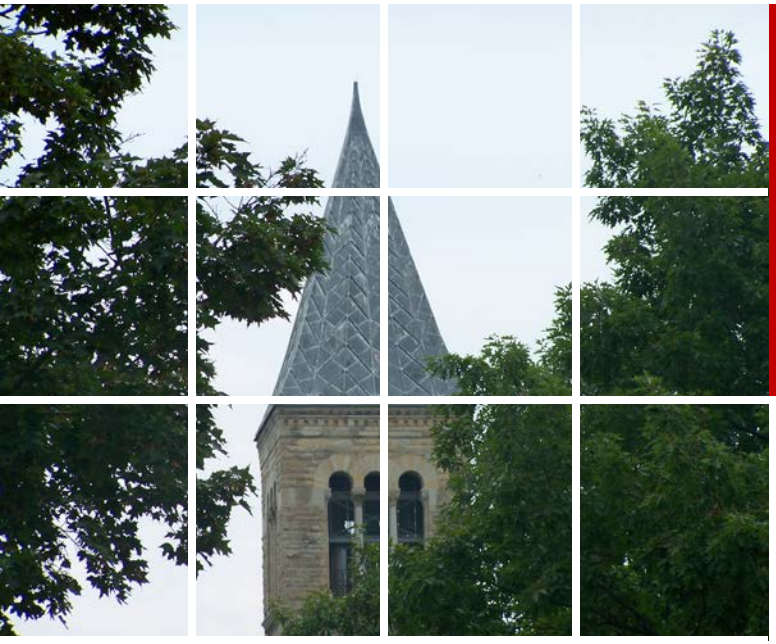
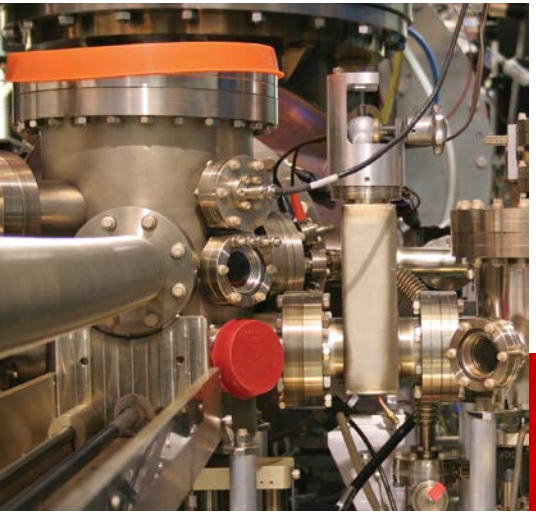


Vacuum Science and Technology for Accelerator Vacuum Systems

Yulin Li and Xianghong Liu
Cornell University, Ithaca, NY



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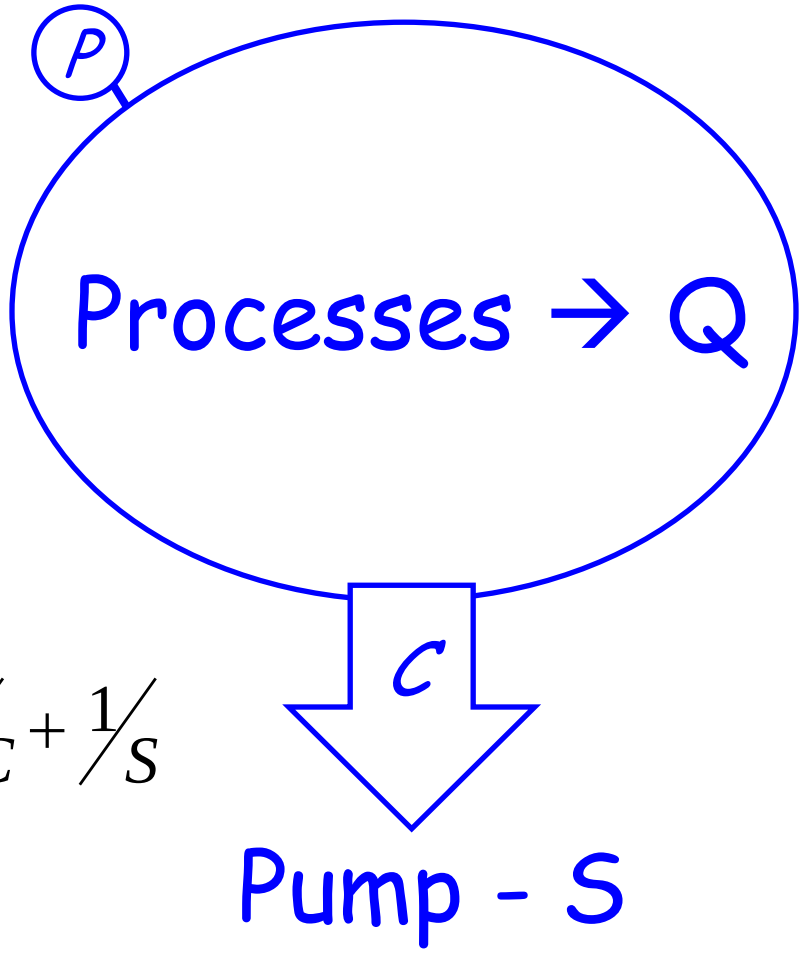
A Generic Vacuum System

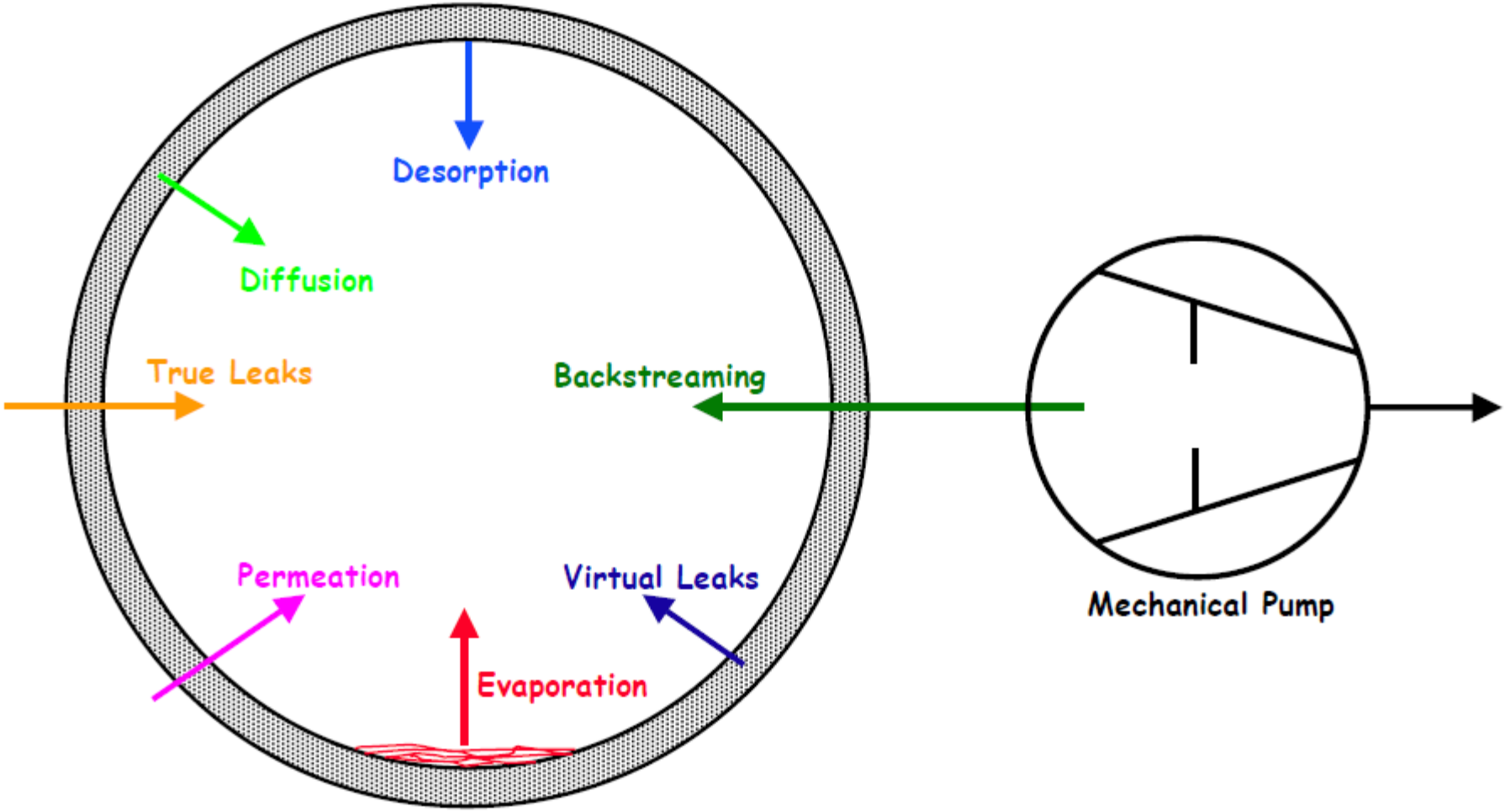
- A vacuum system consists of chamber(s), pipes and ducts, to enable desired process.
- A certain vacuum level (working pressure, **P**) is specified.
- Both the chamber materials and the process produces gases, **Q**.
- Vacuum pump with pumping speed **S** is installed via a conductance (**C**) to achieve the required vacuum level.



$$P = Q / S_{eff}$$

$$1/S_{eff} = 1/C + 1/S$$

Examples of "Static" Gas Loads



"Static" Gas Loads – Leaks

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

"Static" Gas Loads – Leaks

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)

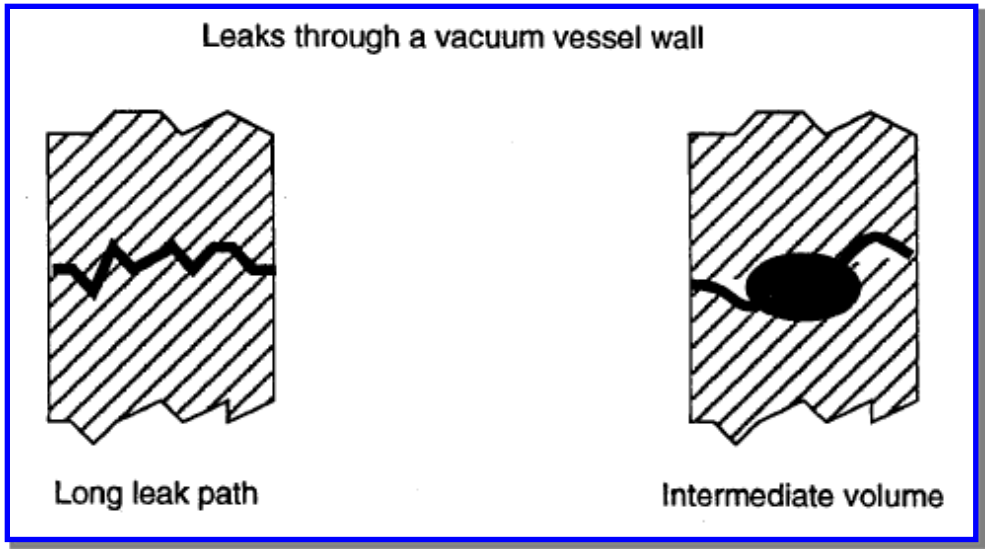
e = 2.7183 base to natural logarithm

t = time (sec)

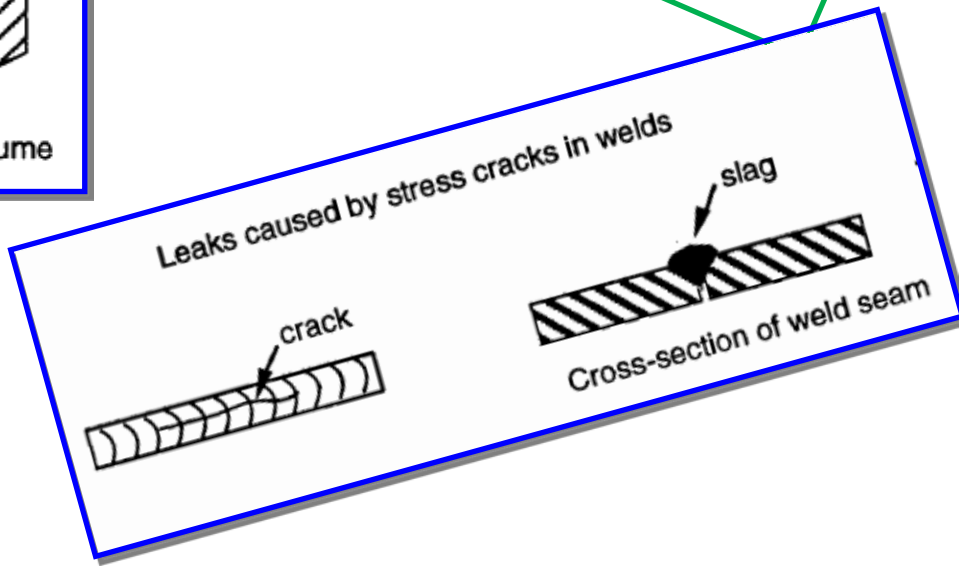
Ref. "Vacuum Technology and Space Simulation", Santeler et al, NASA SP-105, 1966

Examples of True Leaks

Real leak → *physical hole or crack in vessel wall, and/or faulty joint allowing gas to enter the vessel*



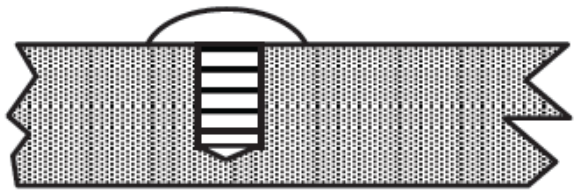
Improper seating of gaskets, etc.



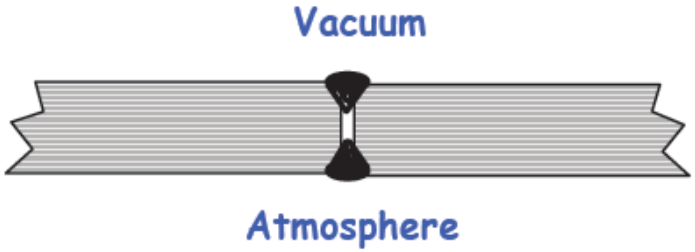
Scratch sealing surfaces, or rolled/nicked knife-edge, etc.

Examples of Virtue Leaks

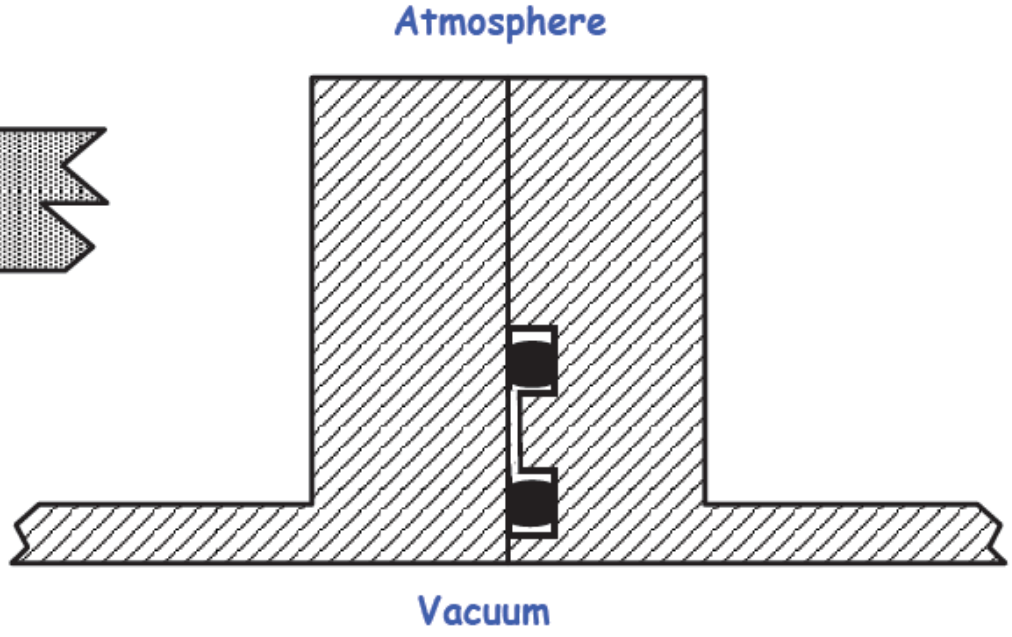
Virtue leak → *A virtual leak is a volume of trapped atmospheric gas that leaks into the vacuum vessel through holes or cracks that that do not go all the way through the vessel wall*



Unvented Screw

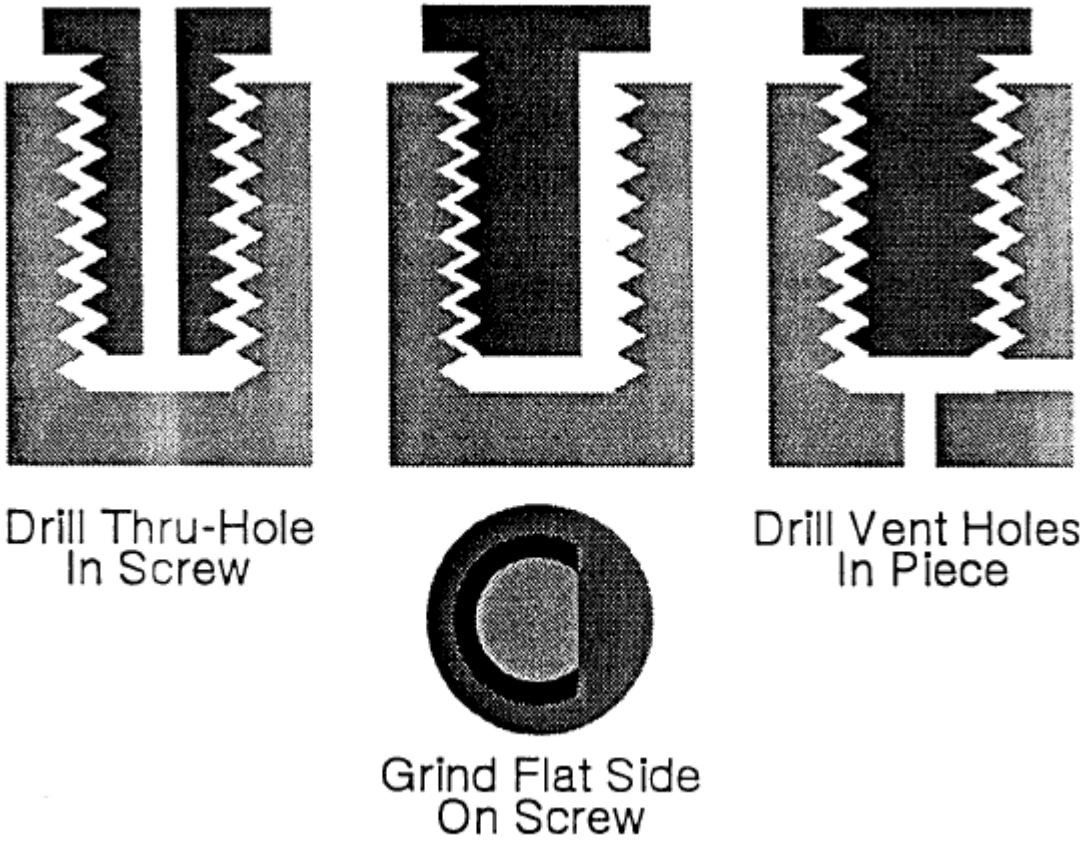


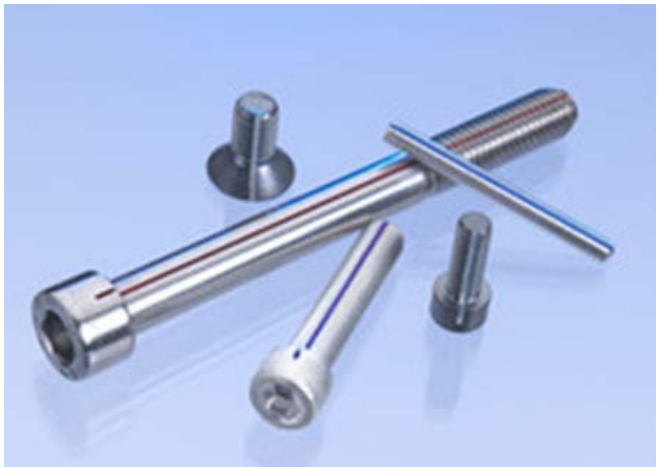
Two Welds in Series



Unvented Double O-rings

Venting the blind holes





Center-vented and slot-vented UHV ready fasteners are readily available for most commonly used sizes

Evaporation

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

where

Q_E = gas-load due to evaporation (Torr-liter/sec)
T = Temperature (K)
M = molecular weight (grams/mole)
P_E = vapor pressure of material at the temperature
P = Partial pressure of evaporating molecules
A = surface area of evaporating material (cm^2)

Assuming a pumping speed **S** to the system, an equilibrium pressure due to the evaporation is:

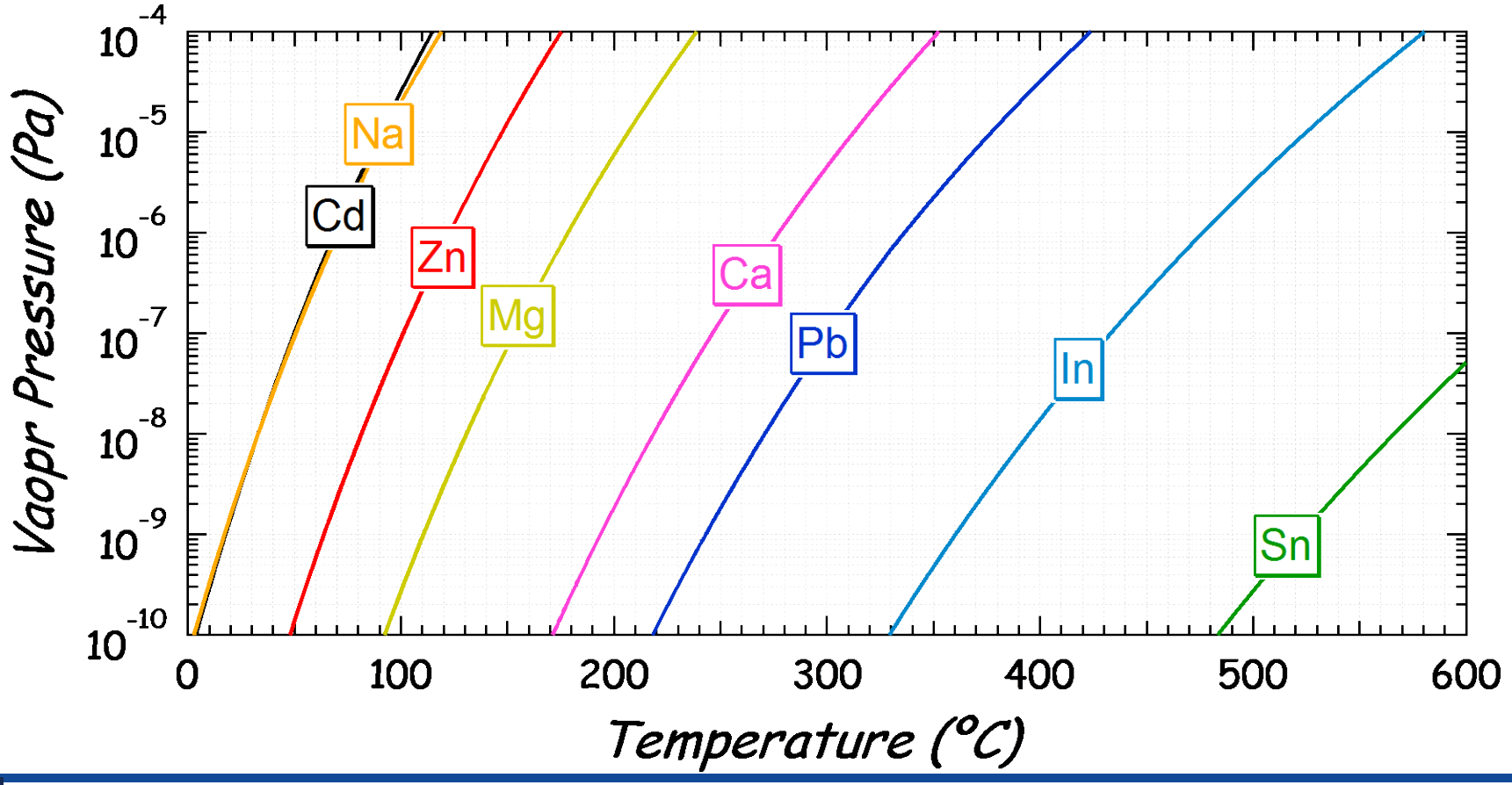
$$P = \frac{1}{1+(S/f)}P_E \qquad f \equiv 3.639\sqrt{\frac{T}{M}}\cdot A$$

Material vapor pressure (P_E) is a strongly dependent on temperature T

Vapor Pressure – Antoine Equation

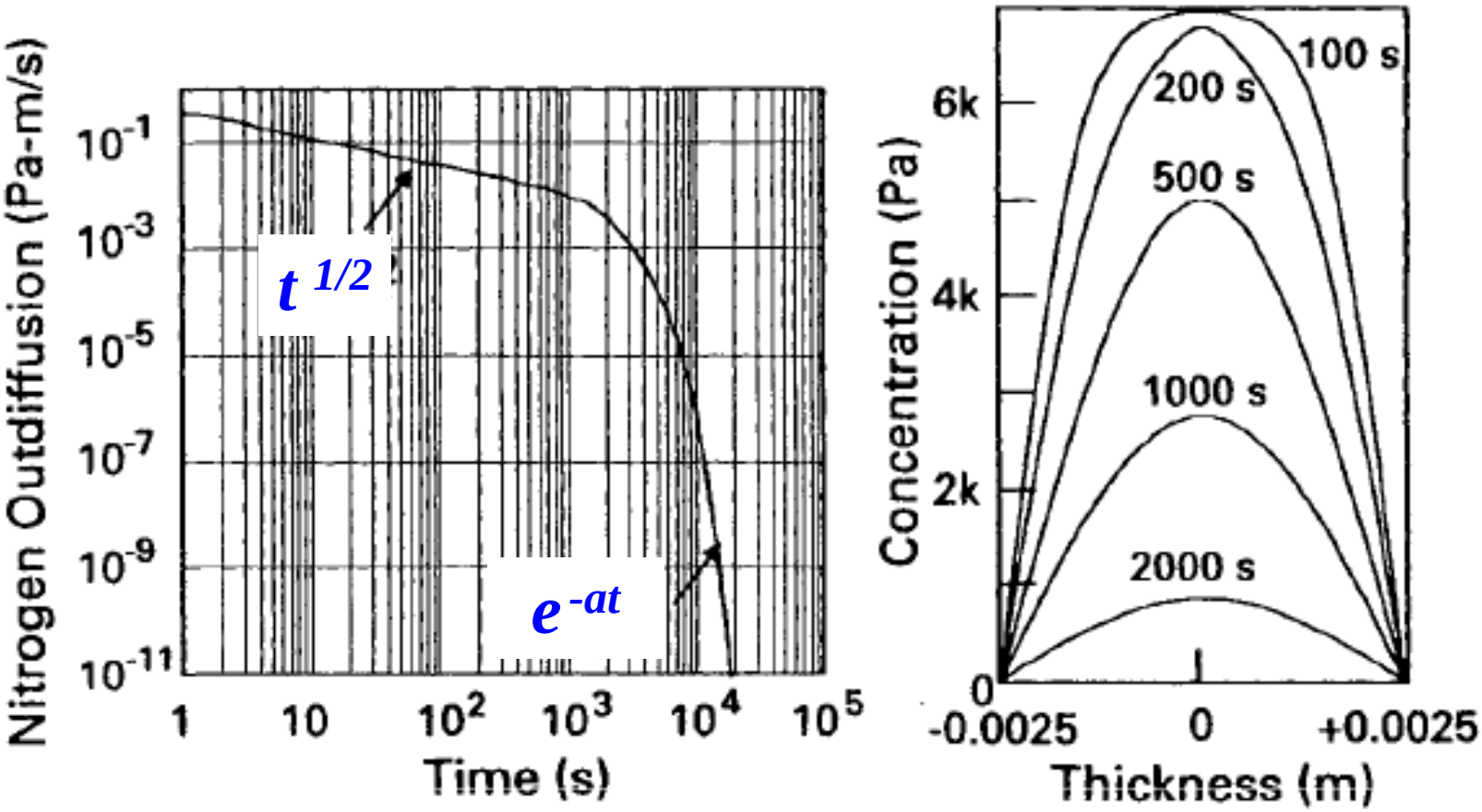
$$\log_{10} P_E = A - \frac{B}{C + T}$$

Coefficients A, B, C are measured for finite temperature ranges



Diffusion from Solid

Diffusion: Transport of gas dissolved in the solid to the interior wall of a vacuum system and followed by desorption.



Thermal Desorption (Outgassing)

Heat-stimulated release of gases or vapors adsorbed on chamber walls (from exposure to environment, or reached inner surfaces by diffusion within.

- ***Physisorption*** – *molecules bonded weakly to the surfaces by van der Waals forces, with typical bonding energy < 50 kJ/mole (0.5 eV). Most condensed gases (such as top layers of water molecules) are physisorption in nature.*

- ***Chemisorption*** – *molecules bonded to surfaces at much higher energies are chemisorbed.*

Thermal Desorption Dynamics (Science)

- Zero-order desorption – from multi-layer of molecules. This is equivalent to evaporation, with a constant rate:

$$\frac{dn}{dt} = K_0 e^{-\frac{E_v}{kT}}$$

- First-order desorption – when less than a monolayer, non-dissociative desorption. A exponential dependence rate of desorption is predicted:

$$\frac{dn}{dt} = n_0 K_1 e^{-\frac{t}{\tau}}$$

- Second-order desorption – diatomic molecules desorption, such as hydrogen on metal surfaces with recombination prior to the desorption:

$$\frac{dn}{dt} = \frac{-K_2 n_0^2}{(1+n_0 K_2 t)^2}$$

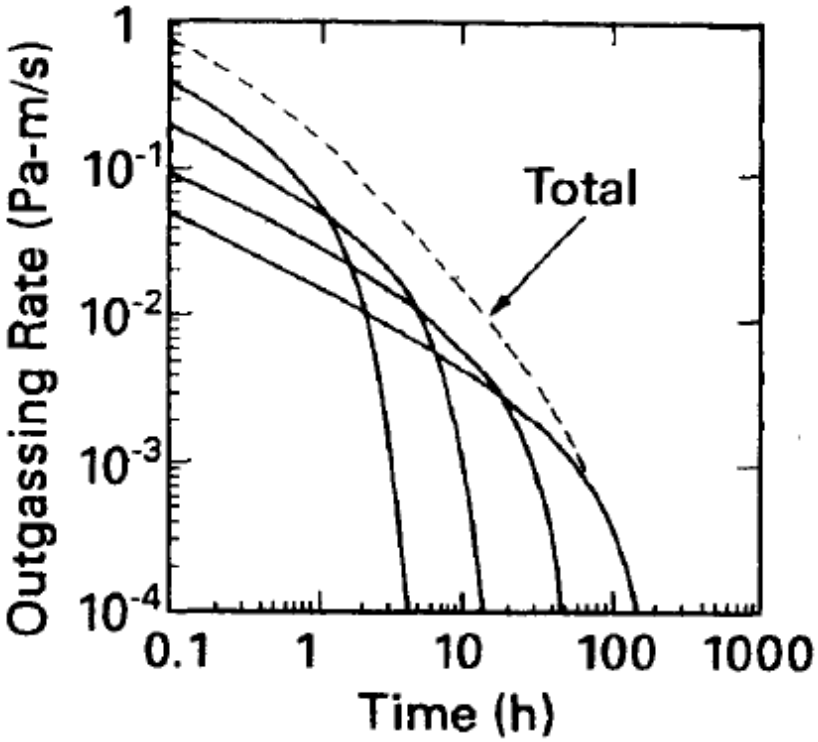
n represents atomic/molecular density on a surface

Thermal Desorption – Real Surfaces

→ In most real vacuum systems, the observed thermal outgassing rate usually varies as:

$$q_n = \frac{q_o}{t^{\alpha_n}}$$

with α_n = 0.5 ~ 2.0, while α_n ~ 1 commonly measured.



→ The $t^{-\alpha_n}$ trend has been explained as a result of averaging over desorptions from multiple surface bonding states

Reduction of Outgassing by Bakeout

- It is well known that bakeout of a vacuum system can significantly reduce the thermal outgassing.
- The baking temperature should be sufficiently high to overcome the binding energy of adsorbed molecules on surfaces. For example, >120°C is needed for removing adsorbed H_2O on most metal surfaces.
- When baking vacuum system, it is imperative that all surfaces be baked. Any cold surfaces (even a small portion of) will contribute exceedingly large gas flux.
- For many UHV system, high-temperature firing of material (especially stainless steels) is proven to reduce dissolved gas in bulk, thus significantly reduce out-diffusion time and thermal outgassing

Measuring Outgassing Rate – Why

- Though there are massive amount published outgassing rate data for most commonly used metallic and dielectric materials, these data should be taken with caution, as the outgassing rates are highly sensitive multiple parameters, such as material preparations, surface texture, alloy grain size, etc.

- In most accelerators, specialty materials (insulators, RF absorbing tiles, etc.) are used at unusual conditions.

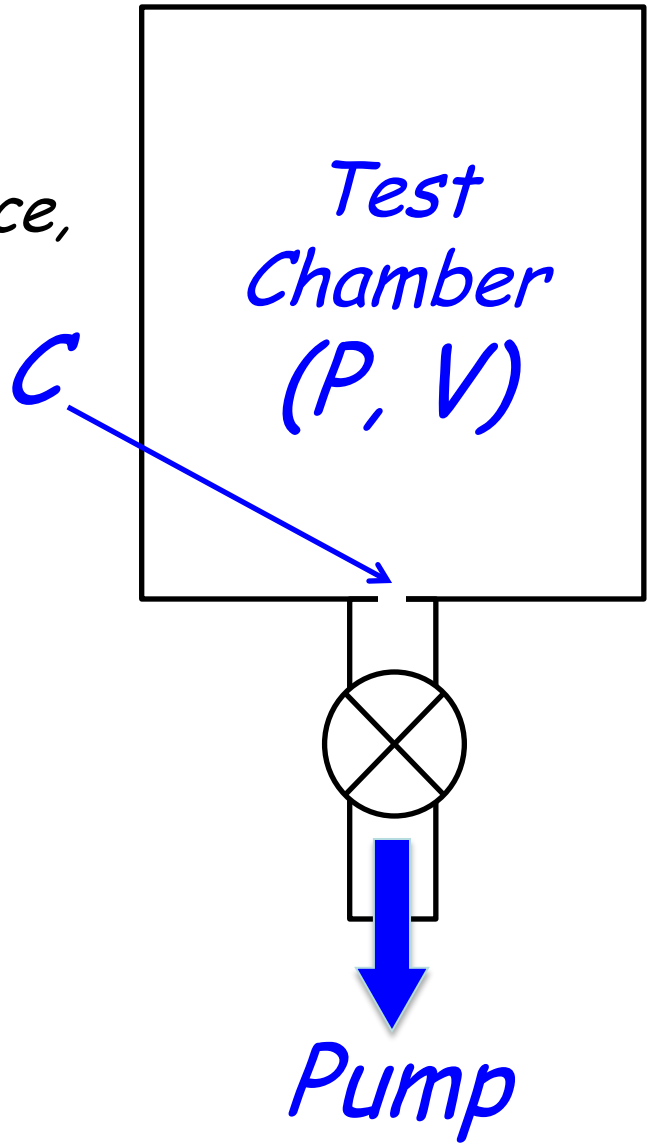
Measuring Outgassing Rate

- Throughput method – Gas from test samples or chamber flow through a defined conductance, usually an orifice, to a vacuum pump

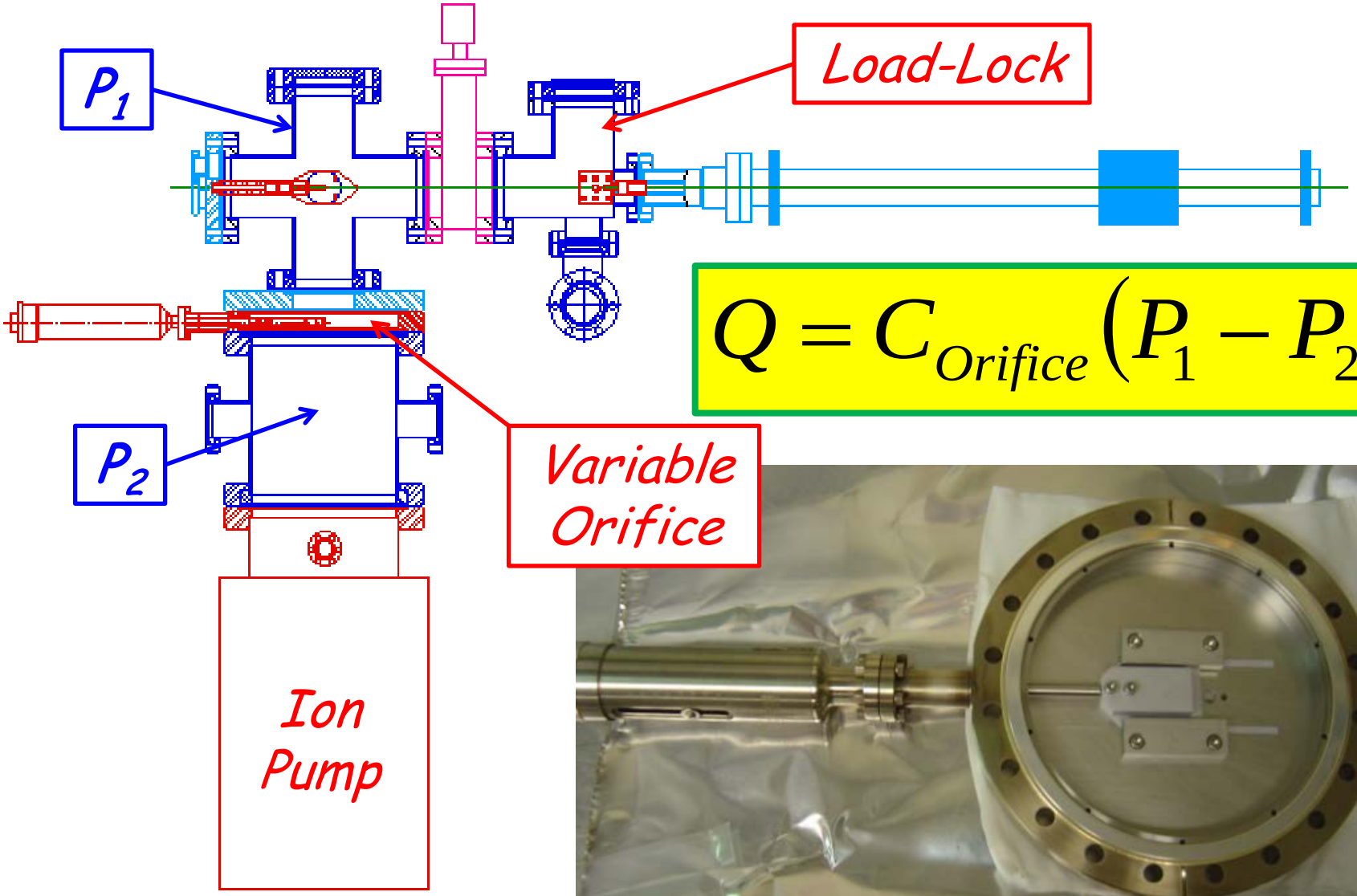
$$q = \frac{C \cdot P(t)}{A}$$

- Rate-of-rise method – Seal off test chamber to allow pressure build-up

$$q = \frac{V}{A}\left(\frac{\Delta P}{\Delta t}\right)$$



Load-Locked Outgas Setup @ CLASSE



$$Q = C_{Orifice}\left(P_1 - P_2\right)$$

Some Unbaked Metal Outgassing Rates

Material	q_1 (10^{-7} Pa-m/s)	α_1	q_{10} (10^{-7} Pa-m/s)	α_{10}
Aluminum (Fresh)	83	1.0	4.3	0.9
Aluminum (anodized)	3679	0.9	429	0.9
Copper OFHC (fresh)	251	1.3	4.8	1.0
Copper OFHC (polished)	25	1.1	2.2	1.0
Stainless Steel	192	1.3	18	1.9
Titanium	53	1.0	4.9	1.0

Ref – A Schram, **Le Vide**, No. 103, 55 (1963)

Note – There are wide spread of outgassing data for similar materials

$$q_n = \frac{q_o}{t^{\alpha_n}}$$

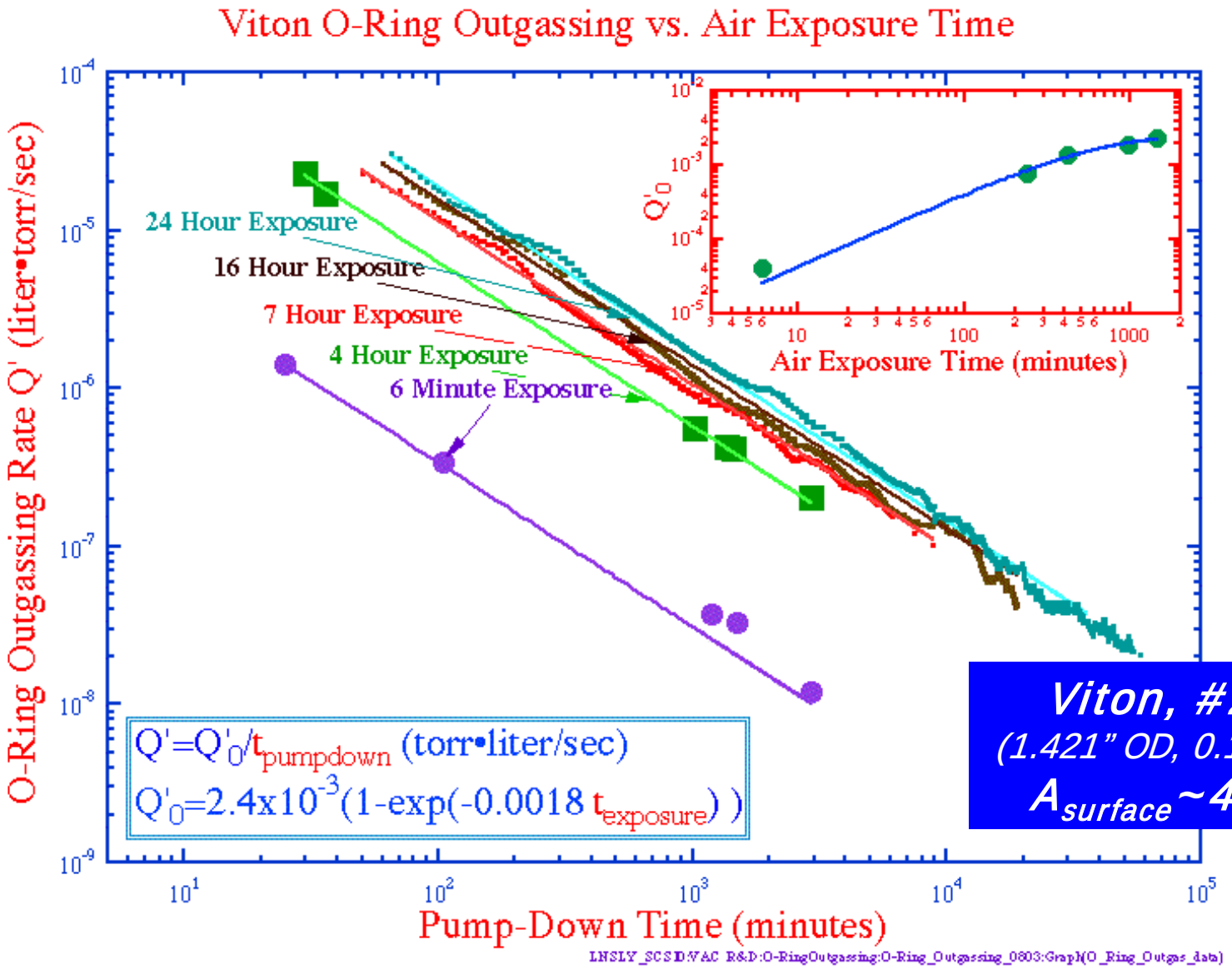
n – hours of pumping

Outgassing Rates of Baked Metals

Material	Treatment	q (10^{-11} Pa-m/s)
Aluminum	15-h bake at 250°C	53
Aluminum	20-h at 100°C	5.3
6061 Aluminum	Glow discharge + 200°C bake	1.3
Copper (OFHC)	24-h bake at 100°C	2.9
	24-h bake at 250°C	0.18
304 Stn. Stl	20-h bake at 250°C	400
	2-h 850/900°C vacuum firing	27

From: J. O'Hanlon, "A User's Guide to Vacuum Technology" , 3rd Ed., Appendix C.1

Example – Measured O-Ring Outgassing



Viton, #2-221
(1.421" OD, 0.139" Width)
$A_{surface}$ ~4.2 cm²

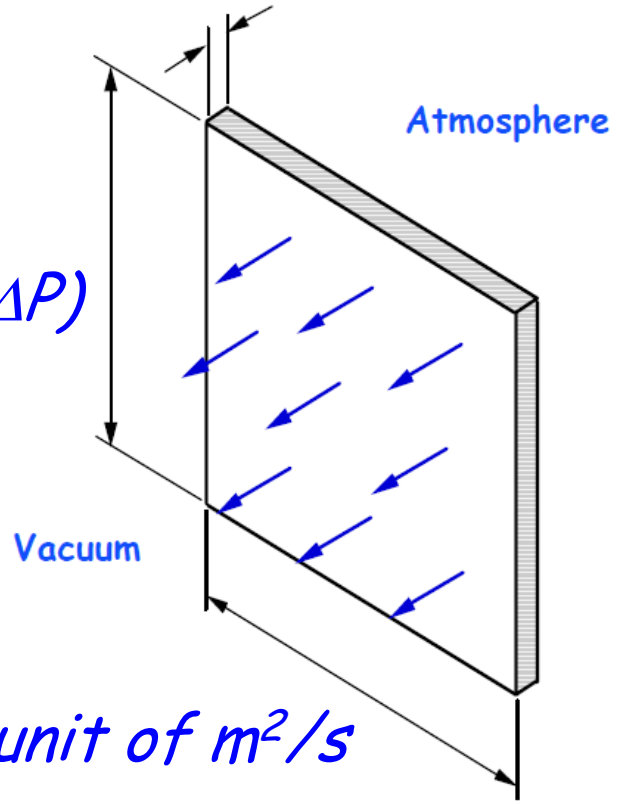
Permeation

Permeation is a three step process. Gas first adsorbs on the outer wall of a vacuum vessel, diffuses through the bulk, and lastly desorbs from the interior wall.

Factors influence permeation rate:

- Material combination
- Temperature
- Permeation thickness (d)
- Gas type and pressure differential (ΔP)

$$Q_p = q_p A = \frac{K_p \Delta P}{d} A$$



In SI, the permeation constant K_p has a unit of m^2/s

Permeation – O-Rings

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

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

Permeability rates of various gases for many commercial polymers are tabulated in Parker O-Ring Handbook.

Example Calculation of O-ring Permeability

What is the approximate He and N_2 permeability rates through a 10" diameter Viton O-ring (no lubrication, with a 20% squeeze) at a Δp = 14.7 psi?

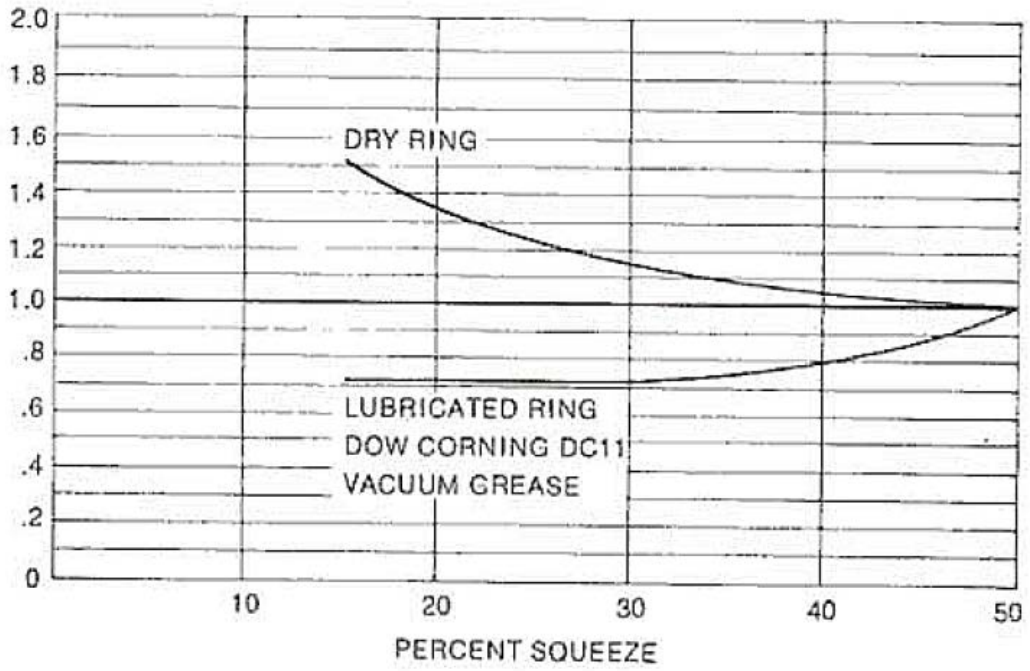
D=10", K=1.35 (see insert), S=0.20

$F_{He}=13.0\times10^{-8}$; $F_{N_2}=3.0\times10^{-8}$ (std.cc/cm^2-sec-bar)

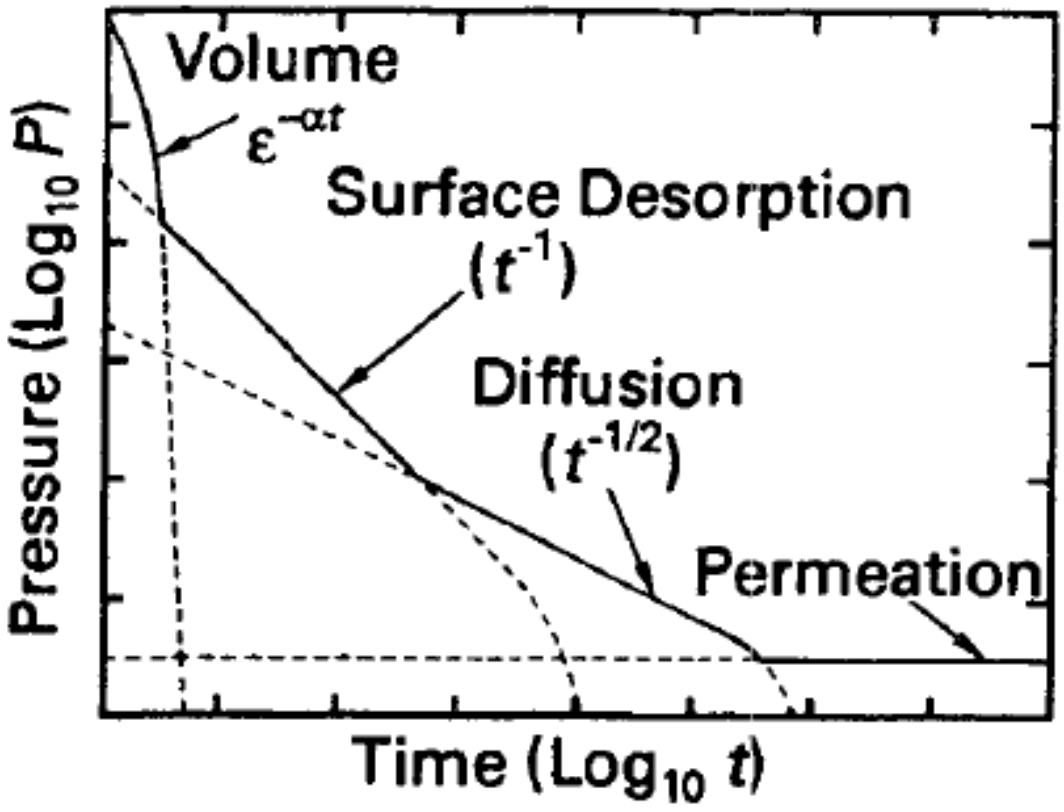
$Q_{He} = 1.2\times10^{-5}$ std.cc/s

$= 8.8\times10^{-6}$ torr-l/s

$Q_{N_2} = 1.6\times10^{-7}$ torr-l/s



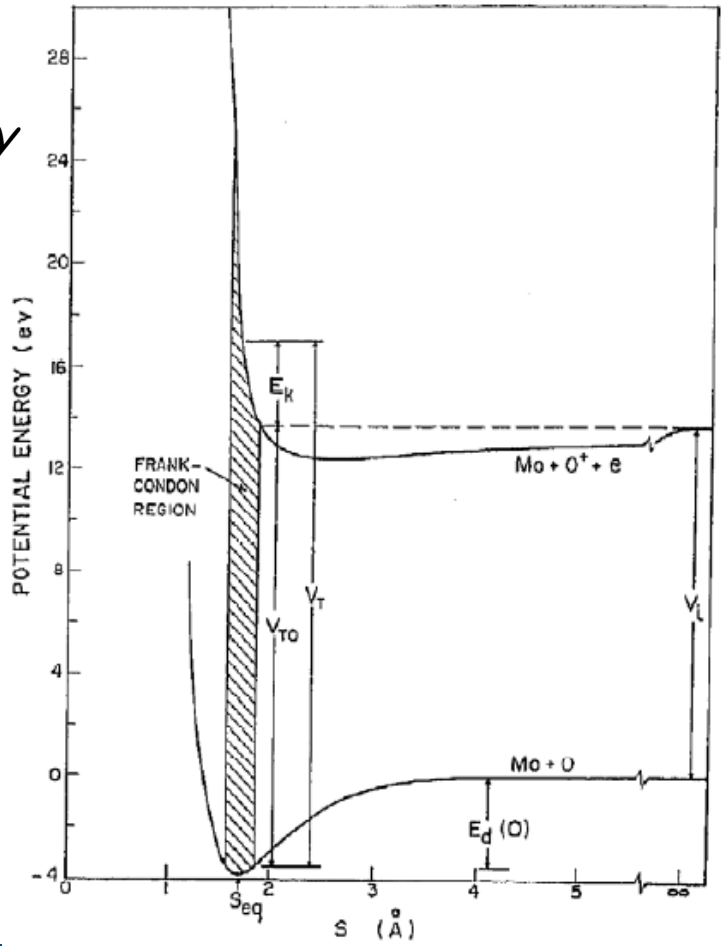
Ultimate Pressure (Static)



$$P = P_o e^{-S \cdot t / V} + \frac{Q_{thermal}}{S} + \frac{Q_{Diffusion}}{S} + \frac{Q_{Permeation}}{S}$$

Induced Desorptions – Dynamic Gas Load

- In particle accelerators, energized particles (ions, electrons and photons) may impinge on vacuum vessel interior walls, and induce desorption of adsorbed molecules. In most cases, these dynamic gas loads are dominate.
- Two possible mechanisms:
  - → Direct 'knock-out' via impact. This is usually for physisorbed multilayer molecules and atoms
  - → Desorption induced by electronic transition (DIET), where a binding electron of the chemisorbed molecule is excited in an anti-bounding state.
- There is a desorption energy threshold of ~ 10 eV
- Desorbed species are dominated by neutral atoms and molecules, with only a small fraction (10^{-2} ~ 10^{-4}) of ions.



Induced Desorptions – Parameters

- Desorption Yield – number of desorbed molecules (N_m) of a given gas species per incident particle (N_i):

$$\eta = \frac{N_m}{N_i}$$

- The yield measurement often requires dedicated setup, in order to quantify both the desorbed molecules and the incident particle flux.

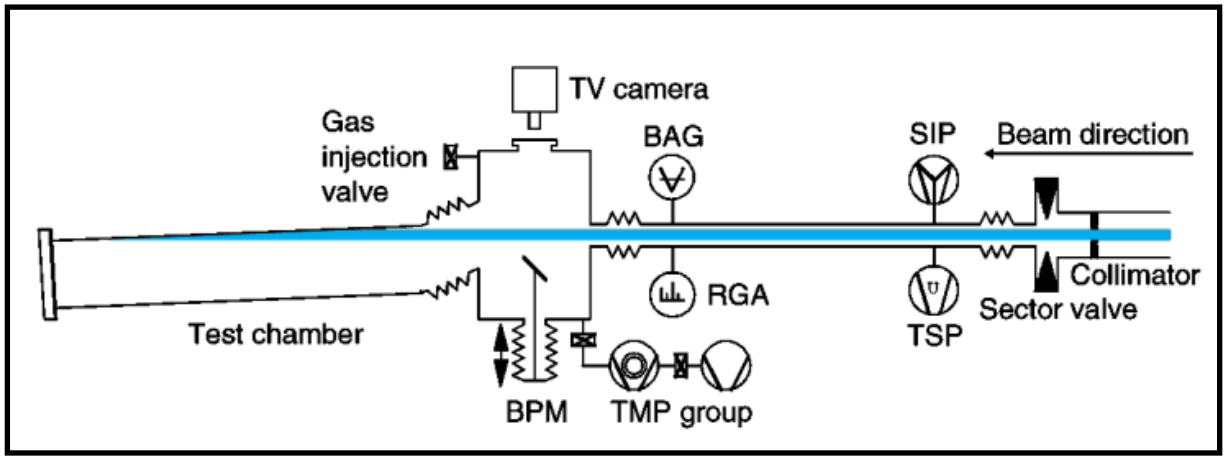
- "Conditioning"– the yield of induced desorption usually decreases with accumulated dose (D_i) of the particles as:

$$\eta = \eta_o D_i^{-\alpha}$$

Ion Induced Desorption (IID)

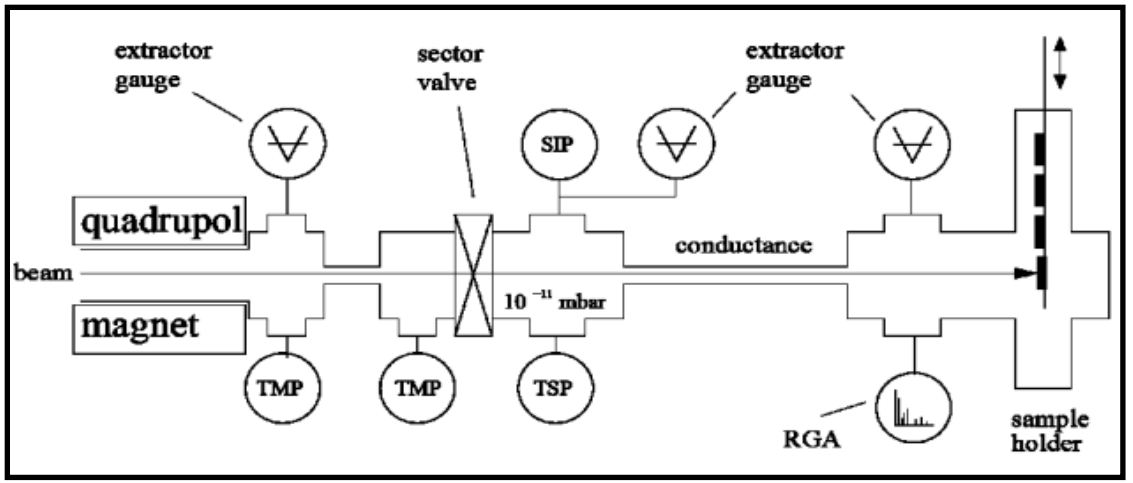
- Relatively low energy (~ keV) ions are routinely used to clean surfaces via IID.
- IID can have significant detrimental impacts on the performance of ion beam accelerators, such as RHIC at BNL, ISR & SPS at CERN.
- There are at least two types of IID:
  - → Ions created by residual gases, and accelerated towards wall by the beam field
  - → Direct beam loss of ion beams, particularly not fully striped ions. Usually deep UHV required to reduce this type of beam losses
- IID usually is associated with very high yield (both molecular and secondary electrons).

IID Yield Measurement Setups



CERN's Setup:
→ Grazing Impact
→ Purposely build test chamber

GSI's Setup:
→ Normal impact
→ Multiple samples



See: E. Mahner, Phys. Rev. ST Accel . Beams 11, 104801 (2008)

IID Yield Measurement

Two measurements used in measuring IID yield

- Continuous heavy-ion bombardment mode

$$\eta_{IID} = \frac{\Delta P \times S}{F_{ion} \times k_B \times T}$$

ΔP – Pressure rise with ion beam
S – Pumping speed
F_{ion} – Impacting ion beam flux

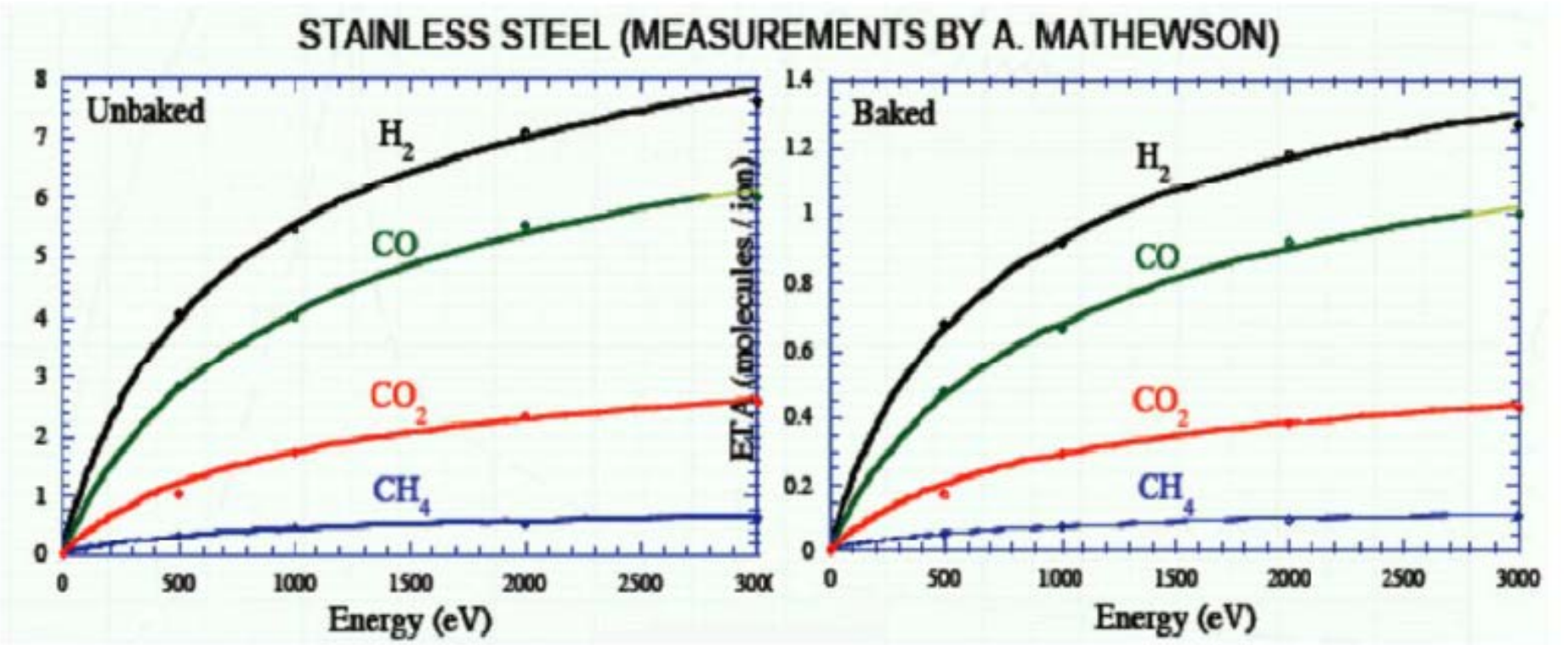
- Single shot mode (isolated setup)

$$\eta_{IID} = \frac{\Delta P \times V}{N_{ion} \times k_B \times T}$$

ΔP – Pressure rise from singe-shot
V – Test setup volume
F_{ion} – Number of impacting ions

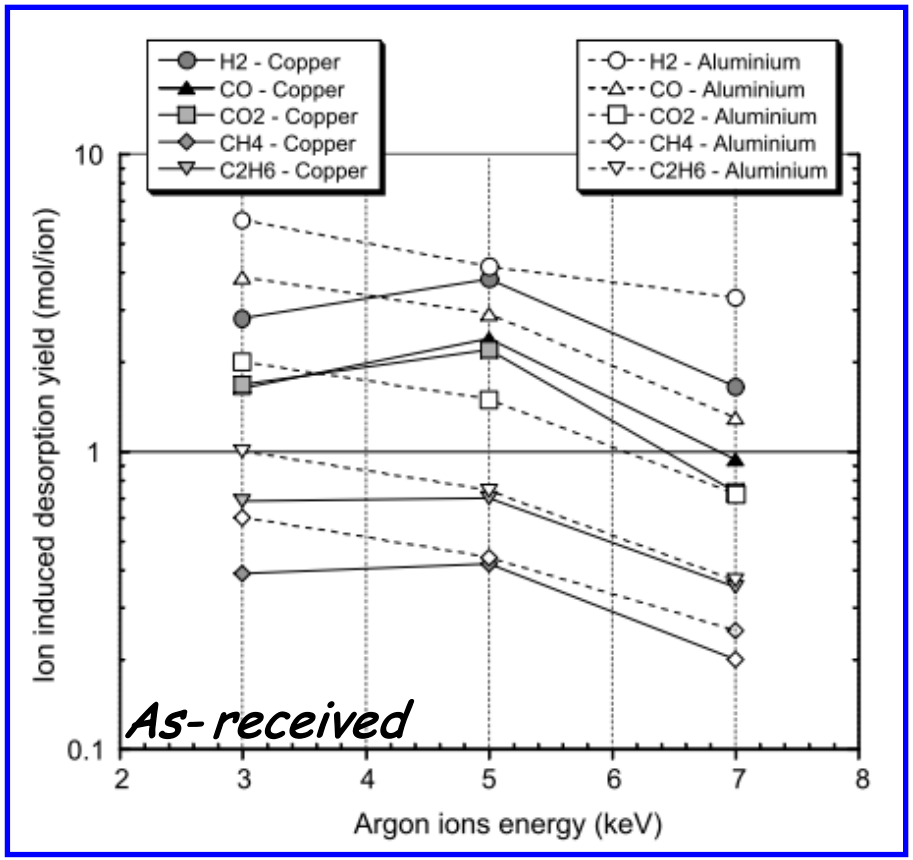
See: E. Mahner, Phys. Rev. ST Accel . Beams 11, 104801 (2008)

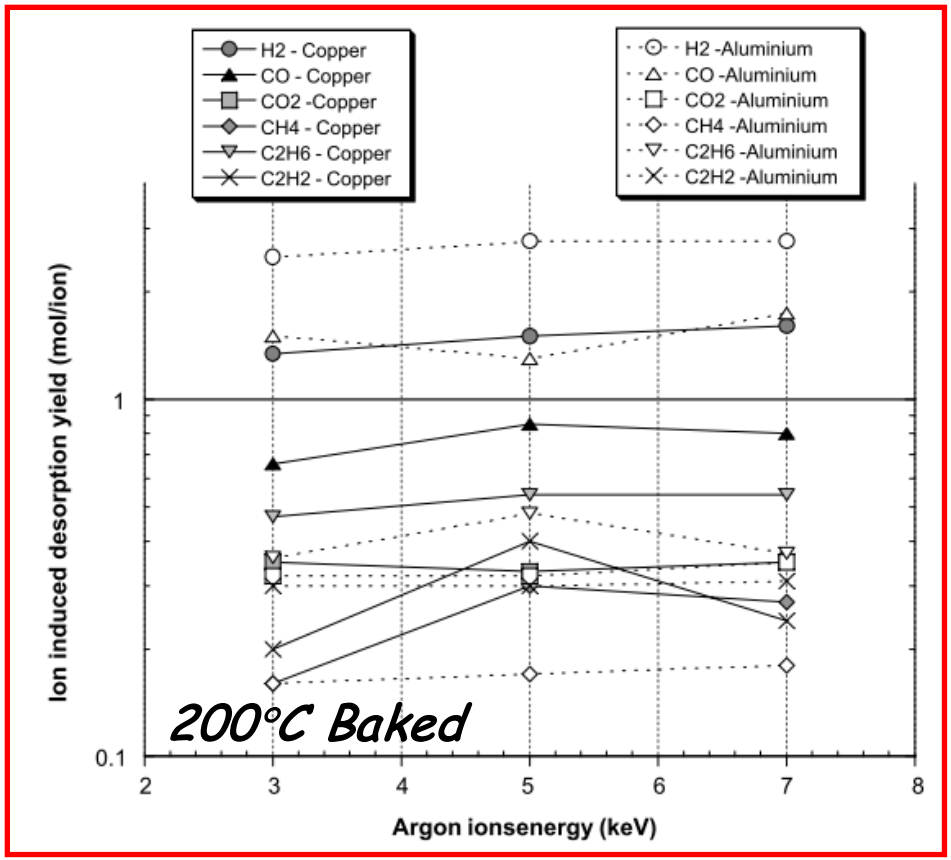
IID – Dependence on Ion Energy (1)



IID by $^{15}N^{+}$ beam (low ion energy)
From: V.V. Mathewson, CERN-ISR-VA/76-5 (CERN, Geneva, 1976)

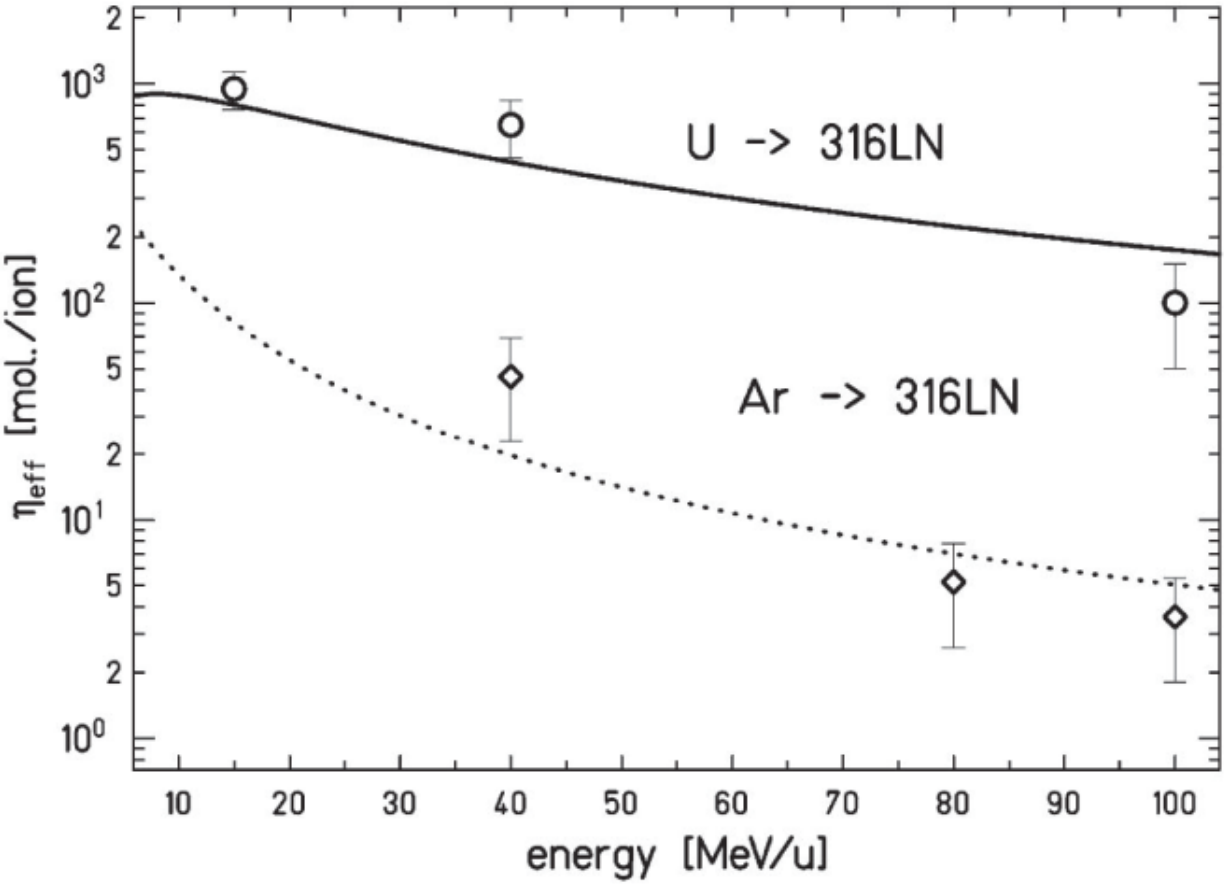
IID – Dependence on Ion Energy (2)





IID by Ar^+ beam (high ion energy)
From: M. P. Lozano, Vacuum 67 (2002) 339

IID – Dependence on Ion Energy (3)



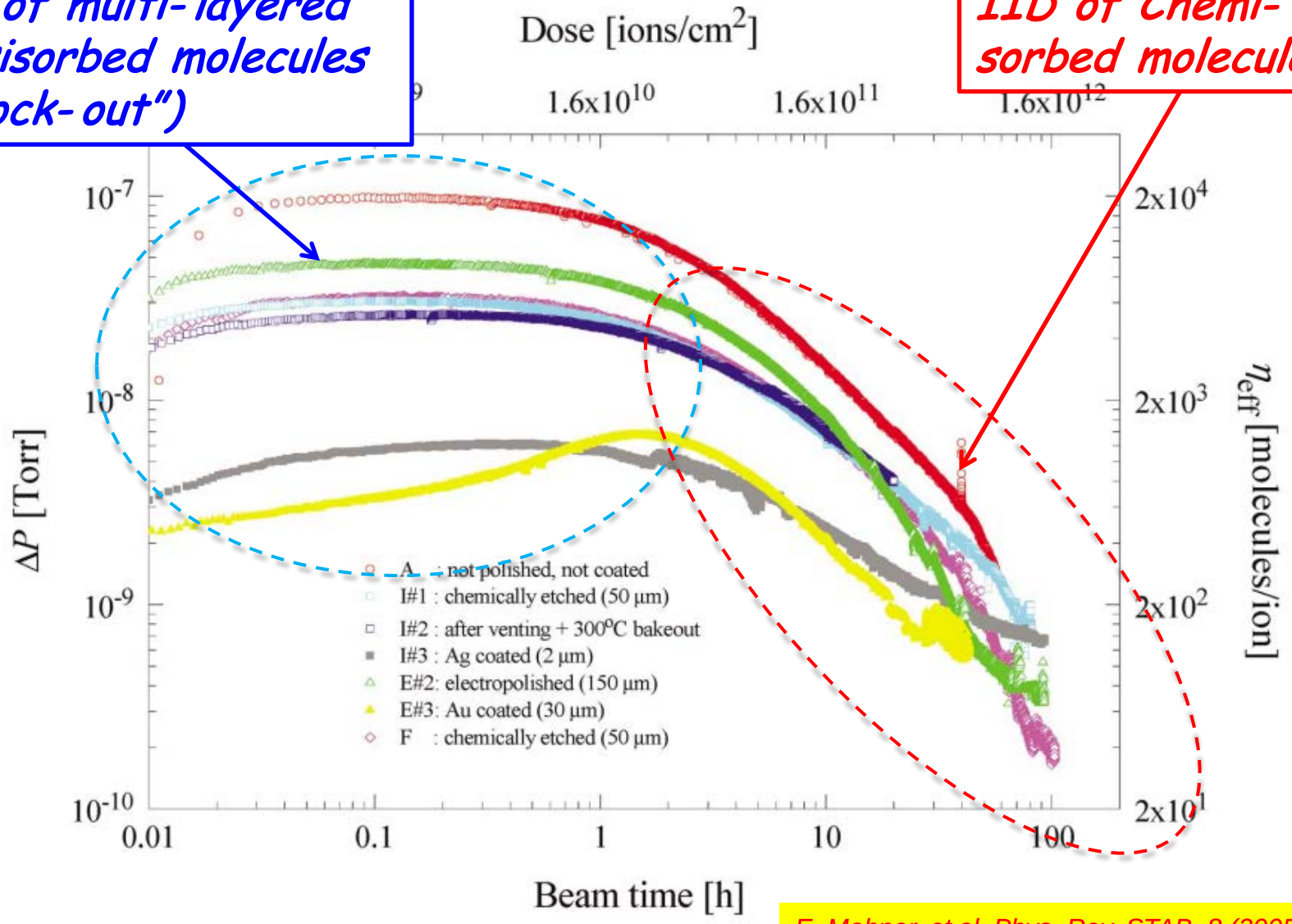
IID by Ar^{10+} and U^{73+} beams (very high ion energy)

See: E. Mahner, Phys. Rev. ST Accel . Beams 11, 104801 (2008)

IID – Heavy Ion Beams (52 MeV/u Pb^{53+})

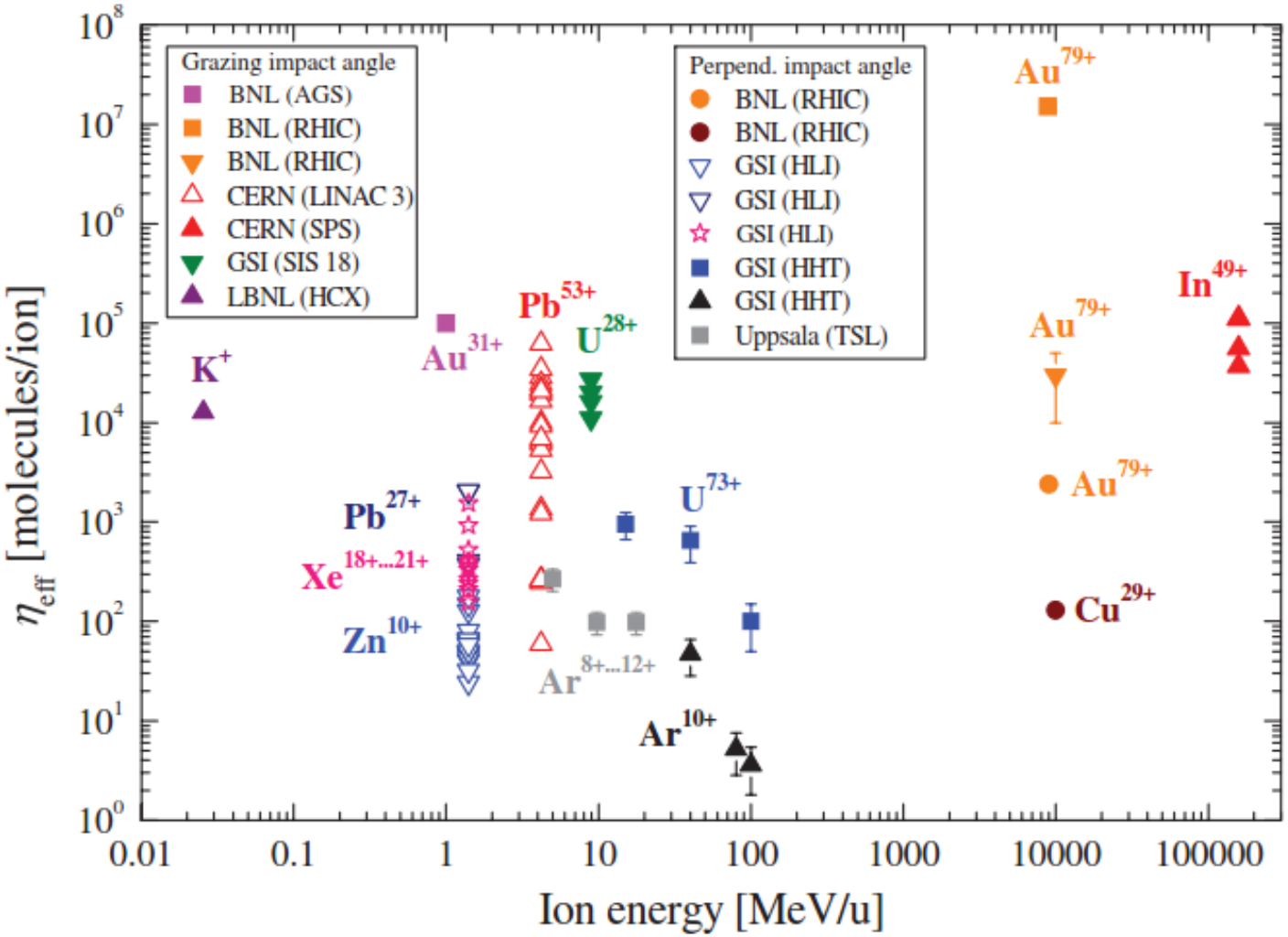
IID of multi-layered physisorbed molecules ("knock-out")

IID of Chemi-sorbed molecules



E. Mahner, et al, Phys. Rev. STAB, 8 (2005) 053201

IID Yields – Heavy Ion Beams

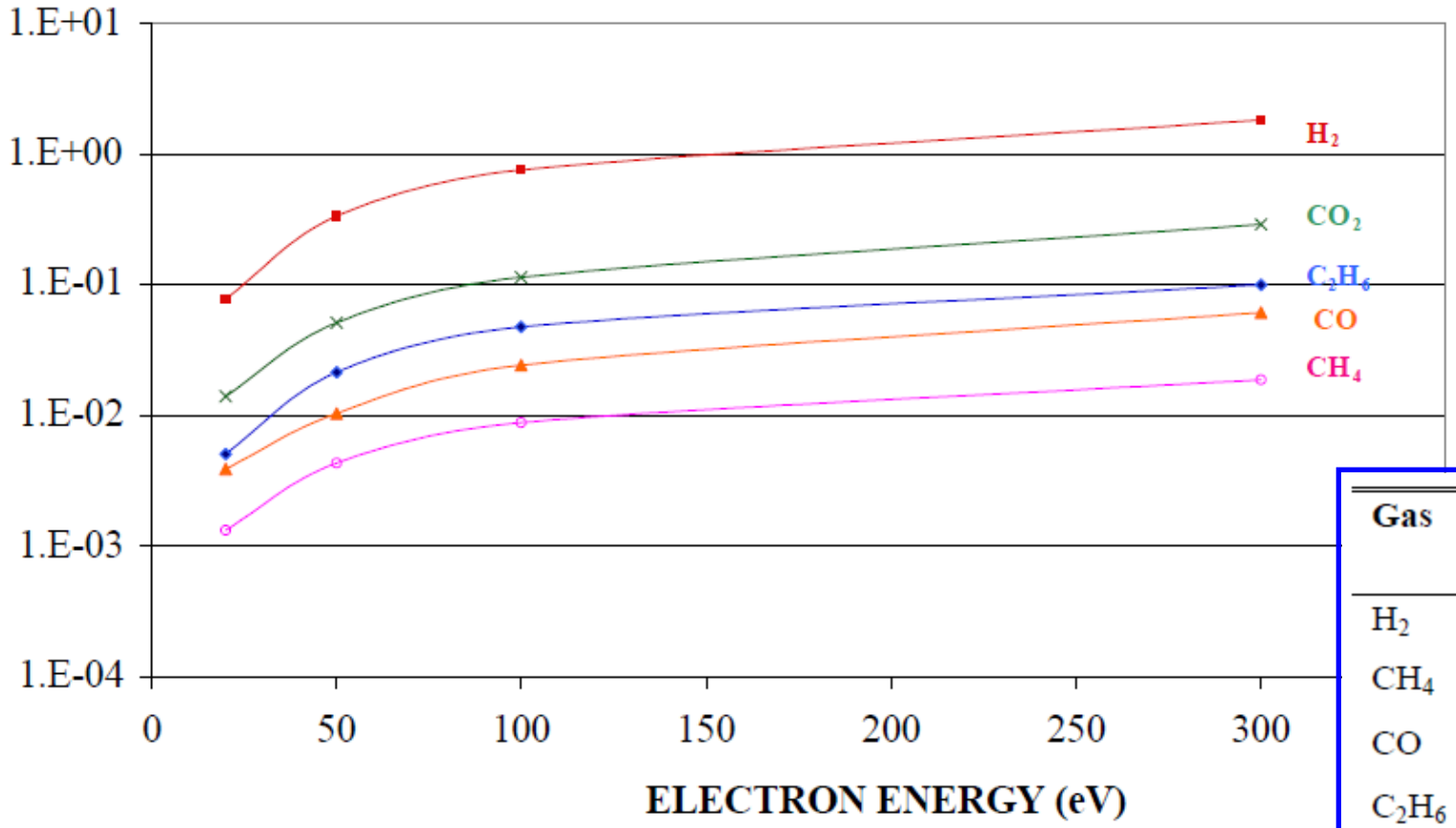


See: E. Mahner, Phys. Rev. ST Accel . Beams 11, 104801 (2008)

Electron Induced Desorption (EID)

- Most studied in accelerator community, related to the study of desorption mechanisms
- Direct EID process becomes significant in the regions of accelerators where electron multiplications can occur, such as in RF cavities and couplers, 'electron cloud' build-up in positive charges beams (positrons, protons and ions, etc.)
- Much lower yield as compared to IID

EID – Dependence on Electron Energy (Copper)

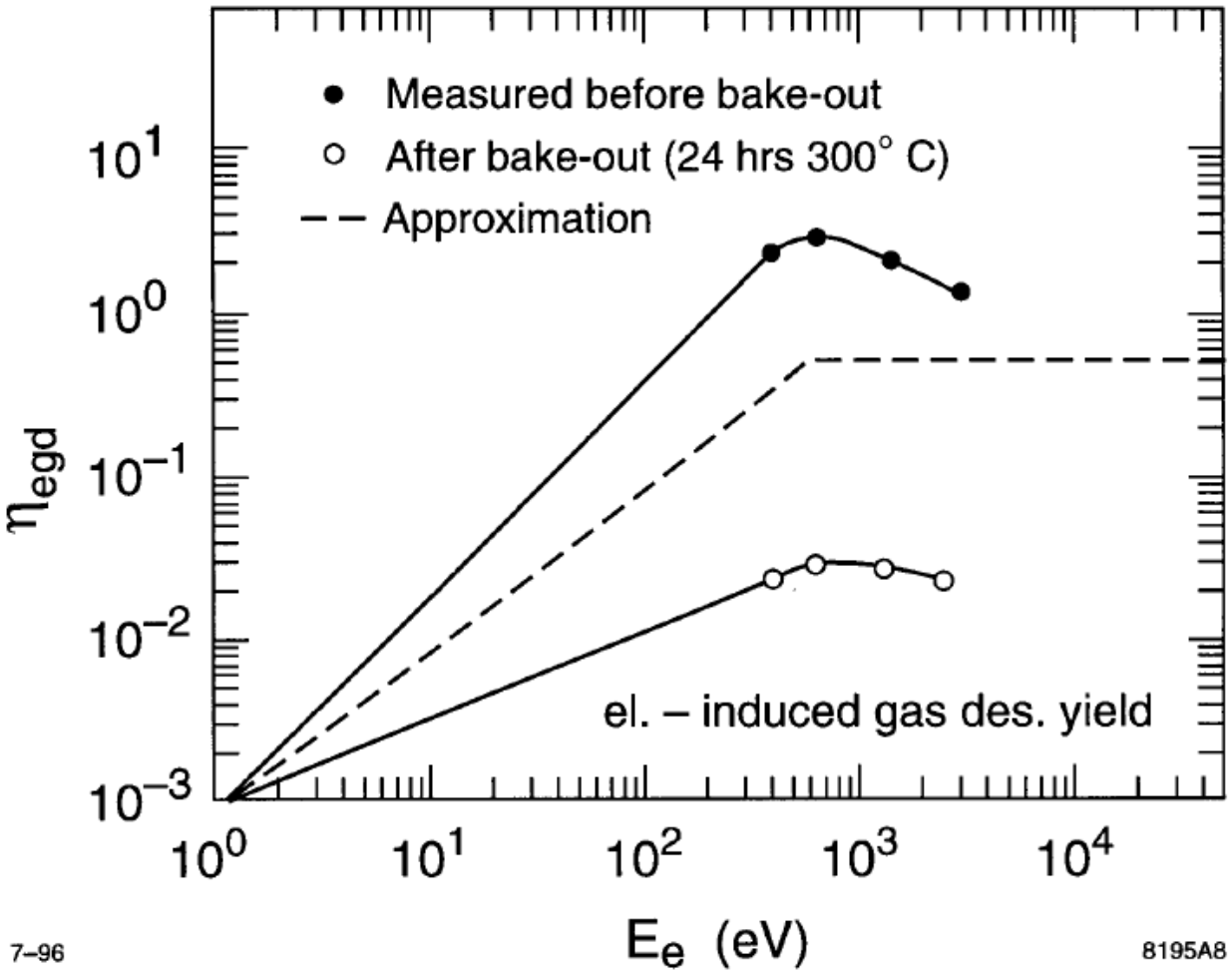


Gas	Threshold energy (eV)
H_2	12.7
CH_4	7.5
CO	7.2
C_2H_6	11.4
CO_2	9.1

Variation of EID yield with electron energy on copper surfaces

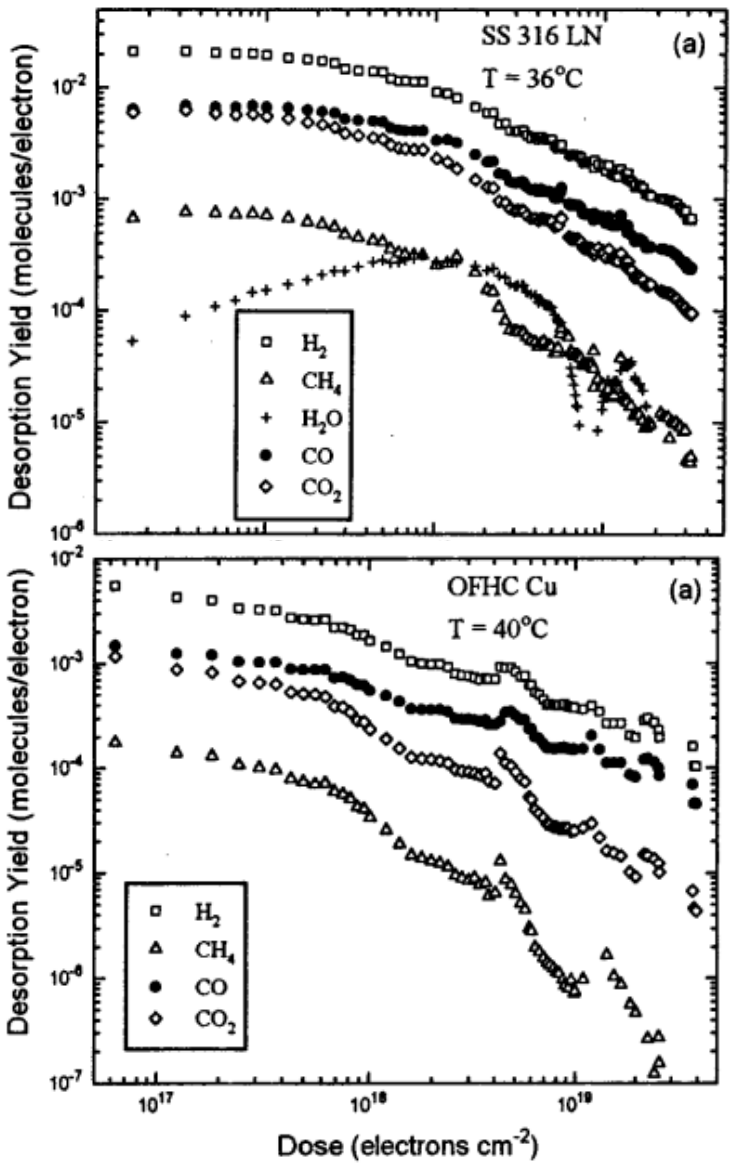
(from: F. Billard, et al, Vac. Tech. Note 00-32 (CERN, Geneva, 2000)

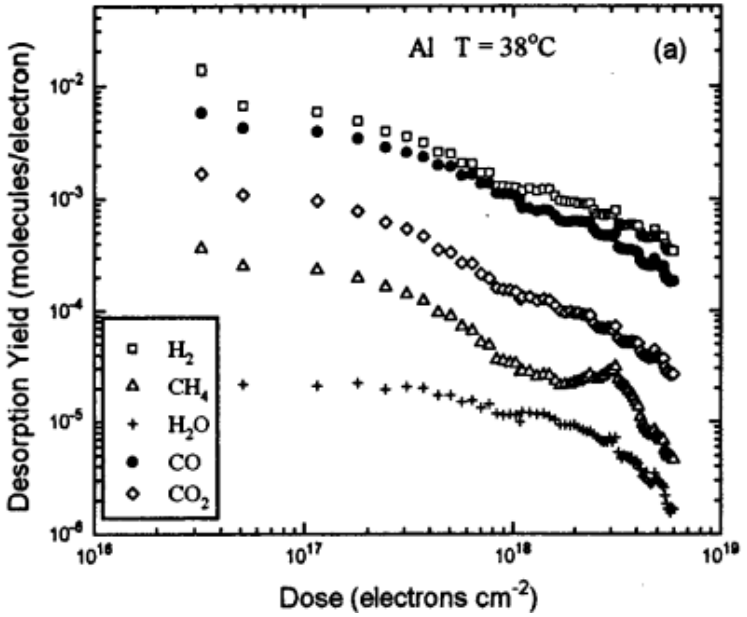
EID – Dependence on Electron Energy (Aluminum)



EID yield vs. electron energy on pure aluminum
(from: Frank Zimmerman, SLAC-PUB-7238, August 1996)

EID – Dependence on Electron Dose





EID yield vs. electron dose (very similar trends as IID)

(from: J. Gomez-Goni , A. G. Mathewson J. Vac. Sci. Technol. A 15 (1997) 3093

Photon Induced Desorption (PID)

- Considerations of PID process is important to the design and operations of synchrotron light sources and electron/positron storage rings, due to the presence of very high intensity of synchrotron radiation.
- The physical process of PID evolves into two steps:
  (1) A photon with sufficient energy hitting wall causes electron emission (with a yield of η_e)
  (2) The emission and later absorption of the photo-electron can desorb neutral molecules from the wall
- The PID has many features similar to the EID/IID.
- PID yield strongly depends on surface materials, surface conditions (treatment) and history.

Photo-Electron Emission Yield

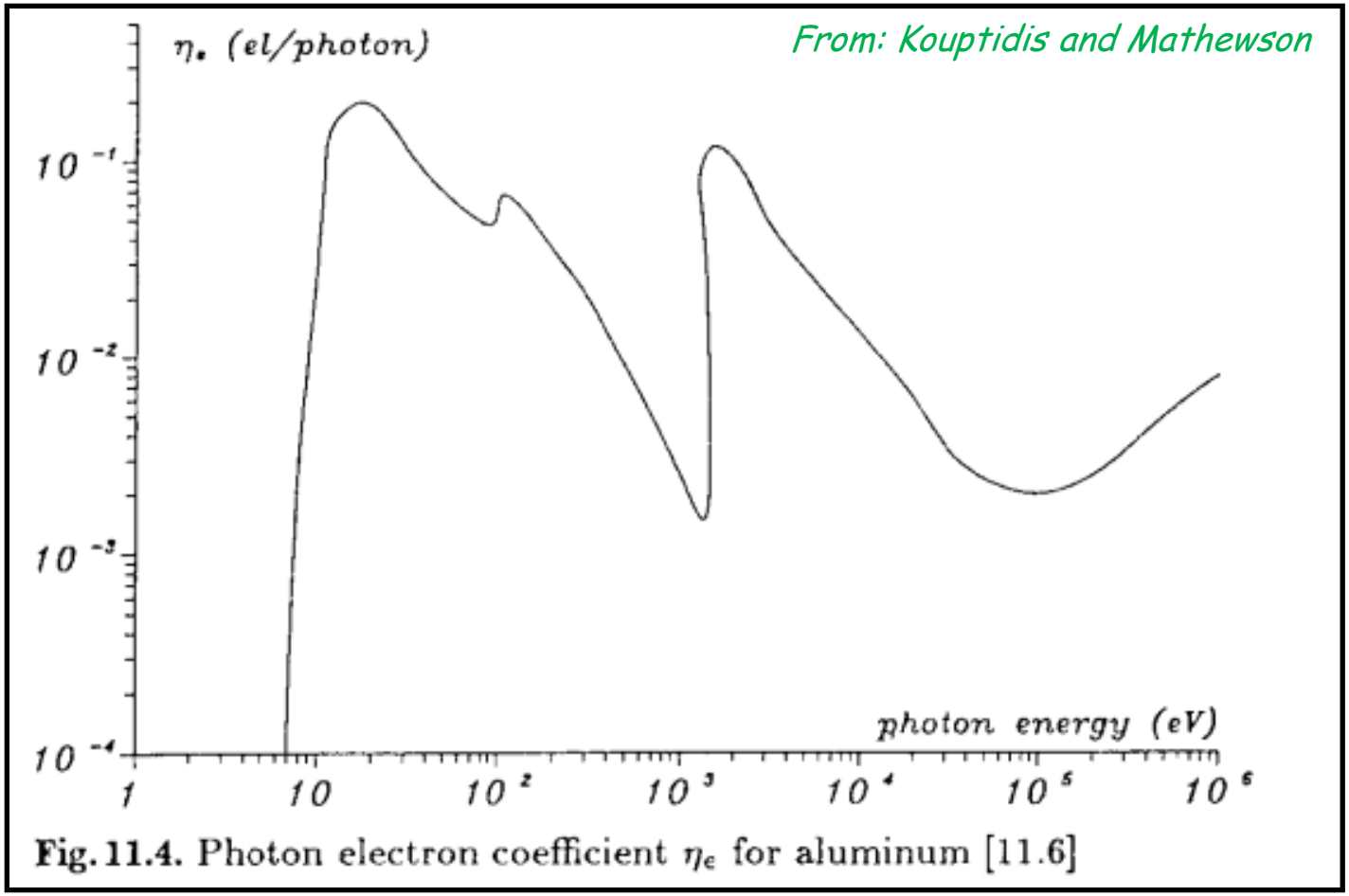


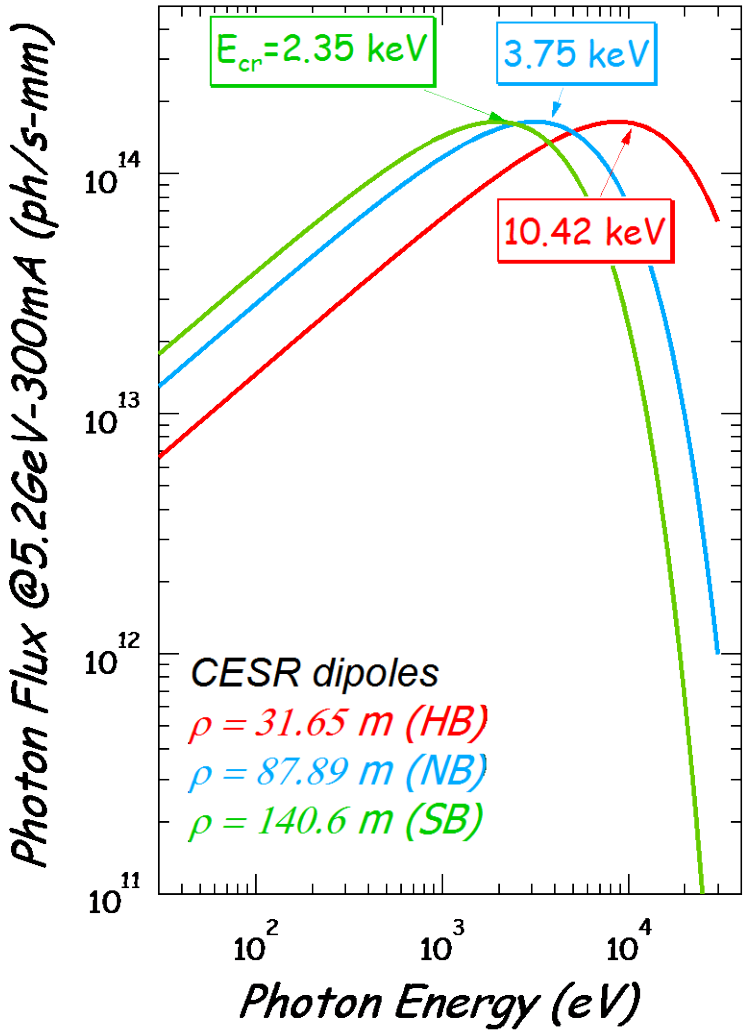
Fig. 11.4. Photon electron coefficient η_e for aluminum [11.6]

There are virtually no photoelectrons (thus no PID) for photon energies of less 10 eV.

Synchrotron Radiation

- When the trajectory of an electron or a positron is bended (by a magnetic field), the electron or positron will radiate photon, with broad spectrum.
- The SR spectrum may be characterized the critical energy, E_{cr}, (where radiation integral = $\frac{1}{2}$)
- Photon flux decrease rapidly beyond E_{cr}

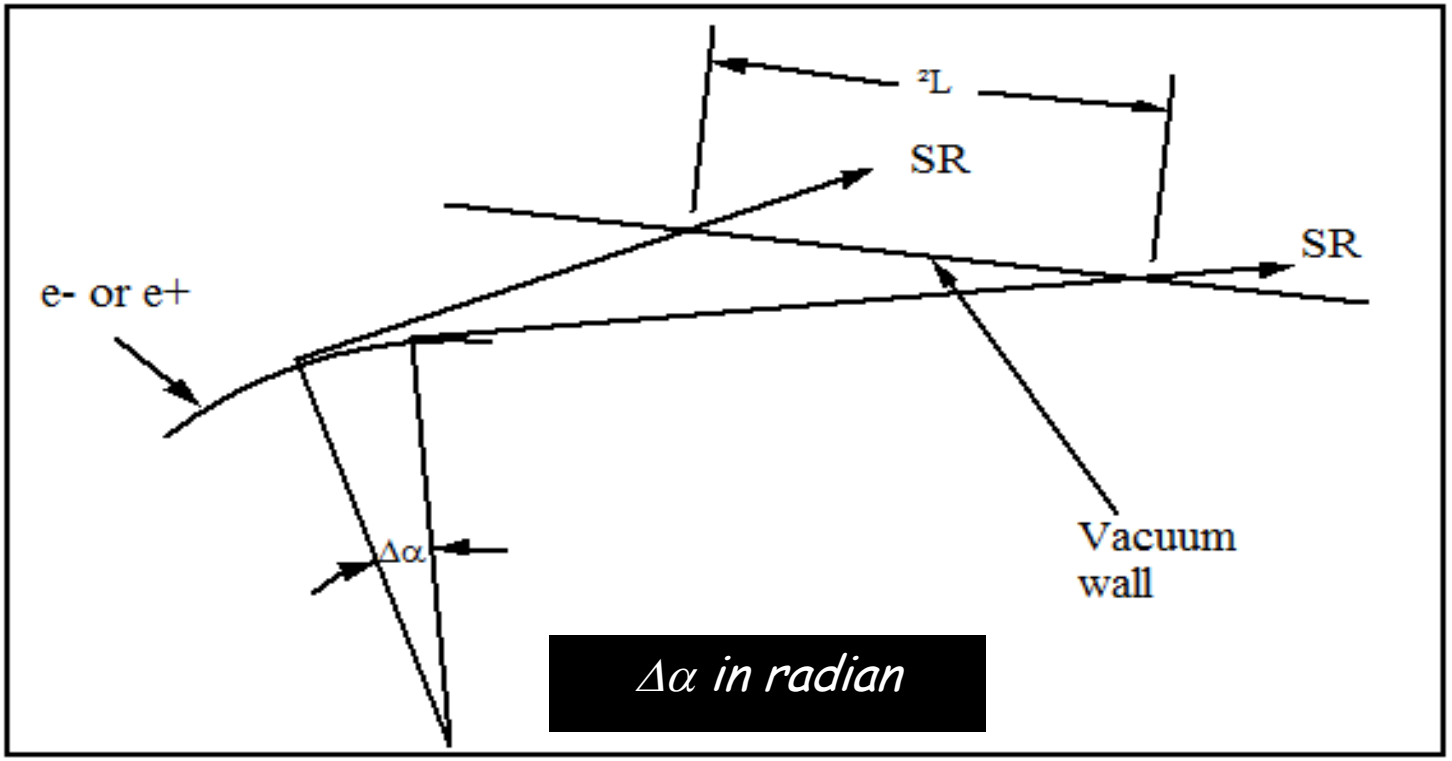
$$E_{cr}(keV) = 2.218 \times \frac{E^3_{electron}(GeV)}{\rho(m)}$$



Synchrotron Radiation Flux

- Total SR flux may be calculated as the following:

$$\Gamma(ph/\sec\cdot mA) = 8.08\times10^{17}\, E_{beam}(GeV)\frac{\Delta\alpha}{2\pi}$$



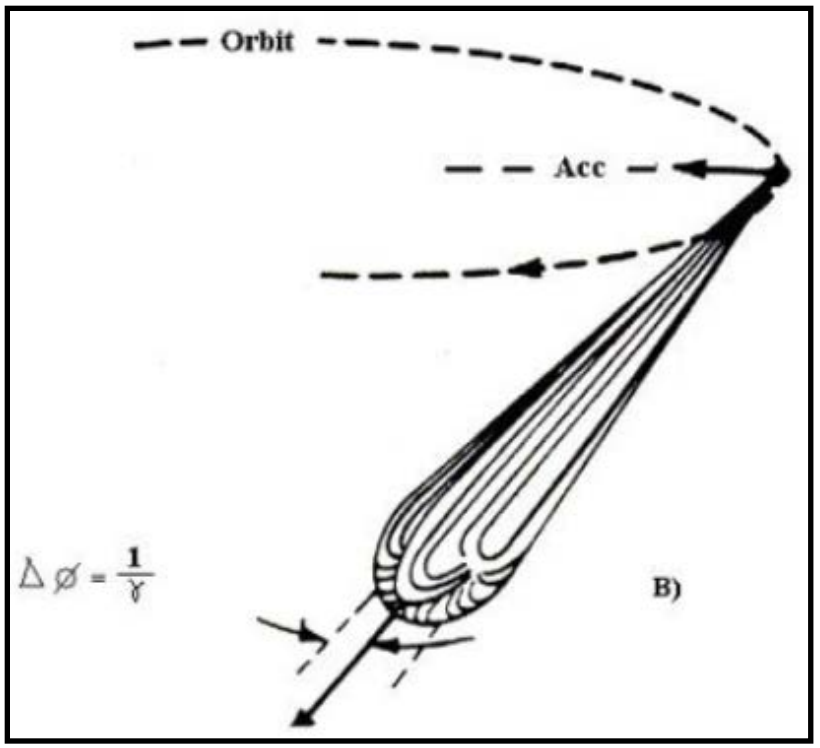
Synchrotron Radiation Power

- Total SR power may be calculated as the following:

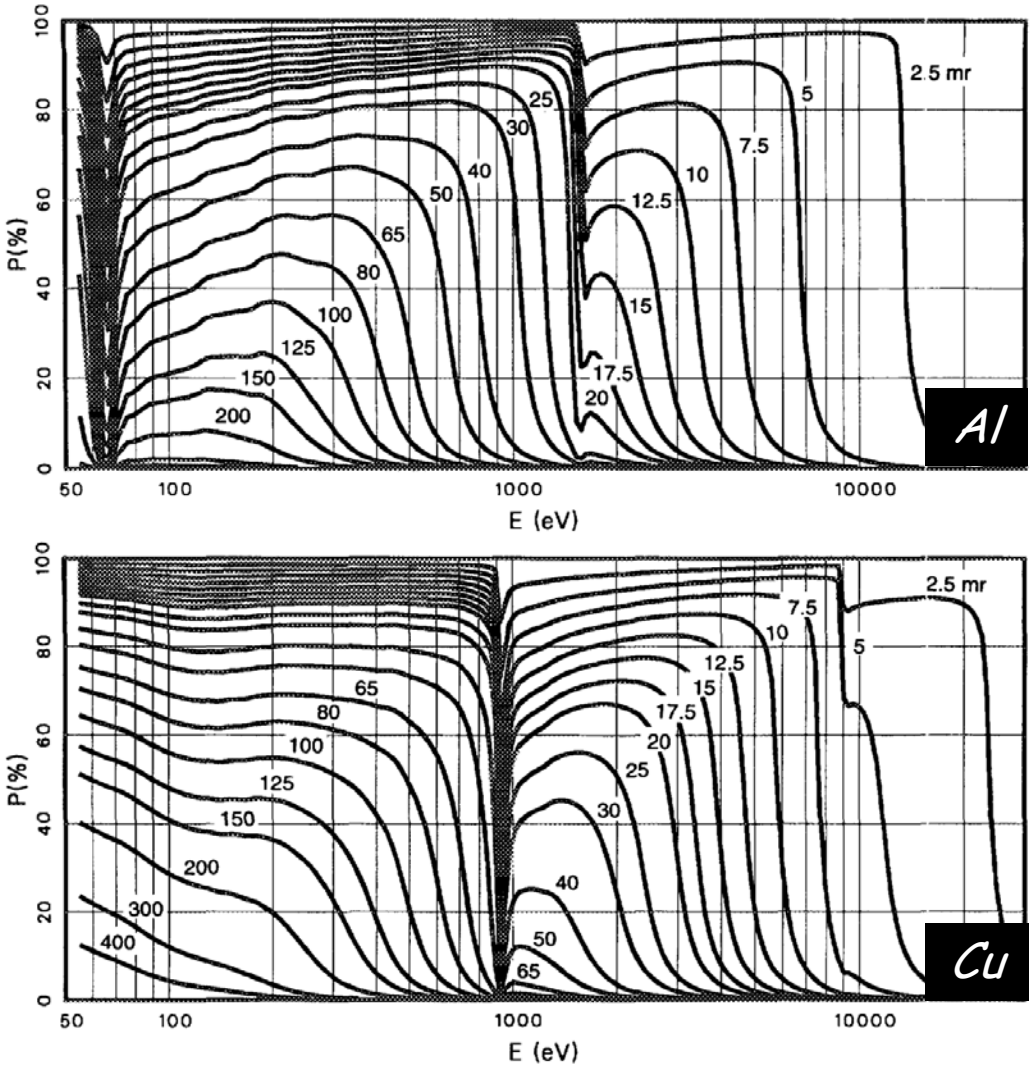
$$P(W/mA) = 88.5 \frac{E^4(GeV)}{R(m)} \frac{\Delta\alpha}{2\pi}$$

- The SR is highly collimated, with angular spread ~$1/\gamma$ ($\gamma = E_{beam}/E_{rest}$; $\gamma = 10^4$ for 5 GeV electron beam)

- SR power density impinging on a vacuum wall can be very high.



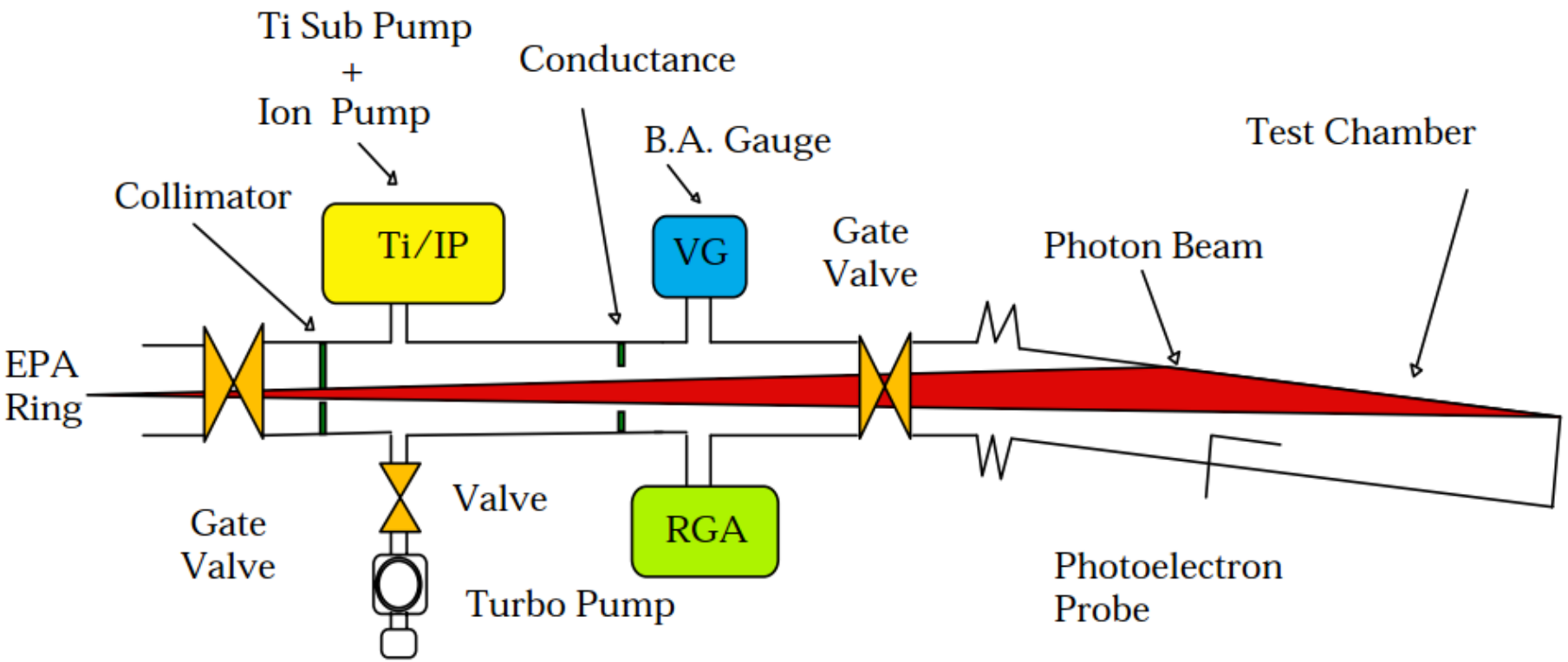
Synchrotron Radiation Reflections



- SR is highly collimated, so the primary SR fan only strike a very narrow strip of outer wall of a vacuum beampipe.
- However, reflectivity of SR photons at low energies is very high at small angles of incidence.
- So majority of inner surfaces of a vacuum beampipe may be exposed to SR photons.

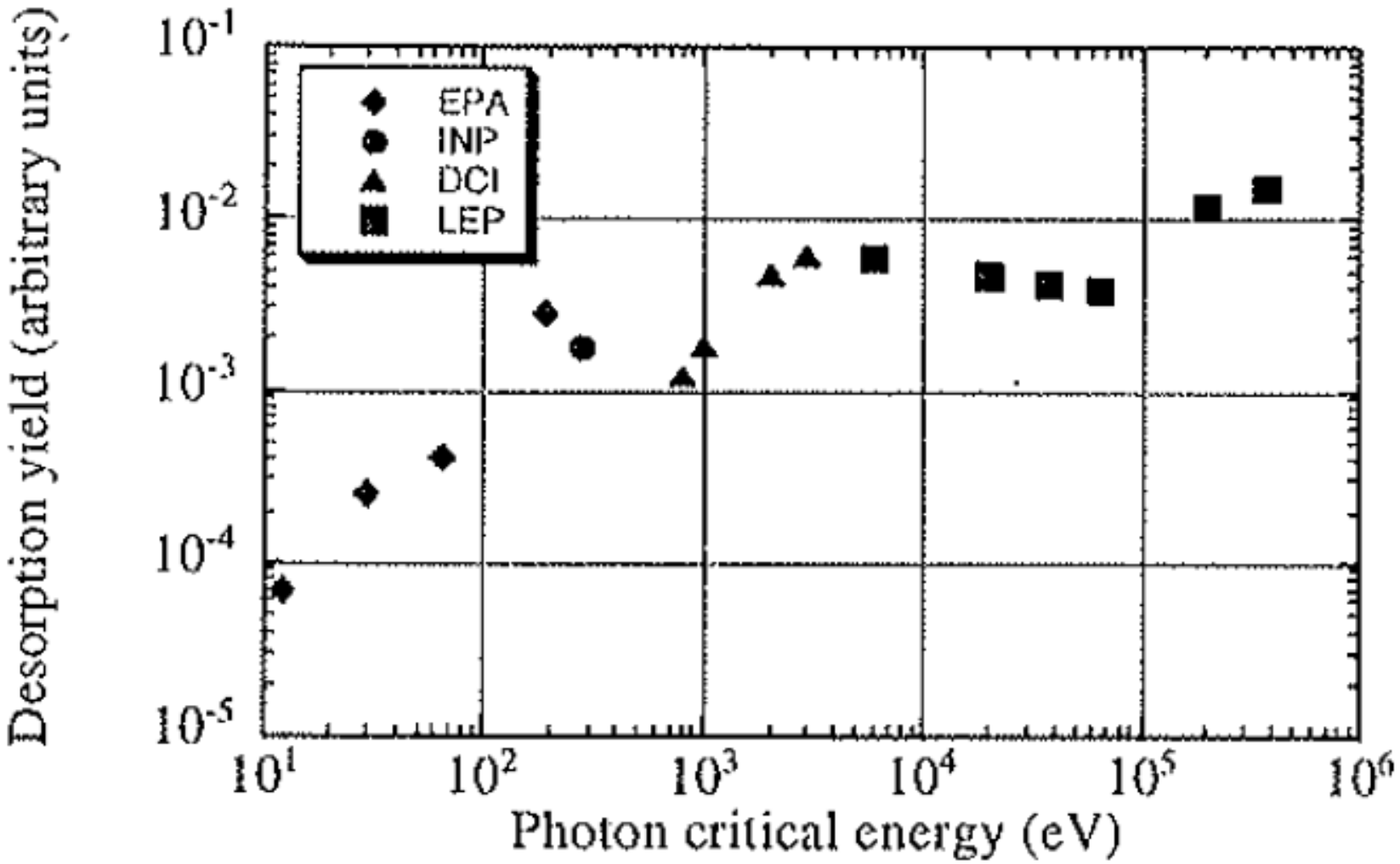
Ref: B.L. Henke, et al: Atomic Data and Nuclear Data Tables **54**, 181-342 (1993)

Measuring SR Desorption Yield



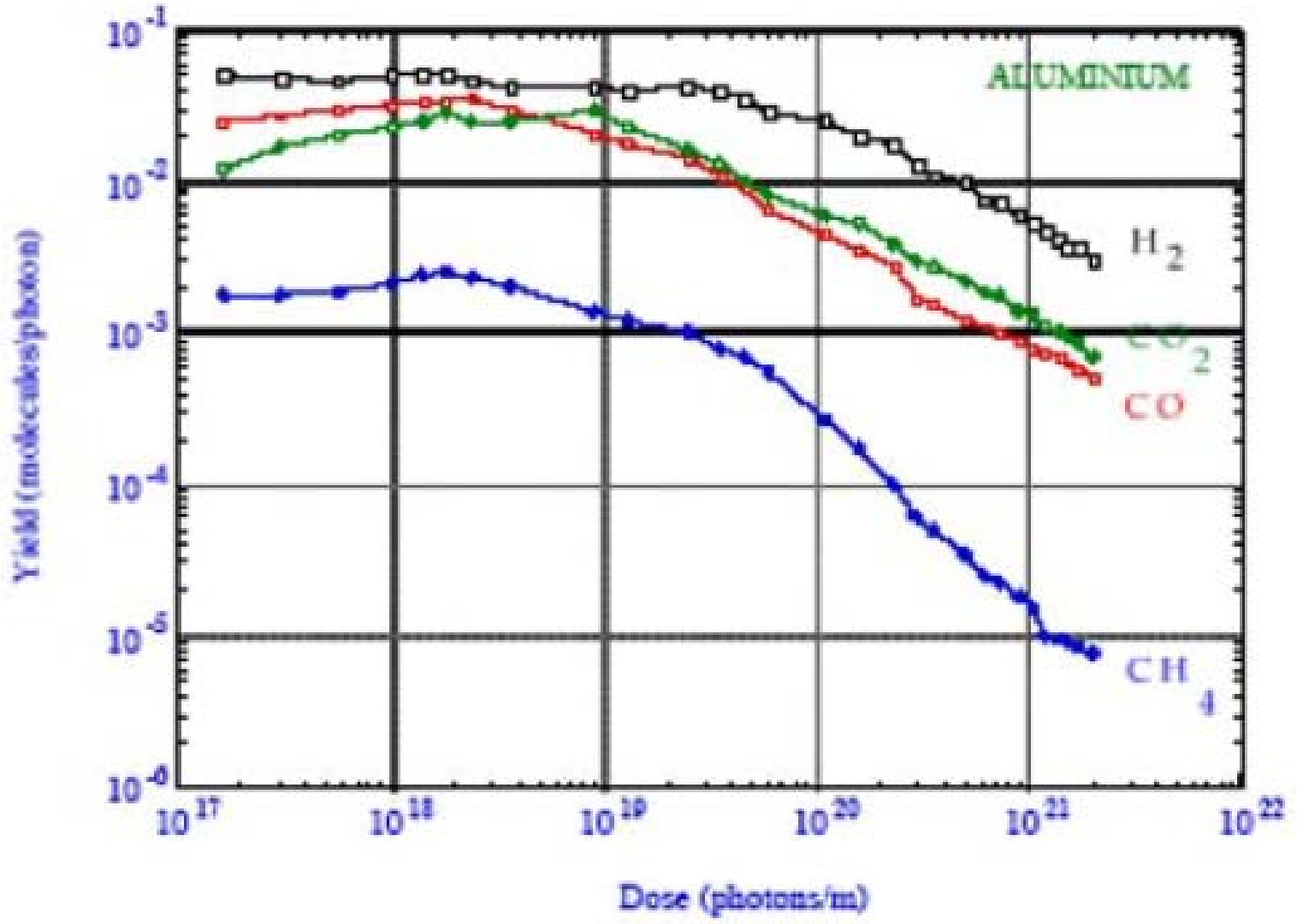
A PID Experimental System at Electron Positron Accumulator Ring (CERN)

PID Yield vs. SR Energy



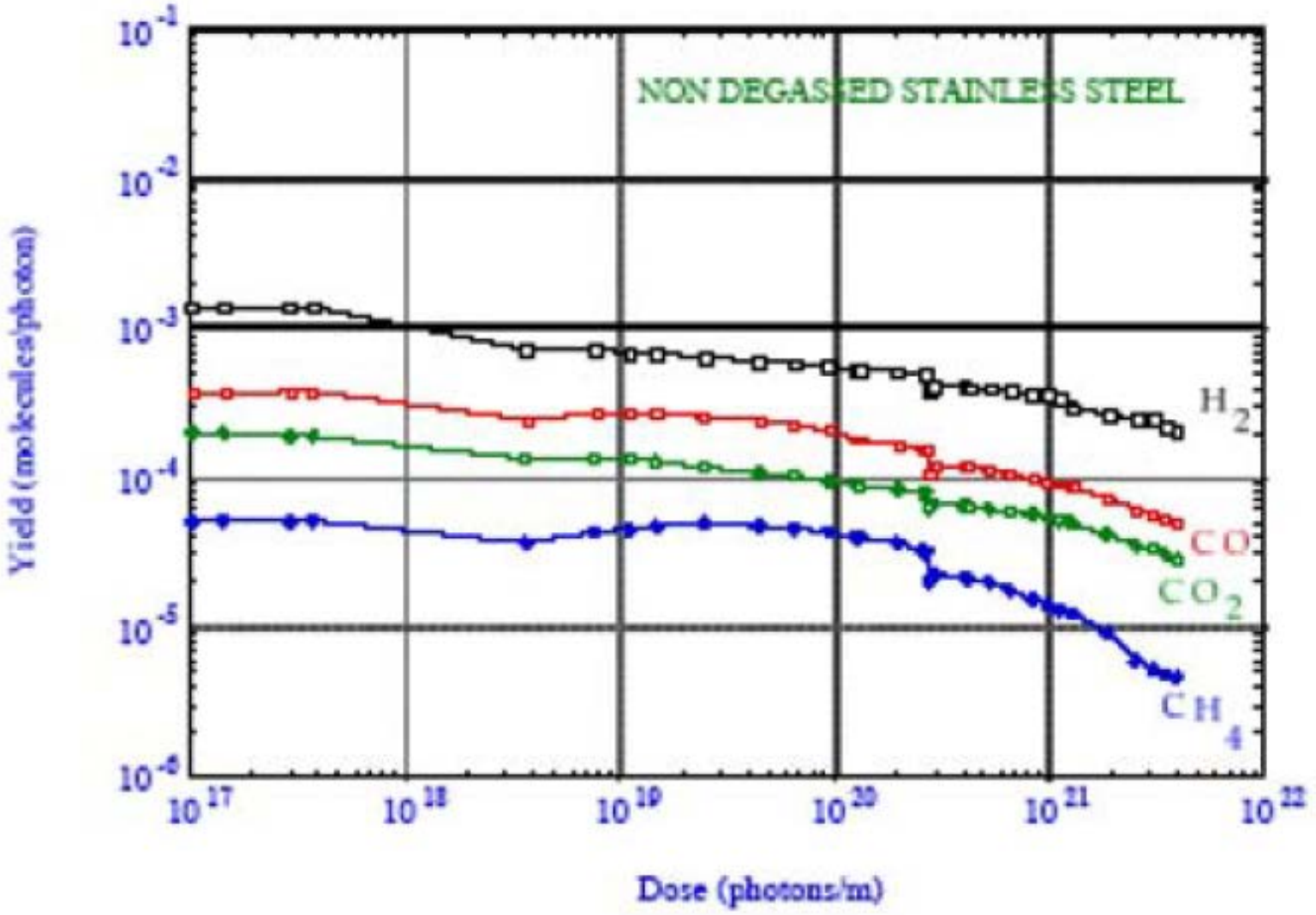
From: O. Grobner, CERN Accelerator School: Vacuum Technology, 1999

PID Yield vs. SR Dose – 6063 Aluminum



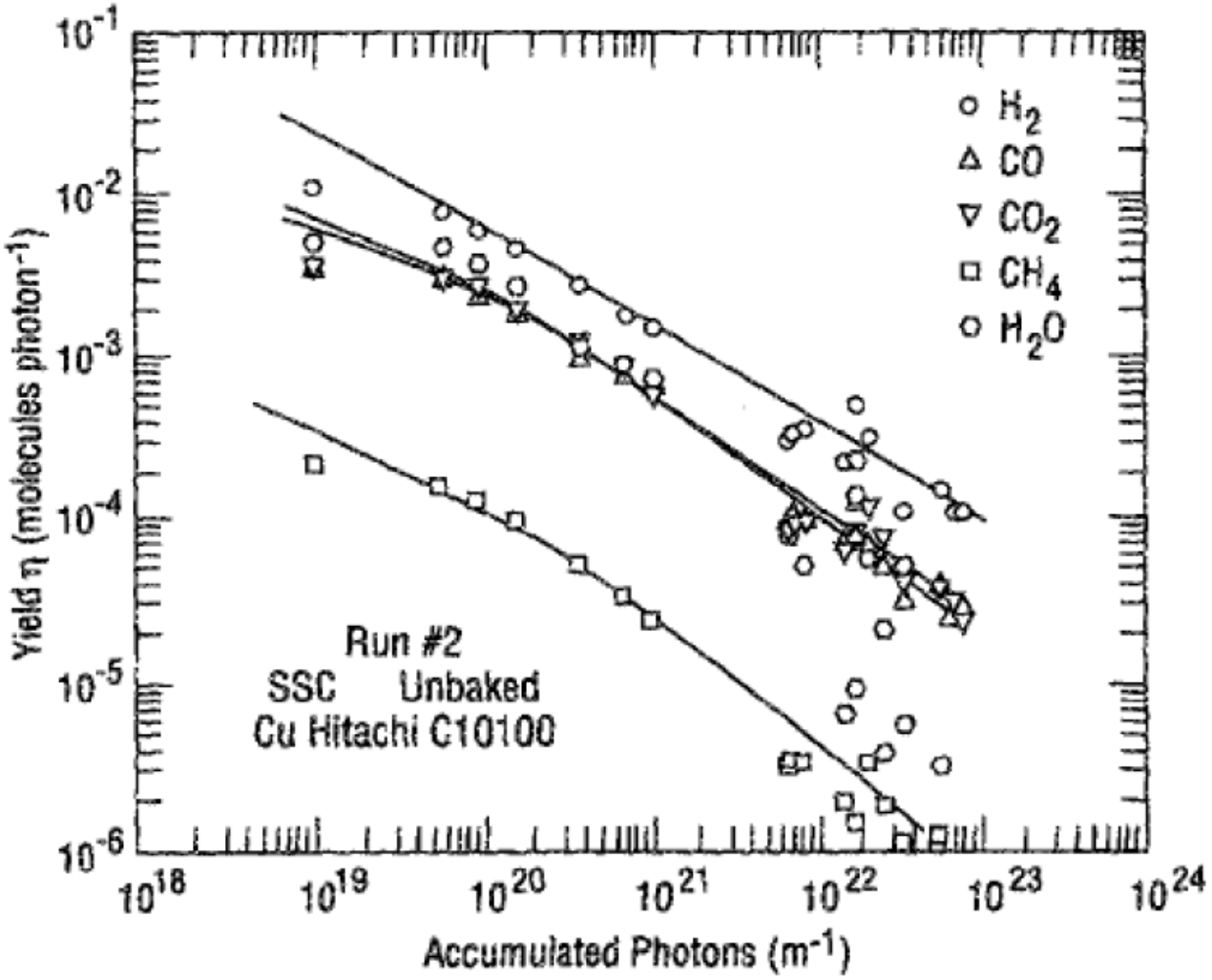
From: O. Grobner, CERN Accelerator School: Vacuum Technology, 1999

PID Yield vs. SR Dose – 304L Stn. Stl.



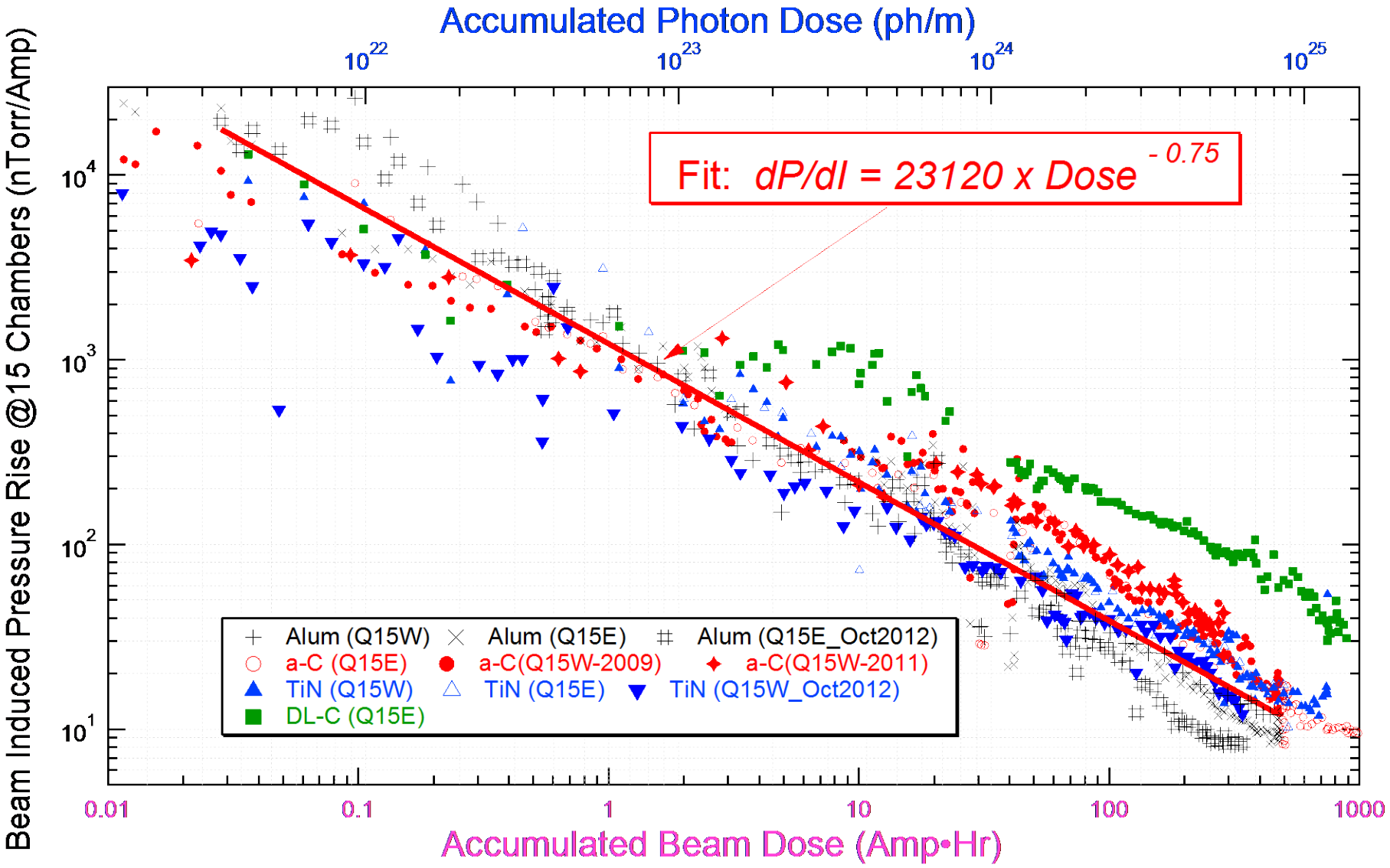
From: O. Grobner, CERN Accelerator School: Vacuum Technology, 1999

PID Yield vs. SR Dose – Copper



From: C.L.Foester, J. Vac. Sci. Technol., A 12 (1994), p.1673

PID vs. SR Dose – CESR Aluminum



Estimate PID Yield in a Real World

- In a CESR dipole center, installed linear pumping speed S_l~100 l/s·m
- A cold cathode ion gauge measure pressure, and provide beam induced pressure rise: dP/dI (in nTorr/Amp)
- The specific linear SR-induced gas desorption:

$$dQ_{SR}/dI = (dP/dI)\bullet S_l = 10^{-7}\ torr\cdot l/s\cdot m\cdot Amp$$
$$= 3.5x10^{12}\ \ molecules/s\cdot m\cdot Amp$$

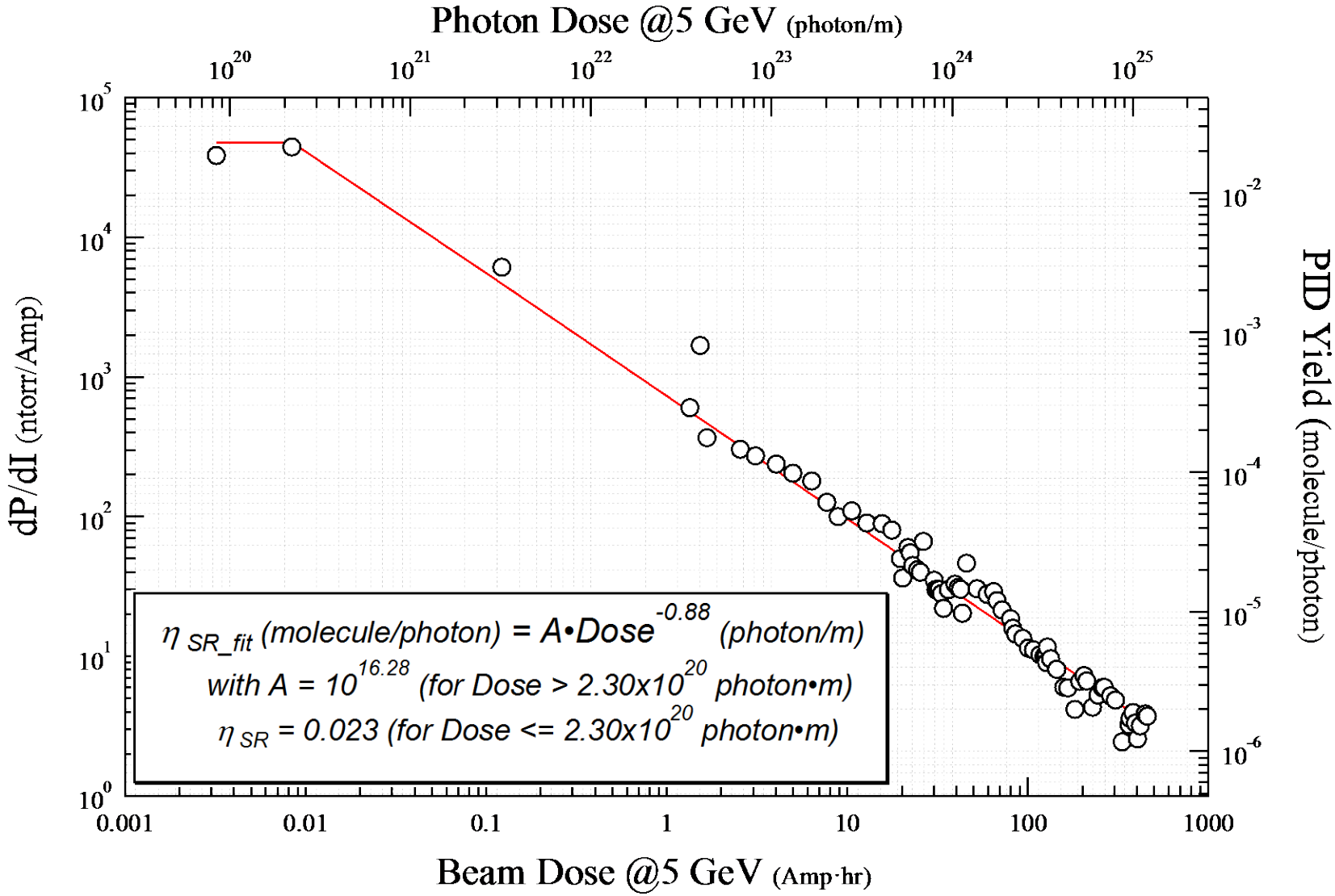
- The specific SR linear flux at a CESR dipole:

$$dF_{SR}/dI = 7.3x10^{18}\ \ ph/s\cdot m\cdot Amp$$

- Thus for measured dP/dI @ 1-nTorr/Amp corresponds to PID yield:

$$\eta_{SR} = \frac{dQ_{SR}/dI}{dF_{SR}/dI} = \frac{3.5\times10^{12}\,molec/m\cdot s\cdot A}{7.3\times10^{18}\,ph/m\cdot s\cdot A} = 4.8\times10^{-7}\,molecule/\,photon$$

PID Yield vs. SR Dose – CESR Aluminum



Sources of Gases – Summary

- A vacuum system's base pressure is limited by static gas sources. Proper vacuum system design, material selection, component cleaning and handling, and assembling can eliminate contamination, leaks, and excessive outgassing. Vacuum bakouts can further reduce base pressure.

- In most accelerator systems, beam induced gas loads (IID, EID and PID) dominate the operational vacuum level. The beam induced pressure rises can be very significant, thus a commissioning (or conditioning) period is always planned in starting accelerator vacuum systems with new components. Again, proper material selection and preparation is the key in shortening the commissioning period to an acceptable length.