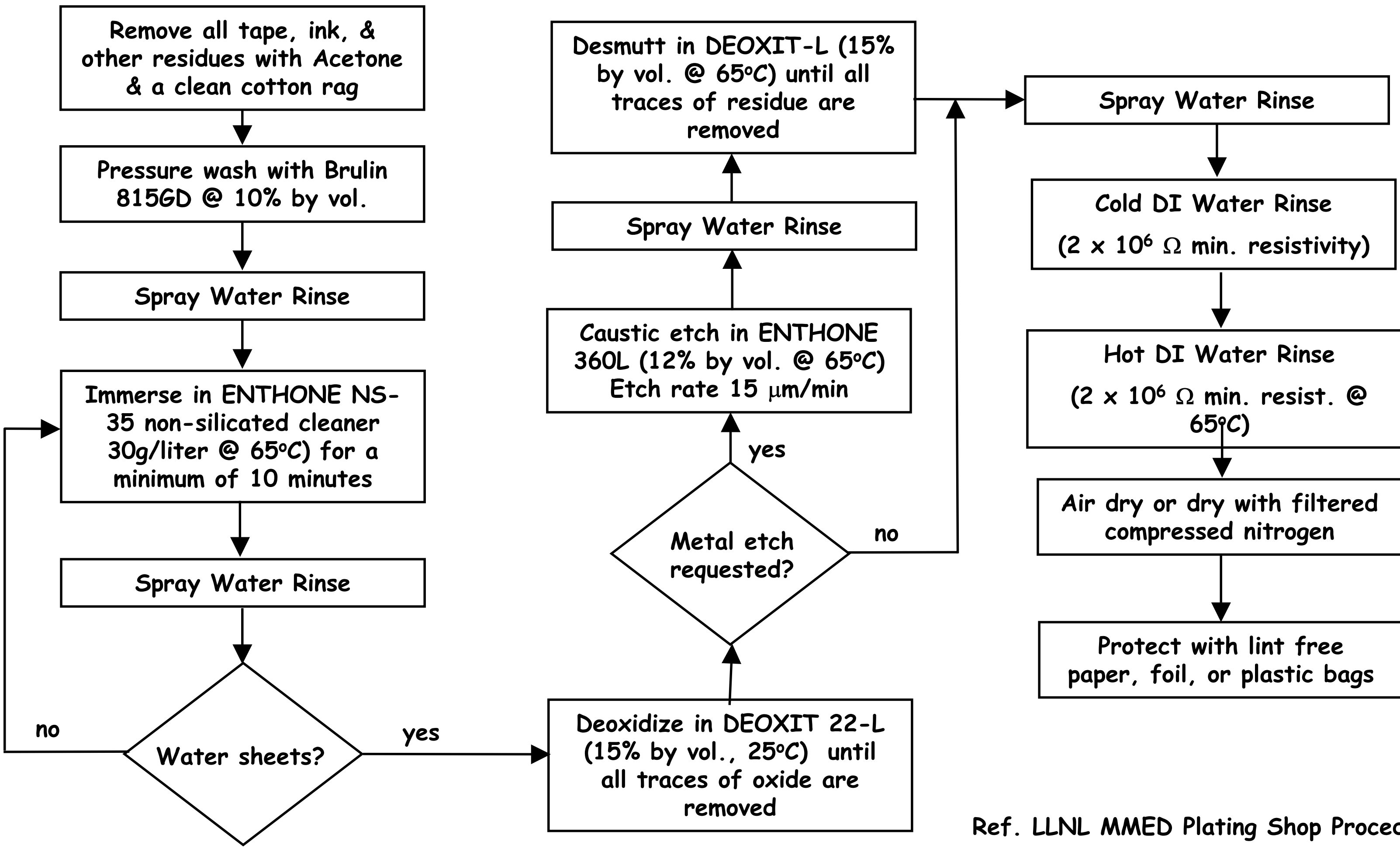
High Pressure Spray

↓

Bake-out

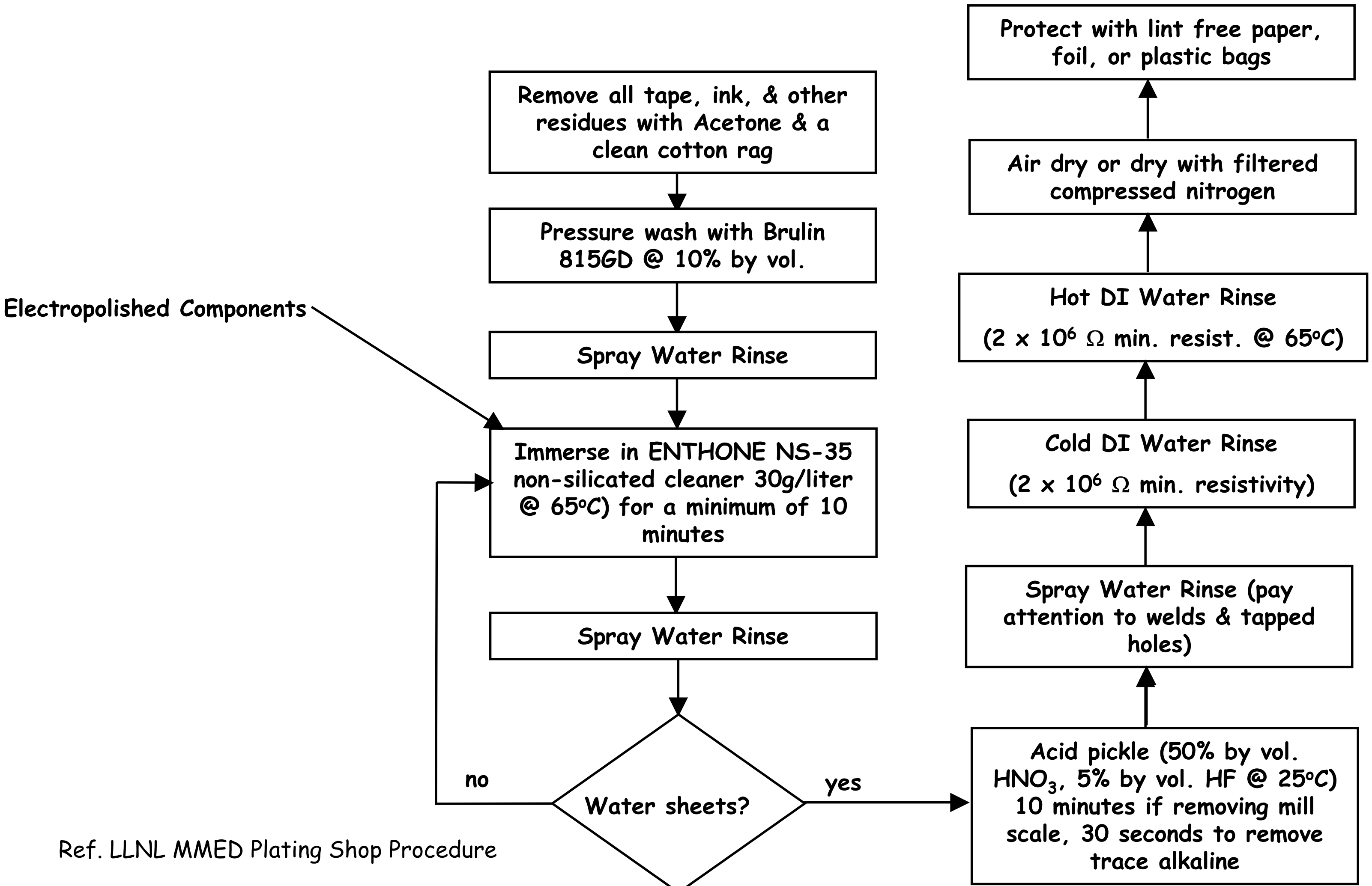
*Typically these steps are proceeded by a water rinse to avoid contamination of subsequent baths.

Cleaning of Aluminum Components



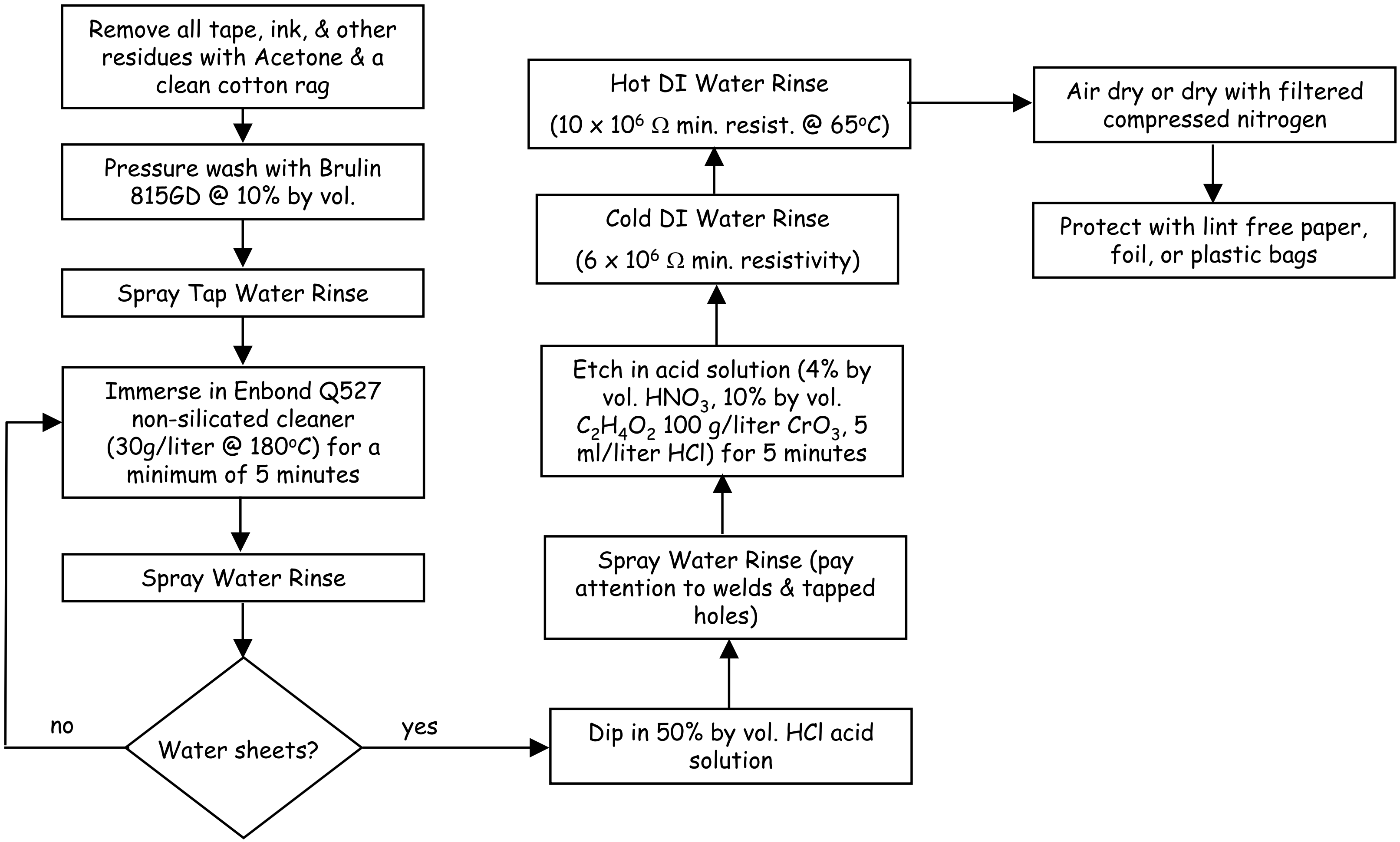
Ref. LLNL MMED Plating Shop Procedure

Cleaning of Stainless Steel Components



Ref. LLNL MMED Plating Shop Procedure

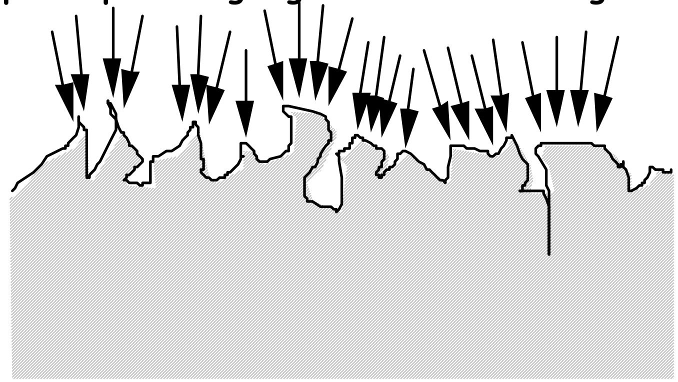
Cleaning of Copper and Glidcop Components



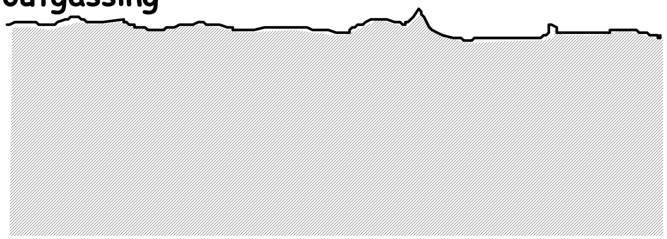
Electropolish

- Consider as a "reverse" electroplating technique.
- Metal is removed from the "high spots" due to higher current density.
- Surface metal is rich in H_2 and fluid until degassed.
- Electropolish produces a bright metallic finish.
- With proper rinsing and a post bake step, very low outgassing rates can be achieved.

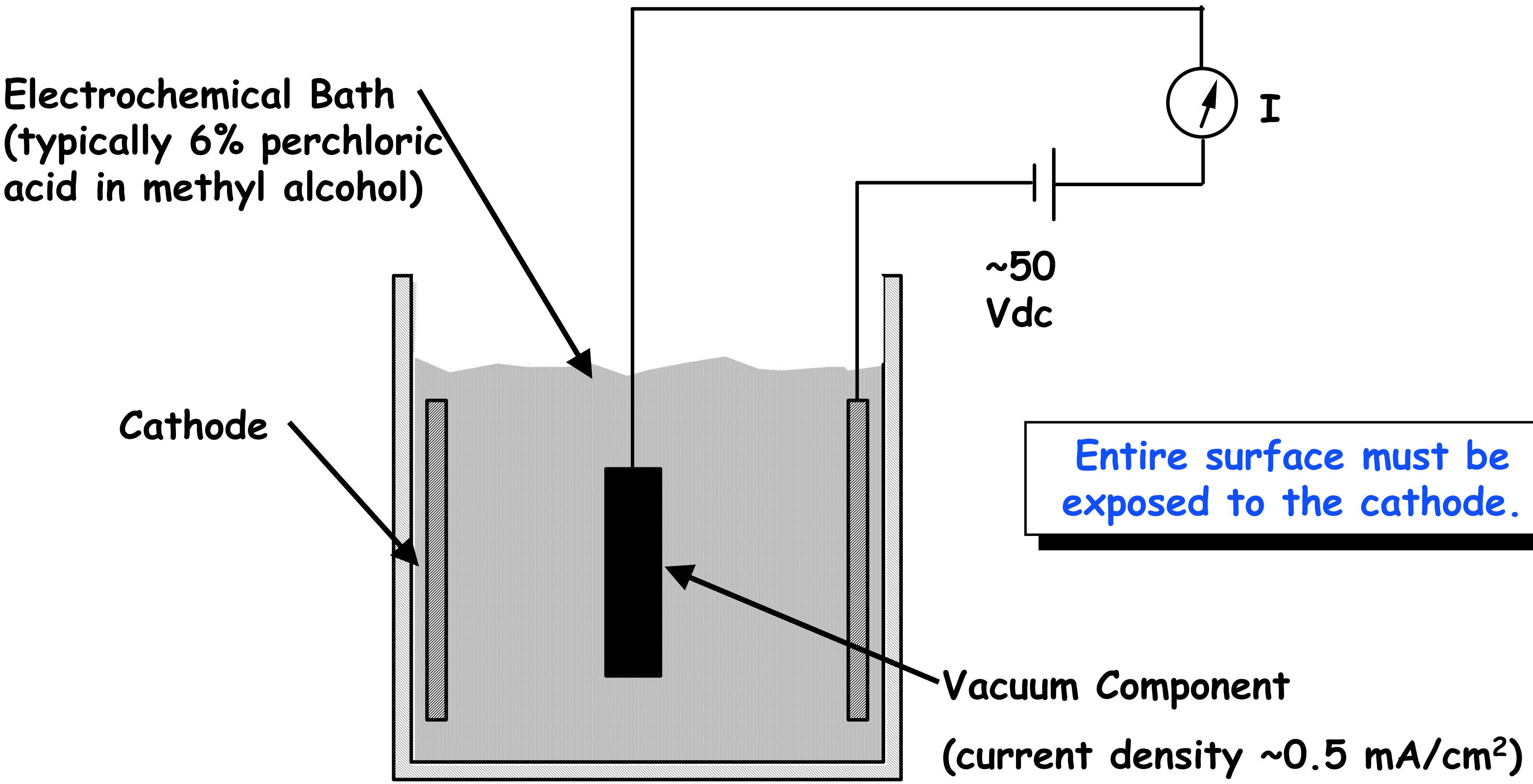
Electric Field Lines are concentrated at peaks producing higher chemical milling rates



Resulting surface has reduced peaks, reduced surface area, and reduced outgassing



Typical Arrangement for Electropolishing

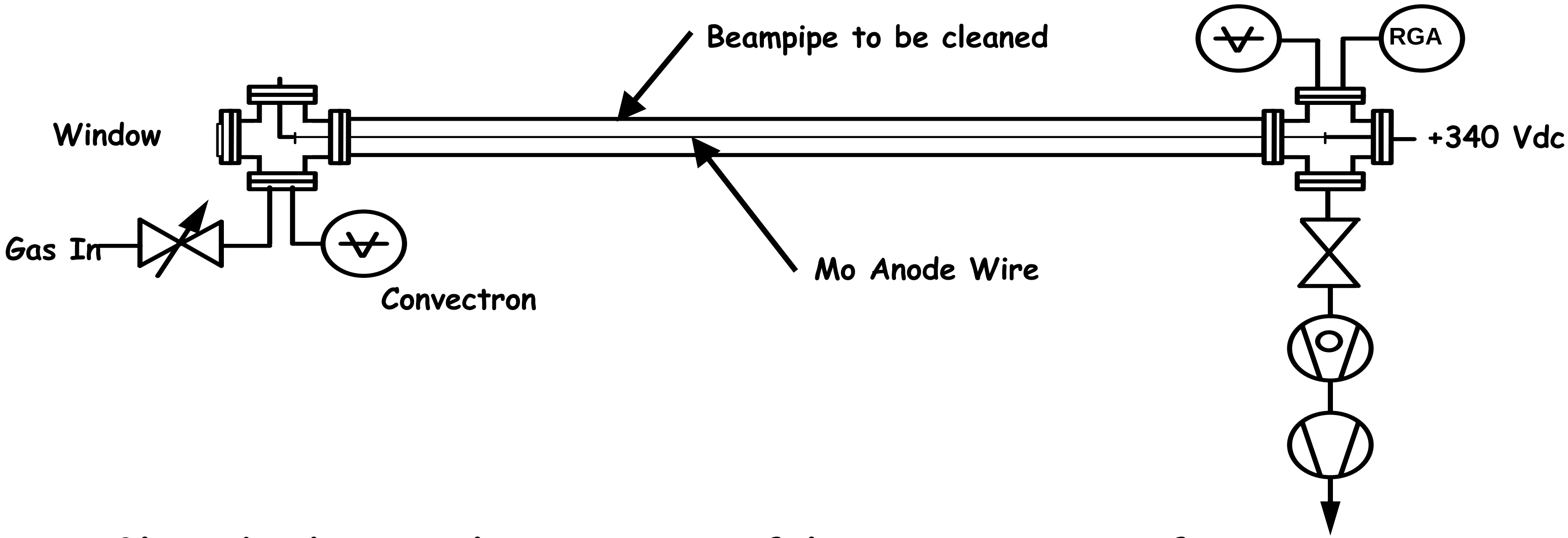


Entire surface must be exposed to the cathode.

High Pressure Spray

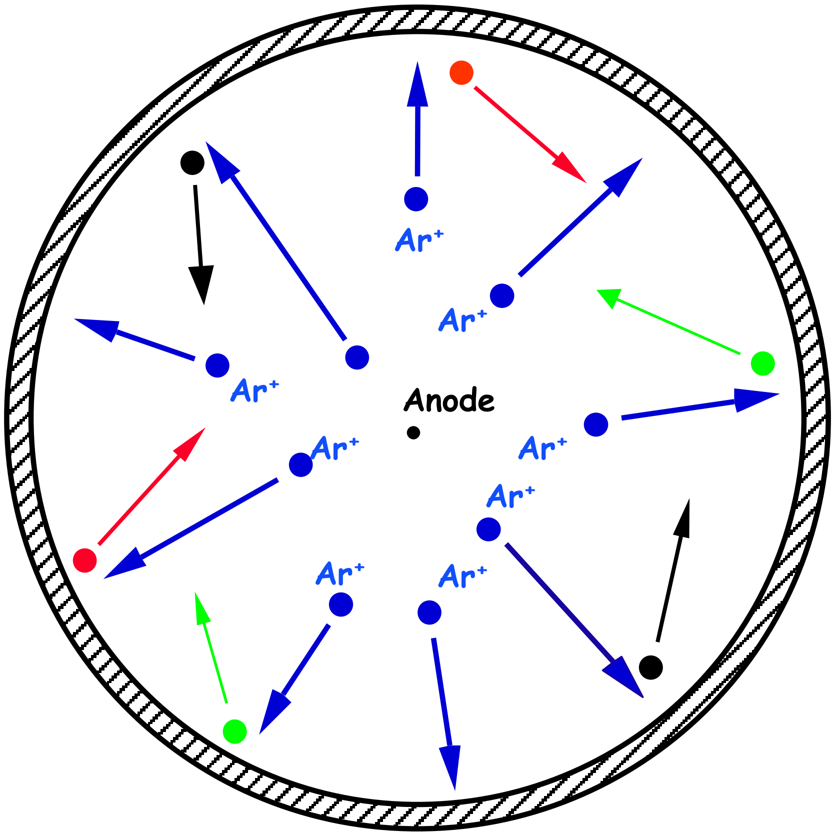
- Fluid used can be tap water, deionized water, or with a detergent to assist in cleaning.
- With a detergent, this process is used early in the cleaning process. With deionized water, it is one of the final steps.
- Use of high fluid velocity to dislodge particles from the surface.
- Most effective cleaning method for particles in the 1 mm range.
- High pressure spray can be effective on large parts, as well as small parts.

Glow Discharge Cleaning Schematic



- Glow discharge cleaning is useful in removing surface contamination such as C, S, H_2O, and organics.
- Must be a flowing system to prevent readsorption.
- Typical gases used are Ar, Ar-O_2, H_2.
- Glow discharge cleaning can leave higher levels of Ar and O_2 in the metal surface.
- A 200°C bakeout is still required after glow discharge cleaning.

Glow Discharge Cleaning



On PEP-II, various surface treatments were evaluated by XPS

Surface analysis by x-ray photoelectron spectroscopy (XPS)

Surface Treatment	XPS Surface Atom %					
	Cu	O	N	C	Cl	Ar
Chem. Cleaning (old SLAC recipe)	22.4	22.5	11.9	41.6	1.6	-
Chem. Cleaning (new SLAC recipe)	43.4	36.8	-	17.9	1.9	-
GDC - 95% Ar, 5% O_2 (2 x 10^{19} ions/cm^2)	50.6	40.0	-	8.0	-	1.4
GDC - 95% Ar, 5% O_2 (2 x 10^{18} ions/cm^2)	48.6	42.0	-	8.0	-	1.4
GDC - 100% H_2 (2 x 10^{18} ions/cm^2)	64.2	23.6	-	12.2	-	-

Ref. "Processing of OFE Copper Beam Chambers for PEP-II High Energy Ring", Hoyt et al, 1995 Particle Accelerator Conference

Bake-out

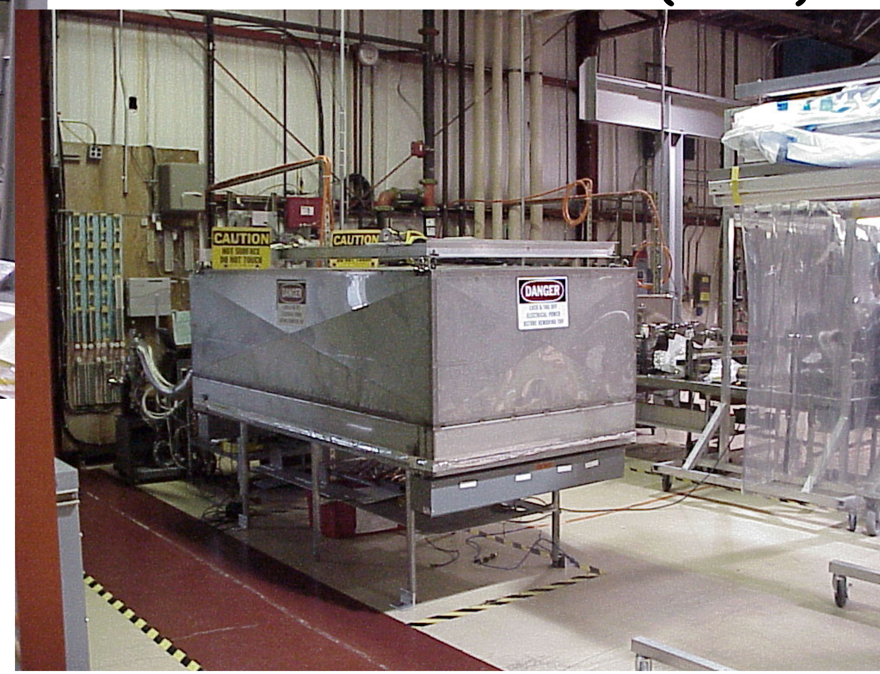
- Vacuum firing of components will result in low outgassing rates
  (T = 800°C - 1000°C, P~10^{-4} Torr for several hours).
  - Bulk H_2 is depleted from metal
  - Works well for stainless steels
  - copper and aluminum are annealed

- Heating systems for bakeout
  - Ovens are the easiest to use
  - Heater tapes with insulation
  - Nichrome wire covered with ceramic beads
  - Calrods or heater bands with insulation
  - Heater blankets (built-in insulation)

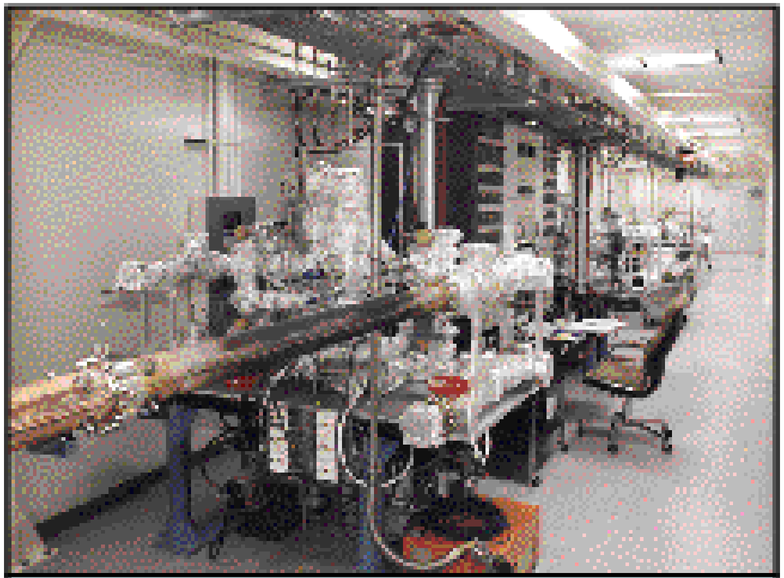
SLAC Glow Discharge and Bakeout Station

Glow Discharge Station

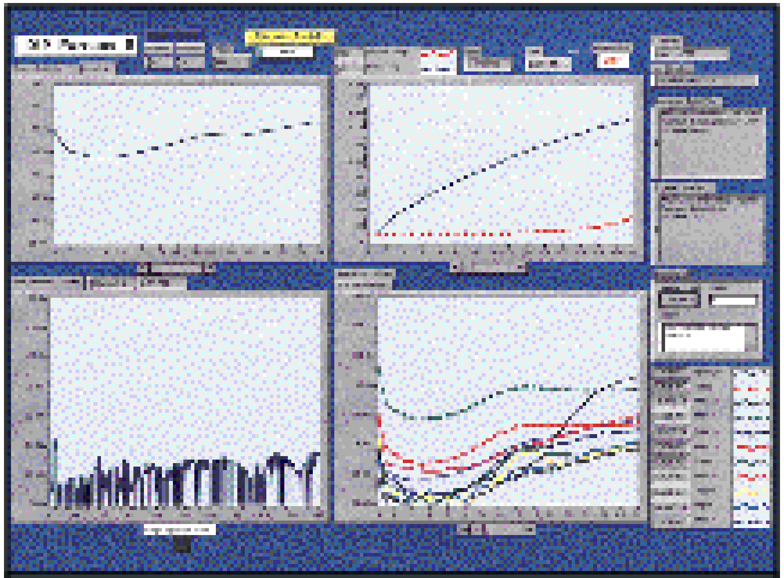
Bakeout Oven Enclosure ($200^{o}C$)



LLNL Glow Discharge and Bakeout Station

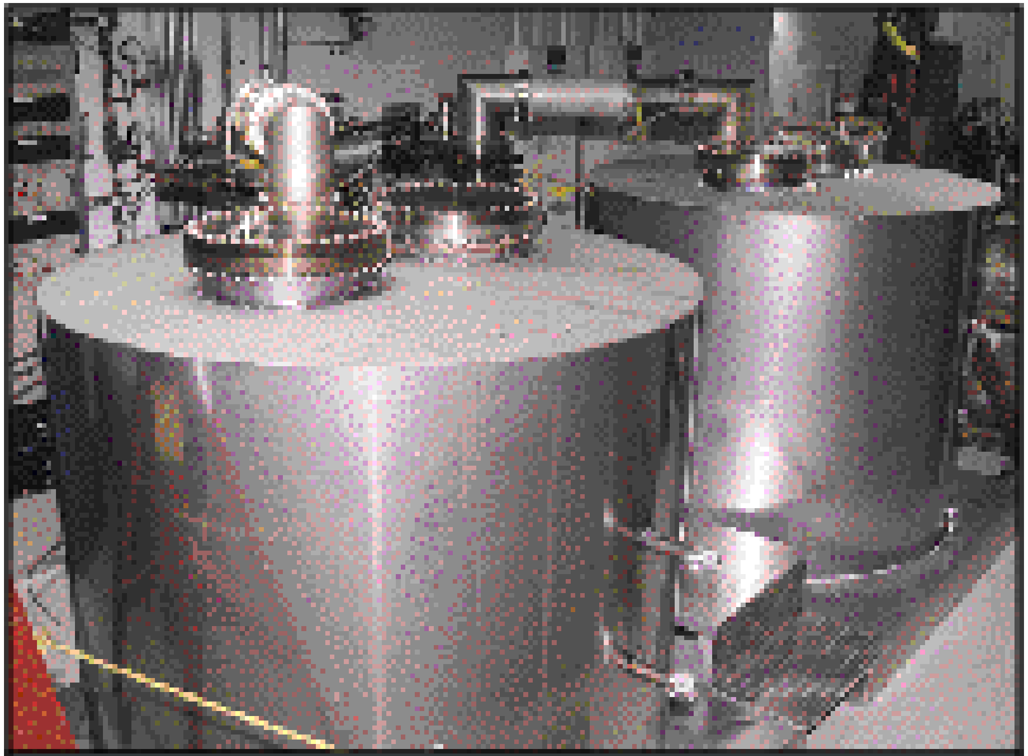


ATEG glow discharge and bake station



RGA and LabView software records the results of processing

LLNL Bake-out Ovens (800°C)



Vacuum firing furnaces process components at 800°C

The US Particle Accelerator School
Supports and Alignment

Lou Bertolini
Lawrence Livermore National Laboratory

January 19-24, 2004

Vacuum System Structural Support Stands

- Structural stands must provide deadweight support for the accelerator and beam line.

- Stands must provide support during seismic events.

- Stands must provide adequate freedom of movement during thermal cycles (operational and bake-out).

- Stands must constrain the accelerator and beamline to maintain positional requirements.

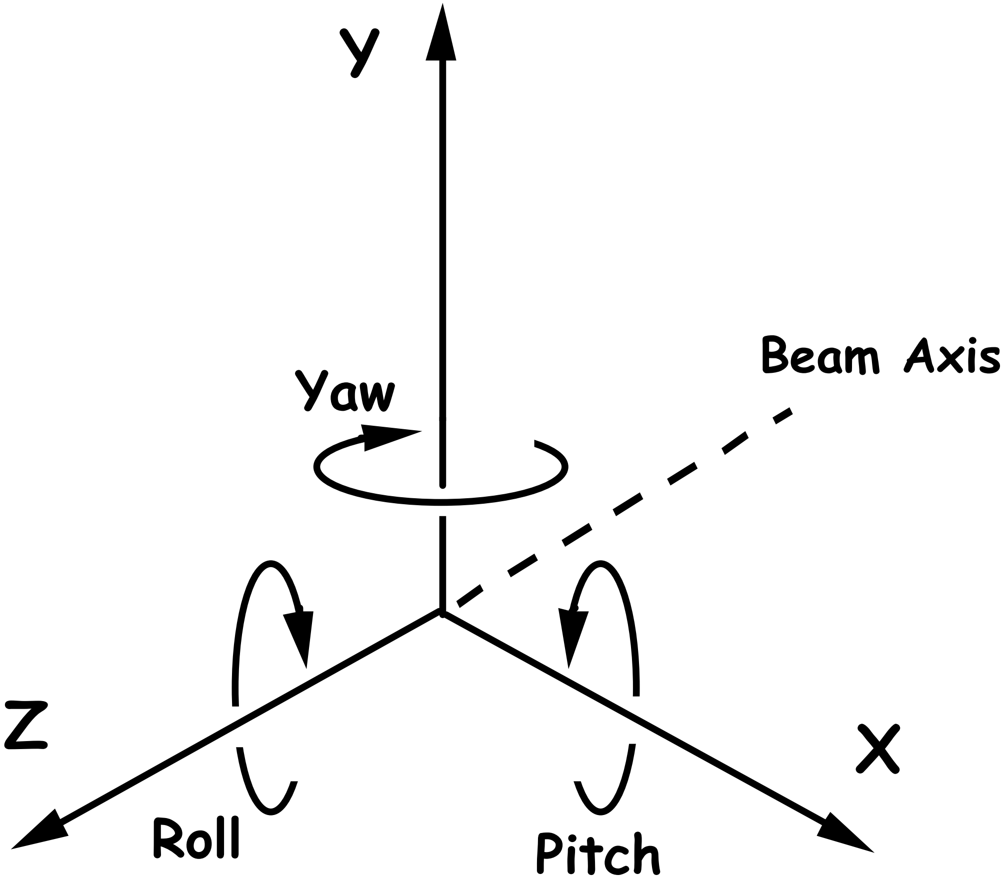
Categories of Support Stands

Kinematic Supports - support system that provide six degrees of freedom (x, y, z, roll, pitch, and yaw).

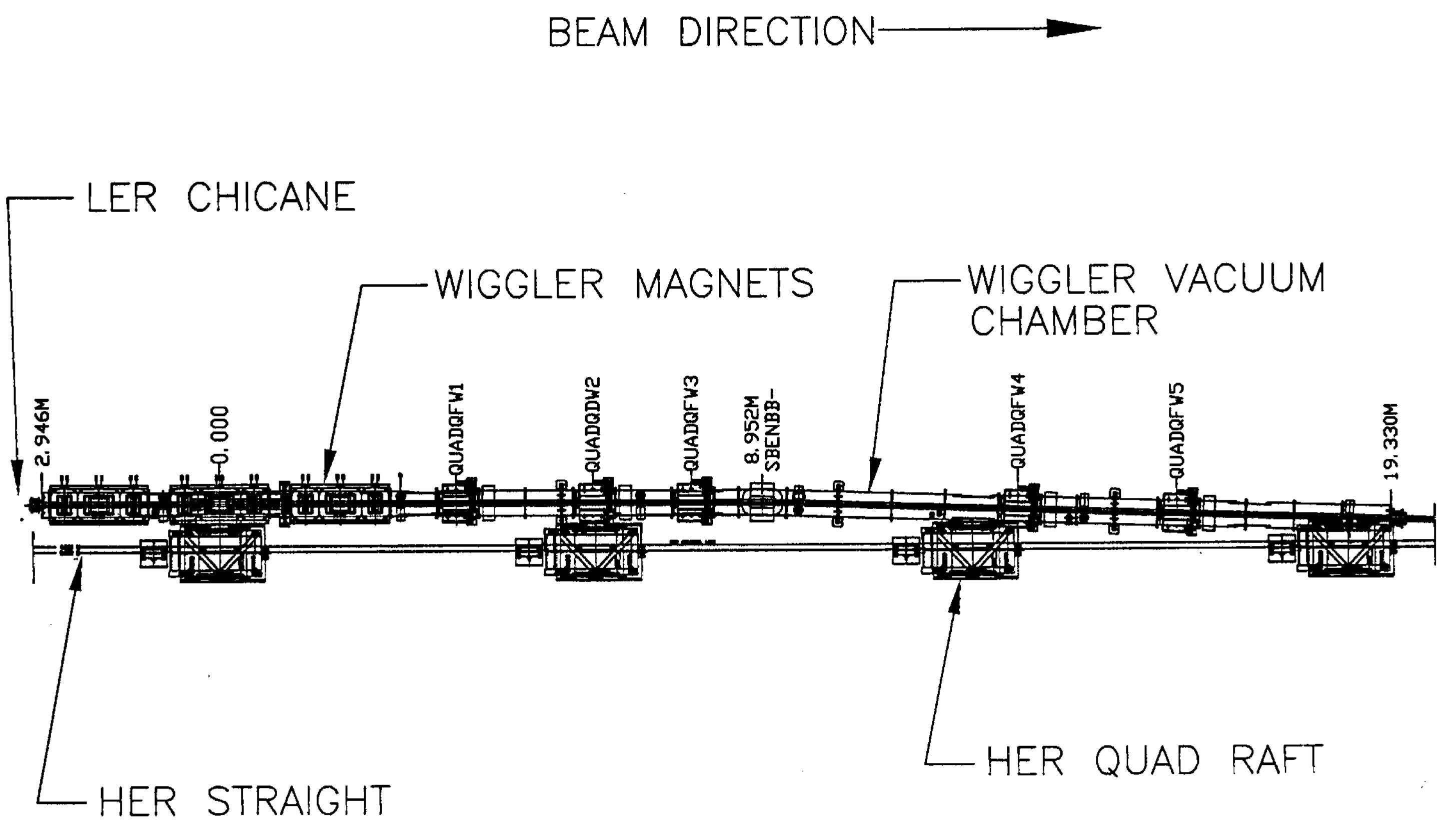
Overconstrained Supports - support system that deforms the vacuum system to control its position.

In reality, most support designs are somewhere in between these two categories.

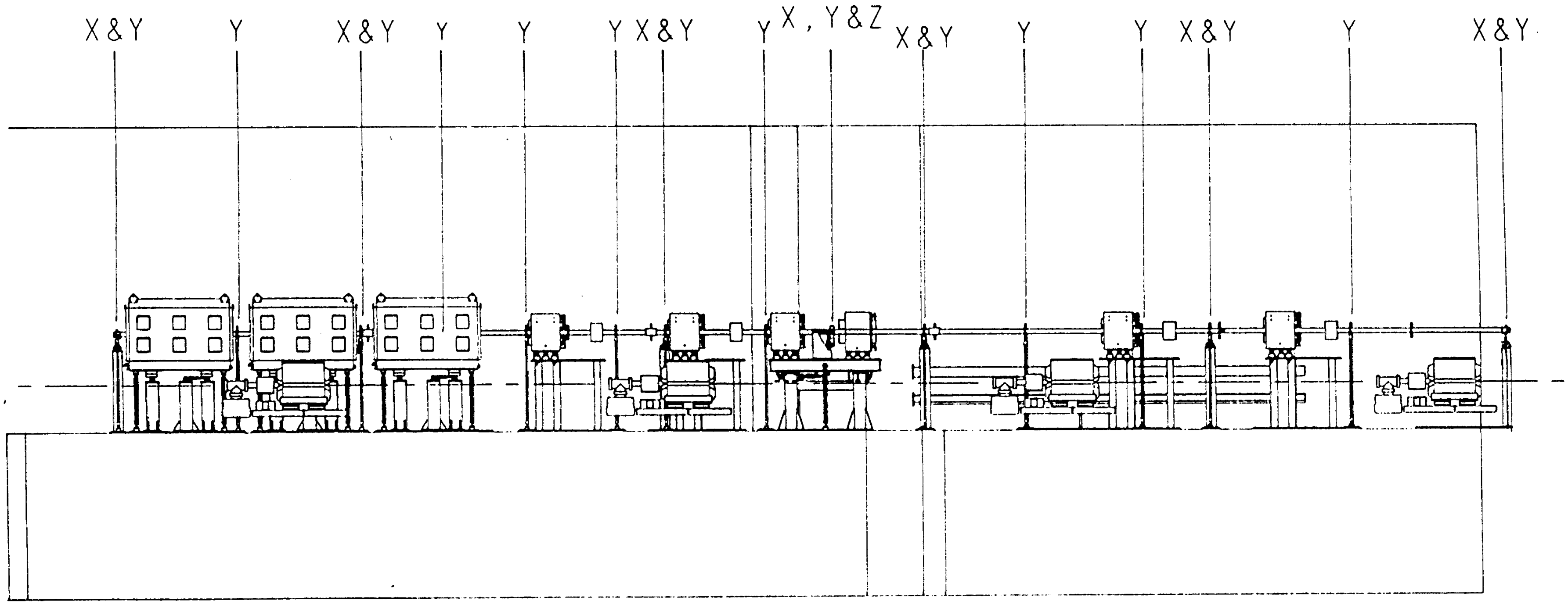
Six Degrees of Freedom



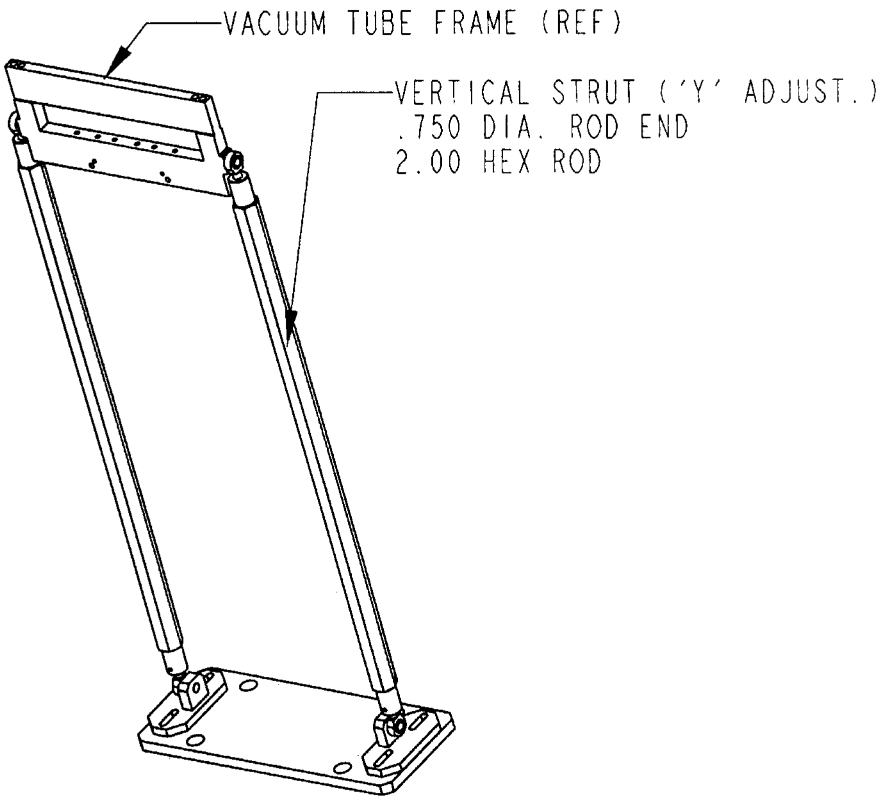
Example - PEP-II LER Wiggler Section Supports

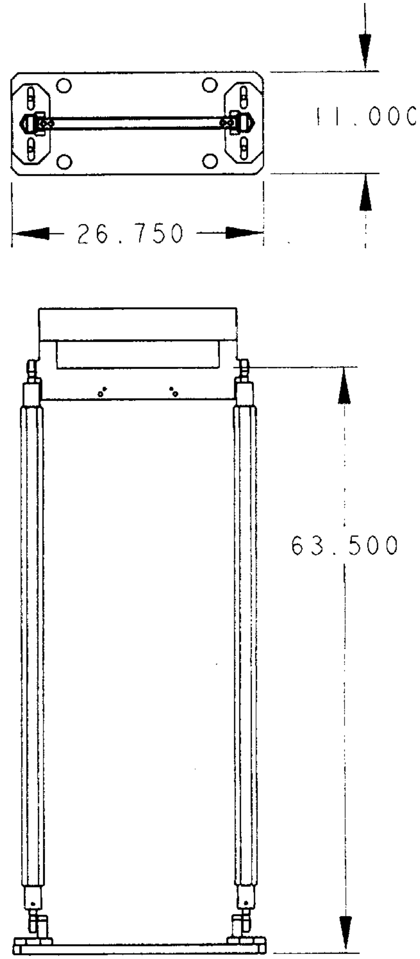


Wiggler Section, X & Y Support Locations



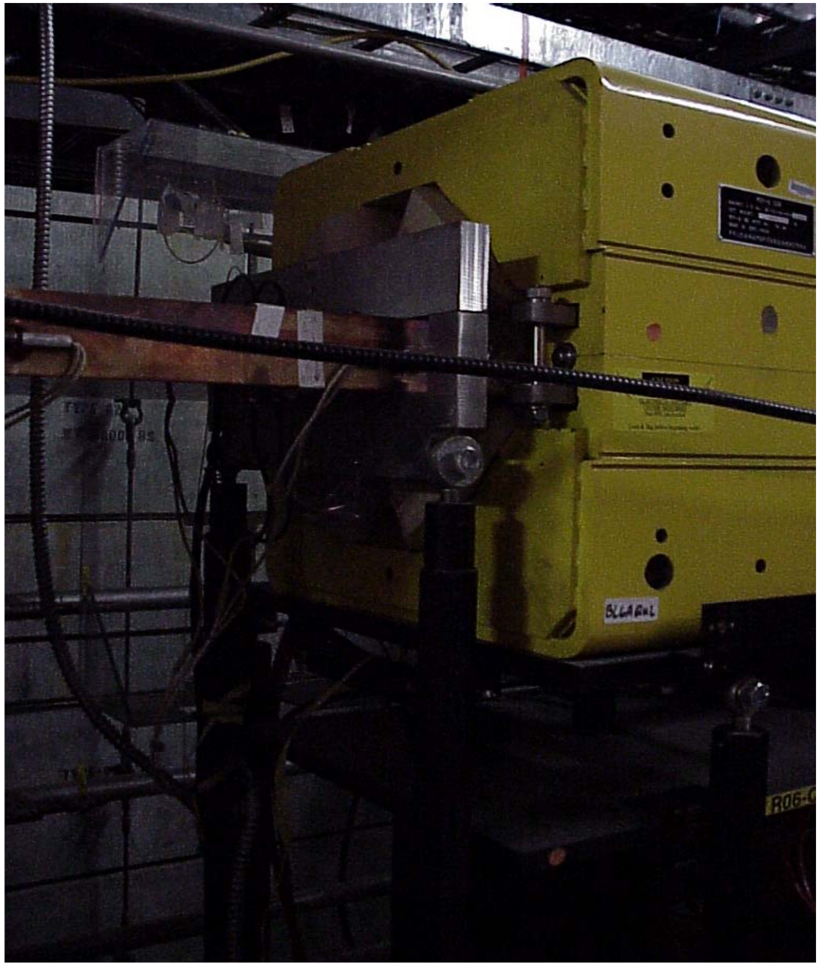
Y-direction Stand for Wiggler Chamber





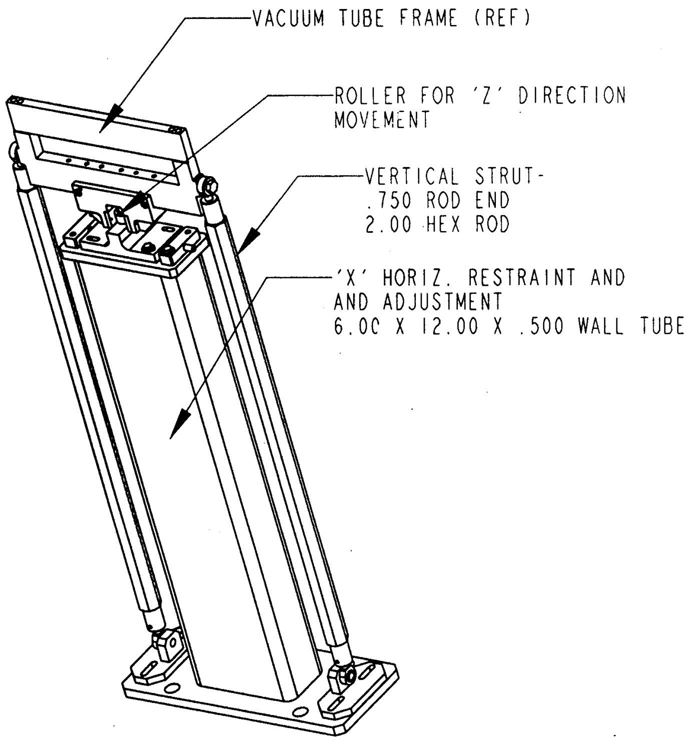
This stand provides support and adjustment capability in the y-direction <u>and</u> roll.

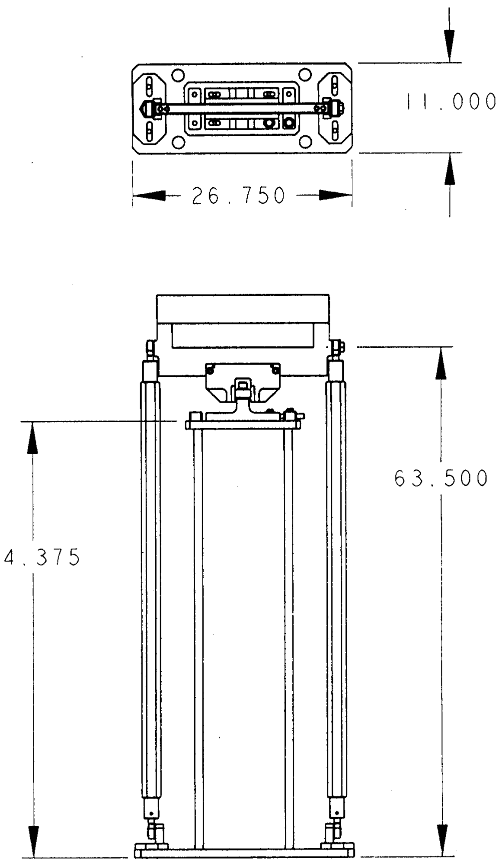
PEP-II Wiggler Vacuum Chamber
Y-direction Support



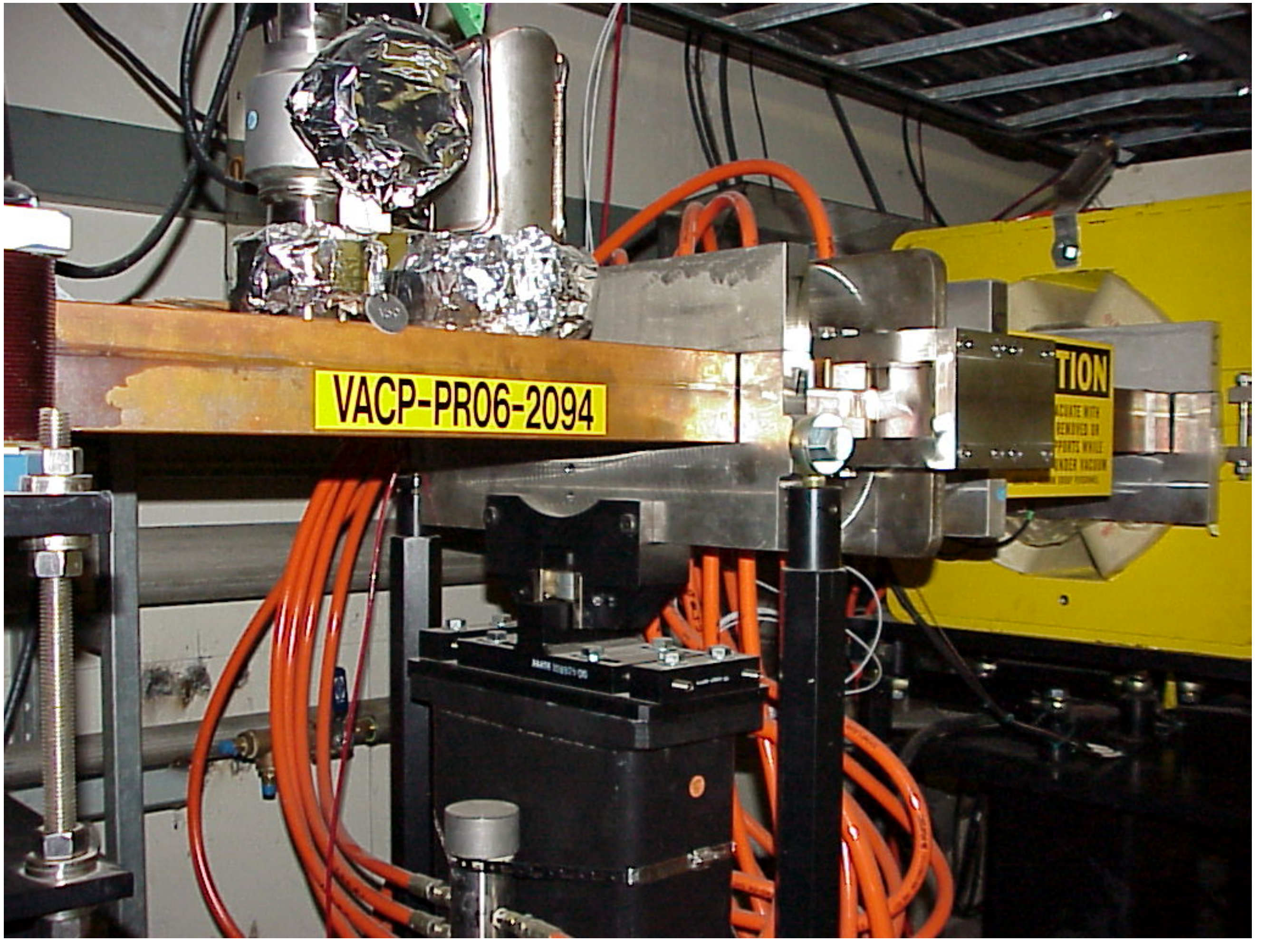
Example of an XY-direction Support Stand

The stand provides support and adjustment capability in the X- and Y-directions as well as roll.

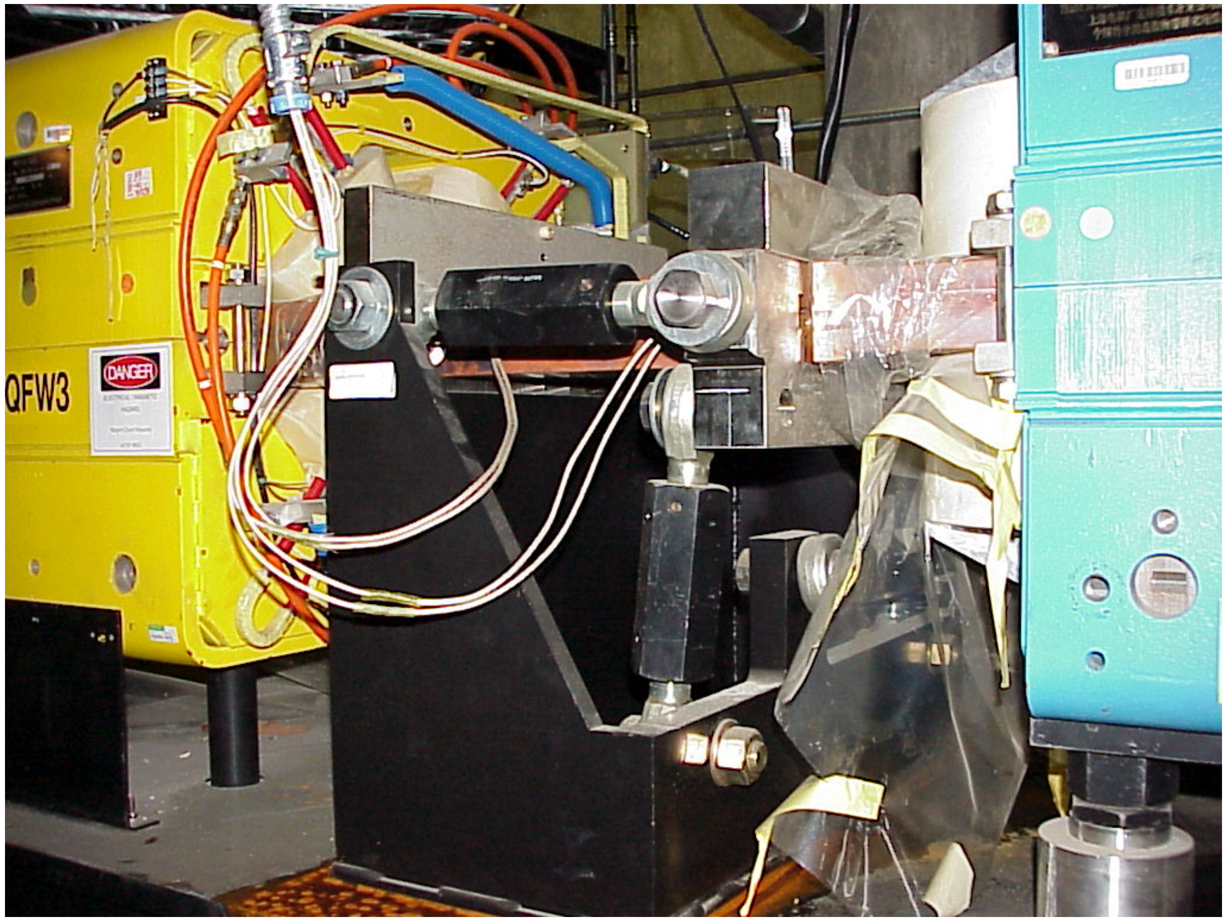




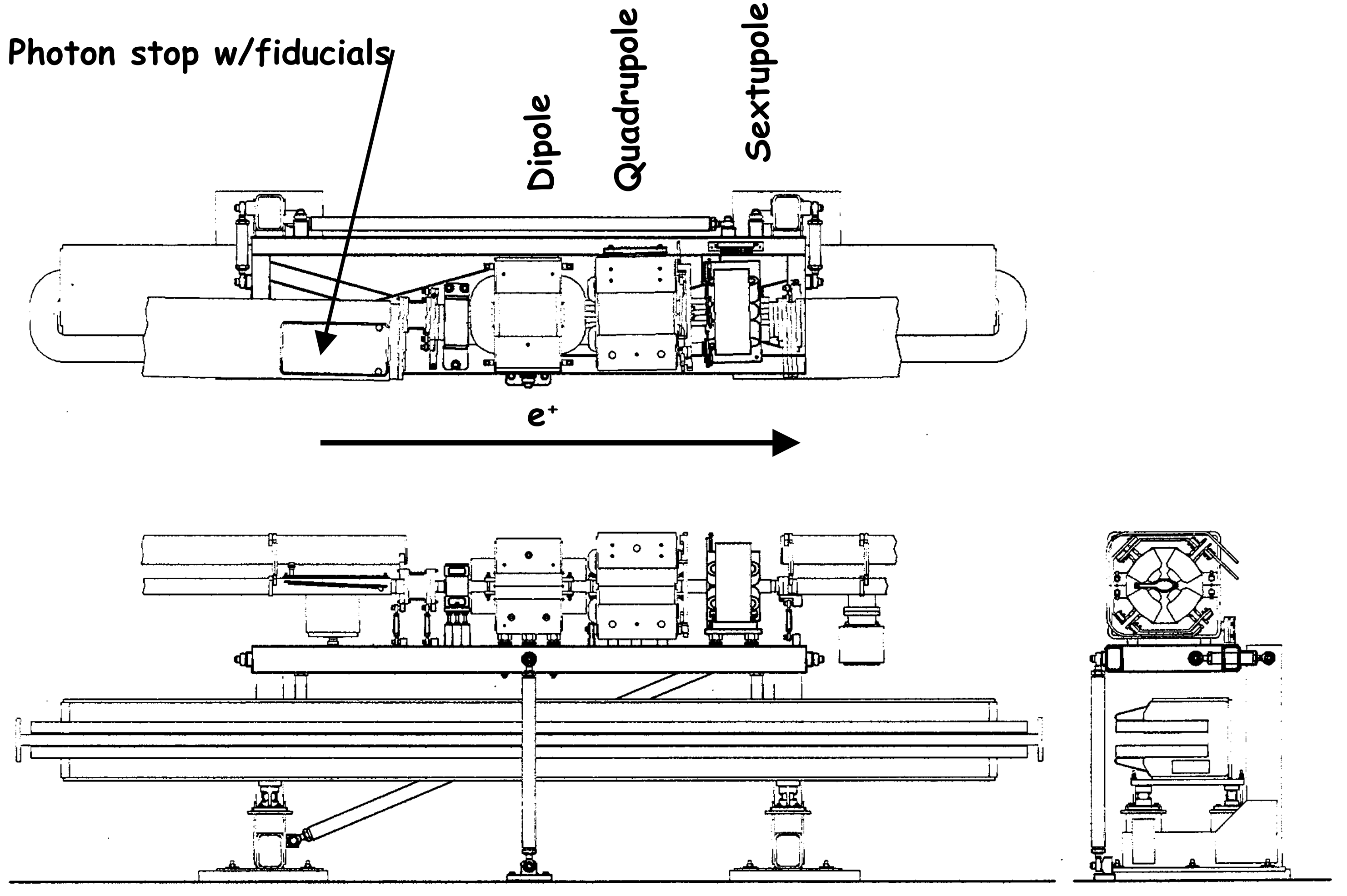
PEP-II Wiggler Vacuum Chamber XY-direction Support



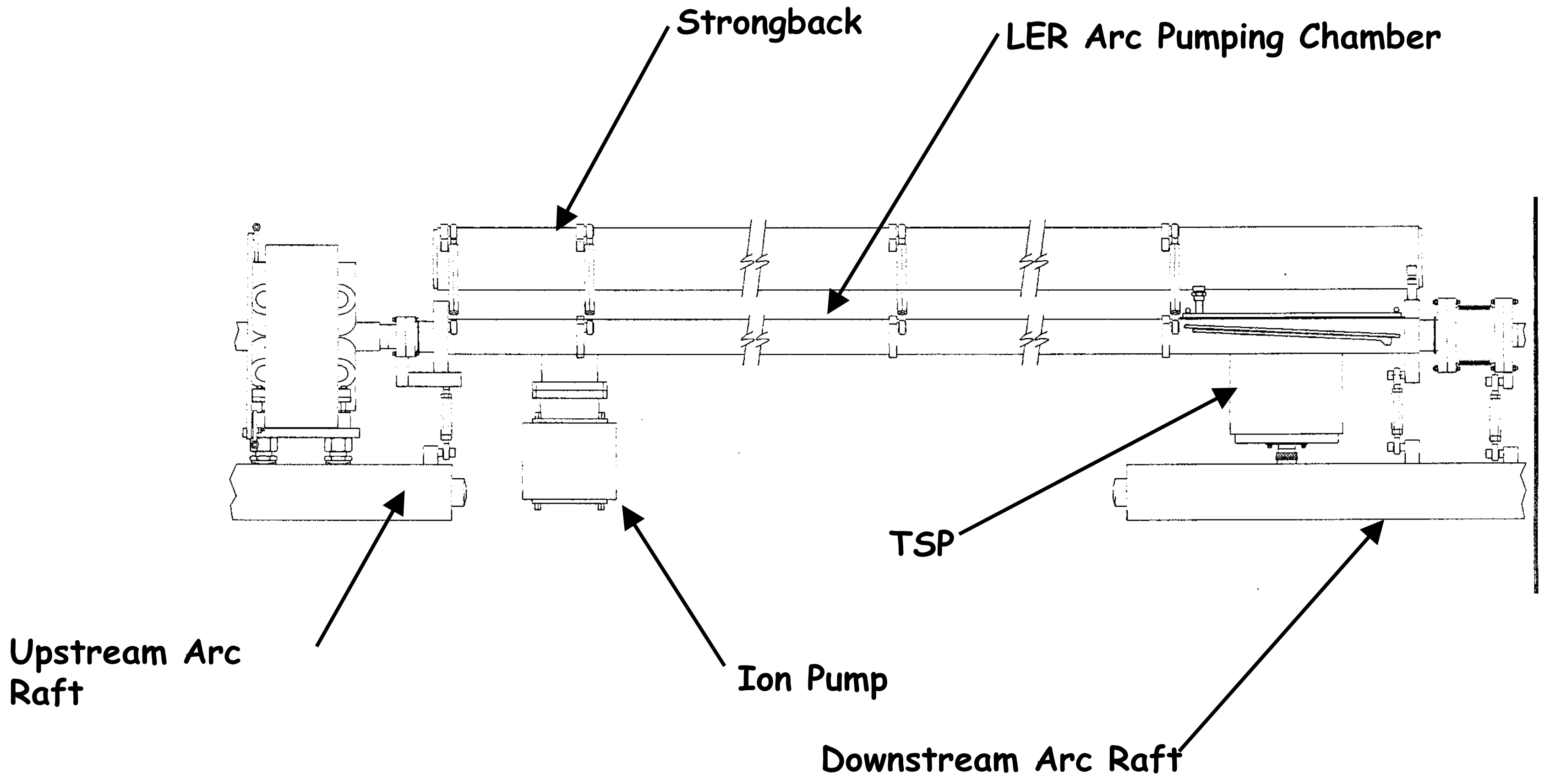
PEP-II Wiggler Vacuum Chamber XYZ-direction Support



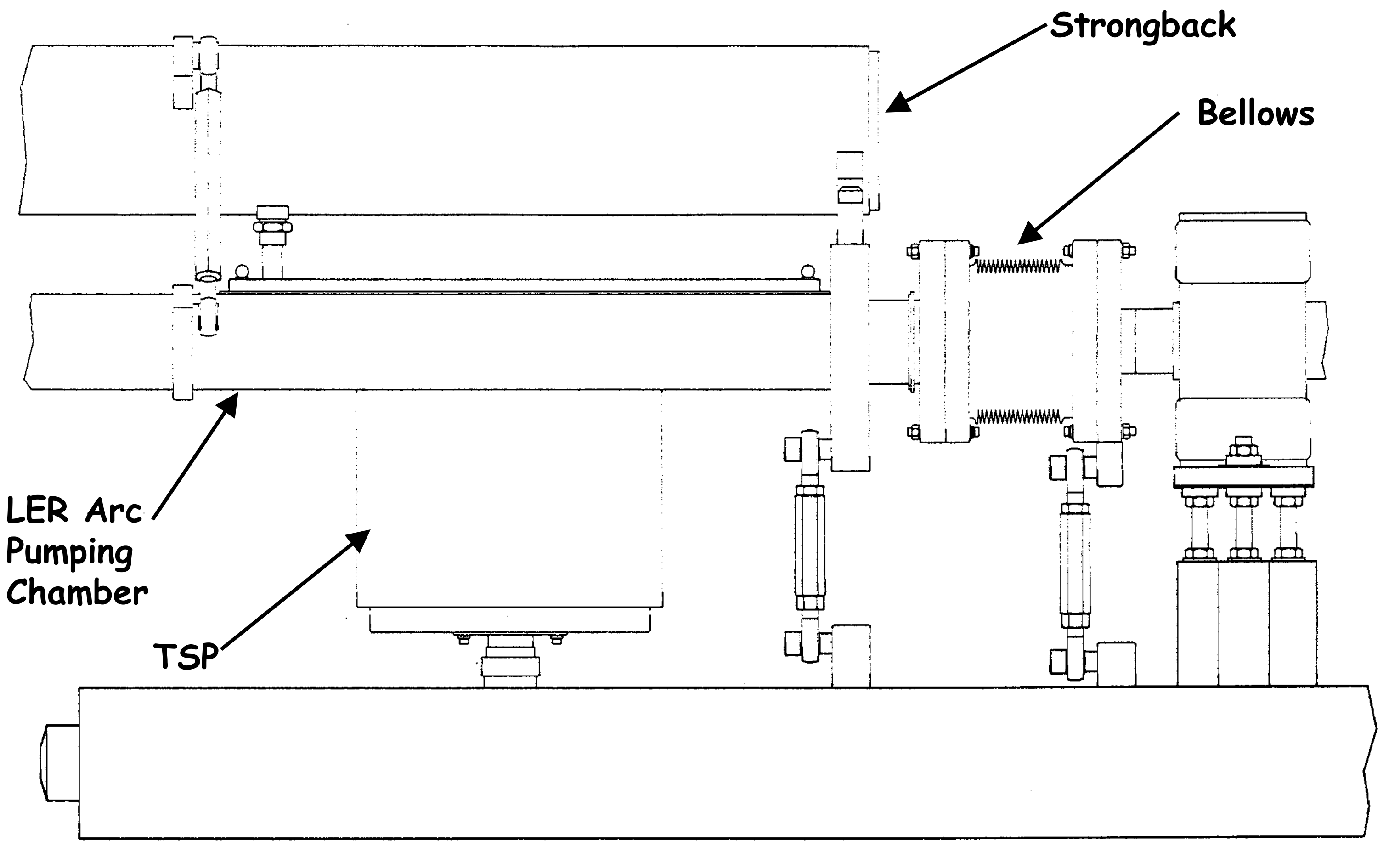
LER Arc Raft Components and Supports



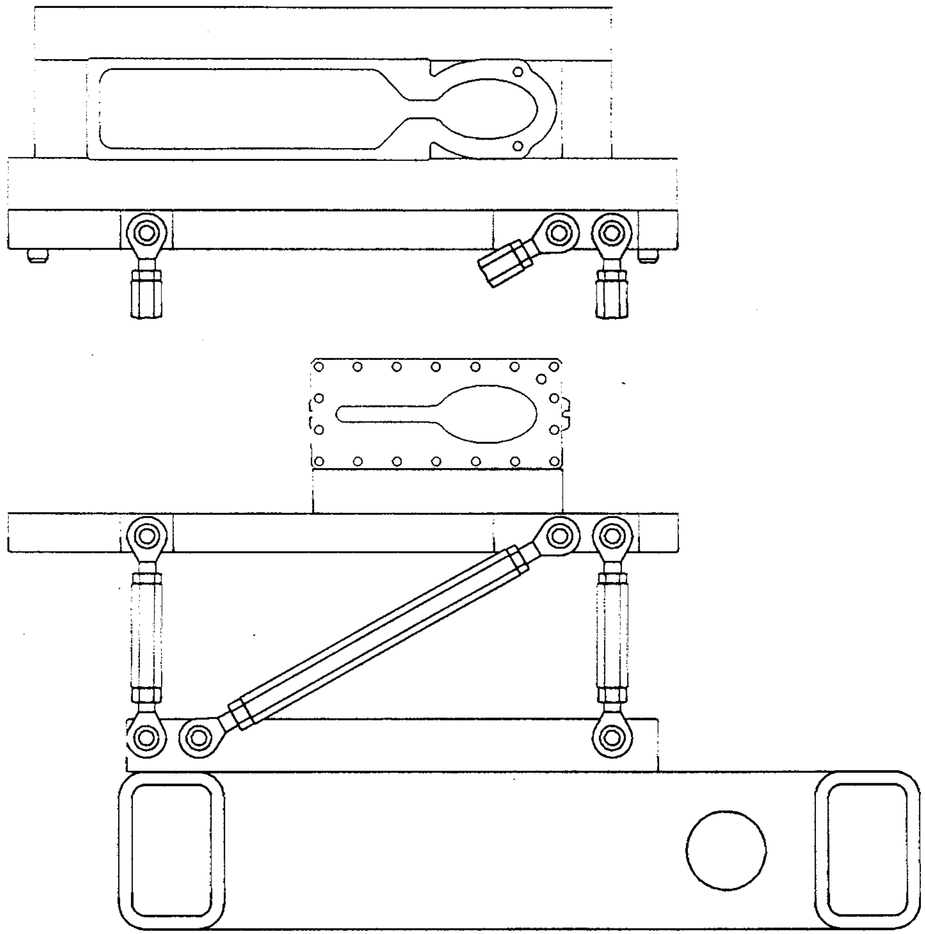
LER Arc Pumping Support Chamber



LER Downstream Raft Support



LER Magnet and Pump Chamber Support



PEP-II LER Arc Pump Chamber "Strongback" Support

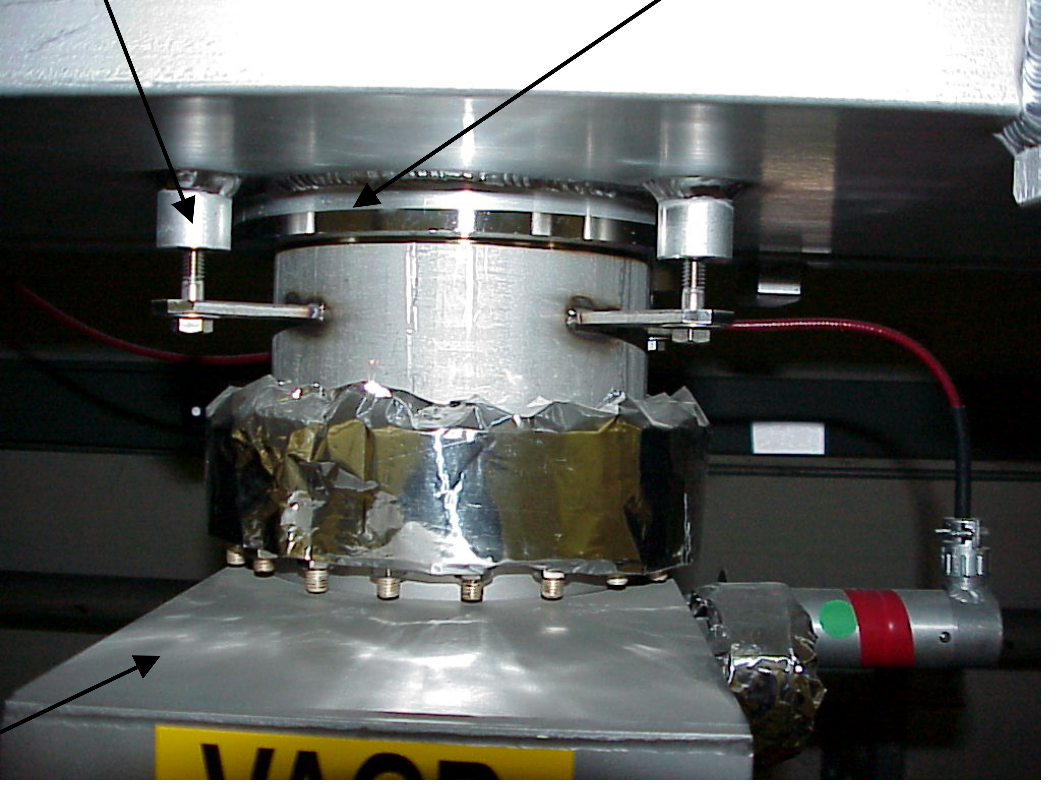
Strongback

Struts adjust in Y-direction & Roll

PEP-II LER Pump Chamber Y-direction Support

Aluminum Half-Coupling

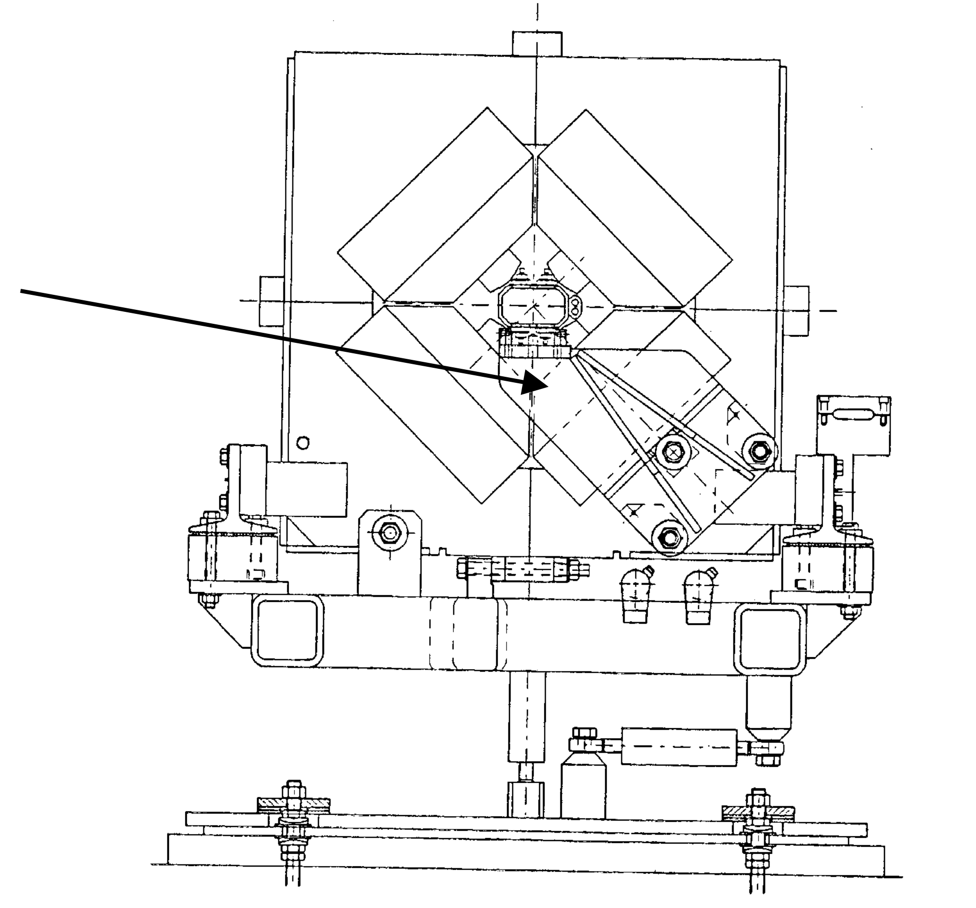
Al-SS Transition



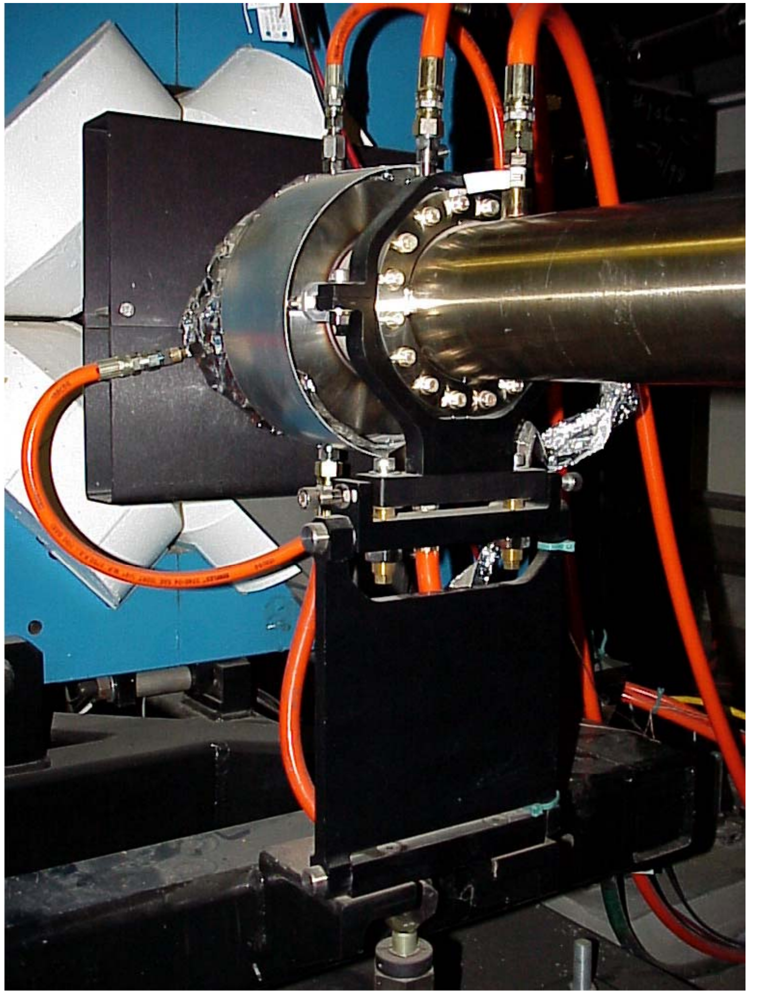
Ion Pump

Example of a XYZ-direction Support

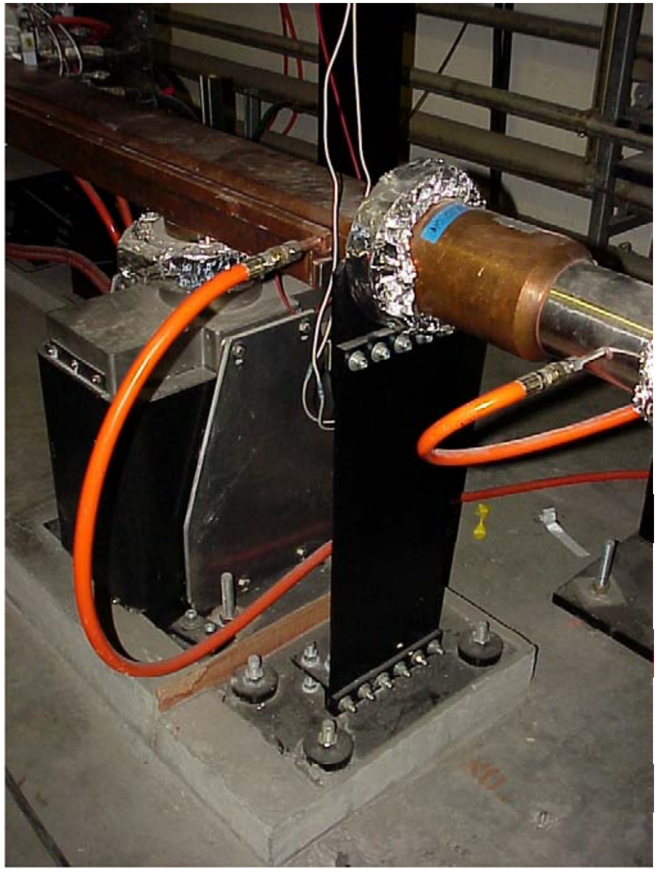
The stand provides support in the X-, Y-, and Z-directions. An XYZ-direction support stand fixes the beamline in all directions.



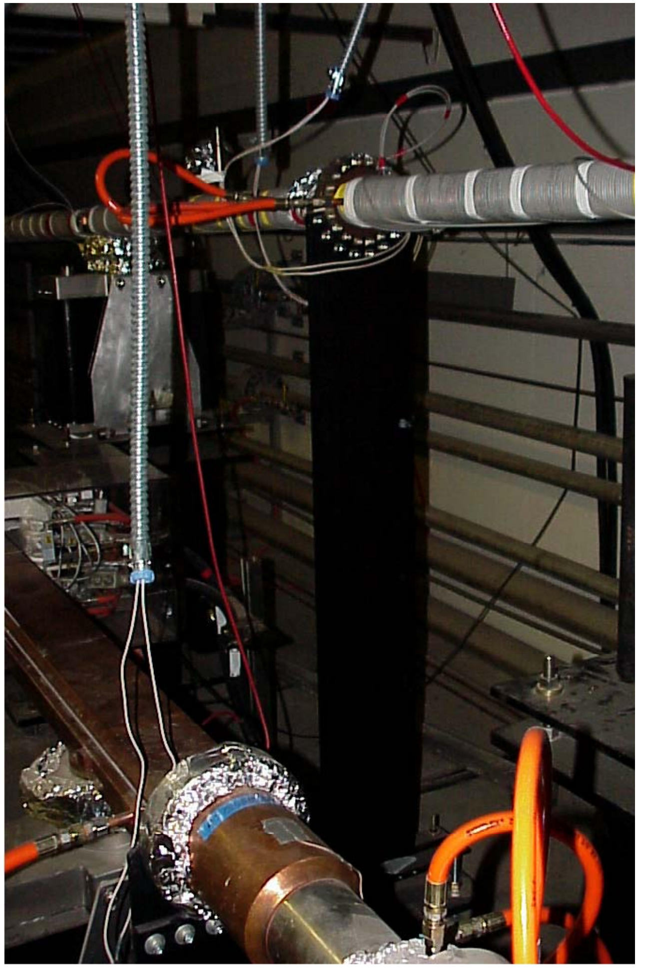
PEP-II HER Straight Section XY-direction (Rotational) Support



PEP-II HER Interaction Region XY-direction (Flex) Support

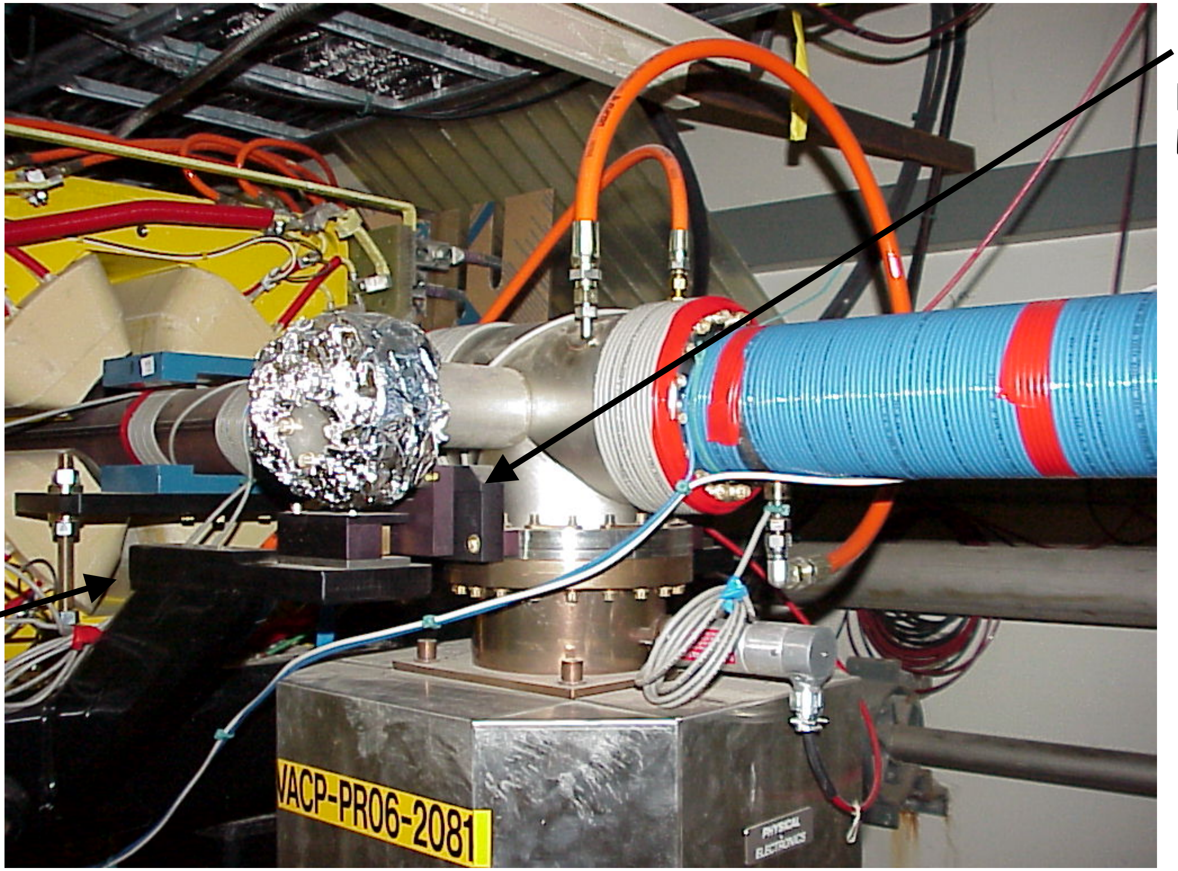


PEP-II LER Interaction Region XY-direction (Flex) Support



PEP-II LER Straight Section XY-direction Pump Support

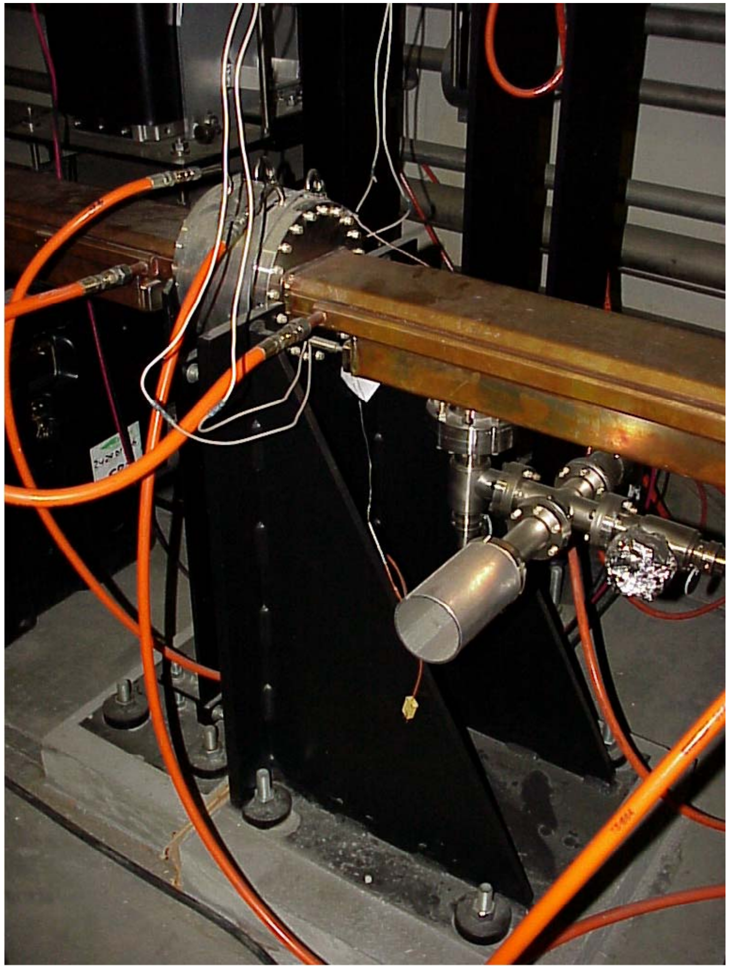
Bracket & Cam Follower attached to Pump Cross



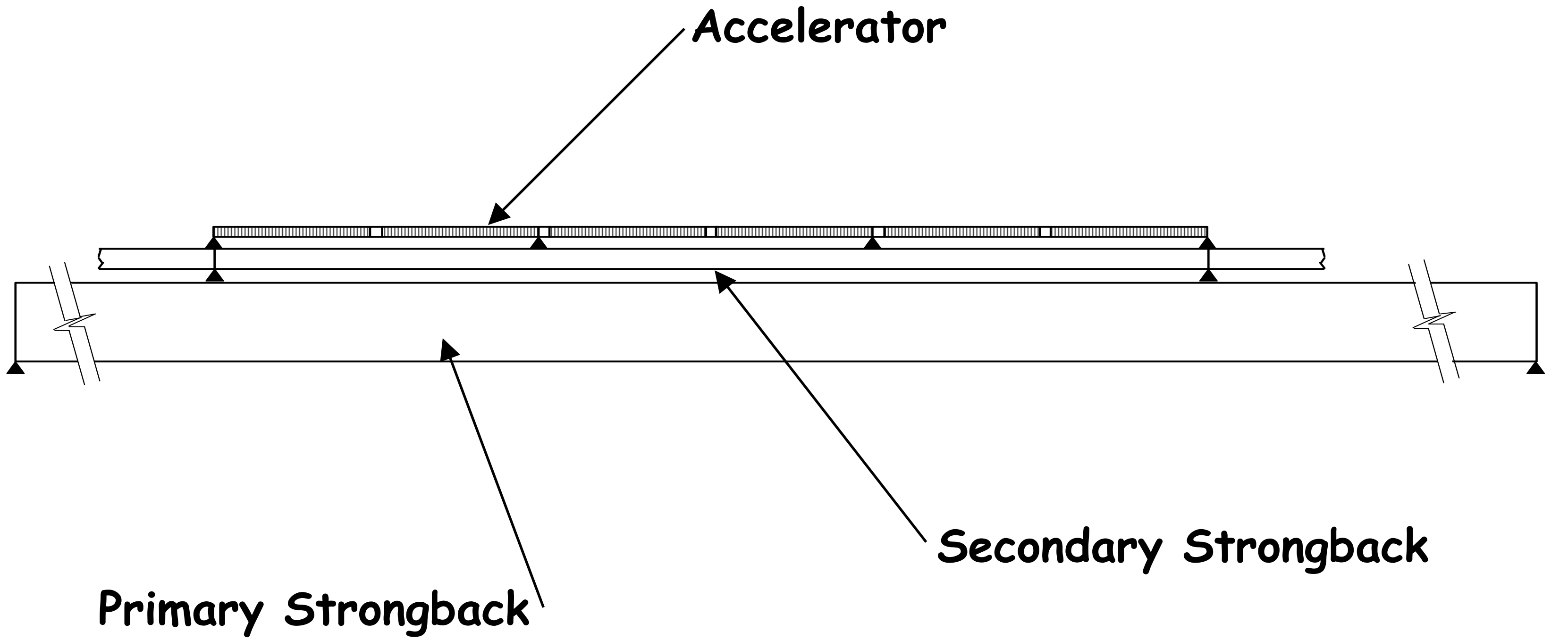
"Diving Board" attached to Quad Magnet Raft

PEP-II Interaction Region Y-direction Pump Support

PEP-II Interaction Region XYZ-direction (Fixed) Support



"Strongbacks" Constrain Vacuum Chambers to Control their Position

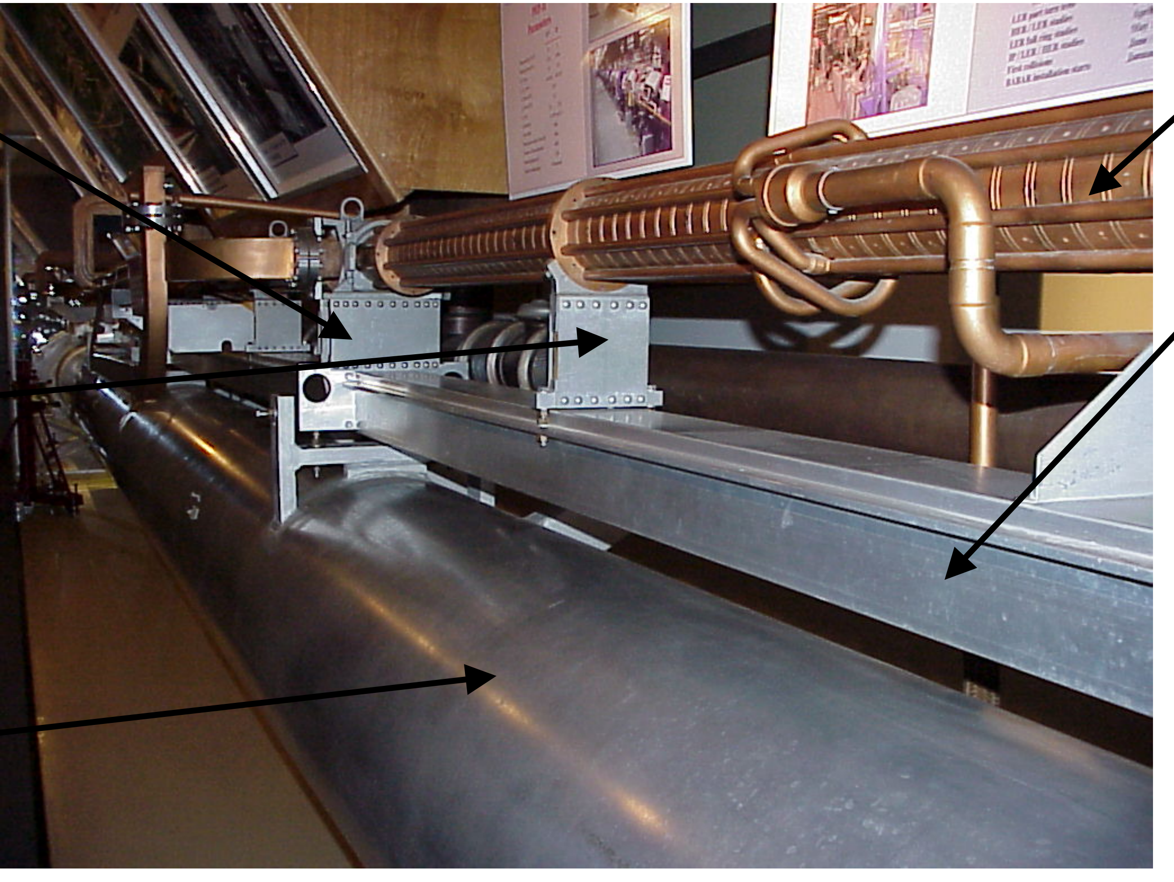


SLAC Linac "double strongback" Support

Fixed Support

Flex Support

Primary Strongback



Linac

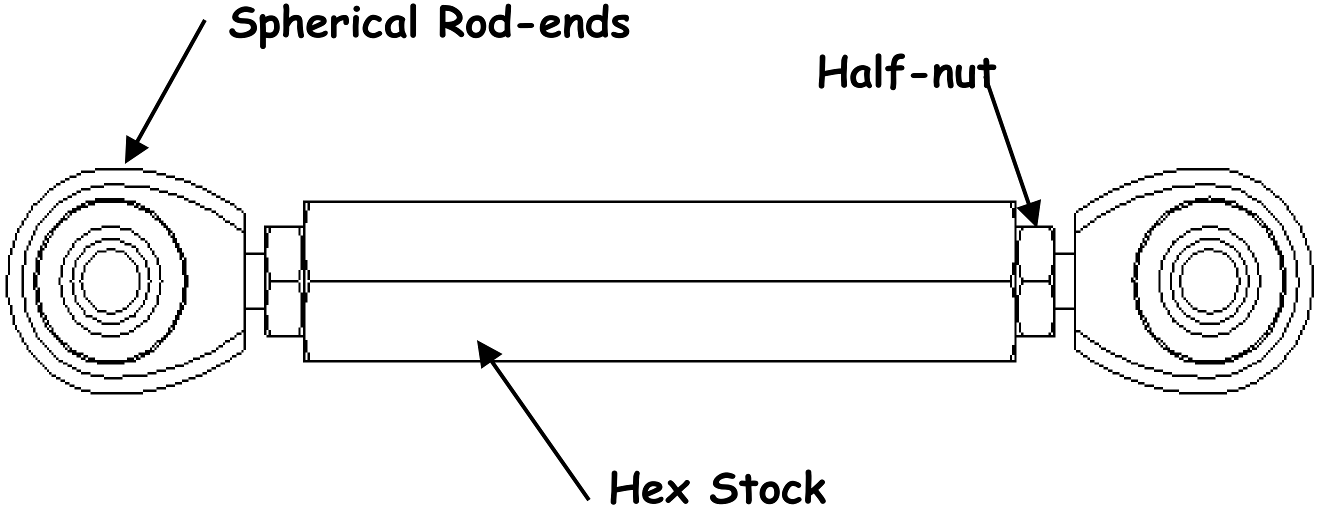
Secondary Strongback

Six-Strut Support Systems

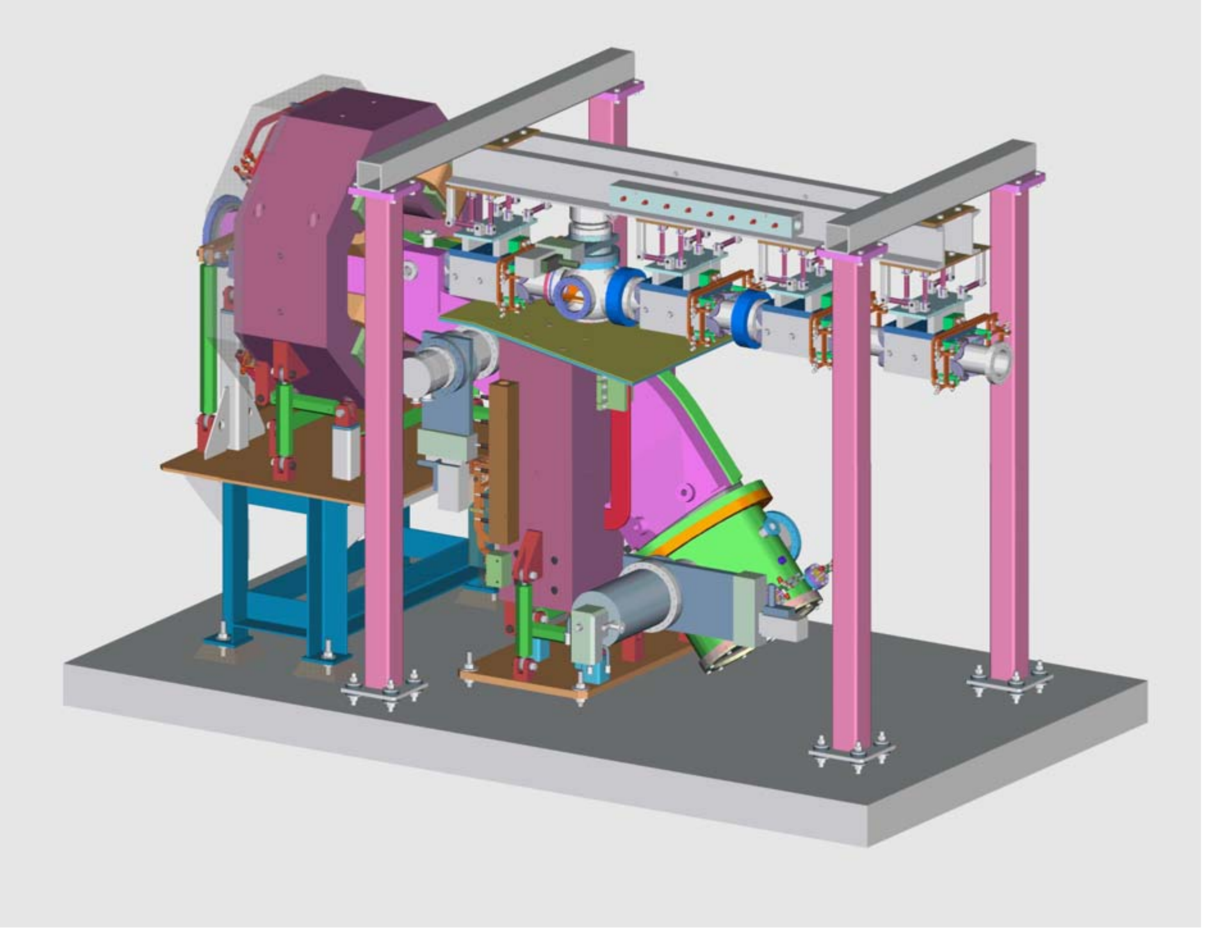
- A support system that uses six orthogonal struts to provide a "kinematic" support (just enough support with no additional constraints).
- Struts have spherical ball joint end connections.
- Each strut is extremely strong and rigid.
- Together the six struts can usually provide a support system with a natural frequency greater than 20 Hz.
- An excellent reference for this style of support system is: "Rigid, Adjustable Support of Aligned Elements via Six Struts", W. Thur et al, Fifith Int. Workshop on Accelerator Alignment, 1997

A Typical Strut

- Struts can be made several ways:
  - Opposing spherical rod-ends both with right-handed threads (one fine thread, one coarse threads)
  - Opposing spherical rod-ends, right- and left-handed threads (fine threads or coarse threads).

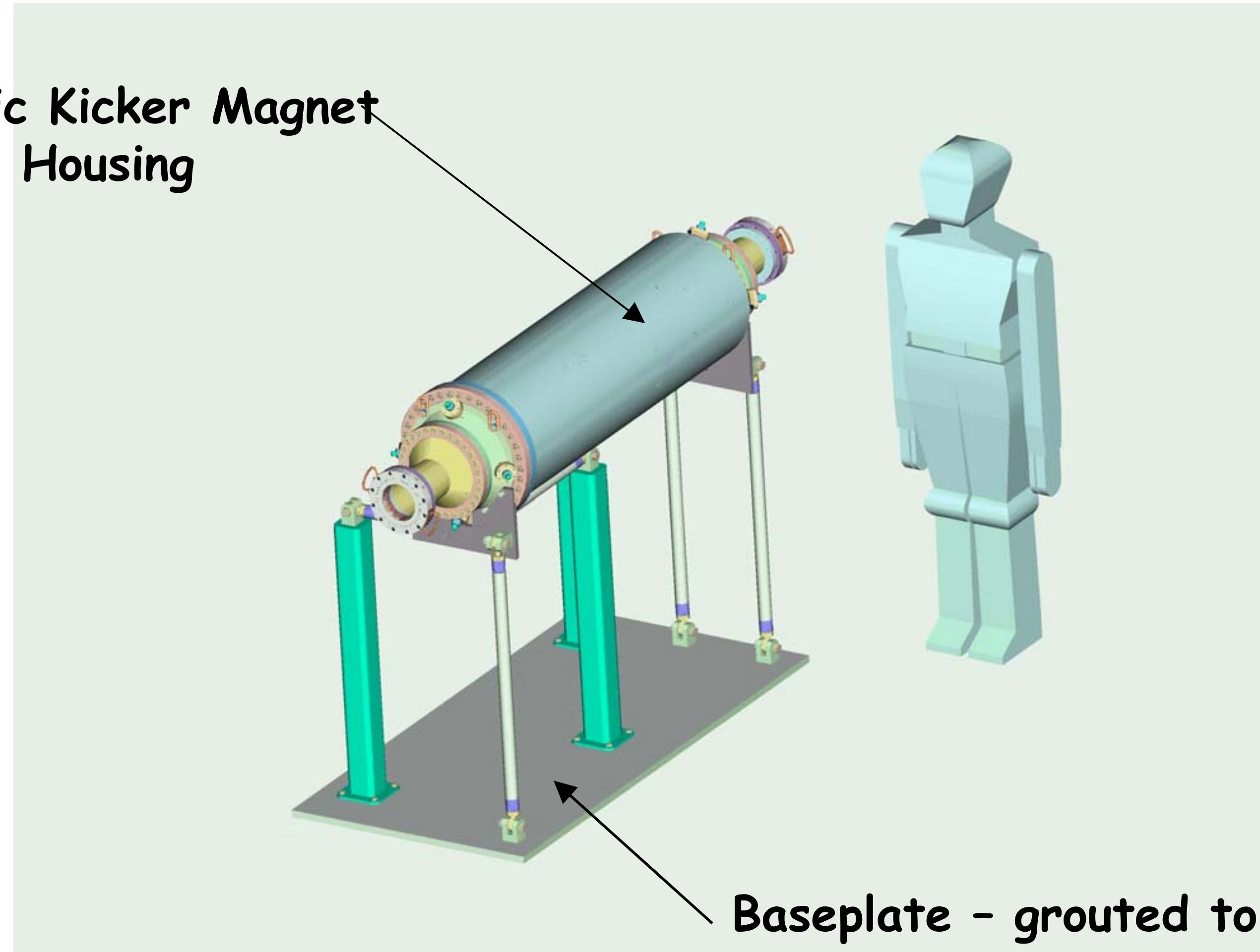


Example of Kinematic Supports (six-strut)

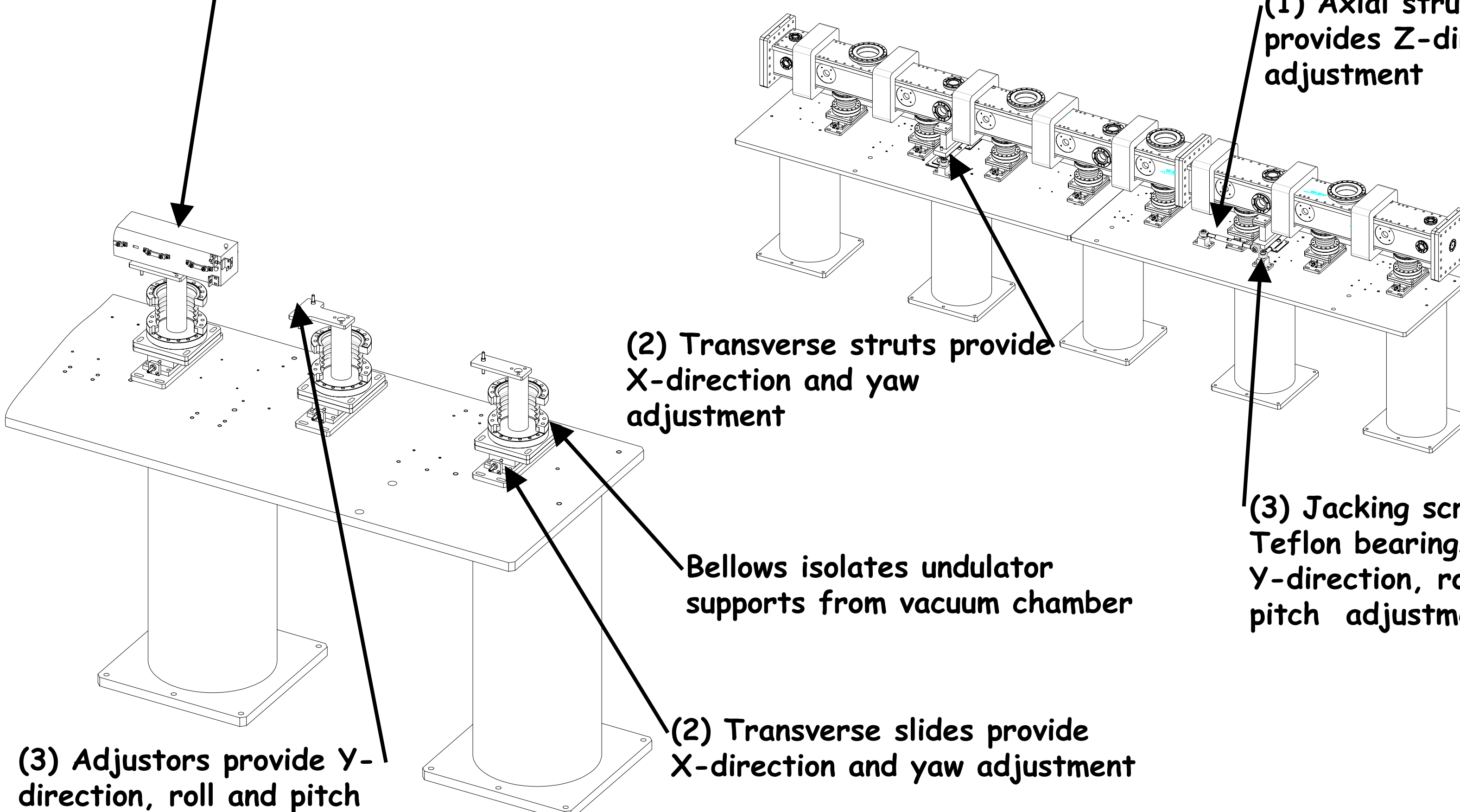


DARHT II Septum Chamber & Magnets, each supported on six struts

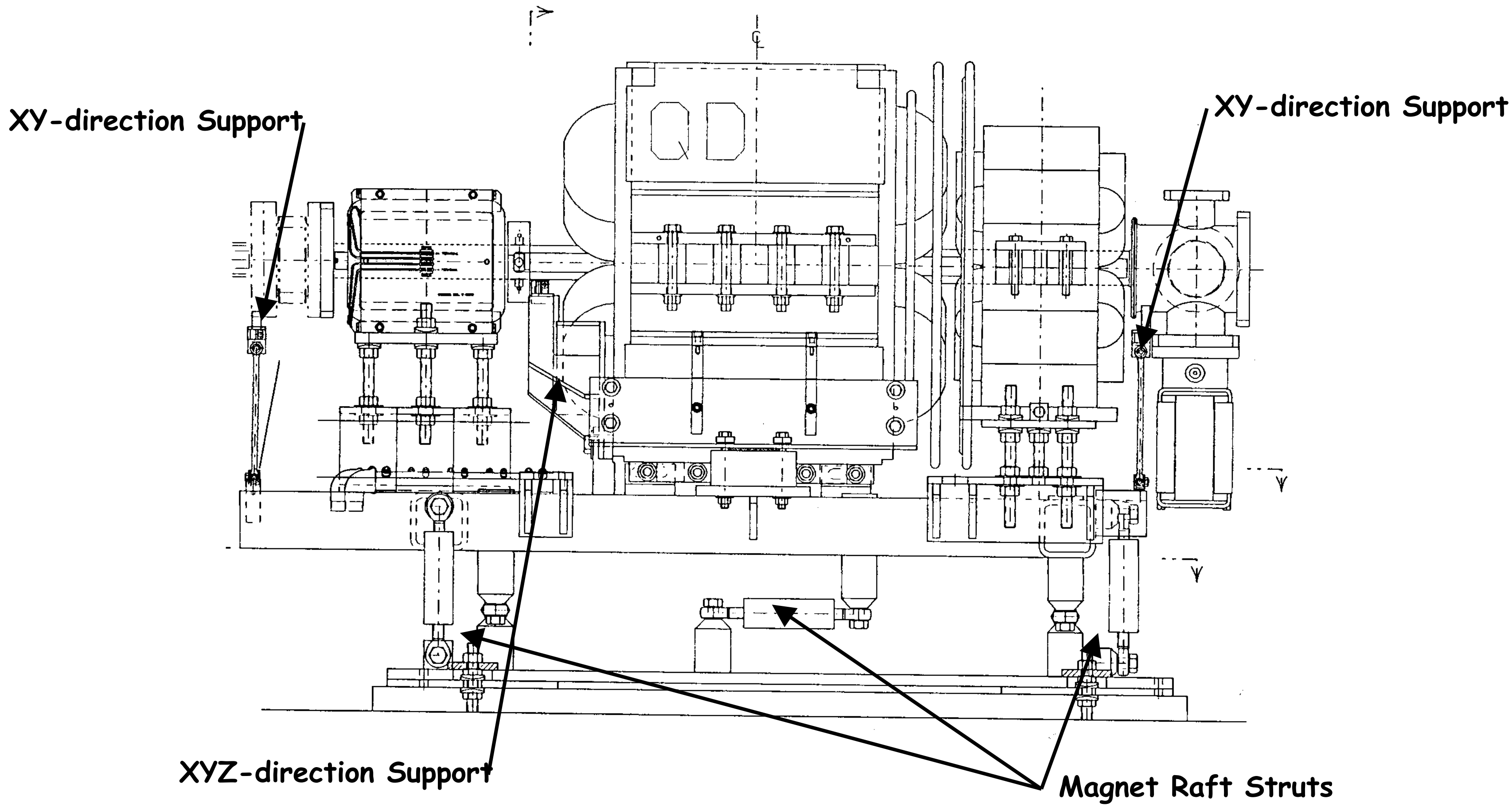
DARHT II Kicker Six-Strut Supports



Two Kinematic Supports in One Design

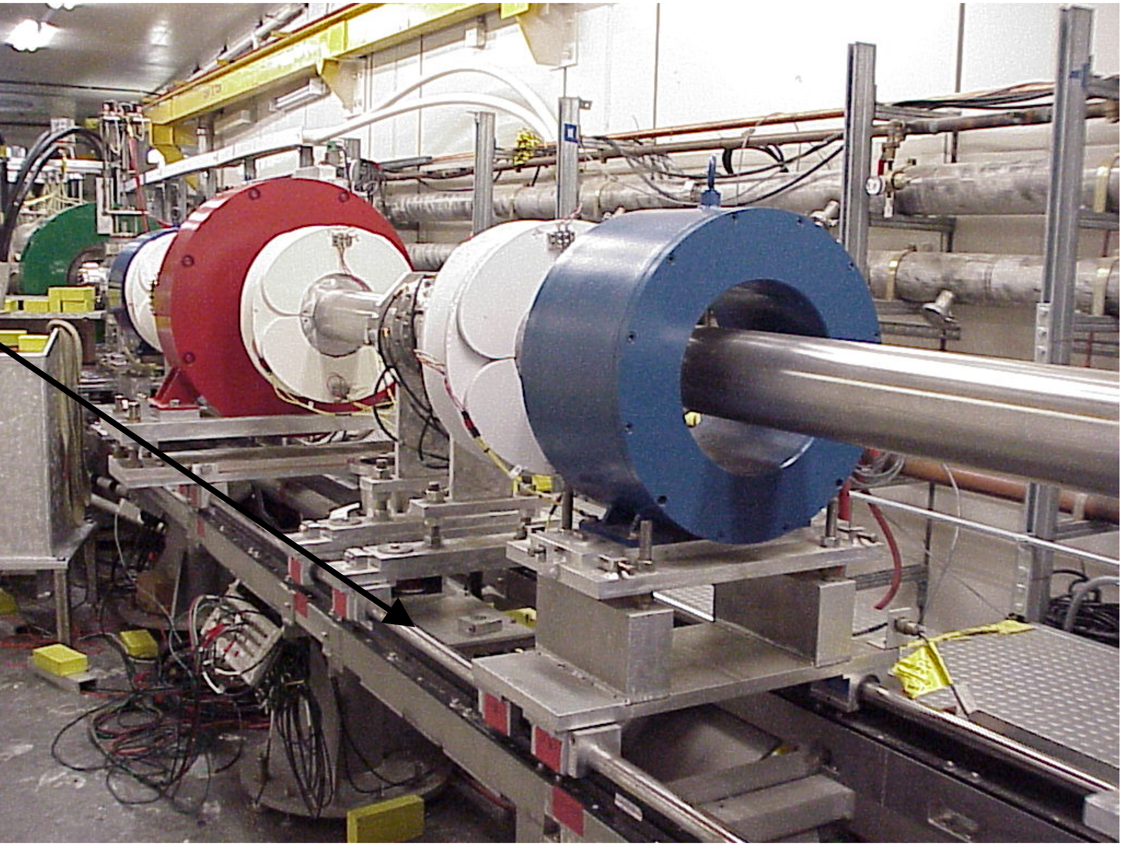


Magnet Raft

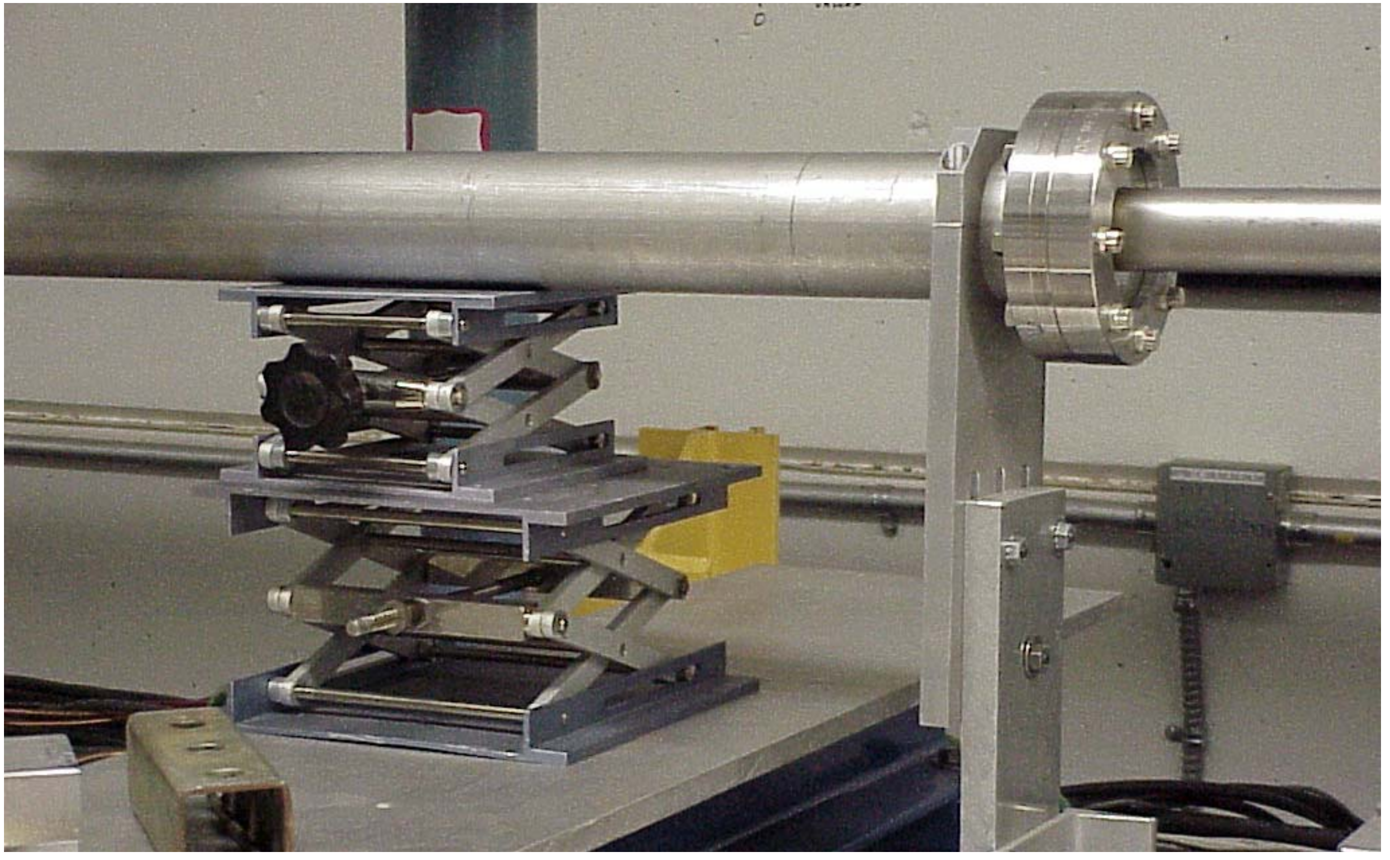

XY-direction Support
XY-direction Support
QD
XYZ-direction Support
Magnet Raft Struts

Support System with Flexibility Built-in

Magnet and Beampipe Supports mounted to Thompson Rails



When all else fails ...

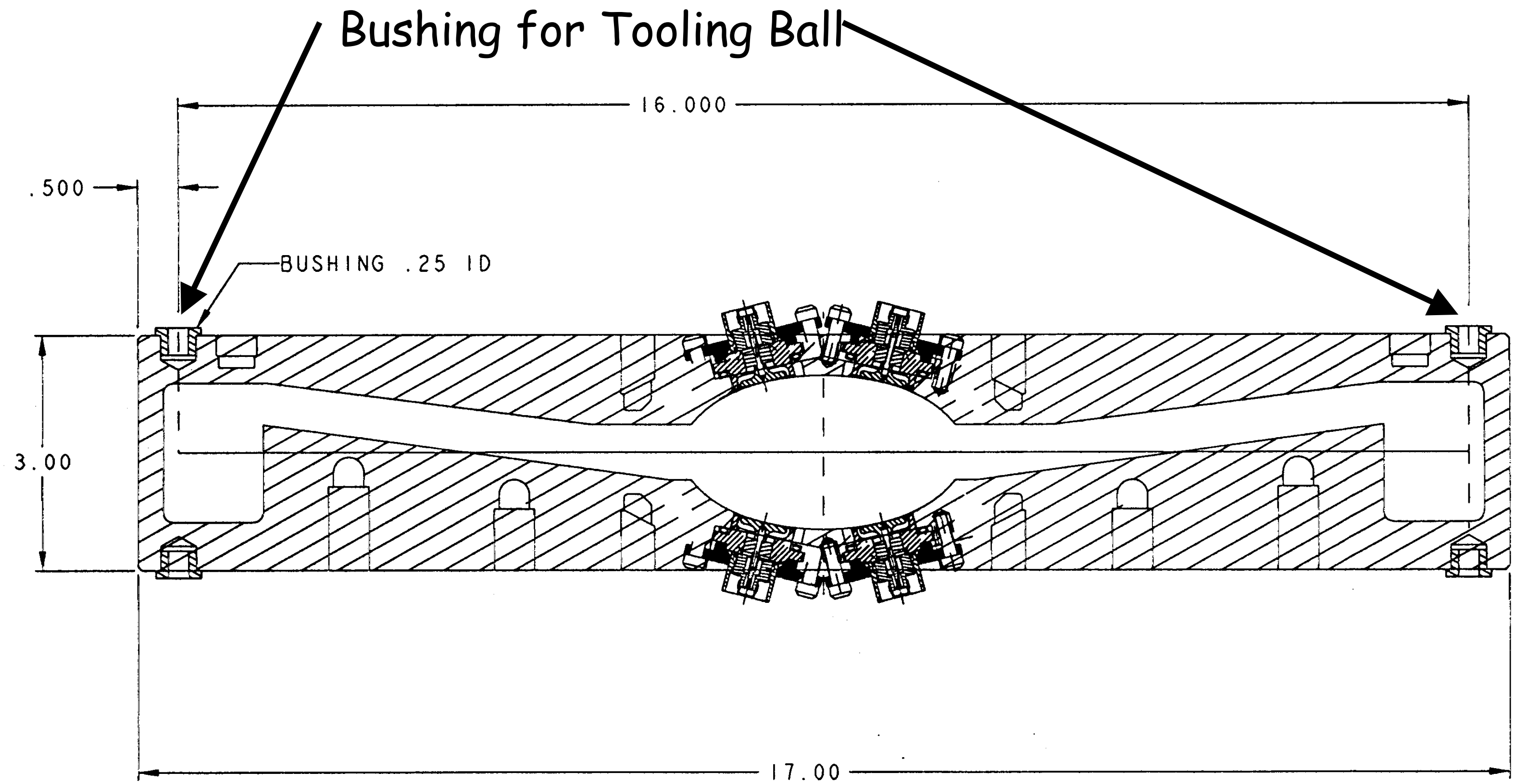


Typical areas of accelerator vacuum systems that require accurate positioning

- RF Cavities
- Beam position monitors (BPM)
- Synchrotron radiation adsorbers or masks

Fiducials are usually located near these components to aid in alignment.

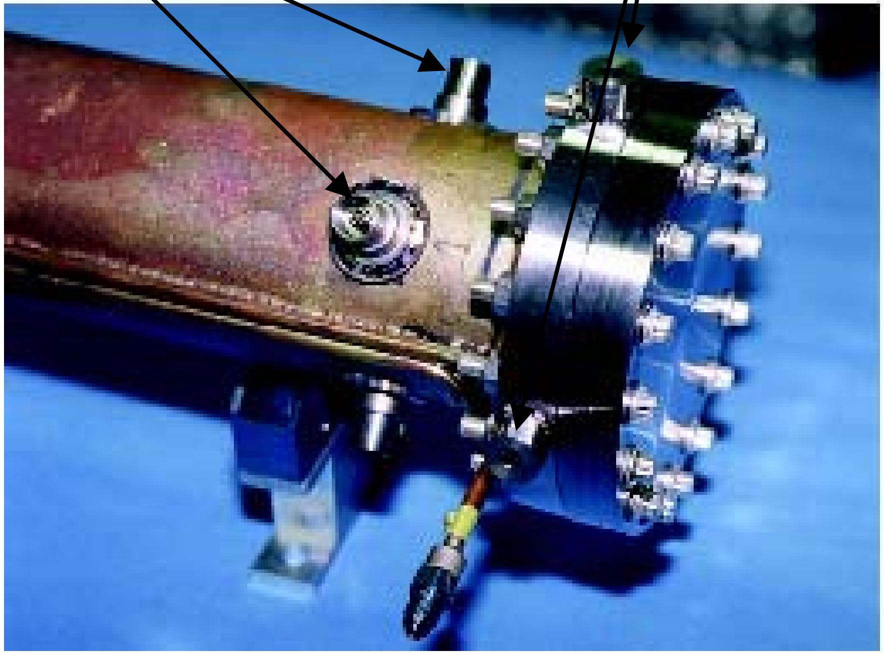
Fiducials on a Wiggler Chamber (near BPM)



Fiducial on Quadrupole Chamber (near BPM)

BPM Buttons

Fiducial Mounts
(reamed holes for tooling balls)



Fiducials on LER Photon Stop