Vacuum Technology in Particle Accelerator

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Outline

- Vacuum in Particle Accelerators
- Vacuum Basics

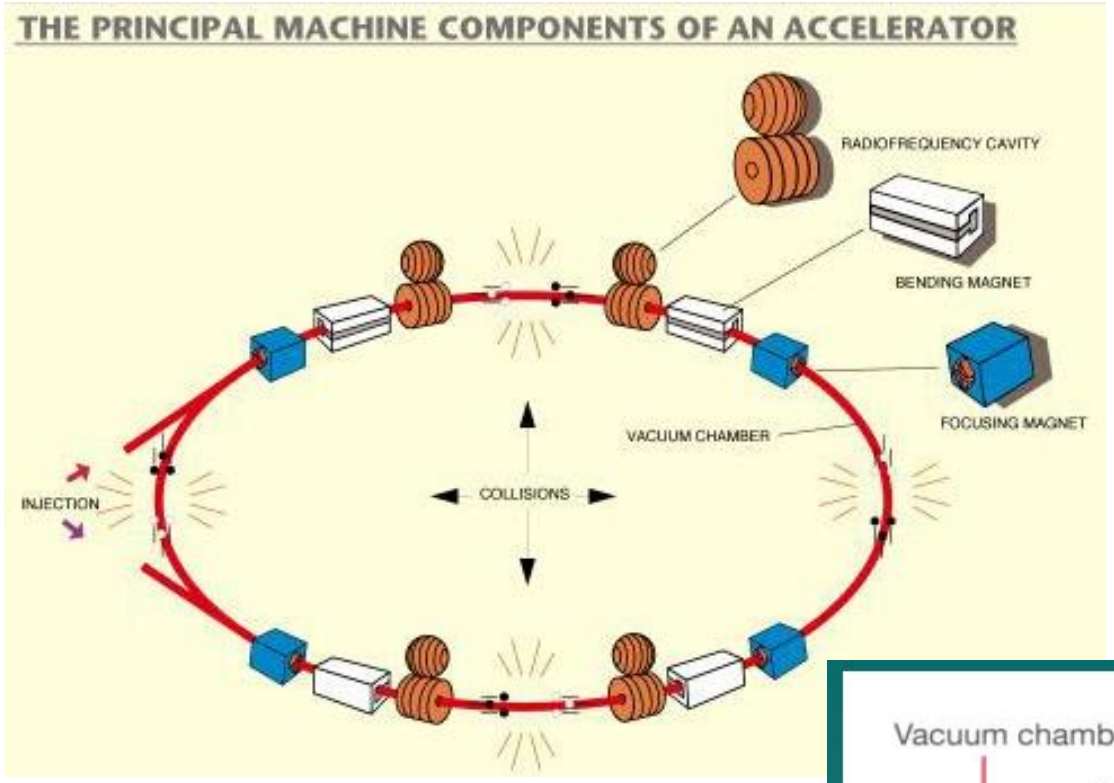
-What is vacuum and vacuum ranges?

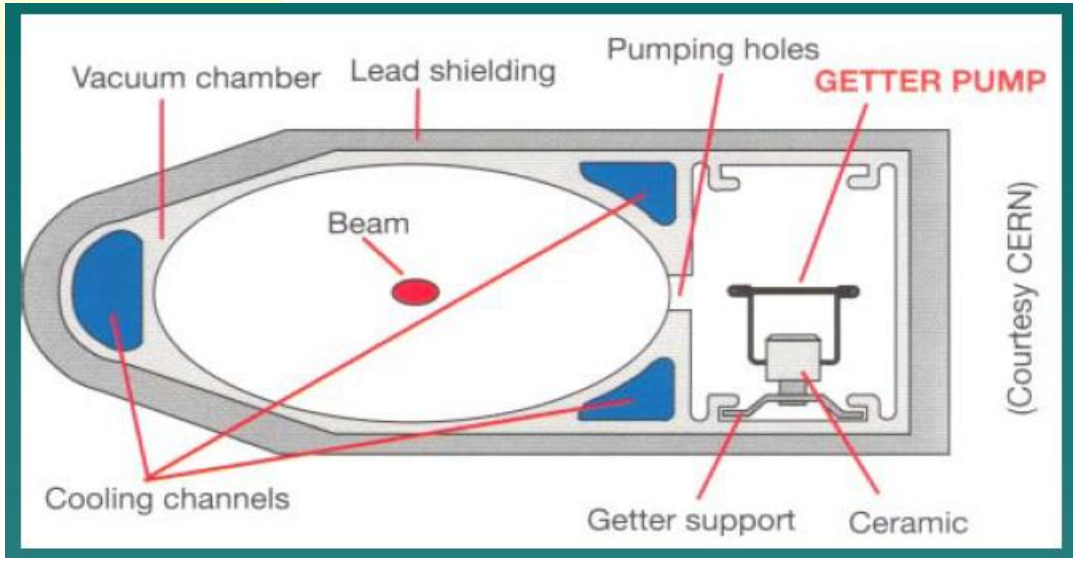
-Ideal gas law.

-Gas flow, conductance and pumping speed.

- Gas sources in accelerators
- Pumping & Instrumentation
- Leak check
- Vacuum material and cleaning
- Vacuum system integration

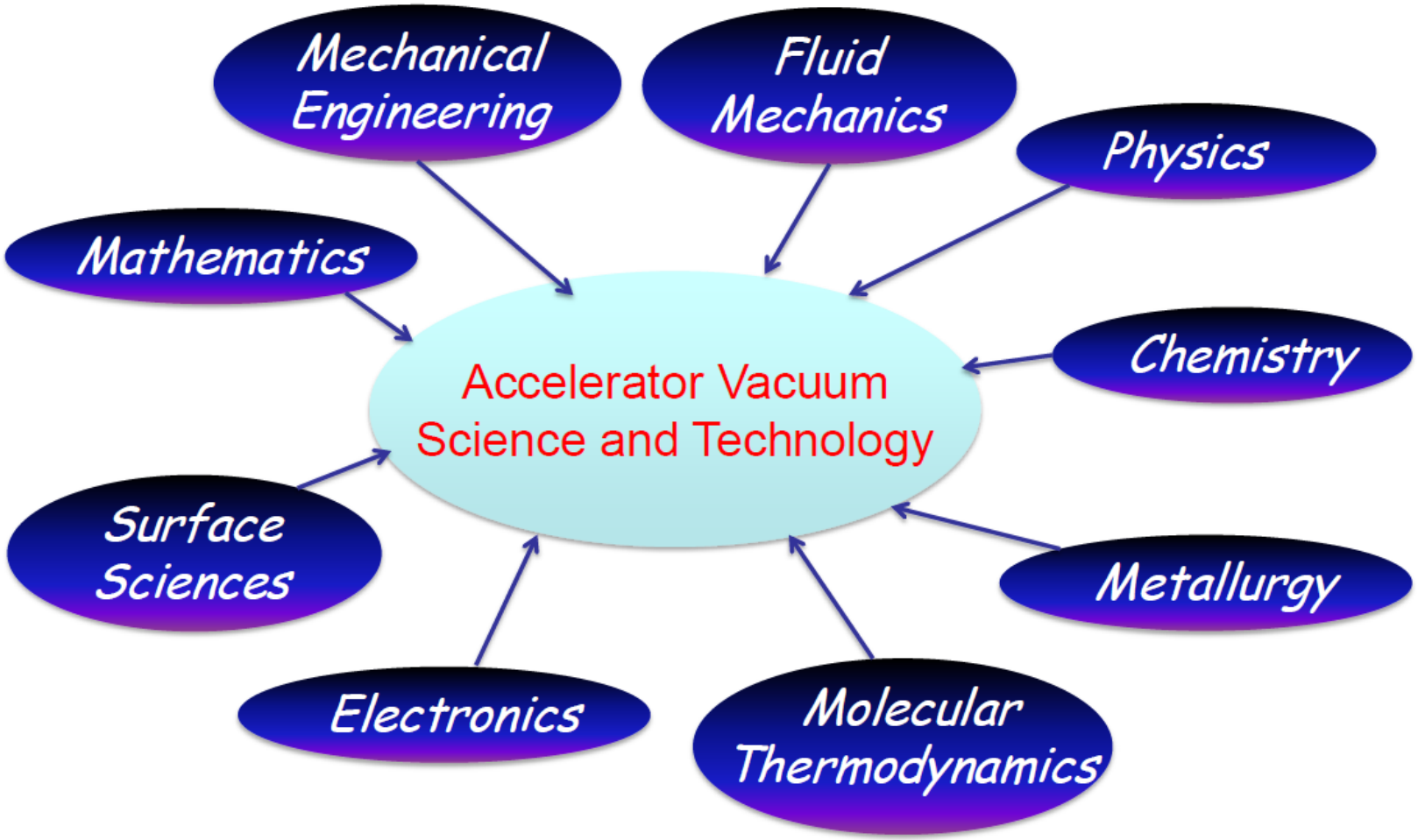
Beam inside Vacuum Chamber





TPS one cell model
(Magnet and Vacuum Chamber)

Accelerator Vacuum – highly interdisciplinary

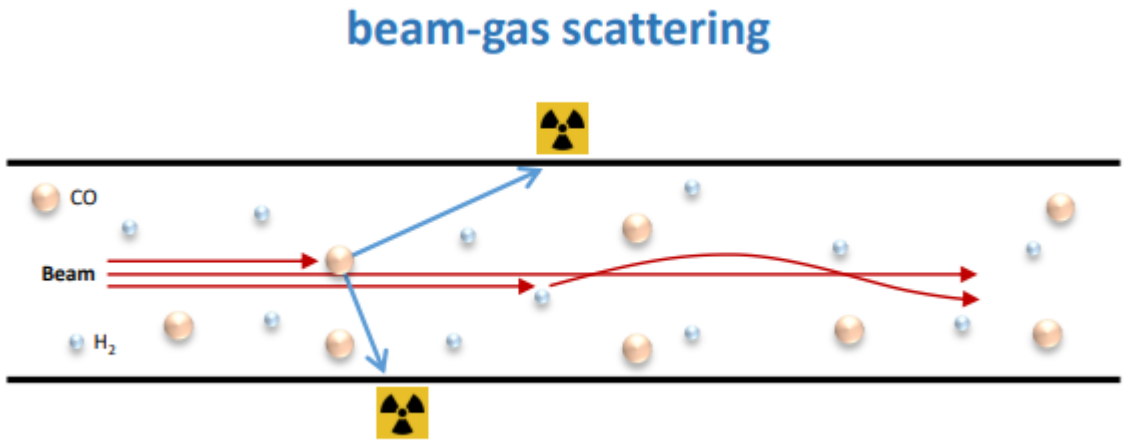


Vacuum in Particle Accelerators

- *Why is Vacuum needed in particle accelerators?*

  Vacuum aims to reduce beam-gas interaction which is responsible for:

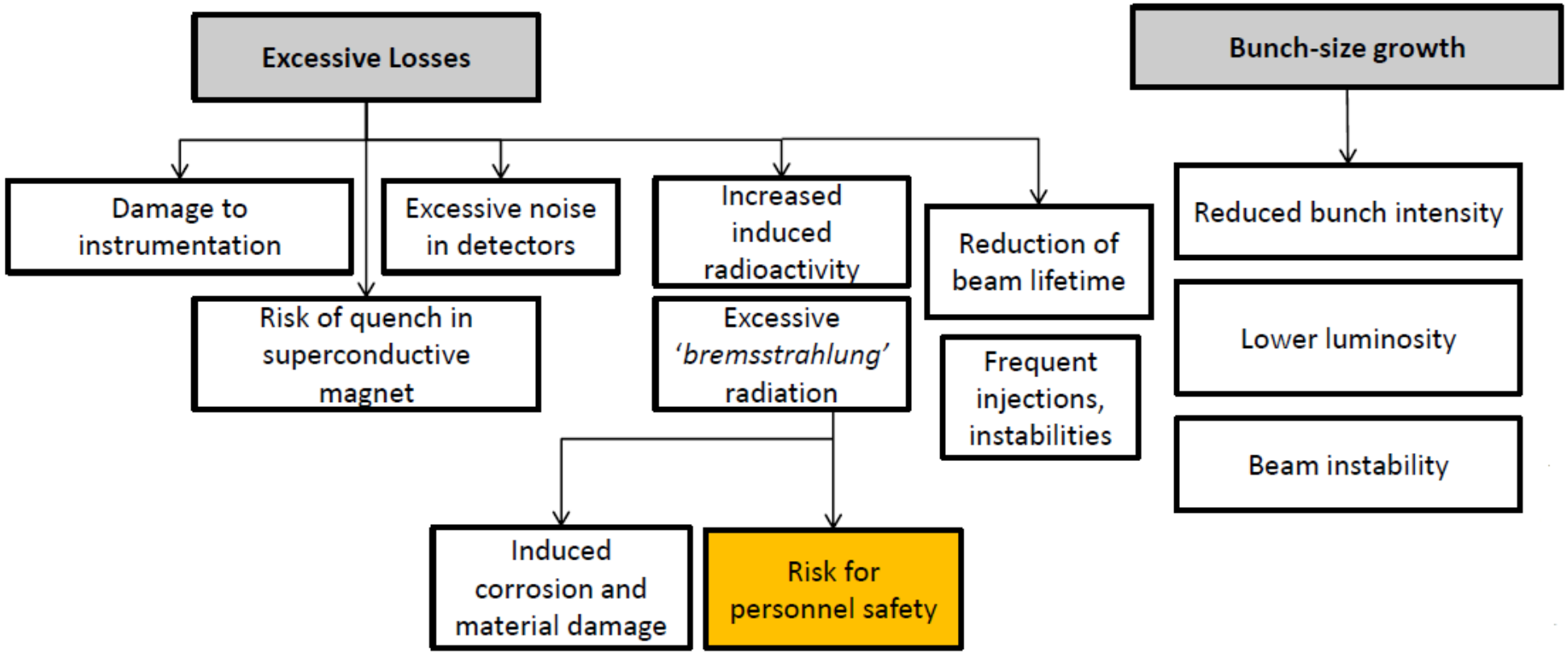
- Machine performance limitations:
  - Reduction of beam lifetime (nuclear scattering)
  - Reduction of machine luminosity (multiple coulomb scattering)
  - Intensity limitation by pressure instabilities (ionization)
  - Electron (ionization) induced instabilities (beam blow up)
- Background to the experiments
  - Non-captured particles which interact with the detectors
  - Nuclear cascade generated by the lost particles upstream the detectors



Why do we need vacuum in accelerators?

Collisions between gas molecules and particles have to be minimized, otherwise:

Particle energy is reduced and trajectories are modified, so that:



Vacuum is also necessary:

- to avoid electrical discharge in high-voltage.
- To thermally isolate cryogenic devices.
- To avoid contamination of optics.

Vacuum in Particle Accelerators

- *What are the Vacuum Engineering constraints?*
  - Beam vacuum pipes are designed to:
  - Minimise beam impedance and HOM generation
  - Optimise beam aperture
  - Intercept heat loads
    - Synchrotron radiation
    - Energy loss by nuclear scattering
    - Image currents
    - Energy dissipated during the development of electron clouds
- Vacuum systems shall be optimised for integration and radiation issues
  - Operation & Maintenance costs

Vacuum in Particle Accelerators

- *What are the Vacuum Engineering constraints?*
  - Basic vacuum requirements
    - Depend more on beam performance than on beampipe sizes
      - Nature of particles, Energy, Intensity, Bunch densities, etc.
    - Dynamic effects dominate when increasing beam energy and intensity,
      - Low energy ion accelerators are an exception
  - Higher beam energy means larger size
  - Requires a trade-off between performance and cost
    - Higher demand on integration and logistics

Basics of Vacuum Physics

Vacuum Basics

- *Physical Quantities*
- A gas in an enclosed space can be physically described by:
  - Volume
  - Space occupied by the gas ; taken to be the volume of the vacuum enclosure since a gas will expand to fill the space in which it is confined; often measured in litters [S.I. in m^3].
  - Temperature
  - A measure of the kinetic energy possessed by the gas molecules; generally determined by the temperature of the surface in contact with the gas molecules; measured in Celcius [° C] or K Kelvin [K]
  - Amount
  - Number of gas molecules; measured in gram-mole [6.022 x 10^23 atoms/mole]

Vacuum Basics

Defining Vacuum

- Ideal
  - Classical metaphysics: a space containing nothing
- Real
  - Any subatmospheric pressure
- Practical
  - any volume which has fewer gas molecules than the same size volume in the surrounding atmosphere

Vacuum Range	Pressure Range (mbar)	Typical applications
Low	$33<p<1.0\times10^{3}$	Vacuum cleaner, mechanical handling, vacuum forming,
Medium	$1.0\times10^{-3}<p<33$	Vacuum drying, vacuum freeze (food industries)…etc.
High (HV)	$1.0\times10^{-6}<p<1.0\times10^{-3}$	Production of microwave, light bulbs, vapor deposition.
Very high (VHV)	$1.0\times10^{-9}<p<1.0\times10^{-6}$	Electron microscopes, X-ray and gas discharge tubes, electron beam welding
Ultra-high (UHV)	$1.0\times10^{-12}<p<1.0\times10^{-9}$	Particle accelerators, space simulators, material research, semiconductors,
Extreme ultrahigh (XHV)	$p\leq1.0\times10^{-12}$	Particle accelerators, space simulators, advanced semiconductor devices

Units of Pressure

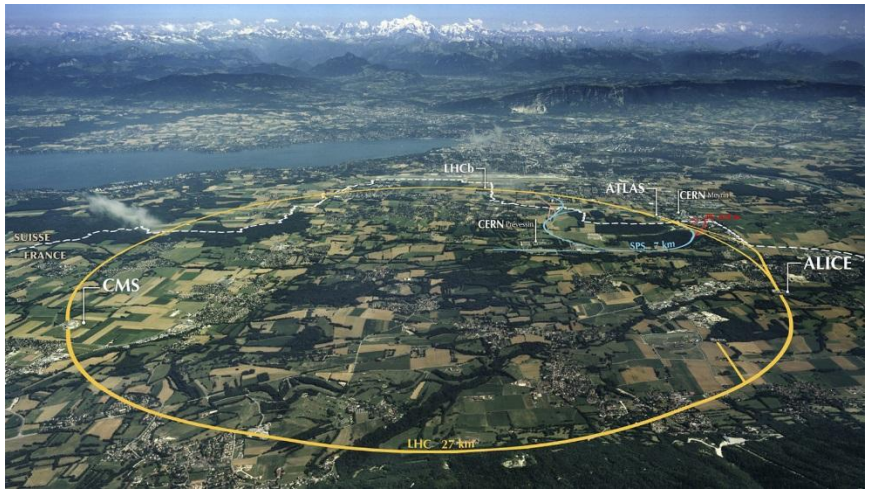
The pressure is the force exerted by a molecule per unit of surface : 1 Pa = 1 N/m^2

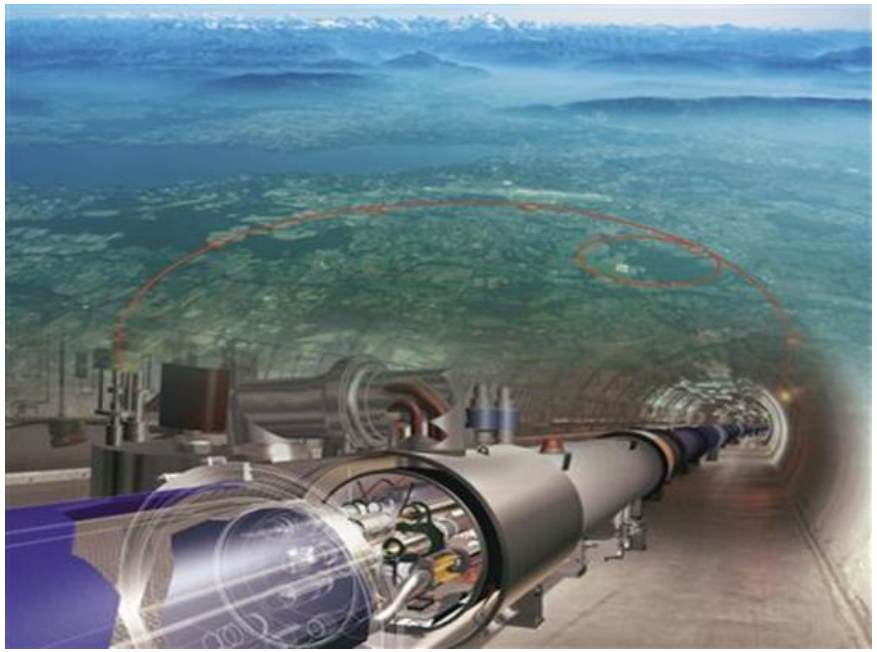
	Pa	kg/cm^2	Torr	mbar	bar	atm
Pa	1	$10.2\ 10^{-6}$	$7.5\ 10^{-3}$	10^{-2}	10^{-5}	$9.81\ 10^{-6}$
kg/cm^2	$98.1\ 10^{3}$	1	735.5	980	0.98	0.96
Torr	133	$1.35\ 10^{-3}$	1	1.33	$1.33\ 10^{-3}$	$1.31\ 10^{-3}$
mbar	101	$1.02\ 10^{-3}$	0.75	1	10^{-3}	$0.98\ 10^{-3}$
bar	$1.01\ 10^{5}$	1.02	750	10^{3}	1	0.98
atm	101 300	1.03	760	1 013	1.01	1

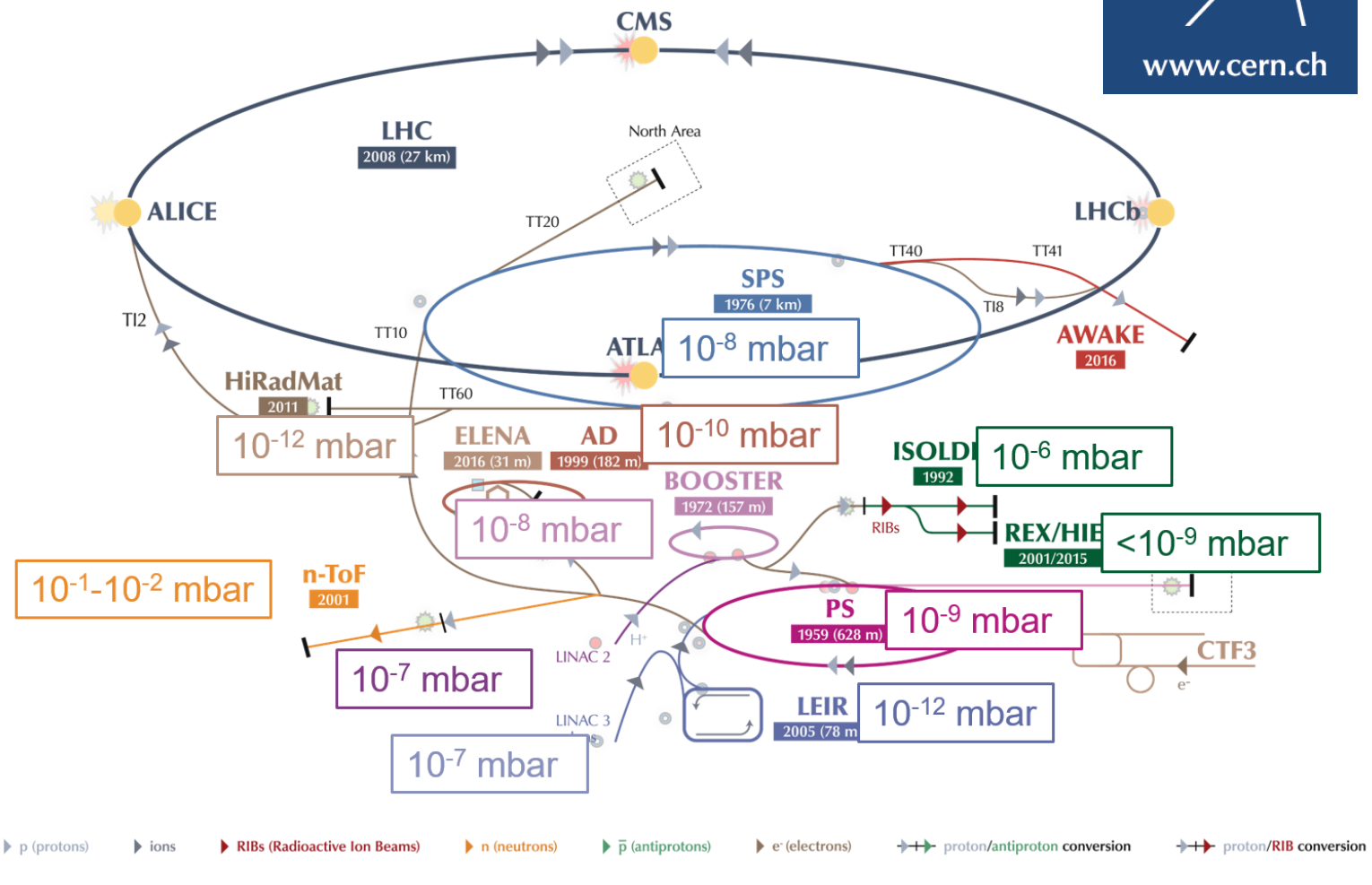
Never forget: Pressure = Force → 1 kg/cm^2 !

Extreme High Vacuum ($P < 10^{-11}$ torr)	*Photo-cathode electron sources (Cornell, JLab,), High intensity ion accelerators, etc.*
Ultra-High Vacuum (10^{-9} to 10^{-11} torr)	*Storage rings, surface sciences, etc.*
High Vacuum (10^{-3} to 10^{-9} torr)	*Device fabrications, medical accelerators, LINACs, mass spectrometry, SEM, etc.*
Medium & Low Vacuum	*Cryo insolation vacuum, coating, vacuum furnaces, beam welders, etc.*

Vacuum ranges in particle accelerators





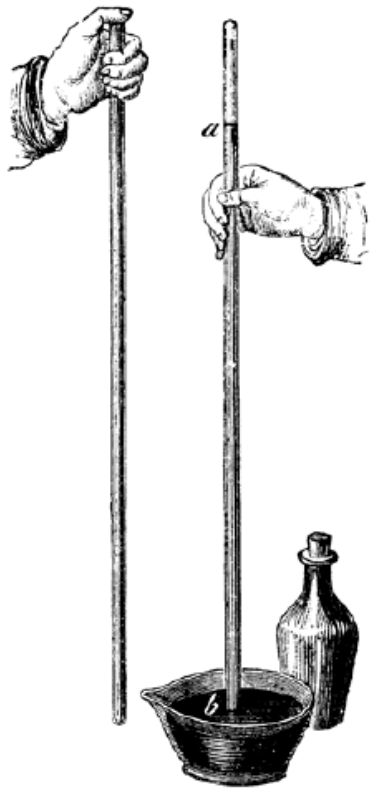


A Brief History of Vacuum: Vacuum Technology is Born

- **Galileo** (1564—1642) attempted to measure the force that a partial vacuum imparted piston

- **Torricelli** (1608—1647) first to produce a vacuum with an inverted Hg column (the first vacuum gauge, barometer, altimeter)

- **Pascal** (1623—1662) put the concept of "horror vacui" to rest by measuring the force of atmospheric pressure on an evacuated space



ISI Unit of Pressure:

1 Pa = 1N/m^2 =7.501 x10^{-3} Torr = 10^{-2} mbar

Otto von Guericke (1602-1686)

Burgermeister of Magdeburg

- Experimenter in vacuum and electrostatics
- Modified water pumps, invented the air pump (1650) and the first manometer (1661)
- “Magdeburg Hemispheres” experiment (1654)

The original Magdeburg hemispheres and Guericke's vacuum pump in the Deutsches Museum, Munich, Germany

Compressing the History of Vacuum:1800-2000

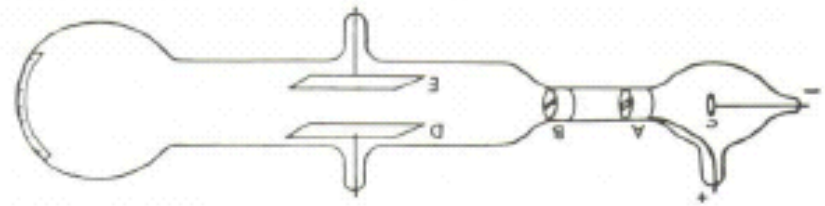
- the pioneer period, Charles, Boyle, etc.
  -fundamental gas laws
- late 1800's
  - McLeod gauge
  - 0.1 to 1 mTorr (mbar)
  - Geissler, Thomson, Edison, "cathode ray" studies, pumps, gauges
- early 1900's
  - diffusion pump
  - capacitance manometer, Pirani gauge
  - 10^{-6} Torr (mbar)
- mid 1900's
  - Bayard-Alpert gauge, ion pump
  - UHV and UHV hardware
- 1970—1990
  - Commercial turbopumps and cryopumps
  - dry pumping (getters)

Edison's Vacuum Pump for His First Lamps: 1879

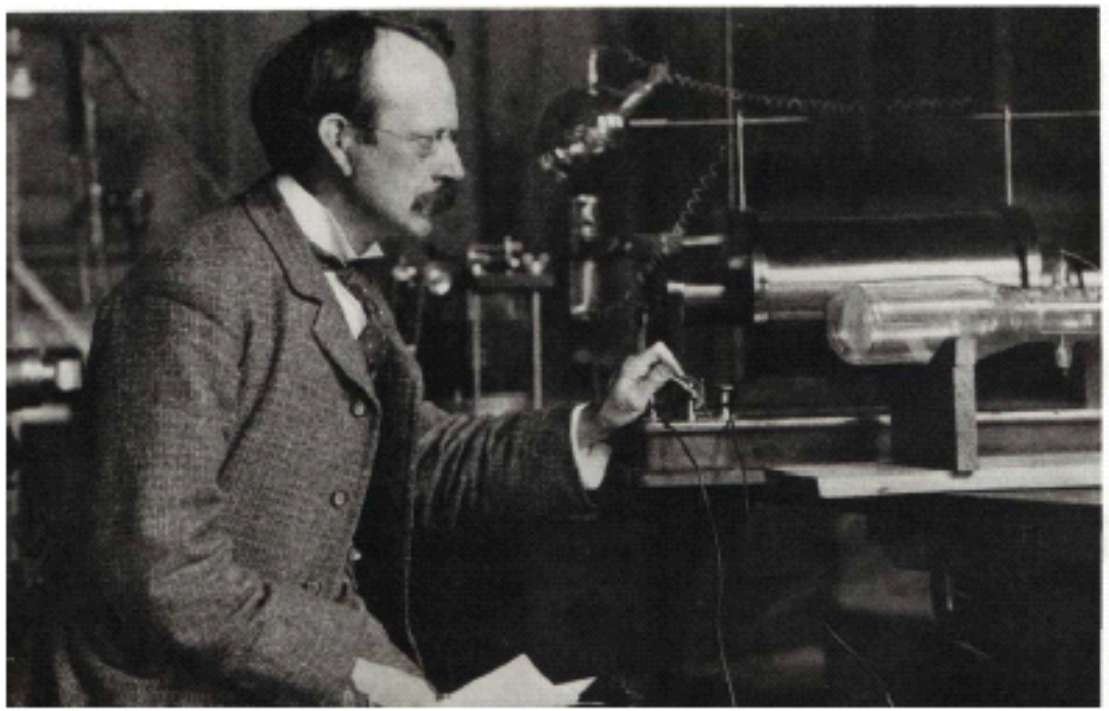
- Mercury Drop Pump developed by Geissler and improved by Sprengel
- Modified by Thomas Edison for his early experiments and then first production of electric lamps
- Likely to have produced vacuum conditions $<10^{-3}$ mbar with chemical gettering of water

Thompson's Discovery of the Electron (1897)

Thomson incorporated Crooke's improvements to Sprengel's pumps and sealing technology to produce the first electron beam unshielded by background ions



- **Thompson's second tube**



J. J. Thompson in his Cavendish Laboratory

Kinetic Picture of a Ideal Gas

Five Assumptions

1. Gases are made up of large numbers of very small particles (atoms or molecules).

2. The particles of a gas are widely separated compared to their size, so they do not interact except when elastic collisions occur between them.

3. The particles are in constant, random motion.

4. The collisions between the particles and the walls of their container are assumed to be perfectly elastic collisions (momentum and kinetic energy are conserved).

5. The particles obey Newton's Laws

Vacuum Basics

Gas Laws (1/2)

- Avogadro's Law
  - Under the same conditions of pressure and temperature, equal volumes of all gases have the same number of molecules: called a *mole*.

$$\left.\frac{6.023\times10^{23}\ particles}{22.4\,l}\right|_{760torr,273^\circ K} = 2.69\times10^{22}\ particles/l\Big|_{760torr,273^\circ K}$$

$$3.3\times10^{19}\ particles/l\Big|_{1torr,293^\circ K} = 2.5\times10^{19}\ particles/l\Big|_{1mbar,293^\circ K}$$

- Boyle's Law
  - Original pressure times original volume equals new pressure times new volume

$$P_1V_1 = P_2V_2$$

- Charles' Law
  - As we cool a gas, its volume gets smaller. If we heat the gas, its volume increase.

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

Vacuum Basics

Gas Laws (2/2)

- Law of Gay-Lussac
  - If the temperature of a volume of gas at 0°C is changed by 1°C, the volume will change (+/-) by 1/273 of its original value.

    Lord Kelvin used this relationship to develop the absolute temperature scale (1 K = -273 °C)

$$V = V_0 + \left(\frac{°C}{273}\right) \times V_0 \quad or \quad V = V_0\left(1 + \frac{°C}{273}\right)$$

- General Gas Law
  - Resulted from the combination of Boyle's and Charles' Laws:

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

Gas Laws

Charles' Law

Volume vs. temperature PV=const. (N, T const.)

Boyle's Law

Pressure vs. Volume V/T=const. (N, P const.)

Avogadro's Law

Volume vs. Number of molecules

V/N=const. (P, T const.)

All these laws derivable from the Ideal Gas Law

They apply to all molecules and atoms, regardless of their sizes

Vacuum Basics

Units of gas density

- The quantity of gas can be presented in number of molecules (N) or in pressure-volume (PV) units.
- The two values are related by the **ideal gas equation** of state:

$$P \cdot V = N \cdot K_B \cdot T \rightarrow N = \frac{P \cdot V}{K_B \cdot T}$$

- The pressure-volume units are transformed to number of molecules when divided by $K_B T$. A given number of molecules is expressed by different pressure-volume values at different temperatures. In general the pressure-volume quantities are quoted at room temperature

$$k_B = 1.38 \cdot 10^{-23} \left[\frac{N \cdot m}{K} = \frac{Pa \cdot m^3}{K} \right]$$

$$k_B = 1.38 \cdot 10^{-23} \left[\frac{Pa \cdot m^3}{K} \right] = 1.04 \cdot 10^{-22} \left[\frac{Torr \cdot \ell}{K} \right] = 1.38 \cdot 10^{-22} \left[\frac{mbar \cdot \ell}{K} \right]$$

$$\text{for } T = T_{RT} = 296\,K$$

$$\frac{1}{k_B T_{RT}} = 2.45 \cdot 10^{20} \left[Pa \cdot m^3 \right]^{-1} = 3.3 \cdot 10^{19} \left[Torr \cdot \ell \right]^{-1} = 2.5 \cdot 10^{19} \left[mbar \cdot \ell \right]^{-1}$$

Maxwell-Boltzmann Velocity Distribution

$$\frac{dn}{dv} = \frac{2N}{\pi^{1/2}} \left(\frac{m}{2kT} \right)^{3/2} v^2 e^{-\left(\frac{m}{2kT} \right) v^2}$$

v – velocity of molecules (m/s)

n – number of molecules with v between v and $v + dv$

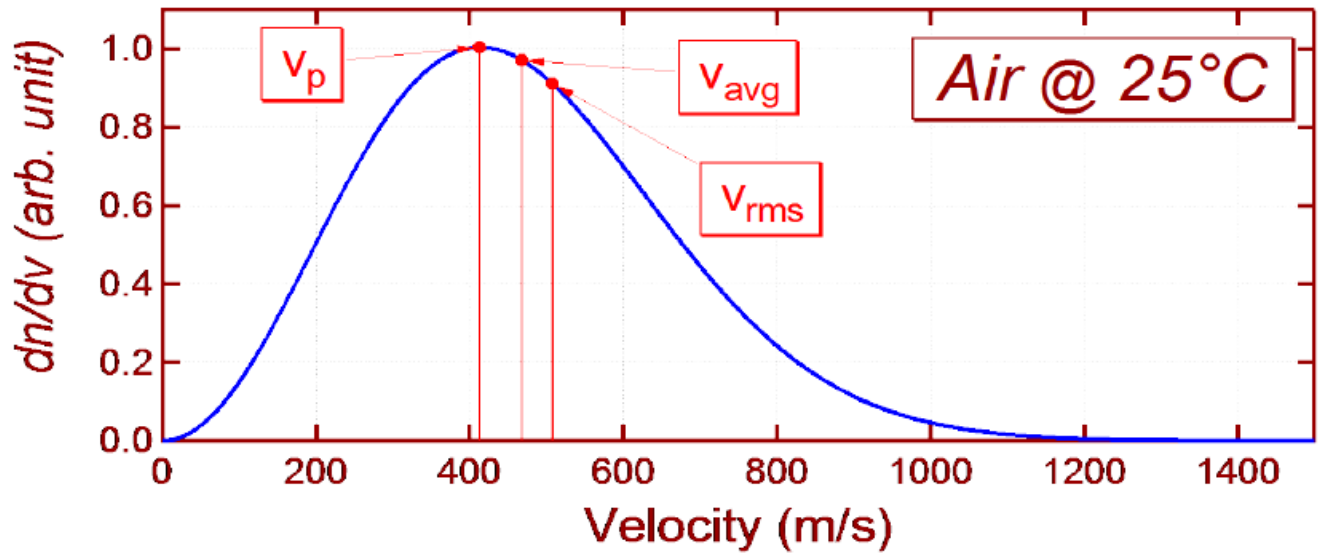
N – the total number of molecules

m – mass of molecules (kg)

k – Boltzmann constant, $1.3806503 \times 10^{-23}$ m^2 kg s^{-2} K^{-1}

T – temperature (kelvin)

Velocity of a gas molecule

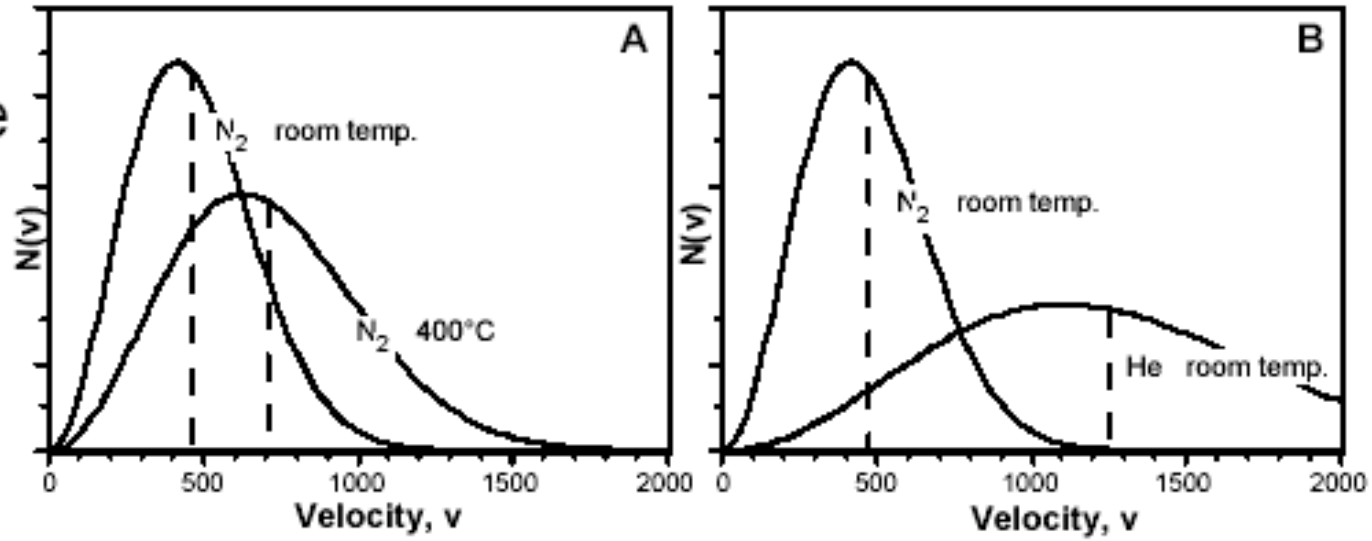


- Most probable velocity (m/s): $v_p = \sqrt{2kT/m} = 128.44\sqrt{T/M_{mole}}$
- Arithmetic mean velocity: $v_{avg} = \sqrt{8kT/\pi m} = 1.128 v_p$
- Root Mean Squared velocity: $v_{rms} = \sqrt{3kT/m} = 1.225 v_p$

Velocity depends on mass and temperature, but independent of pressure

Kinetic Theory of the Gas Molecules: The Maxwell-Boltzmann Distribution

- Velocity of a gas molecule



$$v_{\max} = \sqrt{\frac{2kT}{m}}$$

$$v_{av} = \sqrt{\frac{8kT}{\pi m}}$$

$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

Molecules Moves Fast at Higher Temperatures

Light Molecules Moves Faster

Ave. Molecular Velocities (at room temp)

H_2	1693 m/sec
He	1201
H_2O	566
N_2	454
Ar	380

Maxwell-Boltzmann Energy Distribution

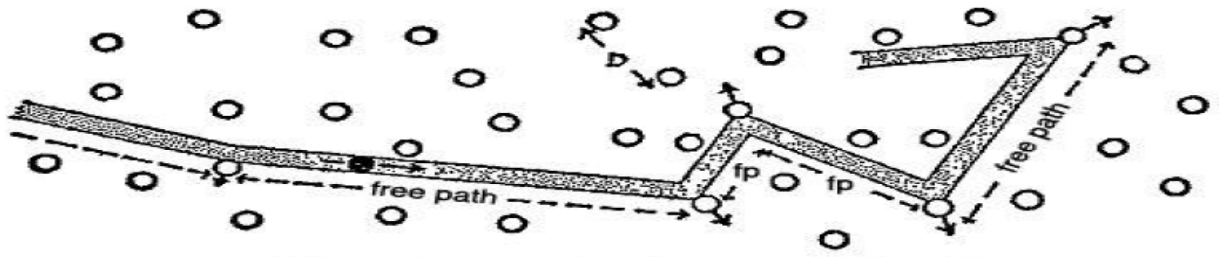
$$\frac{dn}{dE} = \frac{2N}{\pi^{1/2}} \frac{E^{1/2}}{(kT)^{3/2}} e^{-\left(\frac{E}{2kT}\right)}$$

- Average Energy: $E_{avg} = 3kT/2$
- Most probable Energy: $E_p = kT/2$

Neither the energy distribution nor the average energy of the gas is a function of the molecular mass. They ONLY depend on temperature !

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 of a gas molecule

Mean Free Path is determined by:
size of molecules, density (thus pressure and temperature)

Mean Free Path – Air @ 22° C

$$\lambda(cm) = \frac{0.67}{P(Pa)} = \frac{0.005}{P(Torr)}$$

P (torr)	760	1	10^{-3}	10^{-6}	10^{-9}
λ (cm)	6.6×10^{-6}	5.1×10^{-3}	5.1	5100	5.1×10^{6}

$$\lambda = \frac{1}{\sqrt{2}\pi d_0^2 n} = \frac{kT}{\sqrt{2}\pi d_0^2 P}$$

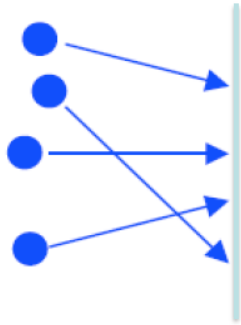
λ - *mean free path (m)*
d_0 - *diameter of molecule (m)*
n - *Molecular density* (m^{-3})
T - *Temperature (Kevin)*
P - *Pressure (Pascal)*
k - *Boltzmann constant,* 1.38×10^{-23} m^2 kg s^{-2} K^{-1}

Particle Flux

***Particle Flux** – rate of gas striking a surface or an imaginary plane of unit area*

Kinetic theory shows the flux as:

$$\Gamma(m^{-2}\cdot s^{-1}) = \frac{1}{4} n v_{avg} = n\sqrt{\frac{kT}{2\pi m}}$$



where n is the gas density

P	n	Particle Flux ($m^{-2}\cdot s^{-1}$)				
(torr)	m^{-3}	H_2	H_2O	CO/N_2	CO_2	Kr
760	2.5×10^{25}	1.1×10^{28}	3.6×10^{27}	2.9×10^{27}	2.3×10^{27}	1.7×10^{27}
10^{-6}	3.2×10^{16}	1.4×10^{19}	4.8×10^{18}	3.8×10^{18}	3.1×10^{18}	2.2×10^{18}
10^{-9}	3.2×10^{13}	1.4×10^{16}	4.8×10^{15}	3.8×10^{15}	3.1×10^{15}	2.2×10^{15}

Typical atomic density on a solid surface: $5.0\sim12.0\times10^{18}$ m^{-2}
Thus monolayer formation time at 10^{-6} torr: ~ 1-sec !

Particle flux is helpful in understanding gas flow, pumping, adsorption and desorption processes.

- The time for monolayer formation: is the time required for a freshly-formed surface to become covered with a monolayer of gas molecules

$$\tau = \frac{n_{mono}}{Z_A}$$

τ monolayer time formation (s)
n_{mono} number of molecules per unit area (around 10^{19} molec/m^2)

p	Pa	100	0.1	10^{-5}	10^{-7}	10^{-9}
	mbar	1	10^{-3}	10^{-7}	10^{-9}	10^{-11}
t_{mono} (air)		$3.6\cdot10^{-6}$ s	$3.6\cdot10^{-3}$ s	36 s	1 h	100 h
t_{mono} (H_2O)		$2.8\cdot10^{-6}$ s	$2.8\cdot10^{-3}$ s	28 s	47 min	78 h
t_{mono} (H_2)		$9.3\cdot10^{-7}$ s	$9.3\cdot10^{-4}$ s	9.3 s	16 min	26 h

for air at room temperture:

$$\tau = \frac{3.2\times10^{-6}}{p}$$

Total and Partial Pressure

- The gas is usually composed of several types of molecules (ex: air, gas in vacuum systems)

$$P_{Tot} = \sum P_i = k\,T \sum n_i$$

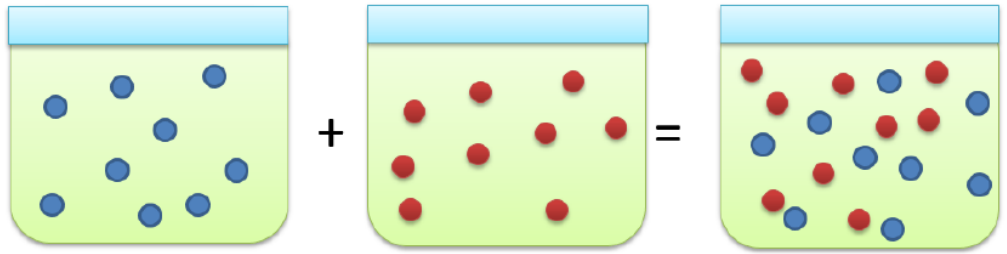
- The **total pressure**, P_{Tot}, is the sum of all the **partial pressure**, P_i (Dalton law)

Partial pressures for atmospheric air

Gas	%	Pi (Pa)
N_2	78.1	$7.9\ 10^4$
O_2	20.5	$2.8\ 10^3$
Ar	0.93	$1.2\ 10^2$
CO_2	0.0033	4.4
Ne	$1.8\ 10^{-3}$	$2.4\ 10^{-1}$
He	$5.2\ 10^{-4}$	$7\ 10^{-2}$

- Dalton's Law: total pressure of a gas mixture is the sum of the partial pressure of the individual components:

$$p = p_1 + p_2 + p_3 + \ldots + p_i = \sum p_i$$



Nitrogen at 1 mbar | Oxygen at 2 mbar | Nitrogen and oxygen at 3 mbar

Using ideal gas law: $p_{total} = (n_1 + n_2 + \cdots + n_n).\,k.\,T$

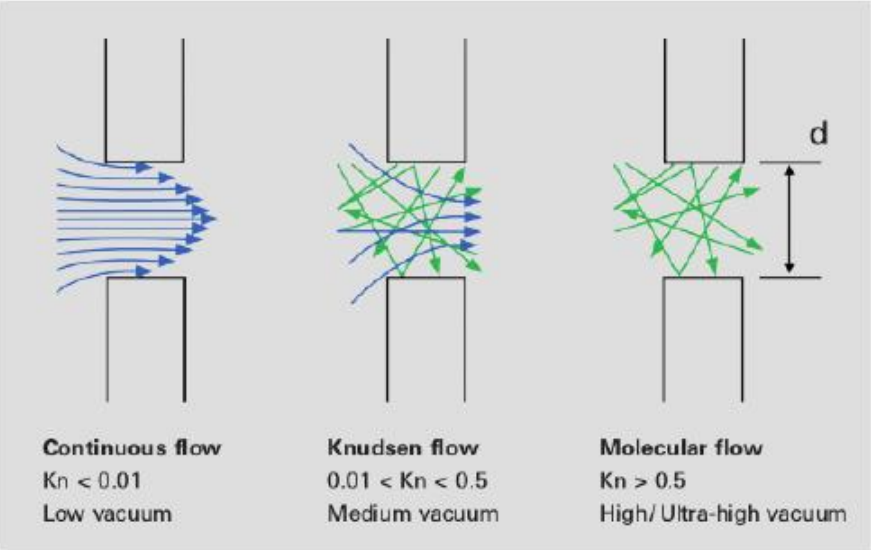
Gas Flow regimes

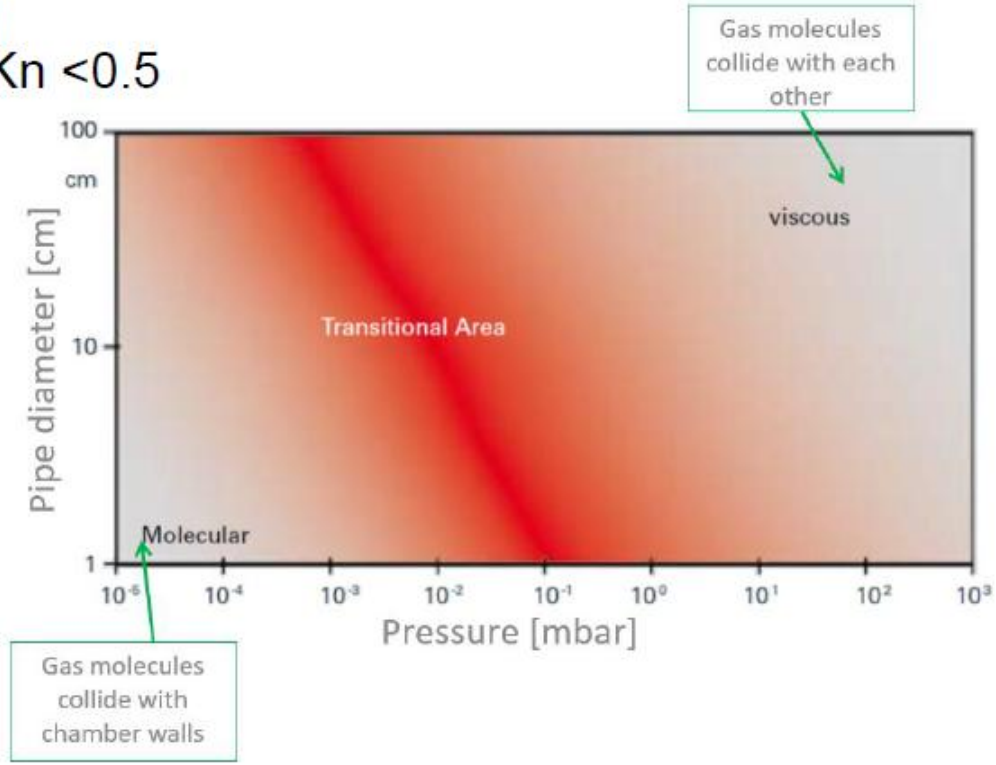
- Knudsen number characterizes the type of gas flow:

$$Kn = \frac{\lambda}{d}$$

d: is the characteristics of the vessel (e.g. chamber diameter))

- Three flow regime:
  - Viscous (continuous) : Kn <0.01
  - Intermediate (Knudsen): 0.01< Kn <0.5
  - Molecular: kn>0.5





Viscous flow *Transition flow*

Gas Throughput

- **The gas throughput defines a gas flow or a pumping speed times the pressure.**

$$Q = \frac{PV}{t} = P \times \frac{V}{t} = PS$$

  - S being defined as the pumping speed (often in l/s)
  - In steady-state or equilibrium conditions, **the throughput is conservative**, the same at one end of a vacuum system as it is at the other

- **Gas Load**
  - The major sources of gas loads in a vacuum system are: leaks, outgassing, contamination and permeation.

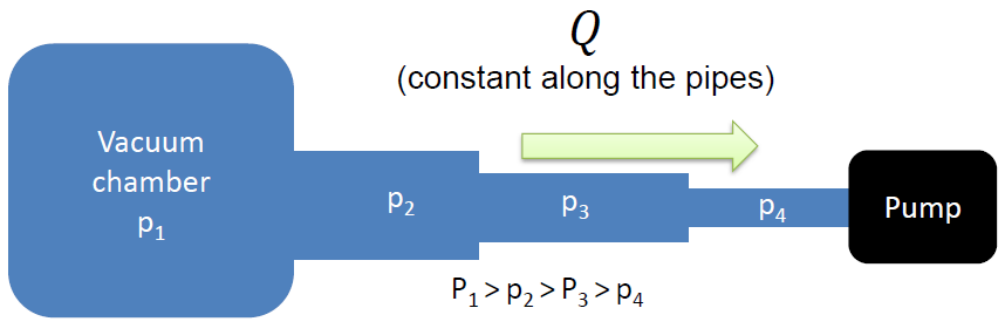
- **Q and Power**
  - The throughput is define as a "work" per unit of time so can be converted in Watts

$$7.50\ torr\ {}^{l}/_{s} = 1\ Watt = 1000\ Pa\ {}^{l}/_{s}$$

Throughput (Q)

- The flow rate as defined earlier could change along the tube, for example at the exit of the flow rate is higher than the beginning as the pressure drops along the tube end.
- Throughput or pV flow:

$$Q = q_{pV} = p.\dot{V} \qquad [Q] = \text{mbar.l·s}^{-1}$$



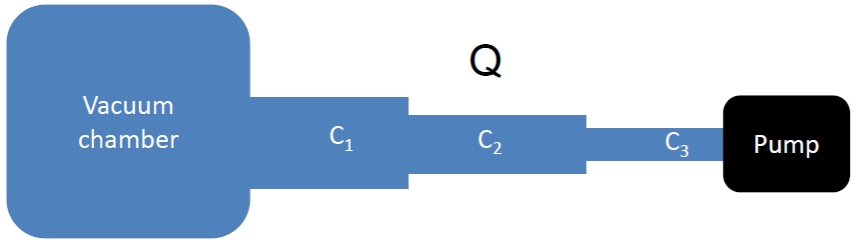
Conductance (C)

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.**
  - Impedance (Z): the gas flow through a pipe with resistance know as impedance (Z).
  - The reciprocal of the impedance is the conductance C [l/s].

$$Q = \frac{(p_1 - p_2)}{Z} = \frac{\Delta p}{Z} = C.\Delta p$$

  - C depends on the temperature, molecules, geometry and pressure (in the viscous regime).



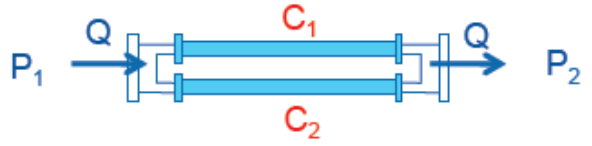
The conductance is defined by the ratio of the molecular flow (Q) to the pressure drop along a vacuum vessel.

- Is a function of the shape of the vessel, the nature of the gas and temperature.

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

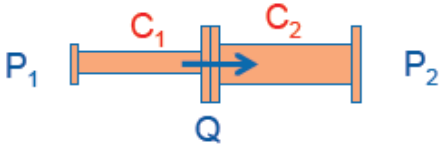
Adding conductance in parallel

$$C = C_1 + C_2$$



Adding conductance in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$



Pumping speed (S)

The pumping speed (S) is the ratio of the flux of molecules pumped (Q) to the pressure (P)

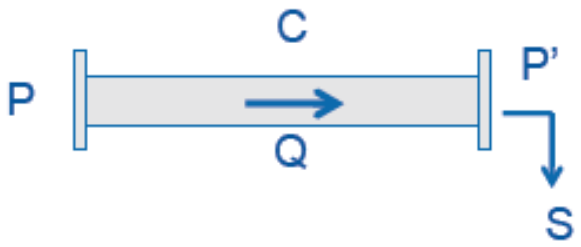
$$S = \frac{Q}{P}$$

Q: l/s, P: mbar.l/s, S: mbar

Coupling of a pump and of a vacuum chamber :

$$\begin{cases} Q = C(P - P') \\ Q = P'S \end{cases}$$

$$\Leftrightarrow S_{eff} = \frac{Q}{P} = \frac{CS}{C+S}$$

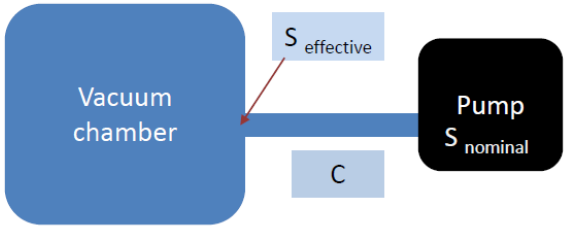


- if C >> S, $S_{eff} \sim S$
- if C << S, $S_{eff} \sim C$

Example :

- Consider a turbomolecular pump of 400 l/s (CHF 15'000) to evacuate a 10 cm diameter tube of 2 m long.
  - S = 400 l/s ; C = 60 l/s so $S_{eff} \sim 50$ l/s … the assembly is conductance limited !
  - Alternative: S = 60 l/s (CHF 5'000) ; C = 60 l/s so $S_{eff} \sim 30$ l/s

The pumping speed at any given point is not larger than the smallest conductance between that point and the pump



$$\frac{1}{S_{effective}} = \frac{1}{C} + \frac{1}{S_{nominl}}$$

- Pumping speed (S): the gas volume flowing through the pump inlet per unit time.

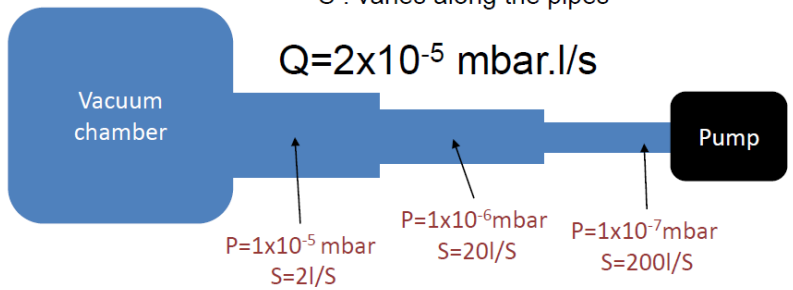
$$S = \dot{V}_{inlet} = q_{V,inlet} \qquad [S]=l/s$$

- The pumping speed relation with the throughput at the entrance of the pump is:

$$Q = p.S$$

Example:

S : varies along the pipes

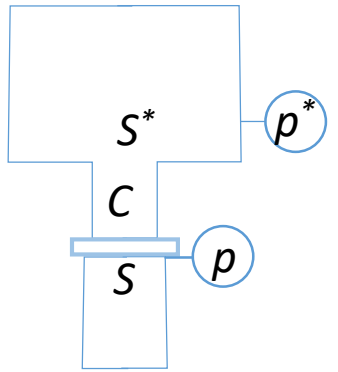


Reduction of pumping speed by connecting pipe

Application of the **combination of conductances in series**.

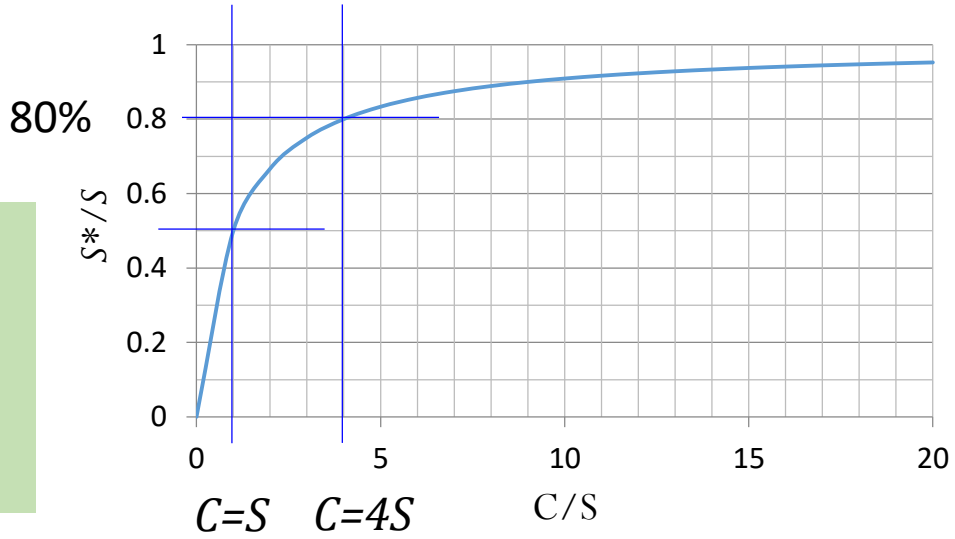
$$Q = C(p^* - p) = S^* \cdot p^* = S \cdot p$$

$$\frac{1}{S^*} = \frac{1}{S} + \frac{1}{C} \quad \text{or} \quad S^* = \frac{S \cdot C}{S + C}$$



S^* effective pumping speed at the chamber
S real pumping speed
p* pressure in the chamber
p pressure at the entrance of the pump
C connecting conductance
Q throughput through the pipe and into the pump

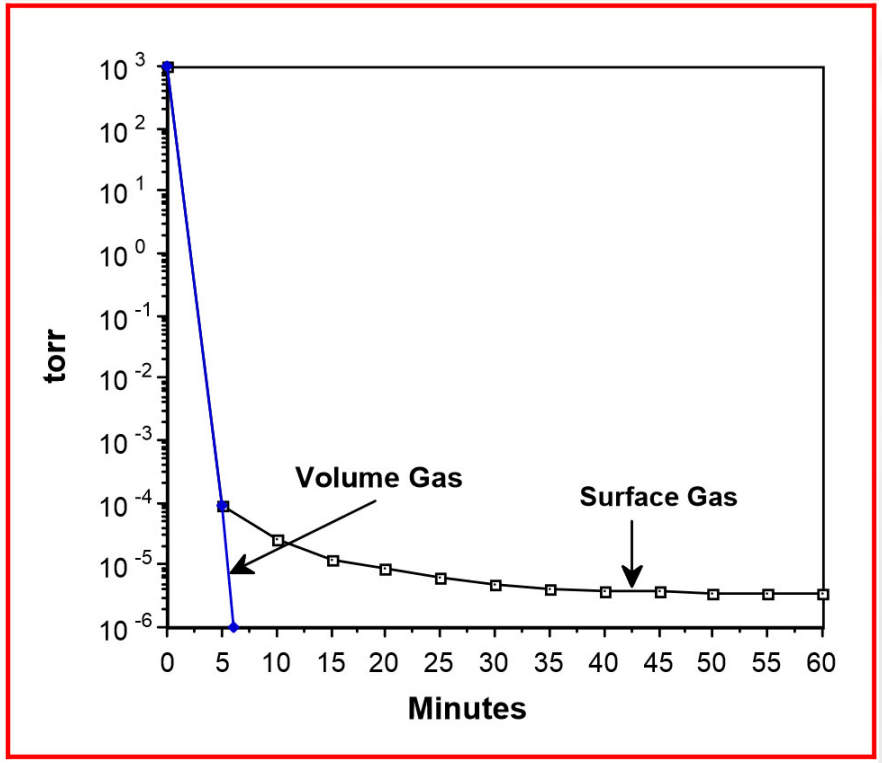
S^* is less than S!
Lets plot S^*/S reduction of pumping speed, against C/S, ratio between conductance and pumping speed

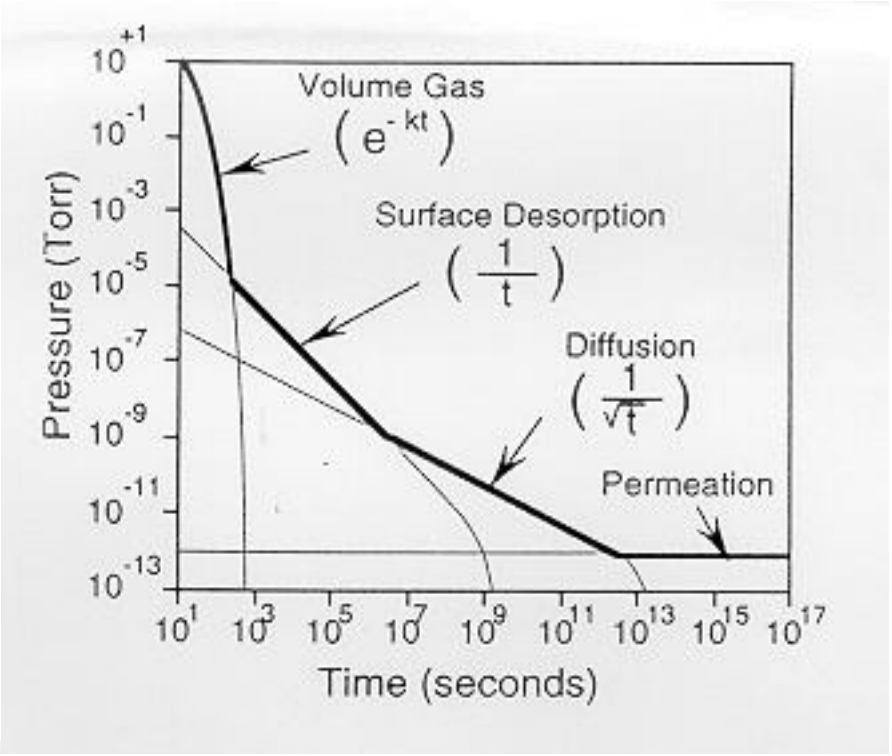


Ex: If the conductance is equal to the pump's speed, we only get 1/2 of it at the vessel. To get 80% pumping speed at the vessel, we need a conductance 4x larger than the pumping speed.

Pump down curve

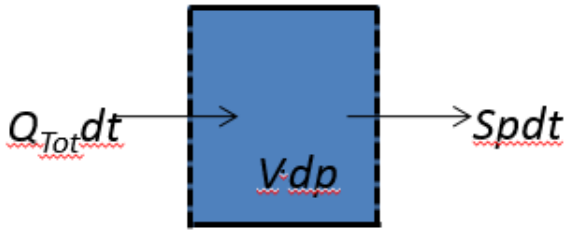
$$-V\left(\frac{dp}{dt}\right) = S \cdot p - Q_{Tot}$$





BASIC EQUATION OF PUMPING – or the Continuity Equation

$$V \cdot dp = Q_{Tot} \cdot dt - S \cdot p \cdot dt$$



The difference between the quantity of gas entering the volume and the one leaving it in a small interval of time *dt* is equal to the net **change** in the quantity of gas in the volume *V*, d(pV)=*V*·*dp*

To go deeper:

For conserved quantities:
«Everything which enters a volume ***minus*** everything which leaves it, ***equals*** the net increase in the quantity in the volume»

Pumpdown: initial phase

$$V\left(\frac{dp}{dt}\right) = \cancel{Q_{Tot}} - S \cdot p \rightarrow Q_{pumped}$$

Initially, the pumpdown process is dominated by evacuation of the free gas in the volume. Let's write $Q_{tot}=0$ and let's call $p_{initial}(t)$ the pressure decrease curve in the initial phase of pumpdown.

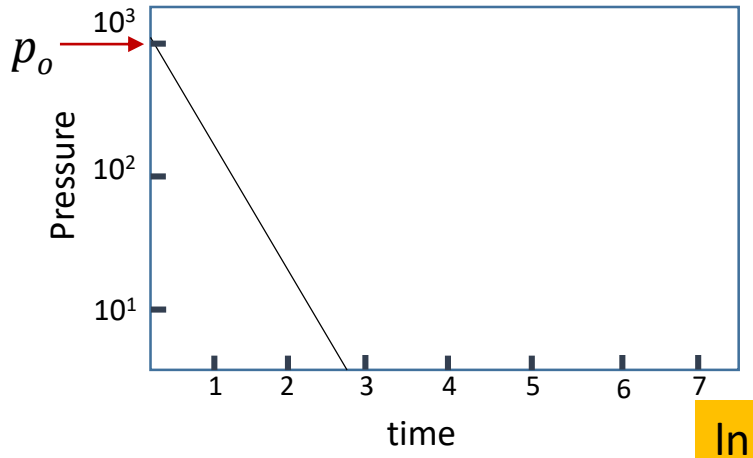
Gas quantity present in the volume (p V) decreases while gas is evacuated by the pump.

$$V\frac{dp}{dt} = -Sp$$

Volume depletion $$\ln p_{initial} = \ln p_o - \frac{S}{V}t$$

$$p_{initial} = p_o e^{-\frac{S}{V}t} = p_o e^{-t/\tau}$$

$$\tau = \frac{V}{S}$$ Characteristic time or time constant



ln p versus t

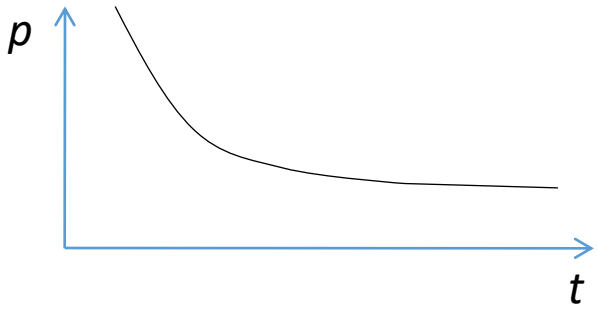
Remember maths! A function which changes with a rate proportional to the function itself is an exponential…

Pumpdown: when outgassing dominates

$$-V\left(\frac{dp}{dt}\right) = Sp - Q_{out}$$

When pressure ceases to fall and becomes constant on the time scale of observation, $dp/dt=0$.
The equation becomes:

$$p_{ultimate} = \frac{Q_{out}}{S}$$



We write $p_{ultimate}$ because this pressure won't decrease on the time scale of observation (ex. 1h)

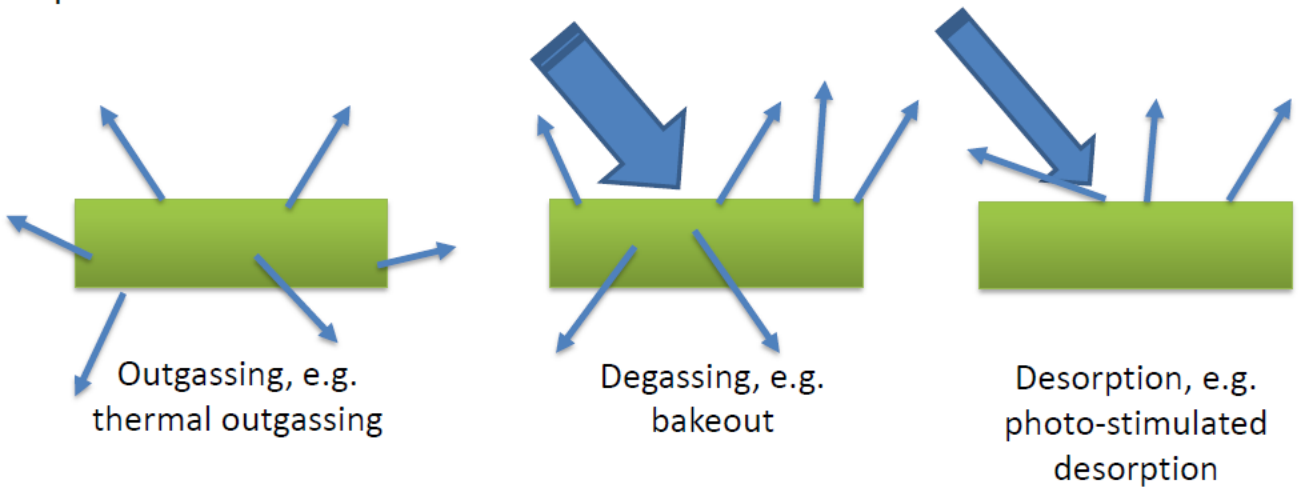
Actually, it decreases, because Q_{out} decreases, but this process is much slower.
The walls of the vessel get progressively emptied from their initial gas contents and gas release to the free volume decreases.

$$p_{ultimate}(t) = \frac{k}{t^n} \quad \Rightarrow \quad Q_{out}(t) = A\frac{\varphi}{t^n} = A\frac{\varphi_{1h}}{t^n}$$

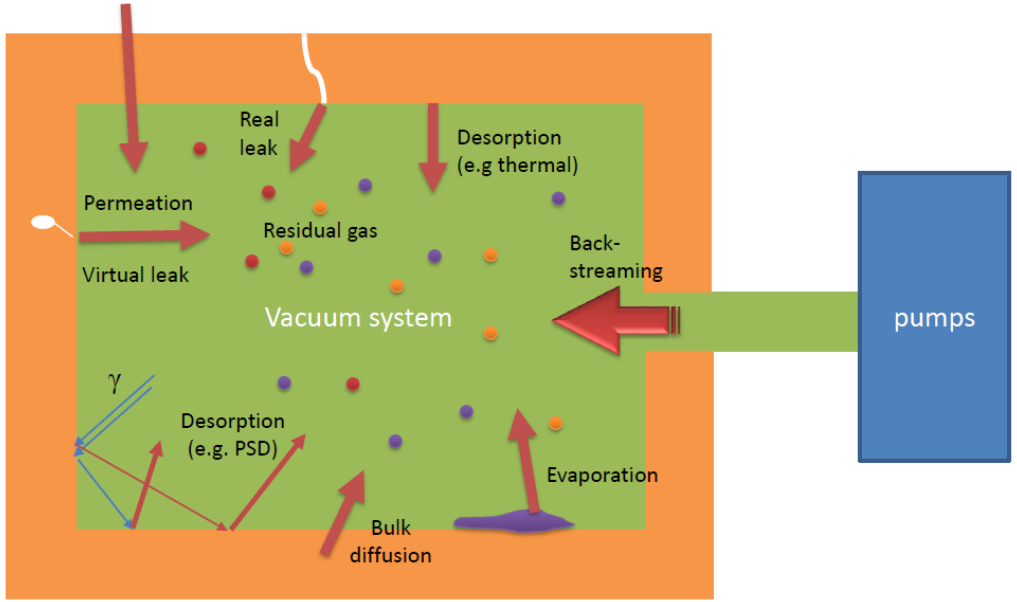
For unbaked metals of standard rugosity, $n=1$, $\varphi_{1h} \approx 3\cdot10^5 \frac{\text{mbar}\cdot\text{l}}{\text{m}^2}$ $Q(t) = \frac{3\cdot10^{-5}}{t[h]}\left[\frac{\text{mbar}\cdot\text{l}}{\text{s}\cdot\text{cm}^2}\right]$

Introduction to the gas sources in accelerators

- Definitions:
  - Outgassing: spontaneous release of the gas from solid or liquid
  - Degassing: deliberate removal of the gas from solid or liquid
  - Desorption: release of adsorbed species from the surface of a solid or liquid.



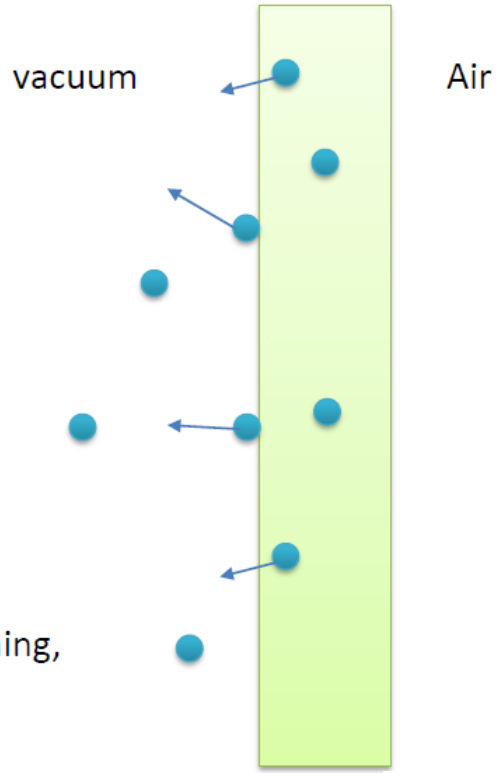
Gas sources



Gas sources in accelerator

Thermal outgassing occurs when:

- Molecules diffusing through the bulk material of a vacuum chamber, entering the surface and desorbing from it.
- Molecules which have been adsorbed previously, usually during venting of the vacuum chamber, that desorb again, when the chamber is pumped to vacuum



- Thermal outgassing depends on: material, cleaning, history, treatments, pump down time,… etc

Thermal outgassing: example of outgassing rates after one hour in vacuum at room temperature:

Material	K_1 (mbar l s^{-1} cm^{-2})
Aluminium (fresh)	9×10^{-9}
Aluminium (20 h at 100 °C)	5×10^{-14}
Stainless steel (304)	2×10^{-8}
Stainless steel (304, electropolished)	6×10^{-9}
Stainless steel (304, mechanically polished)	2×10^{-9}
Stainless steel (304, electropolished, 30 h at 250 °C)	4×10^{-12}
Perbunan	5×10^{-6}
Pyrex	1×10^{-8}
Teflon	8×10^{-8}
Viton A (fresh)	2×10^{-6}

Beam induced desorption (BID): outgassing stimulated by photons, ion or electrons created by high energy, high intensity beams.

Beam stimulated desorption is characterised by η - the desorption yield:

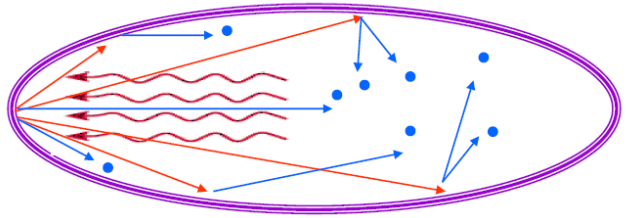
$$\eta = \frac{number\ of\ desorbed\ molecules}{number\ of\ particle\ impinging\ the\ surface}$$

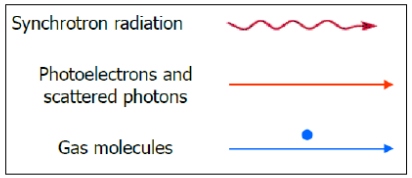
η – depends on many parameters:

- incident particle: type and energy,
- material,
- surface roughness,
- cleanliness of the surface,
- history of the material.
- Temperature.
- Integrated dose
- Particle flux.

Gas sources in accelerator

Photon-stimulated desorption (PSD)





When photoelectrons arrive or leave the surface, they desorb the gases from the surface.

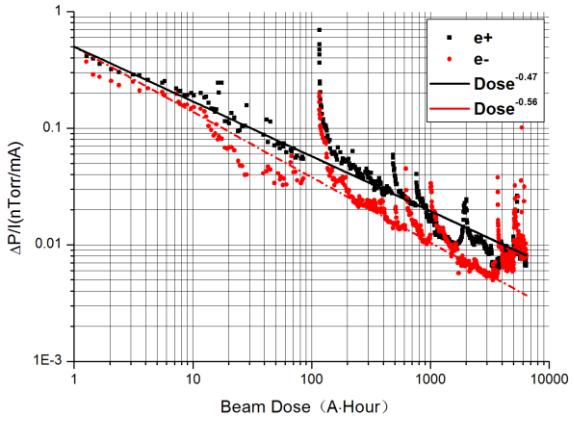
Photon-stimulated desorption (PSD)

Conditioning is the process of which reduction of the BID yield (η) with the accumulated dose (D_i) of the particles:

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

$$Q = Q_{PSD} + Q_{thermal}$$

Q_{PSD} =24.2 EIη
E-Beam Energy[GeV]
I-Beam Current[A]
η-Desorption Yield

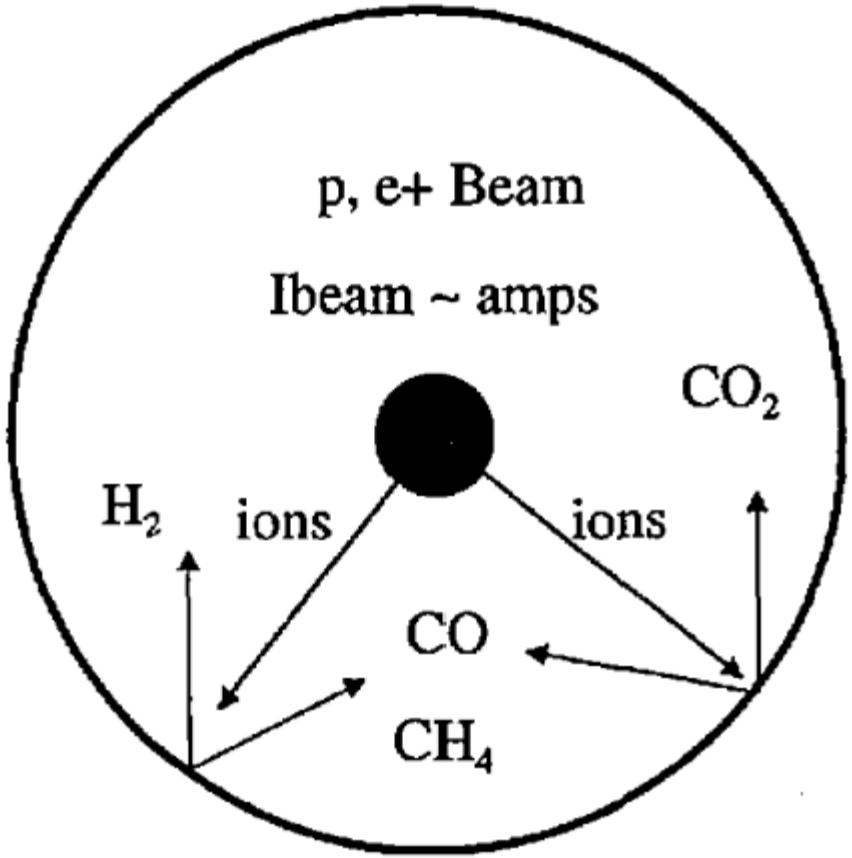


Ion induced desorption:

In positively charged rings, the created ions from the residual gas are repelled from the positive beam to the walls.
Ions can gain energies which are effective in desorbing the molecules bounded to the chamber walls, as there is more gas more ionization occurs, resulting a continues increase in the pressure.

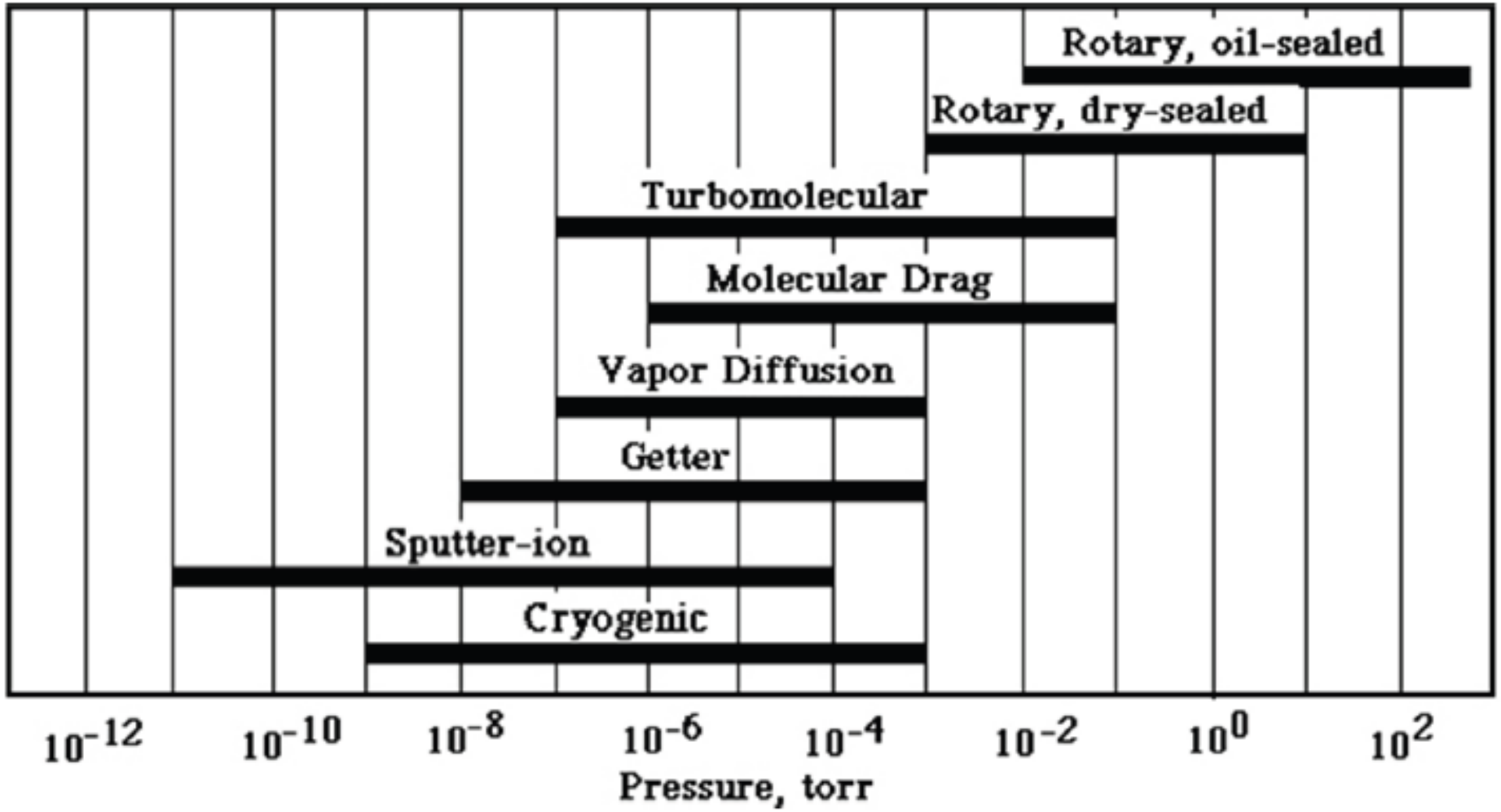
$$Q = \eta\sigma p\frac{I}{e} + Q_{thermal}$$

- η: the molecular desorption yield (molecules/ion).
- σ the ionization cross section of the residual gas molecules
- p: pressure
- I: average beam current
- e: the unit charge.
- $Q_{thermal}$: thermal outgassing



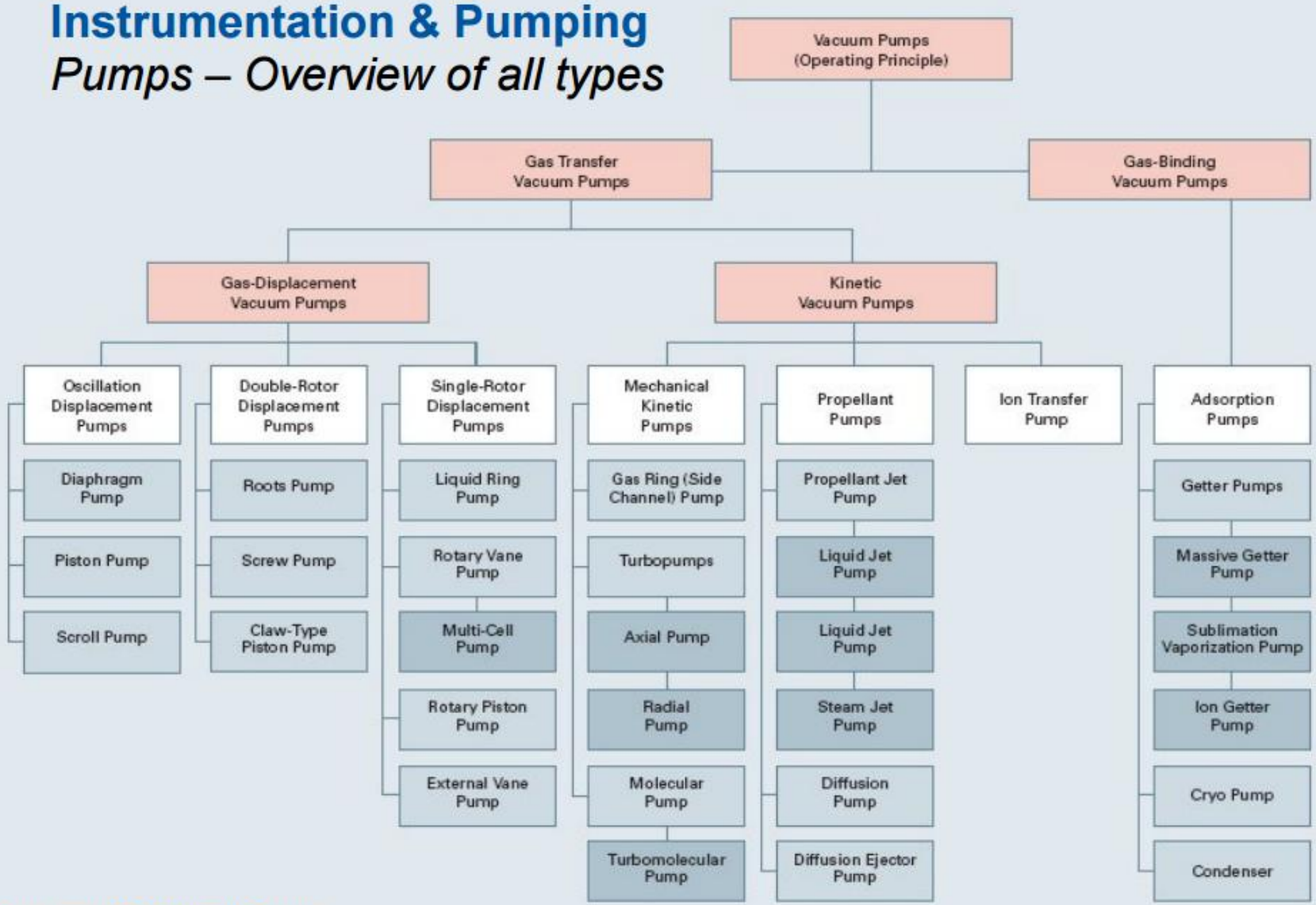
Pumping & Instrumentation

Useful range of standard pumps



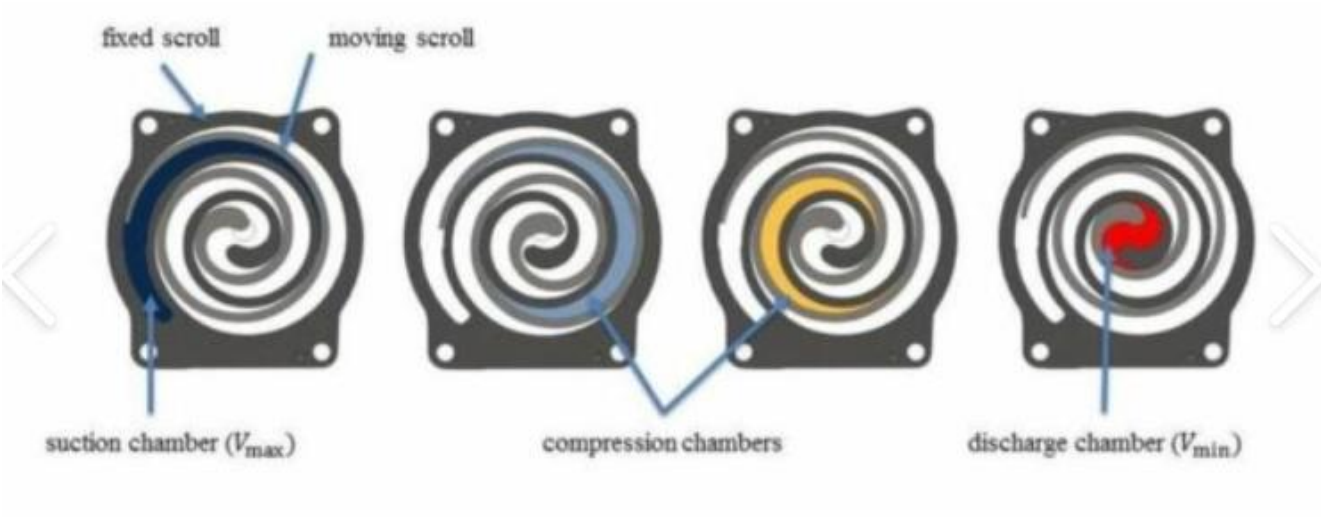
Instrumentation & Pumping

Pumps – Overview of all types



Courtesy of Pfeiffer Vacuum
www.pfeiffer-vacuum.com/know-how/

Gas-Displacement Vacuum Pumps:

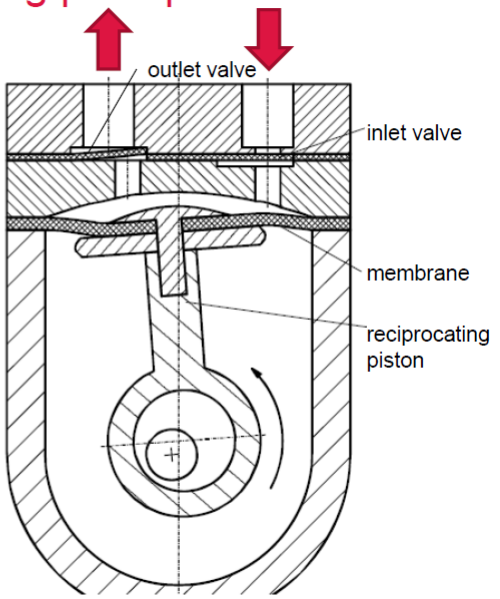


Scroll Dry Pump

Membrane pumps – working principle

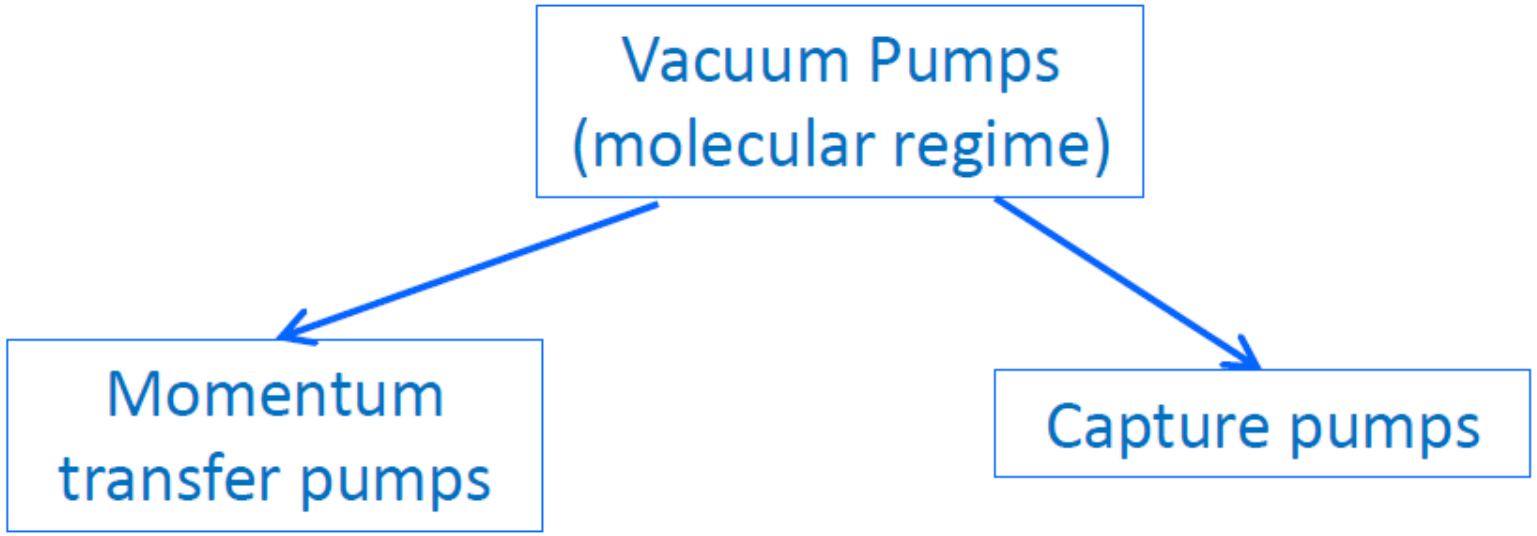
- Membrane is moved back and forth by means of a reciprocating piston drive
- Working principle
  - During the suction step the membrane fills the pump room with gas. The exhaust valve is closed
  - During the exhaust step the membrane compresses the gas towards atmosphere. The inlet valve is closed

Animation_Membranpumpe.mp4



Diaphragm(Membrane) Pump

Pumps used in the accelerator vacuum system



Example: Turbomolecular Pump

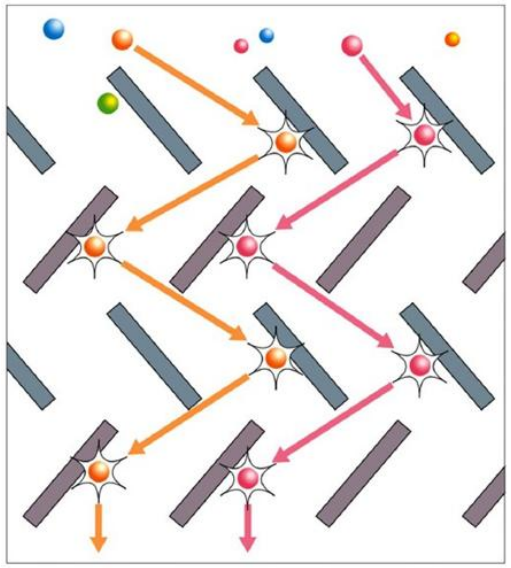
Gas is transmitted as momentum is transferred to the gas molecules thereby achieving a directed movement.

The momentum transfer take place through a quickly turning blades of a turning rotor.

Example: Sputter Ion Pump, Getter pump, Cryo pump

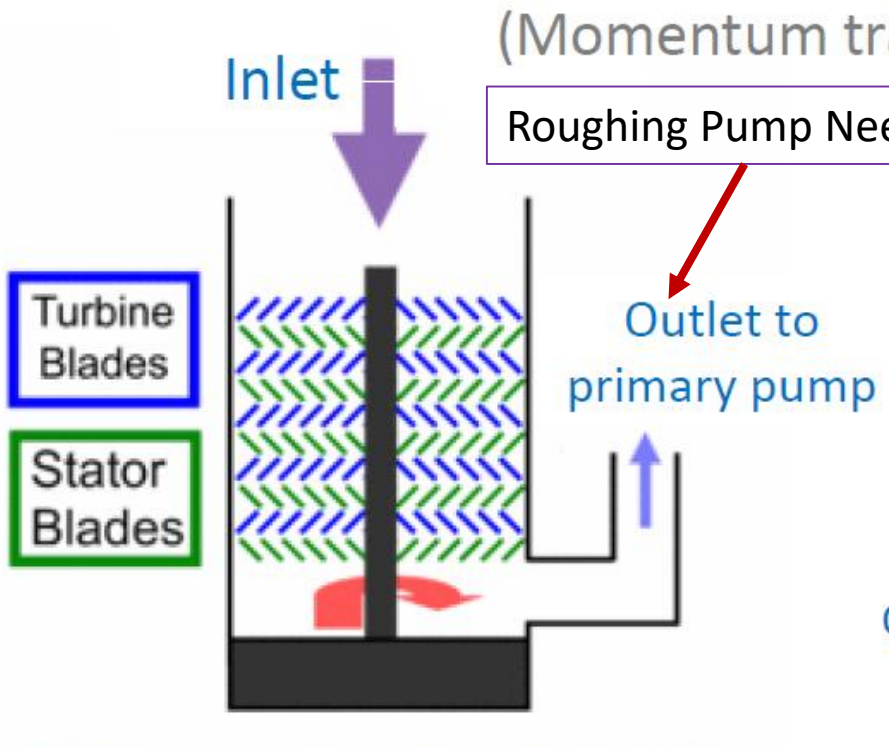
Principle: gas molecules are fixed to a surface inside the wall of the pump.

Turbomoleucular Pump



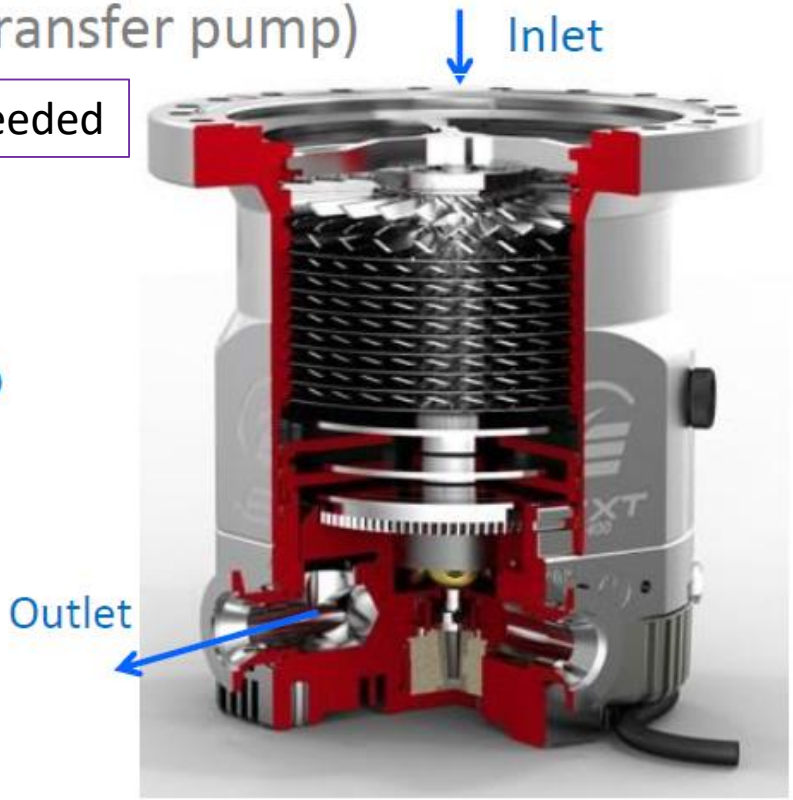
Turbomolecular pumps are widely used in particle accelerators for:

- evacuating vacuum systems from atmospheric to ultra high vacuum,
- Testing (leak tests),
- Conditioning (bakeouts),
- High gas loads,
- For accelerator operation with beam capture pumps take over,



Blade rotational speed 1000 – 1500 Hz

Pressure range: 10^{-1} till 10^{-10} mbar,
(with backing pump connected in series).
Usual operational pressure < 10^{-5} mbar.



S (pumping speed) does not depend significantly on the mass of the molecule.

(compression ratio) $K_o = \frac{P_{outlet}}{P_{inlet}}$

depends exponentially on the wall speed and square root of the gas molecule mass.

Capture Pumps

Capture pumps are vacuum pump in which the molecules are retained by sorption; chemical combination or condensation on internal surfaces within the pump. store gases that are pumped

•Sputter ion pumps.

•sublimating the reactive metal *in situ:* evaporable getters or sublimation pumps,

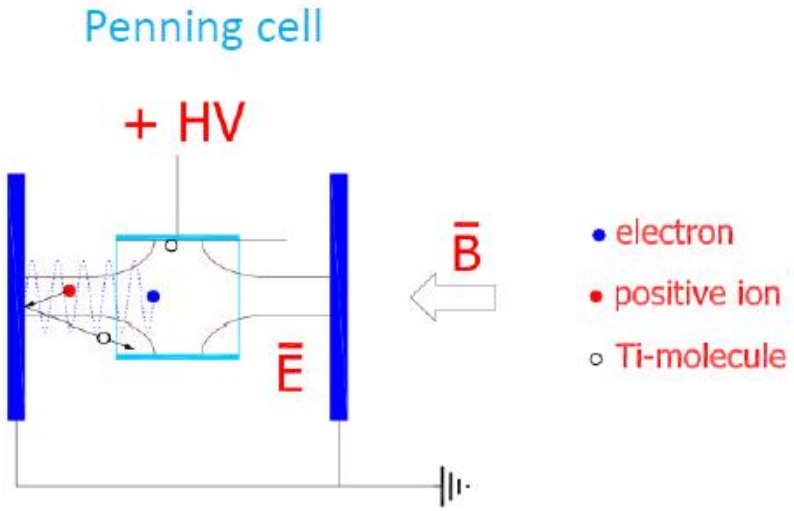
•dissolving the surface contamination into the bulk of the getter material by heating: non-evaporable getters (NEG); the dissolution process is called activation.

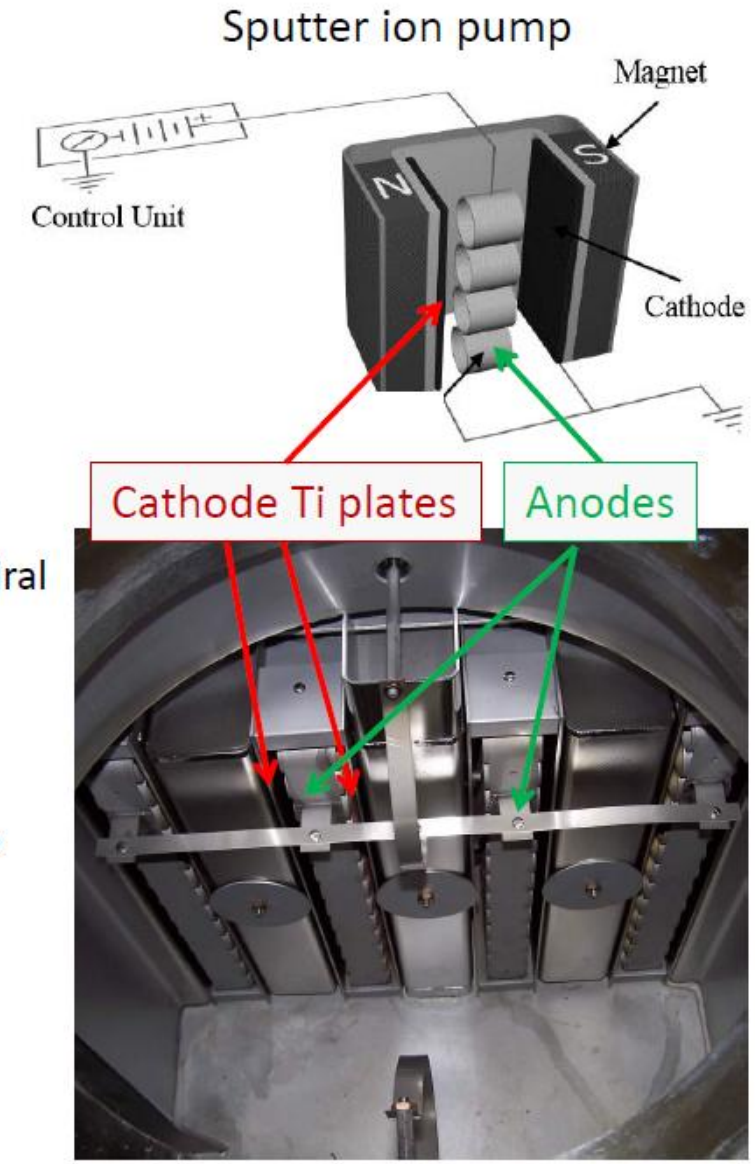
SIP

TSP

NEG

Sputter Ion Pump(SIP)





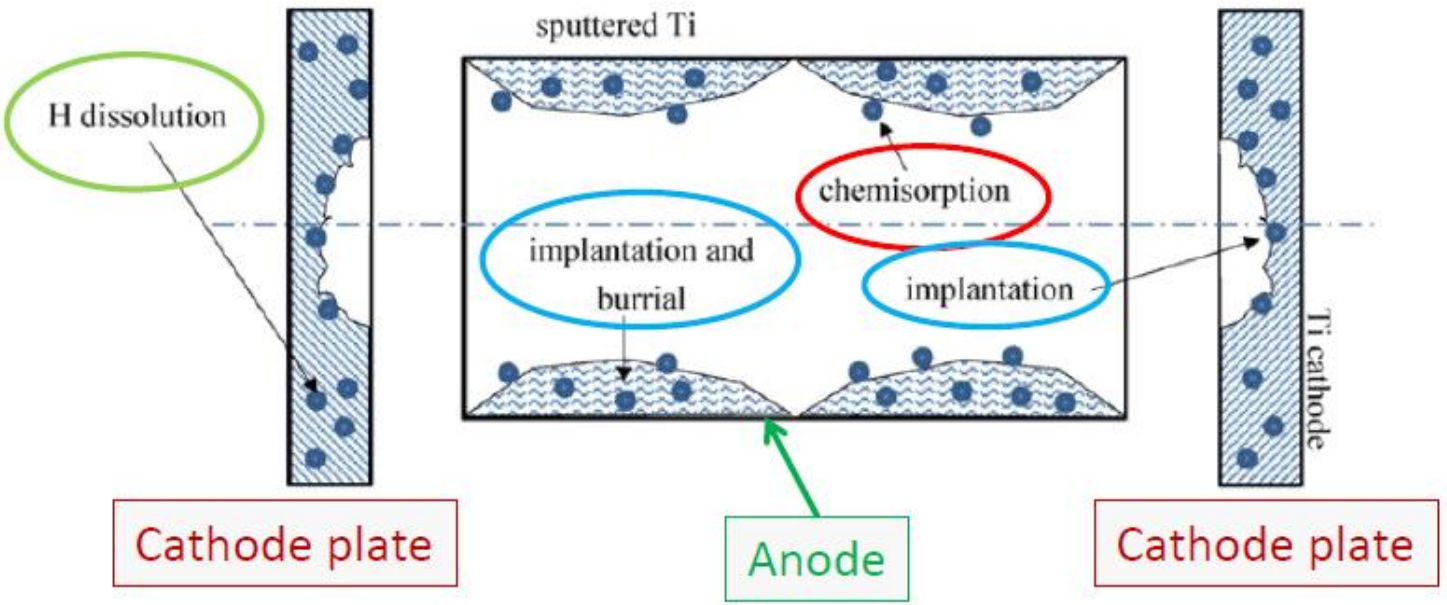
- The high magnetic field cause the electrons to go into spiral paths (preventing them from reaching to the anode).
- While this the electrons strike the molecules and ionize them.
- Ions forced toward the cathode at high velocity.
- Ions strike the cathode and impact case sputtering of the cathode material.
- The cathode material will cover the internal walls of the pump.
- The ions are chemically and physically reacts with the cathode material.

SIP pumping mechanisms

Sputter ion pumps has three pumping mechanisms:

- **Chemical adsorption onto the reactive metal layer (Ti) deposited on anode** and subsequent burial by additional metallic atoms of gas molecules: all gases except rare gases,
- **Implantation of gas ions in the cathode** (not permanent), and of energetic neutrals bounced back from the cathode in **the deposited film**: only mechanism of pumping for rare (noble) gases,
- **Diffusion** into the cathode and the deposited film: only H_2

Diode configuration (cell cross-section)

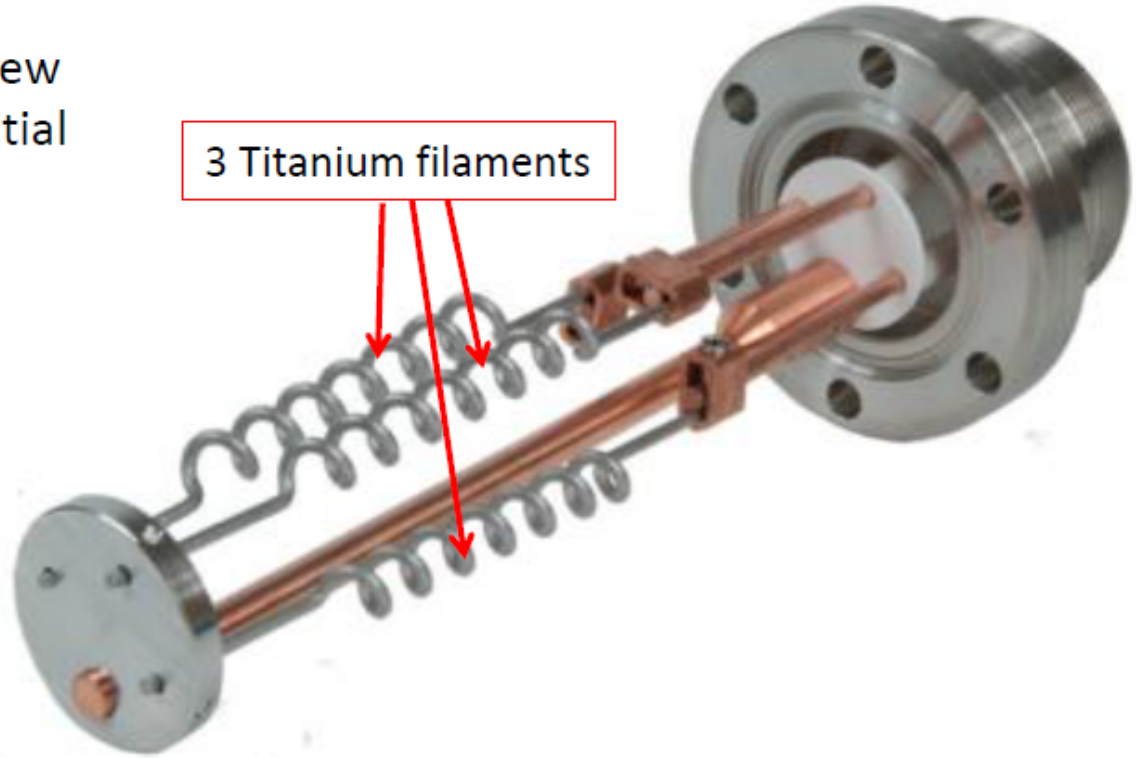


Evaporable Getters

Evaporable getters: TSP – Titanium Sublimation Pump

Ti is the **sublimated** metal. Ti filaments are heated up to 1500°C reaching Ti vapor pressure which is deposited on the surrounding surfaces creating a chemically active surface where gas molecules are captured.

When the deposited film is saturated, new sublimation is needed to recover the initial pumping speed.



Sticking probablities:

H_2: $0.01 \leq \alpha \leq 0.1$

CO: $0.5 \leq \alpha \leq 1$

Film capacity:

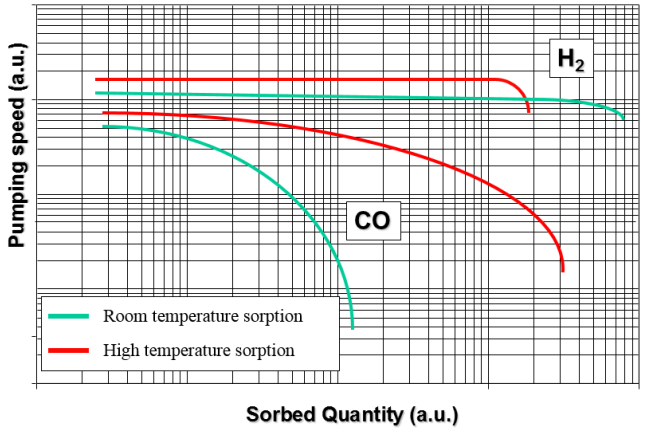
- For CO, one monolayer adsorbed,
- For of O_2 several monolayers,
- For N_2 fraction of monolayer

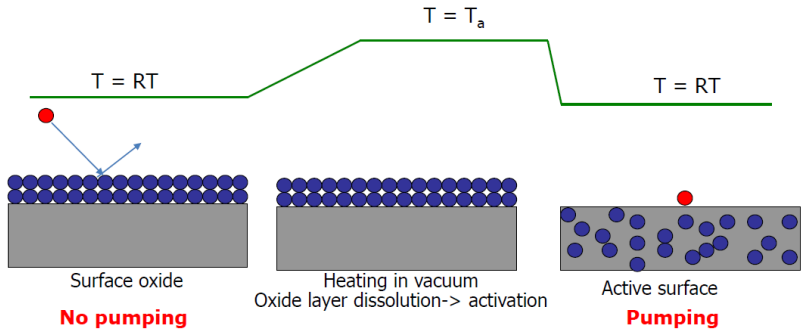
Hydrogen diffuses in the Ti film → much higher capacity

NEG: Non-Evaporable Getters

- NEG pumps sorb gases by a chemical reaction. They use very reactive alloys, generally made of Ti, Zr, which are configured in a high efficiency getter cartridge structure.
- Pumping of the different gases:
  - Active gases, like O_2, N_2, H_2O, CO, CO_2 impinging on the cartridge surface are dissociated and permanently trapped, in the form of stable chemical compounds.
  - Hydrogen is very effectively pumped by the NEG. hydrogen atoms diffuse inside the getter bulk and dissolve as a solid solution.
  - Noble gases (and CH_4 at room temperature) are not pumped

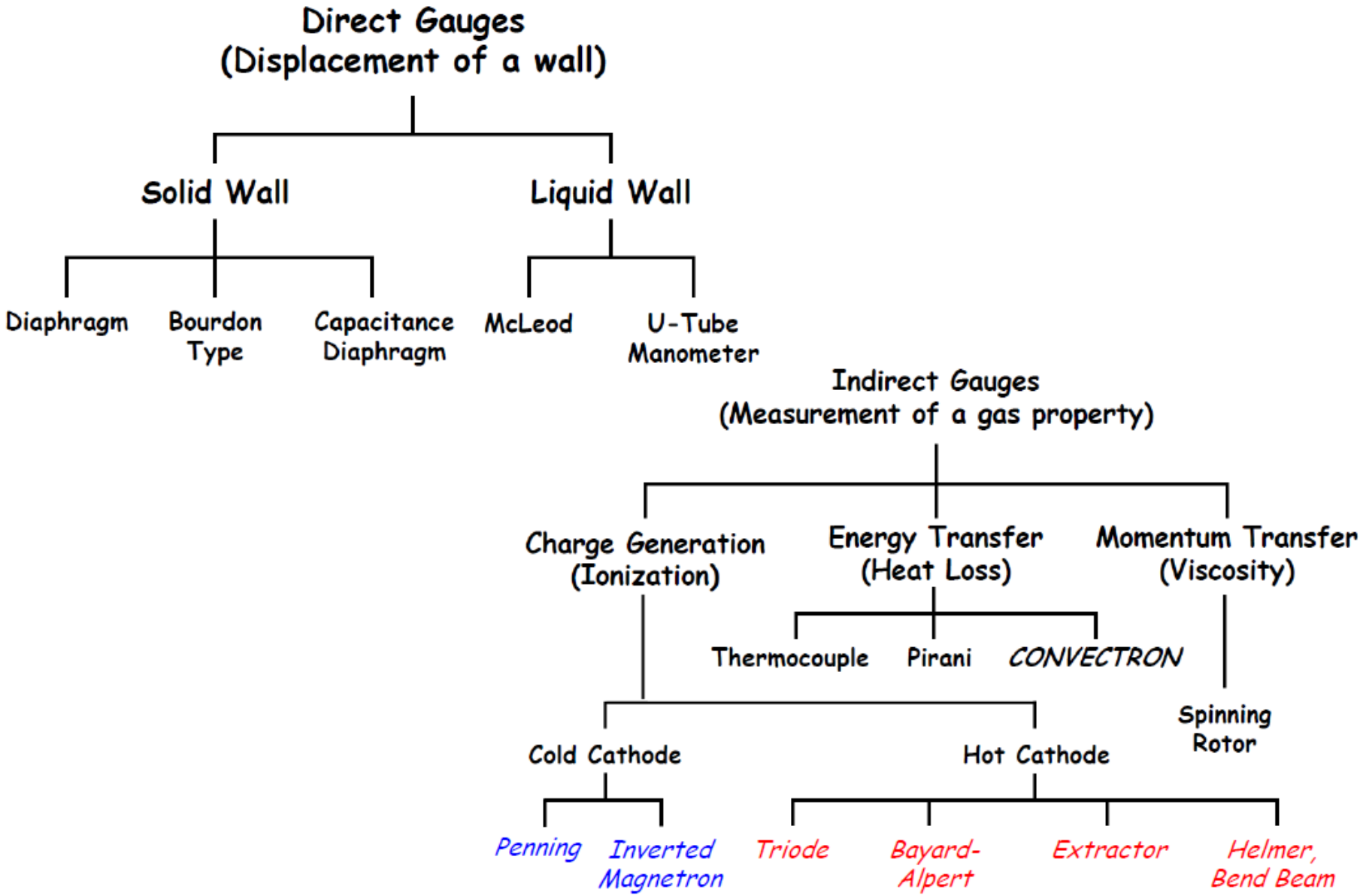
Typical sorption curves for NEGs





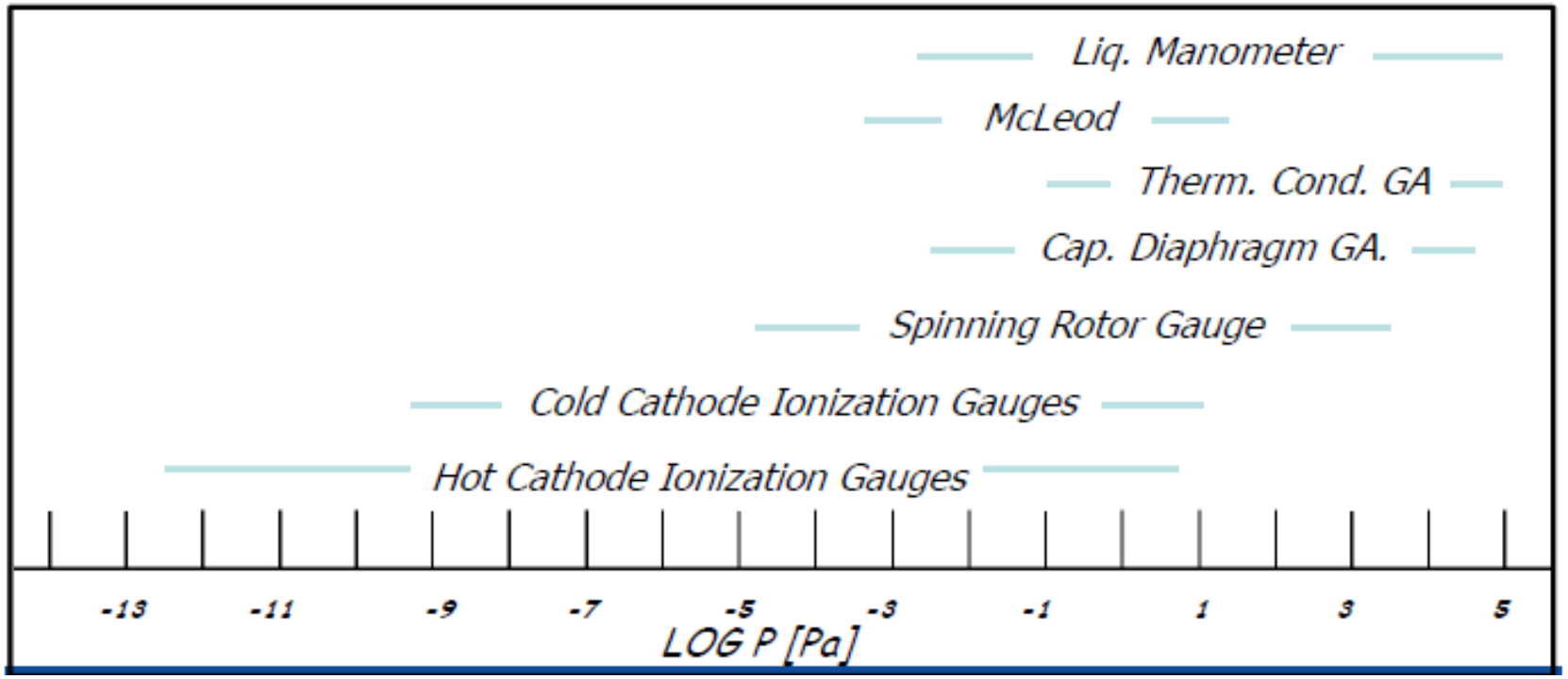
On activation the oxide layer at the surface of NEG is diffused to the bulk of the material creating clean, chemically active surface where gas molecules are captured.

Direct and Indirect Gauges at a Glance



Vacuum Pressure Ranges

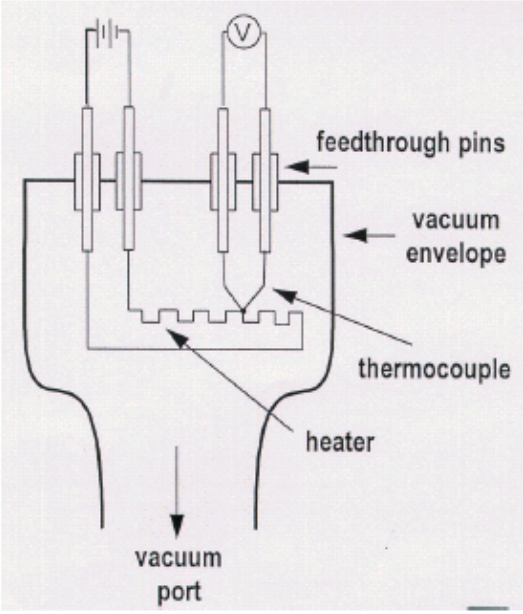
- *In today's scientific research and industrial processes, vacuum measurements cover over 17 decades of range, from atmospheric pressure (10^{5} Pa) down to 10^{-12} Pa.*
- *For most applications, a combination of multiple types of gauges is needed .*



Vacuum Pressure Ranges-Low to Medium vacuum

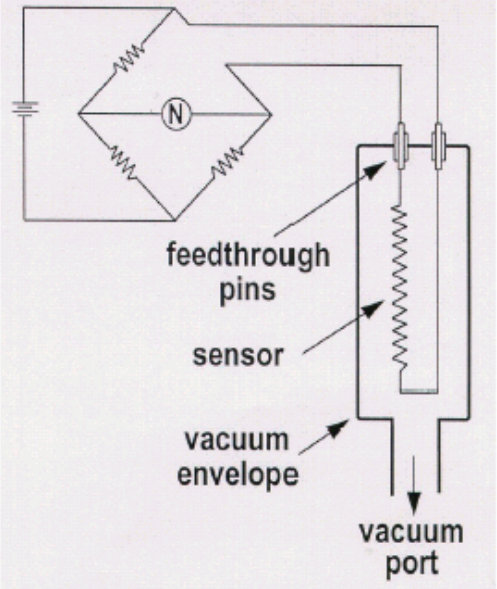
Thermocouple Gauges

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



Pirani Gauge

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

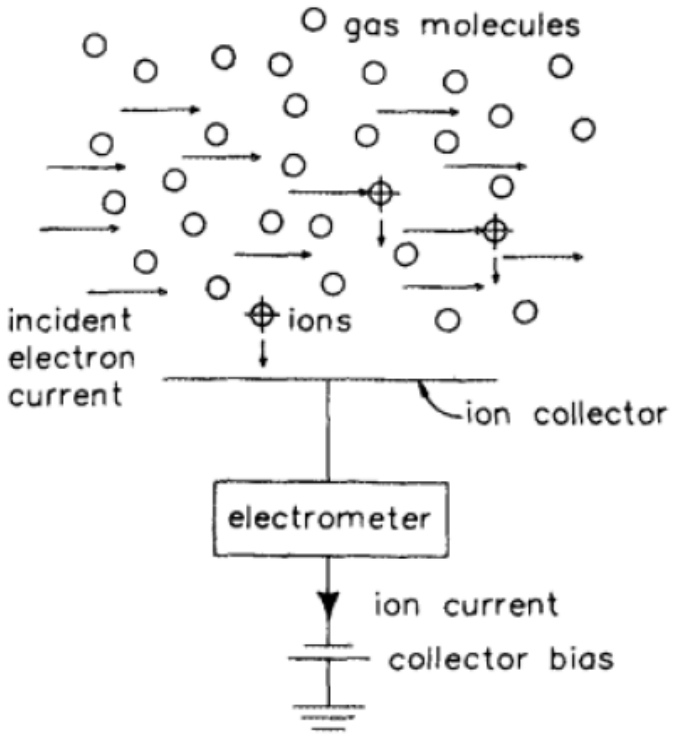


Vacuum Pressure Ranges-High to Ultra-high vacuum

Ionization Gauges – General

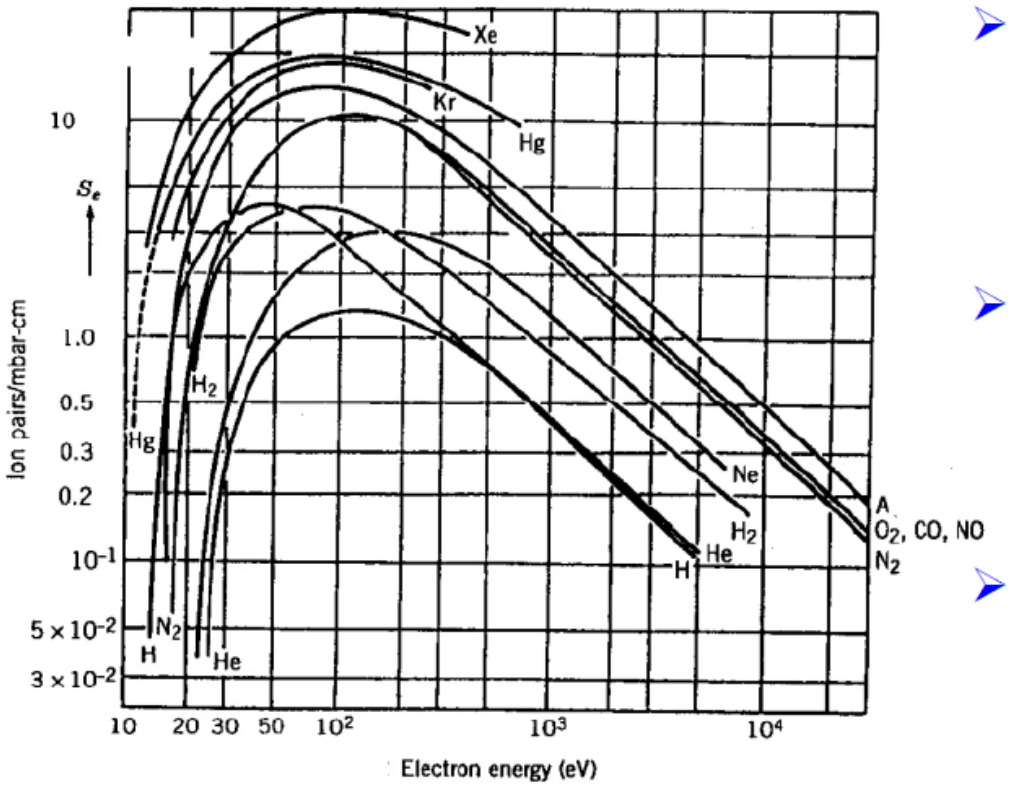
- *At pressures below 10^{-5} Torr (high vacuum) direct measurement of pressure is very difficult*
- *Thermal conductivity gauges have exceeded their operational limits*
- *Primary method for pressure measurement from 10^{-4} to 10^{-12} Torr is gas ionization & ion collection/measurement*
- *These gauges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

Ionization Gauges – Principle



- *Gas atoms and molecules are normally without charge or "**neutral**", they have equal numbers of protons and electrons*
- *The neutrals may be 'ionized' via electron impact, to form **ions**.*
- *Ions, being positively charged and heavy, can be manipulated by magnetic and electrical fields.*
- *The ionization rate (or the measured ion current) is usually proportional to the gas density, the base for the ion gauges.*
- *An atom has a probability of being ionized that is dependent on the atom itself and the energy of the colliding electron. Thus the ion gauges are gas type dependent.*

Electron Impact Ionization

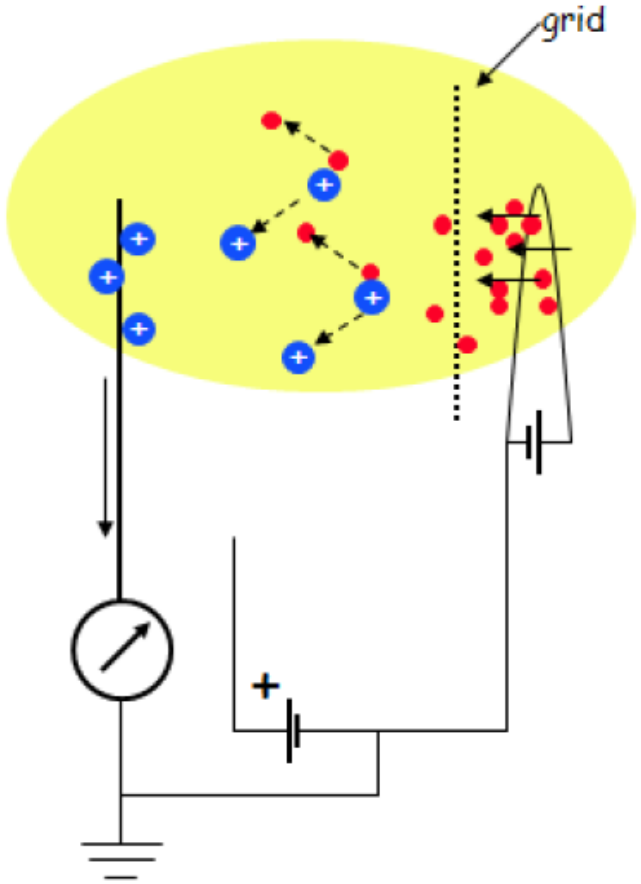


Ions per centimeter electron path length per mbar at 20C versus energy of incident electrons for various gases

- *Electron impact ionization rate peaks at electron kinetic energy 50~200 eV for more gases.*
- *For hot filament gauges, electrons are emitted thermionically, and accelerated by an electric field.*
- *For cold cathode gauges, electrons are initiated by field-emission (or radiations), then trapped/amplified in a cross-field (electric and magnetic fields)*

Hot Cathode Ionization Gauge –Principle

- *Hot filament (cathode) emits electrons.*
- *Electrons collide with molecules and create positive ions*
- *The positive ions that are created inside the grid volume are attracted to the collector and measured as ion current.*
- *The gauge controller electronics converts the collector ion current to a pressure reading.*



HC Ionization Gauge – Sensitivity

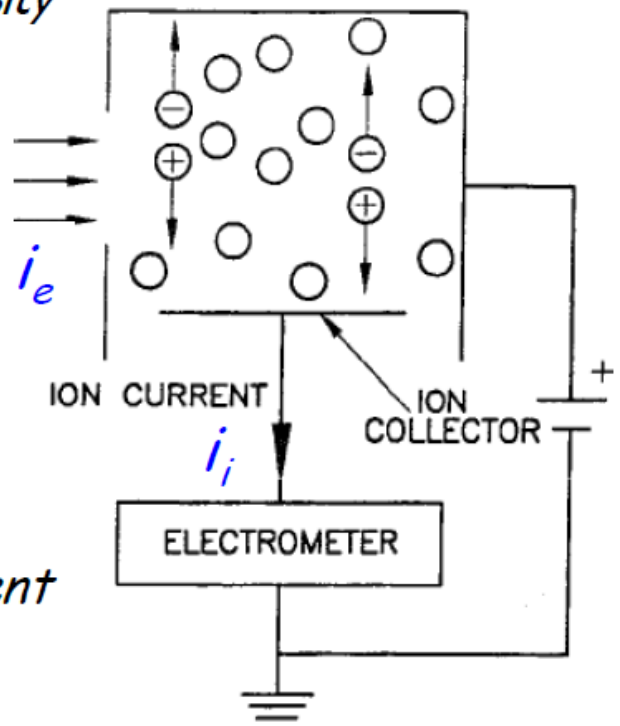
- *For an electron beam with a path length L, the ionization yield (ions generated per electron) is:*

$$nL\sigma_i = \frac{\sigma_i L}{kT} P$$

σ_i – ionization cross section
n=P/kT is molecular density

- *If the electron current (emission current) is i_e, the total ion current:*

$$i_i = \frac{\sigma_i \cdot L}{kT} \cdot i_e \cdot P = K \cdot i_e \cdot P = S \cdot P$$



$$K = \frac{\sigma_i \cdot L}{kT} = \frac{i_i}{i_e} \cdot \frac{1}{P}$$ *known as gauge coefficient*

$S = K \cdot i_e$ *is known as gauge sensitivity*

HC Ionization Gauge – Relative Sensitivity

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

$$P_{Gas} = P_{Gauge}^{N_2} \Big/ S_{Gas}$$

HC Ionization Gauge – Limitations

- *For all HC ion gauges, the detected ion current always consists of a pressure dependent value, and a residual signal (i_r) that is not related to gas pressure.*

$$i_i = K \cdot i_e \cdot P + i_r$$

- *The residual signal (i_r) sets the lowest measurable pressure by a HC gauge.*

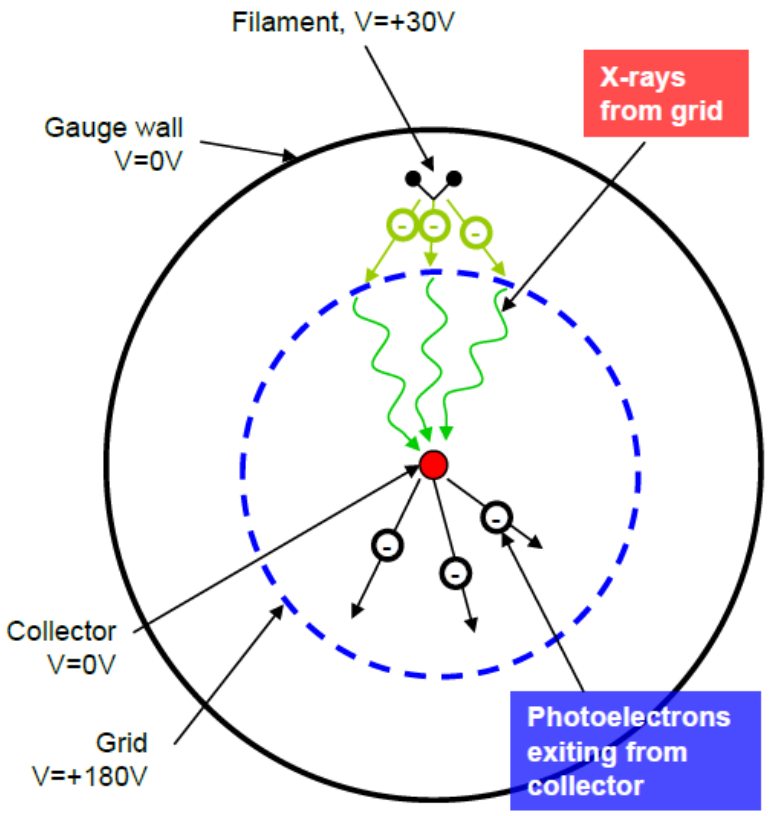
- *There are two major sources of the residual current:*

  → *Soft X-ray induced current*

  → *Electron Stimulated Desorption (ESD)*

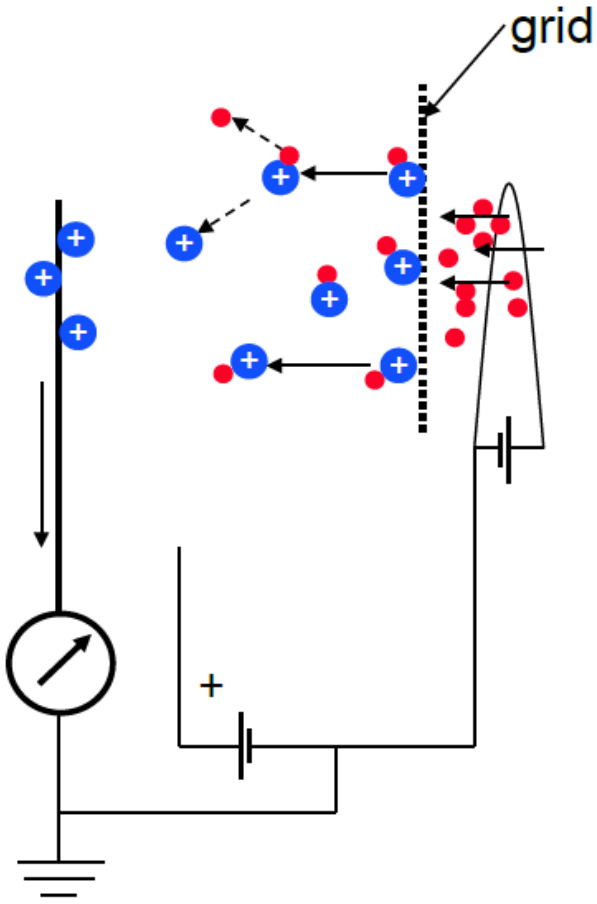
HC Ionization Gauge – Soft X-Ray Limit

- *Some electrons emitted from the hot cathode impact the grid and produce x-rays.*
- *Some of the x-rays impact the collector and produce photoelectrons.*
- *The exiting photoelectrons simulate positive ions arriving at the collector.*
- *The photoelectron current adds to the ion current producing an error in the pressure reading.*
- *Historic triode vacuum gauges had X-ray limit of 10^{-7} Pa. Modern HC gauges use much smaller anode to lower the limit below 10^{-9} Pa.*



Electron Stimulated Desorption in HC Gauges

- *Gas molecules are adsorbed on the surface of the grid.*
- *Electrons emitted from the cathode strike the grid and desorb the gas molecules.*
- *The electrons also ionize some of the gas molecules on the grid when they are desorbed.*
- *The additional gas molecules and positive ions contribute to an increase in the gauge pressure reading.*



Cold Cathode Gauges

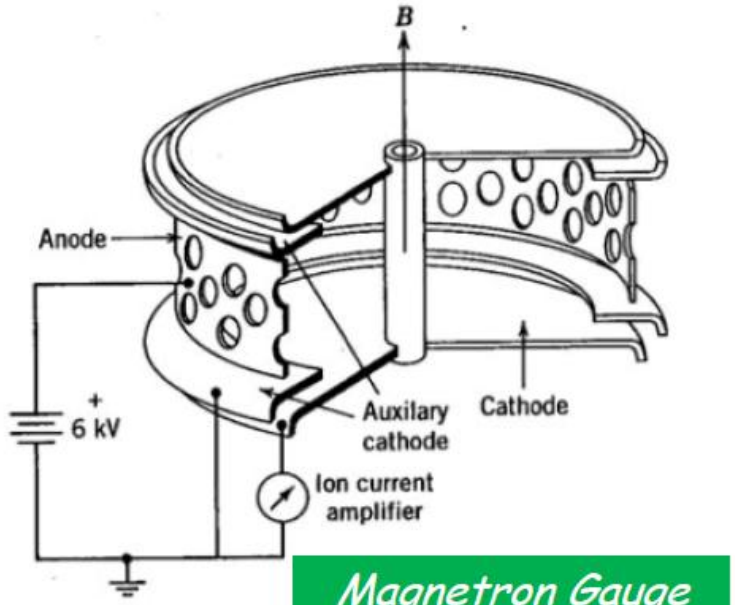
- *With a DC high voltage between a pair of electrodes in vacuum, discharge occurs. The discharge current depends on the pressure (non-linearly). However, the sustainable discharge stops around 1 Pa.*
- *In CCGs, a magnetic field is added, with the B-field 'perpendicular' to the E-field (thus the cross-field). A electron 'cloud' is created by trapping electrons in the cross-field volume. Electrons gain energy through cyclic motions in the cross-field.*
- *Ionization of gas molecules by electrons in the e-cloud extends the lower limit of CCGs.*
- *CCGs are gas-dependent in a similar way as HCGs.*
- *In a CCG, the ion current is related to pressure as:*

$$i_g = K \cdot P^n \qquad n = 1.0 \sim 1.4$$

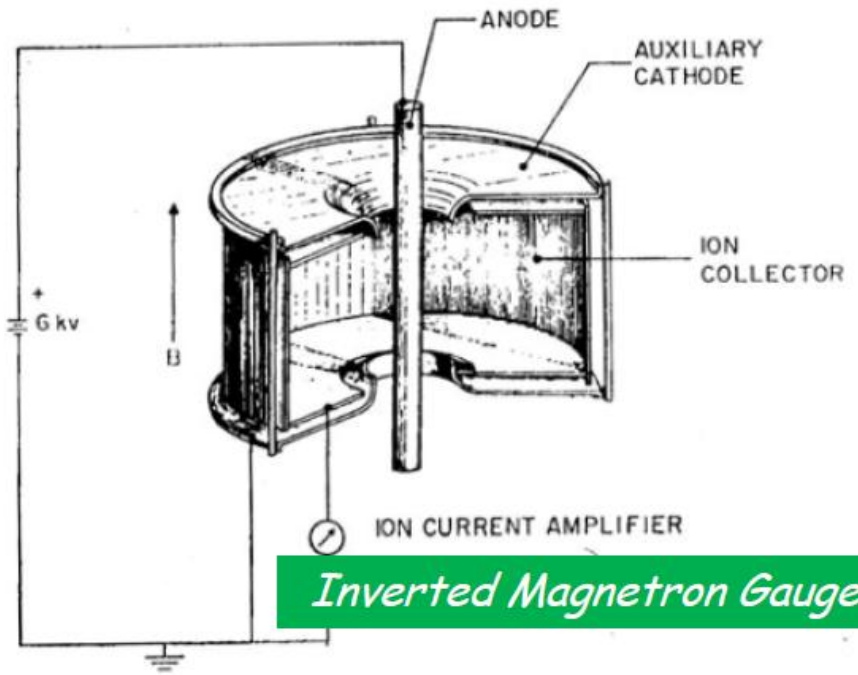
CCGs – Magnetron and inverted magnetron

Same advantages as Penning, improvement on drawbacks

- Electrode geometry evolved from Penning configuration
- Anode changed to a rod and auxiliary (shield) cathode added



Magnetron Gauge



Inverted Magnetron Gauge

- *Both types were developed by Redhead and Hobson in late 50's*
- *Much more efficient electron trapping, and more stable e-cloud (no mode-jumping) over pressure range from 10^{-3} to 10^{-12} torr.*
- *With guard rings, IMG is less sensitive to field emission.*
- *MG usually has higher sensitivity, due to its larger ion collector.*

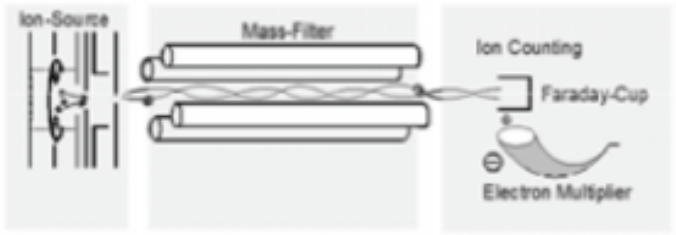
Both HCGs and CCGs are variable gauges in the range of 10^{-4} to 10^{-11} torr

	HCGs	CCGs
Pros	✓ Linear gauge response ✓ Higher gauge sensitivity ✓ Possible extension to XHV	✓ Inherently rugged ✓ Very low residual ion current ✓ Low power and heating ✓ Very good long-term reliability
Cons	✓ Higher X-ray and ESD limits ✓ Filament lifetime ✓ High power and heating ✓ Filament light	✓ Sensitive to contamination (oil, dielectric particulates, etc.) ✓ Discontinuity and nonlinearity ✓ Long ignition time at UHV ✓ Stray magnetic field

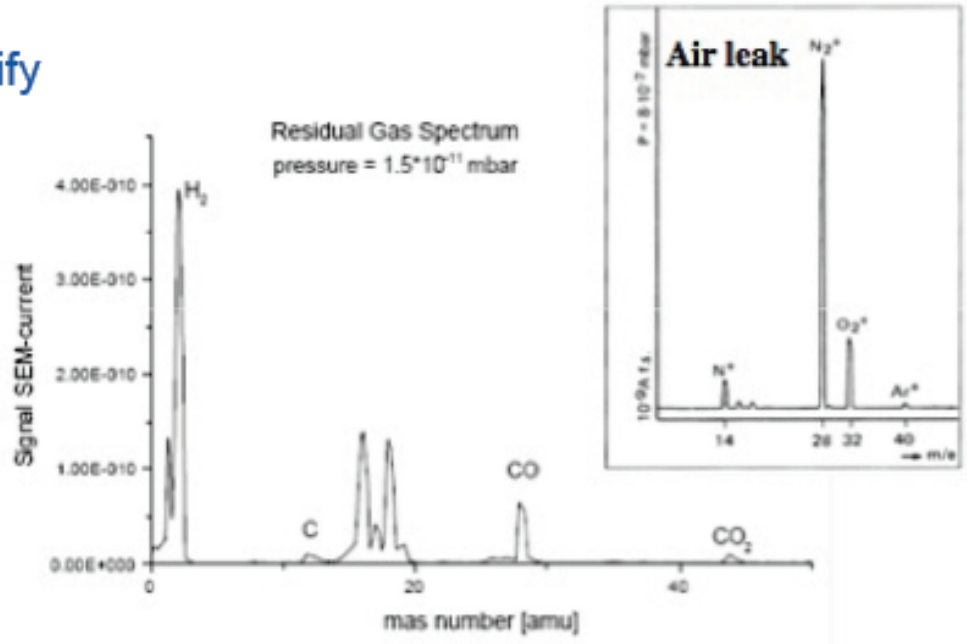
Residual Gas Analyzer (RGA)

Residual Gas Analysers are used in the range 10^{-4} -10^{-12} mbar. Their purpose is to do gas analysis

- A filament produces electrons which ionise the residual gas inside a grid. A mass filter is introduced between the grid and the ion collector. The ion current can be measured in Faraday mode or in secondary electron multiplier mode.
- It is a delicate instrument which produces spectrum sometimes difficult to analyse
- It can be also used to identify and find leaks (Ar, N_2)
- The RGA needs to be calibrated…



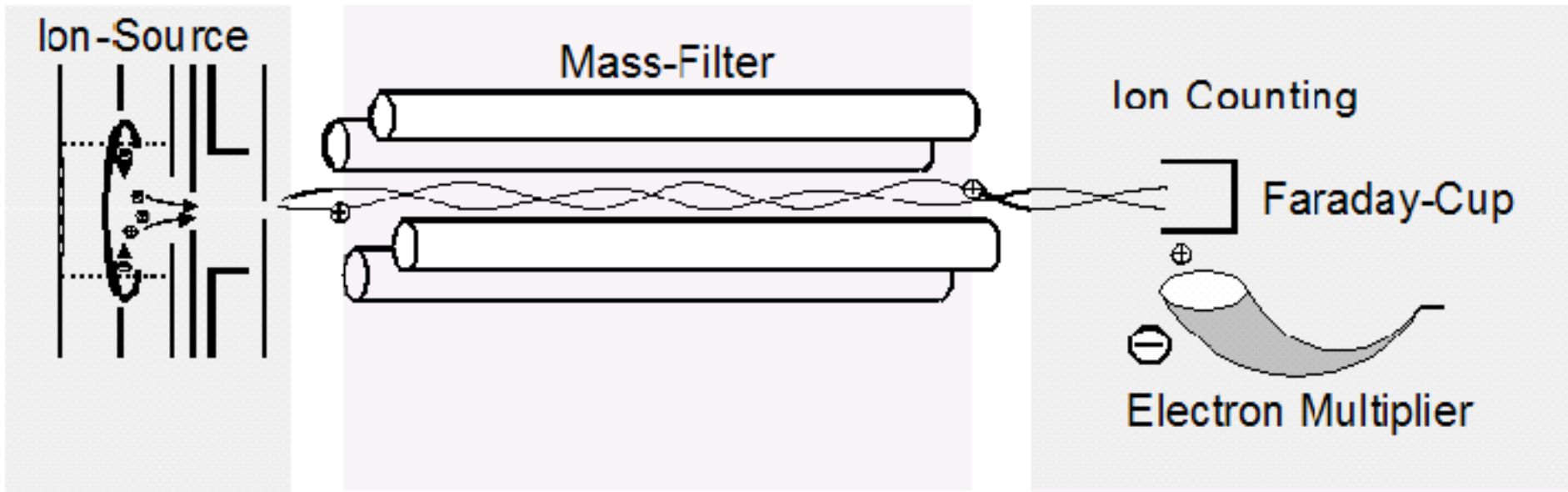
G.J. Peter, N. Müller. CAS Vacuum in accelerators CERN 2007-003



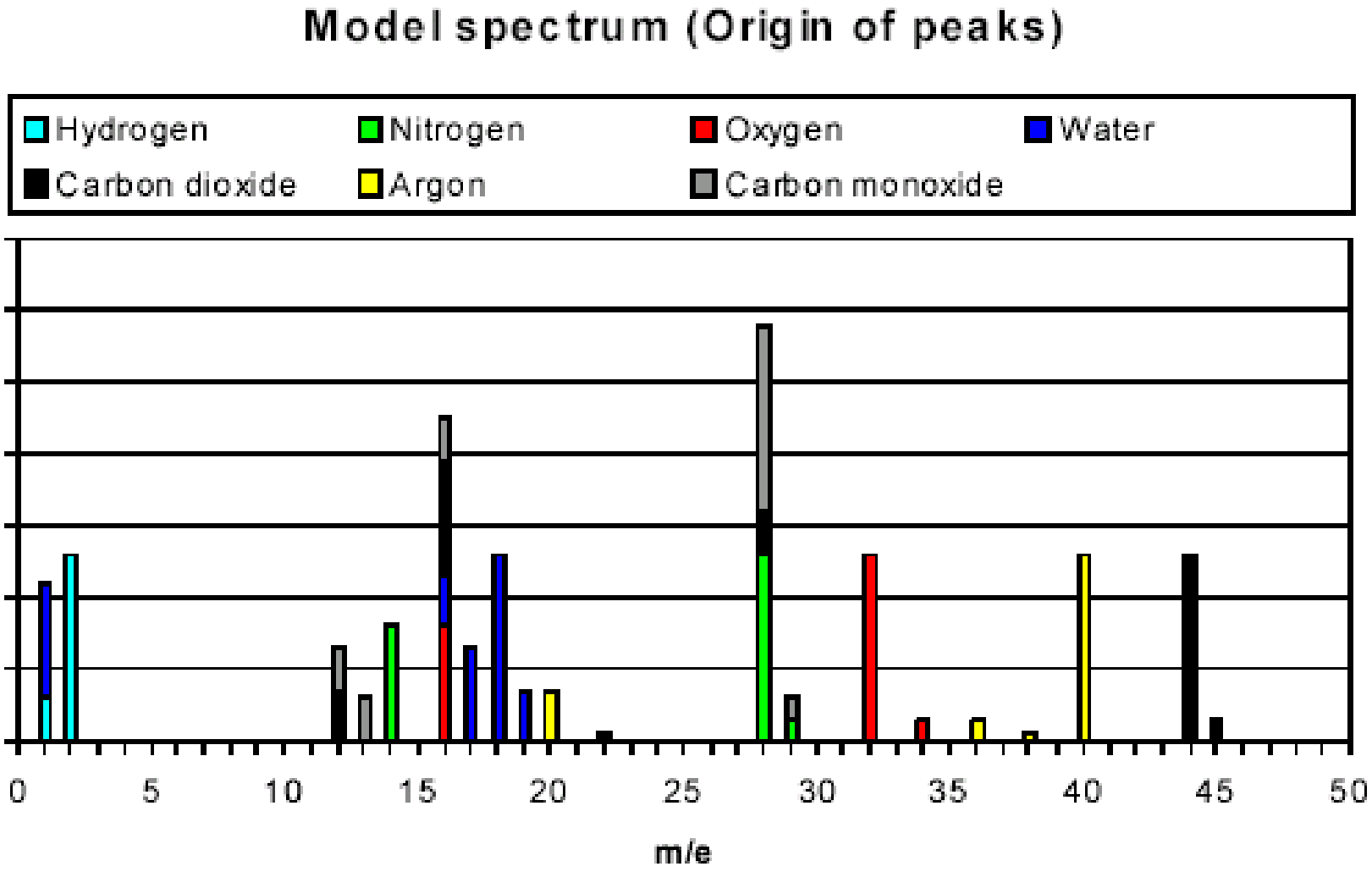
Why Residual Gas Analyzers

- *All the gauges discussed earlier measures total gas pressure or density, no information on the gas composition.*
- *Residual gas analyzers are usually incorporated into critical vacuum system as vacuum diagnostic instrument.*
- *In most cases, qualitative mass spectral analysis is sufficient. Sometimes quantitative analysis is need, but rather difficult.*
- *A RGA measures relative signals verse mass-to-charge ratio (m/e), often in unit of AMU (atomic mass unit). (AMU is defined by C^{12}, that is, C^{12} has exact 12.0000 AMU)*

Functional units of a quadrupole mass spectrometer



Interpretation of Residual Gas Spectra



Interpretation of Residual Gas Spectra

Different molecules have the same mass, for example
N_2 and CO

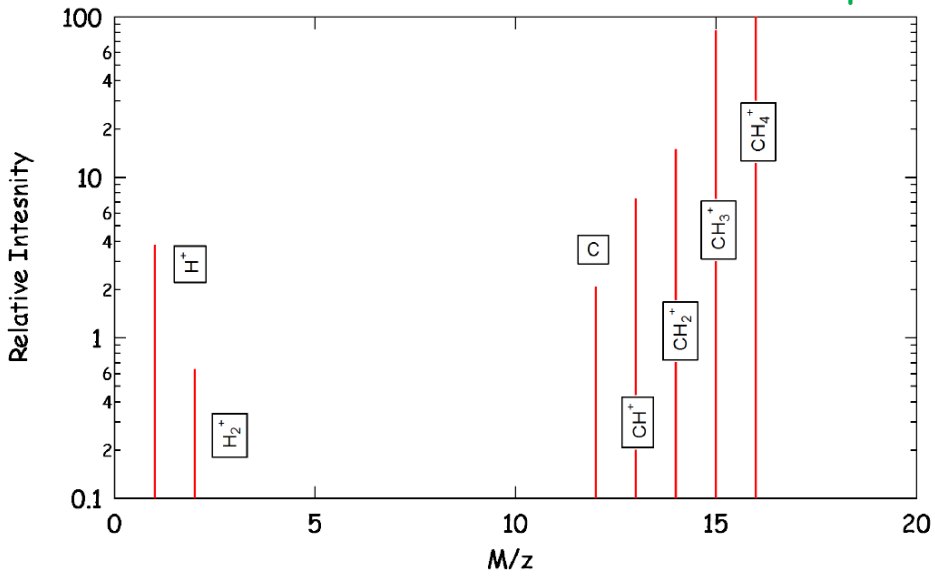
The gas molecules will be ionised and fractionised, for example water will give a signal at m/e = 1,2,16,17 and 18 corresponding to ions such as H^+, H_2^+, O^+, OH^+ and H_2O^+

This can result in rather complex spectra.

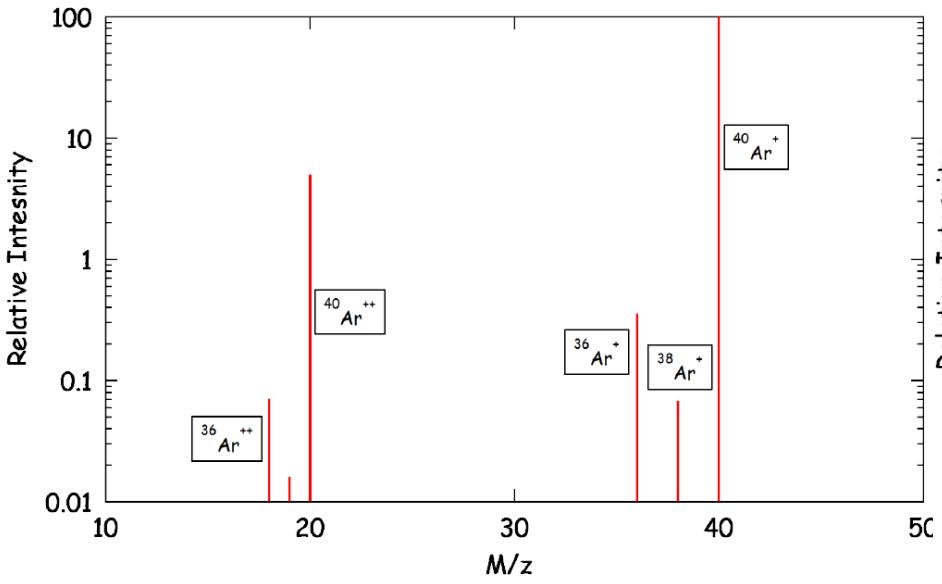
Analysis of Mass Spectra

* Fragmentation or cracking patterns
  - Dissociative ionization
  - Isotopes
  - Combined effects

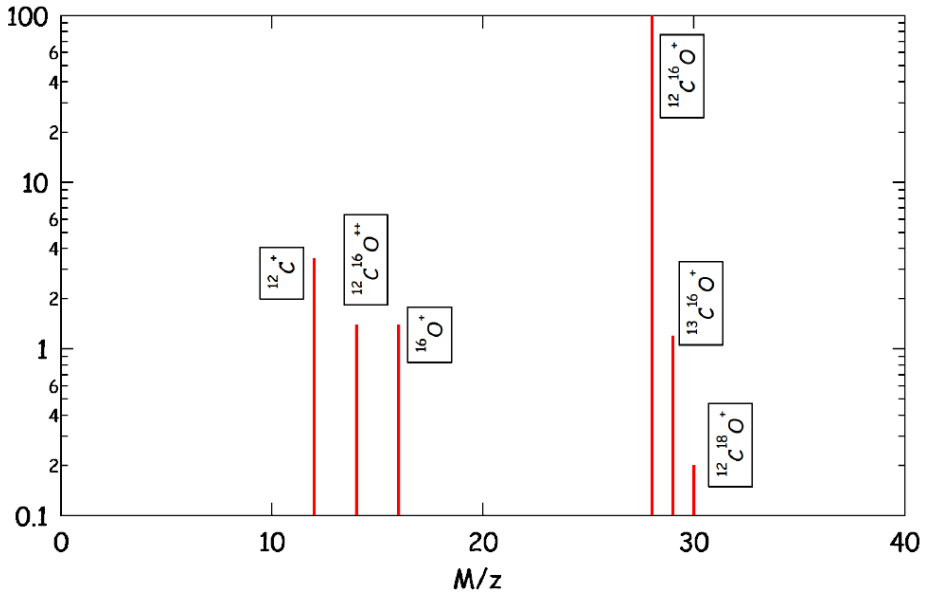
Dissociative ionization – CH4 as example



Isotope Effect – Ar as example



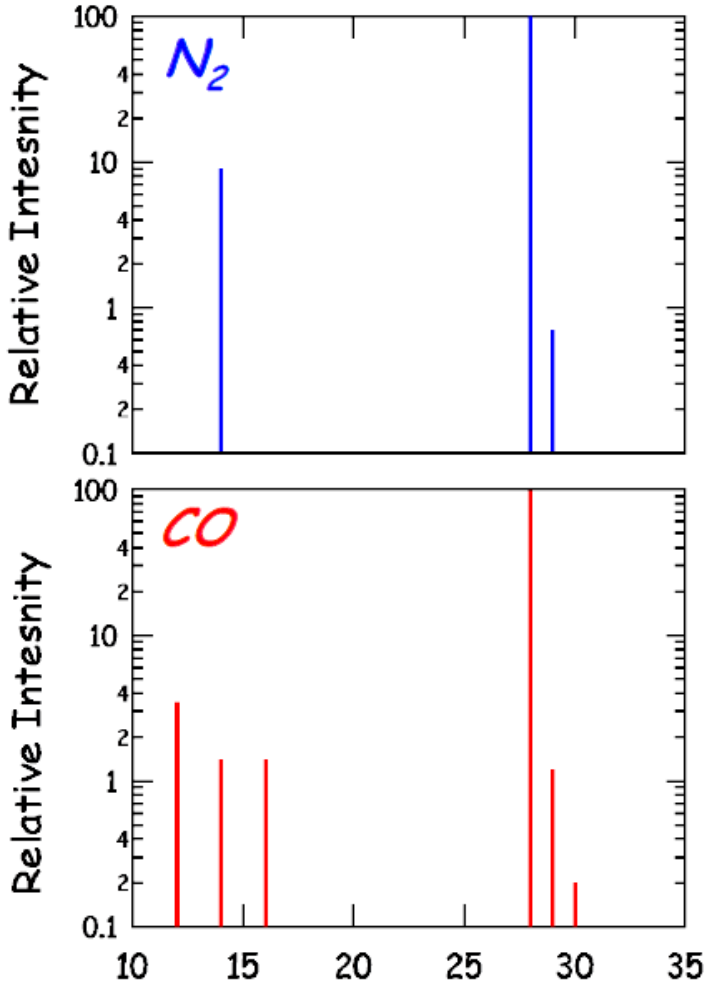
Combined Effect – CO as example



Cracking Patterns – "Fingerprints"

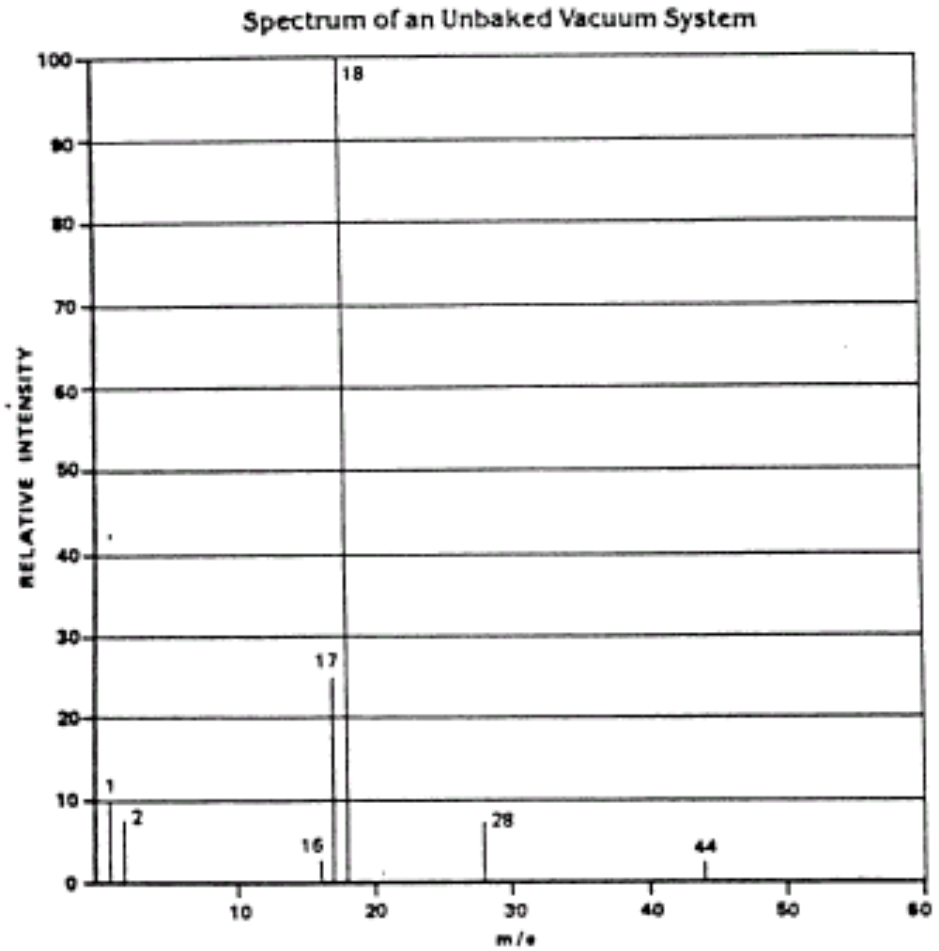
Be careful with tabulated patterns

- *Cracking patterns are commonly used as "fingerprints" of a gas or a vapor, for qualitative gas analysis.*
- *Cracking patterns of many common gases and vapors can be found in the literatures.*
- *Published cracking patterns should be used as a guidance, and they not only depend on gas/vapor, but also vary with instrument conditions.*
- *Many commercial RGA systems have 'build-in' gas library. NIST also maintain a online mass spectrum data.*

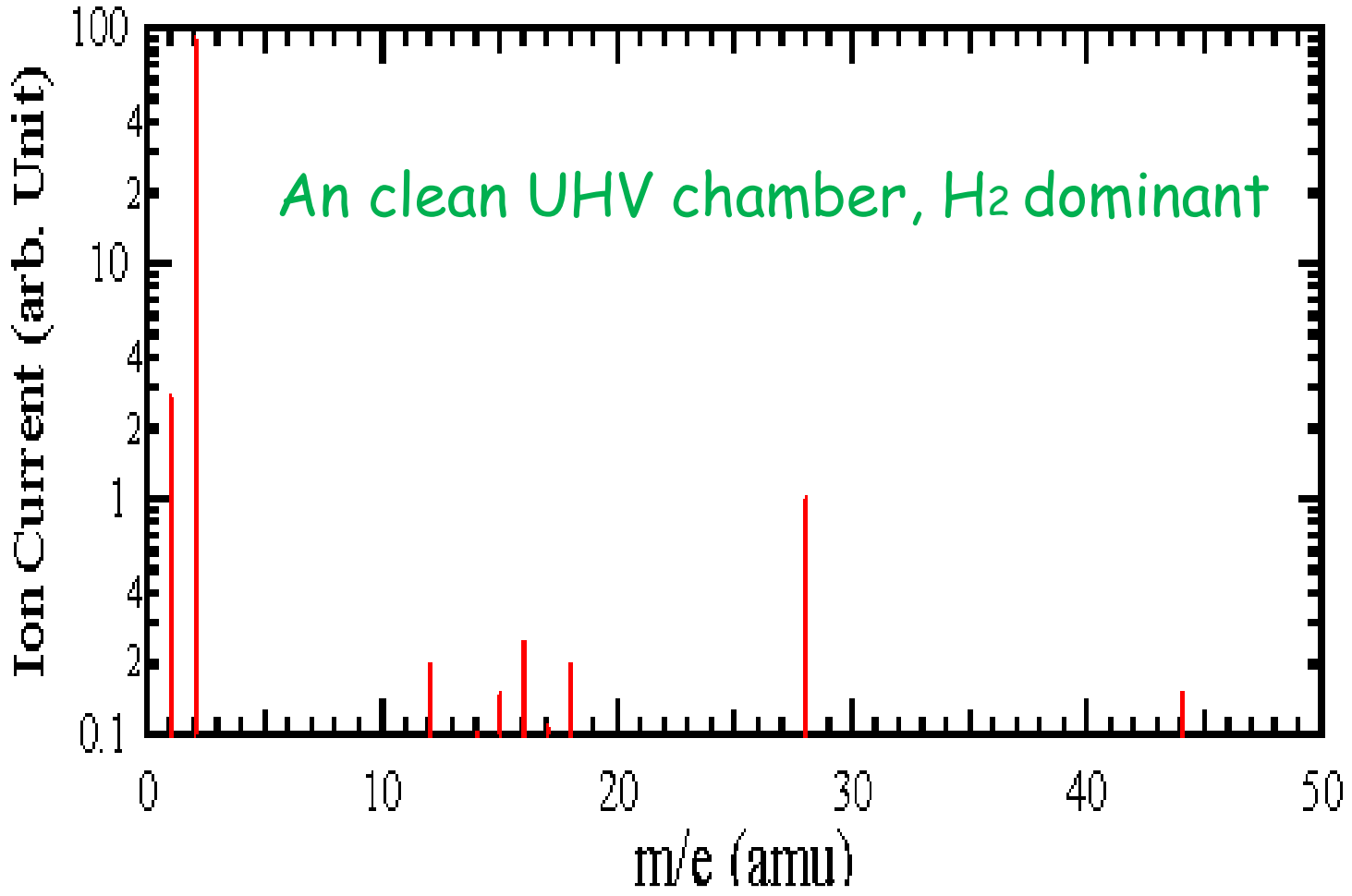


Spectrum of an Unbaked Vacuum System

An unbaked vacuum system, H_2O dominant



Spectrum of an clean vacuum system



Leak Checking

Why Leak Checking?

- For a clean vacuum system, leak(s) may limits the achievable ultimate pressure.
- Even for relatively small leak, certain types of molecules in the gas may affect accelerator performances (such as Ar, O_2, H_2O, etc.) For example, Ar atoms have much higher beam-gas scattering cross-section, as comparing to hydrogen; O_2 and H_2O may 'poison' surfaces of electron gun cathodes (both photo-emitting or thermionic emitting).
- Leak may have impact on long term performance of the vacuum systems, especially for getter-pump dominated systems.
- Leak (even small) may be a sign or defects on a vacuum joint that may develop into operational issue.

Leak Types

- **Fixed connections**
  - brazed, welded, glued
  - glass-metal, ceramics-metal
- **Pores (mechanical, thermal stress), hair cracks**
  - always present ⮑ must be small enough
- **Flanged connections**
- **Cold/warm leaks (reversible) at extreme temperatures**
- **Virtual leaks**
  - excavations, etc. ⮑ needs long time to pump
- **Indirect leaks from e.g. supply lines**
  - cooling water
  - gas/liquid supply lines (He, N_2) for cryogenic systems
- ***Permeation*** ⮑ **natural porosity of material**
  - rubber seals
    - Perbunan ($2 \cdot 10^{-2}$ mbar·l·mm/s/m²): HERA insulating vacuum tank $2 \cdot 10^{-5}$ mbar·l/s/m

avoid potential leaks already during design and fabrication!

Leak Detection Methods

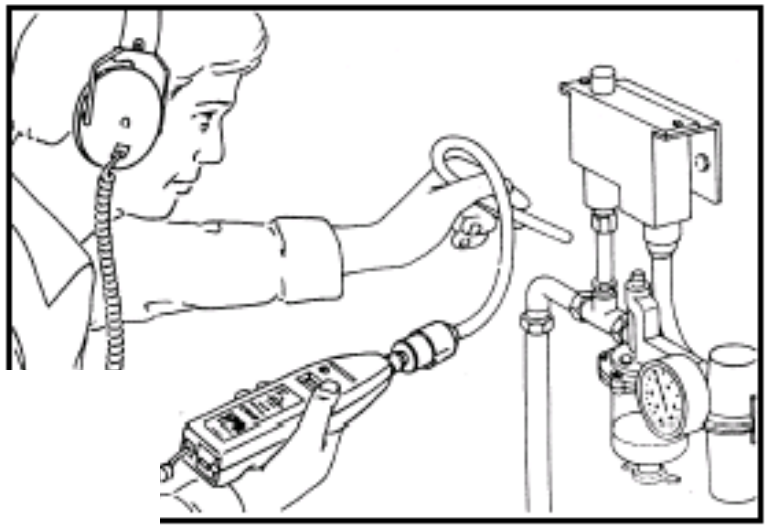
Goals:

localize leak

determine leak rate (locally/total)

➥ **various methods**

- **Mechanical effects**
  - ultra sound
    - ➥ $Q_l > 10^{-2}$ mbar·l/s
  - bubbles
    - ➥ $Q_l > 10^{-4}$ mbar·l/s



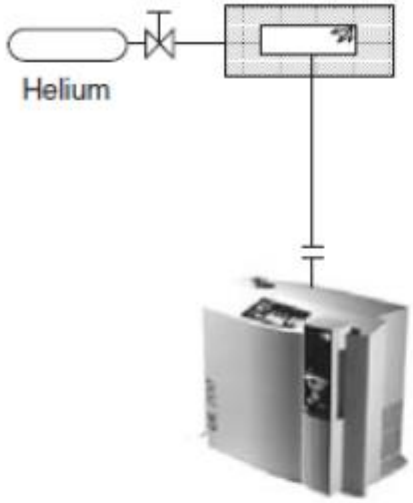
1. Vacuum method – Outside-in

- *Acoustic*
- *Mass Spectrum Leak detector*
- *Residual gas analyzers*
- *Rate-of-rise*
- *Vacuum gauges sensitivity variation (helium vs. air/N_2)*

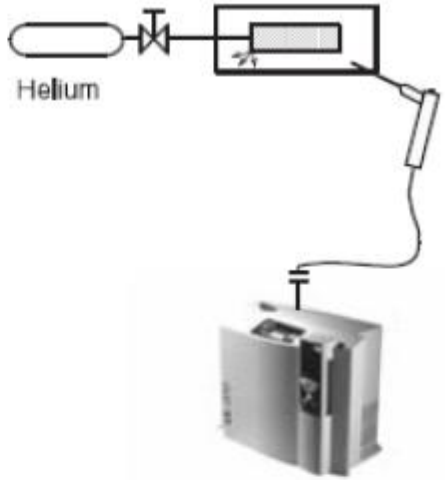
2. Positive pressure method – Inside-out

- *'Bubbling'*
- *Foam spray*
- *'Sniffing' with a leak detector*
- *Pressure drops*

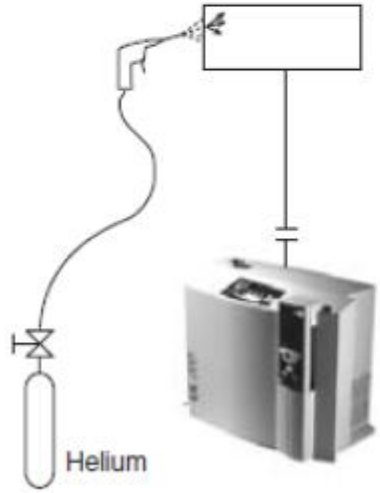
Leak Detection – Localized or Integral



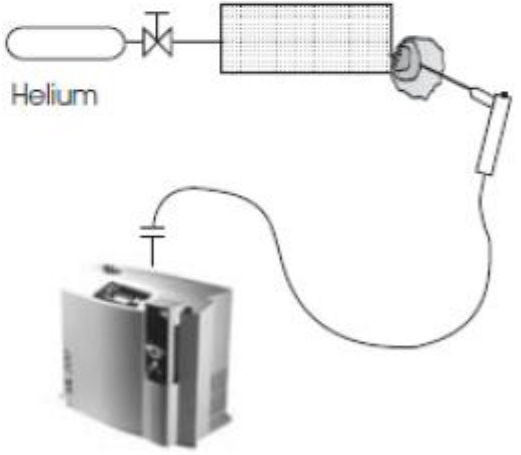
a: Integral leak detection; vacuum inside specimen



c: Integral leak detection (test gas enrichment inside the enclosure); pressurized test gas inside specimen



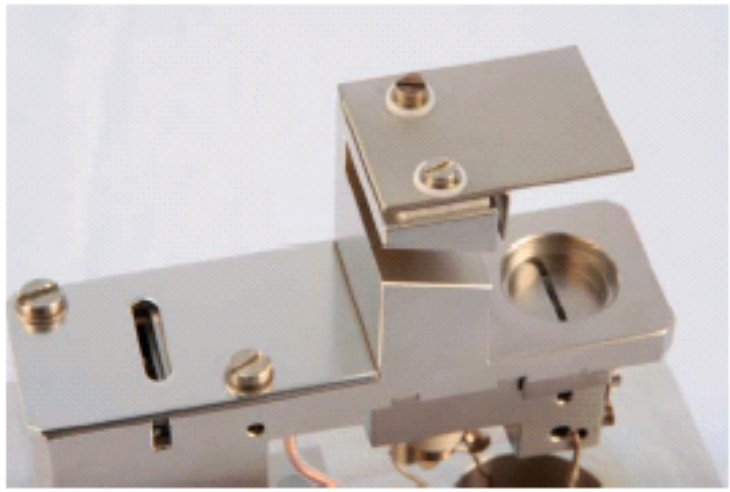
b: Local leak detection; vacuum inside specimen

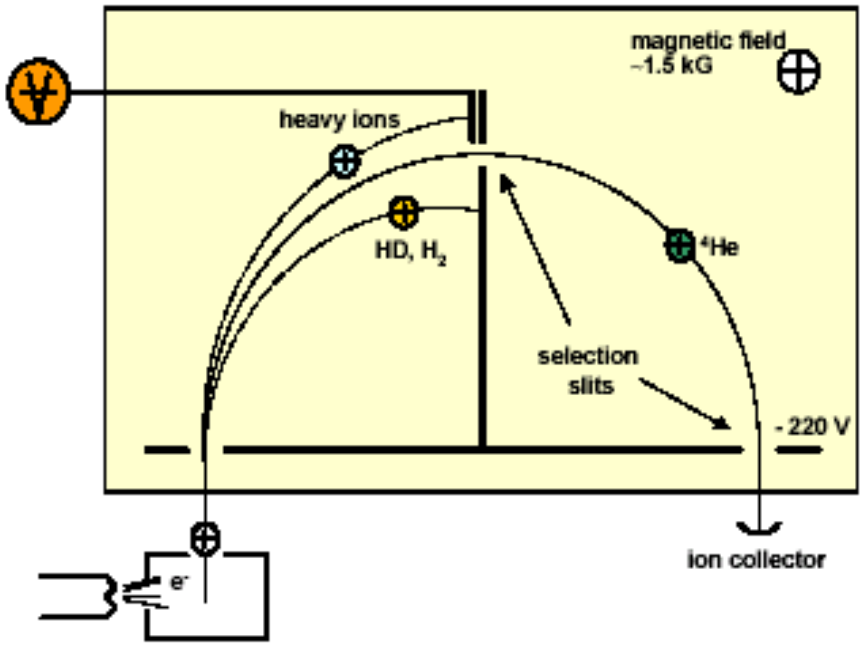


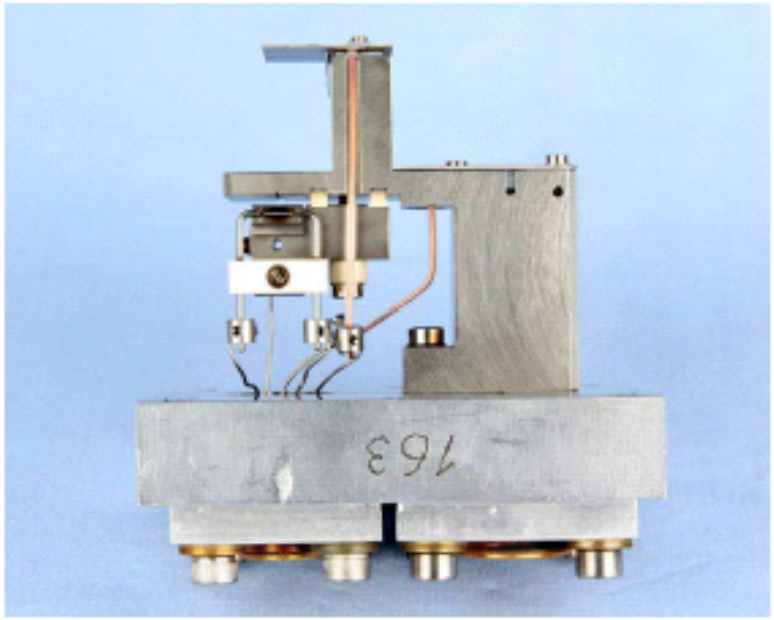
d: Local leak detection; pressurized test gas inside the specimen

Helium Leak Detectors

- Operating pressure p < 10^{-4} mbar
- In principle any type of RGA possible
- Most sensitive/safe ➥ mass spectrometer with 180° magnetic sector field
  - optimized for mass 4 (3,2)







Helium is the most common gas used as a "tracer"

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 chemsorption pumps
- Is not well pumped by cryogenic pumps

Leak Check – A key step in QC

- *Leak check is the most critical measure of vacuum system quality assurance and control.*
- *For complex system, every vacuum components must be leak checked prior to installation, particularly for those components difficult to access in the field.*
- *For vacuum chambers that involve multiple vacuum brazes and welding, intermediate leak checking may be necessary. In most those cases, leak check fixtures should be designed and prepared.*
- *Components and chambers with small volume may use helium leak detector, while large vacuum chambers and systems will need a turbo pump equipped with RGA and calibrated helium leak.*

Leak Detection, Tips & Tricks

- *Always test the connecting lines first!*
- *Isolate O-rings to prevent permeative "masking" of real leaks*
- *Slow down tracer (helium) flow rate, with solvent "bubbling calibration"*
- *When introducing helium, start at top and work down (Tracer probe)*
- *Know the air flow. Start from down-stream and work up-stream.*
- *Avoid "plugging" potential leak(s)*

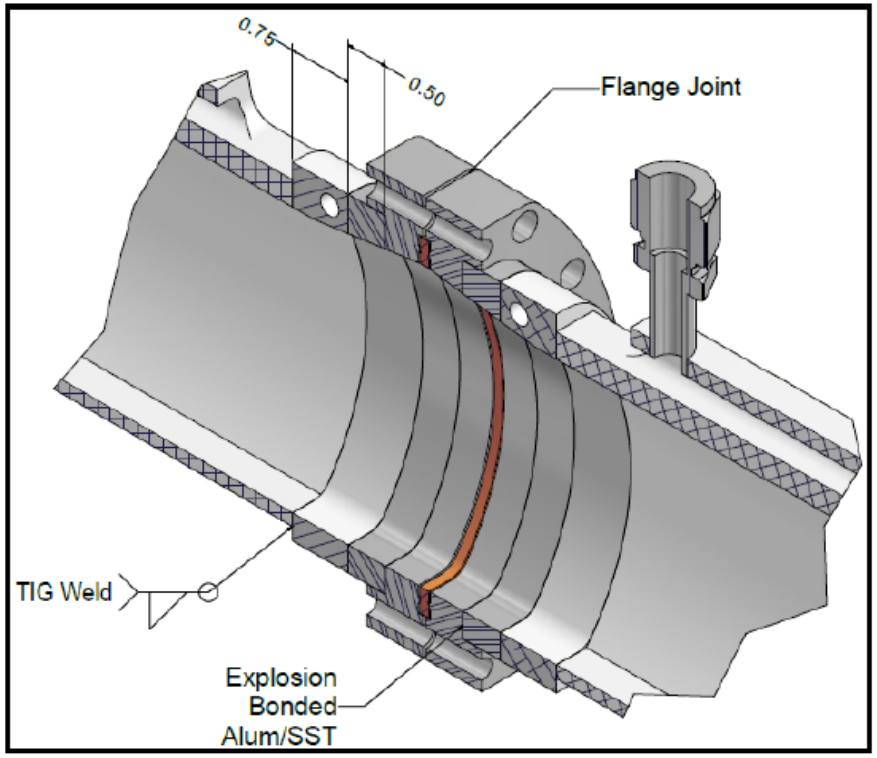
Techniques for Detecting Small Leaks

- *Flow all pumped gases through the HMSLD., or the RGA, if possible, turning off all other system pumps*
- *Use low-flow tracer probe technique*
- *Keep Helium away from permeable materials (elastomers)*
- *Make use of "bagging" and "taping" techniques*

Locating a leak near multiple joints

- *It is sometime a difficult task trying to locate a leak at a location with multiple adjacent joints.*
- *Some of the tips are:*

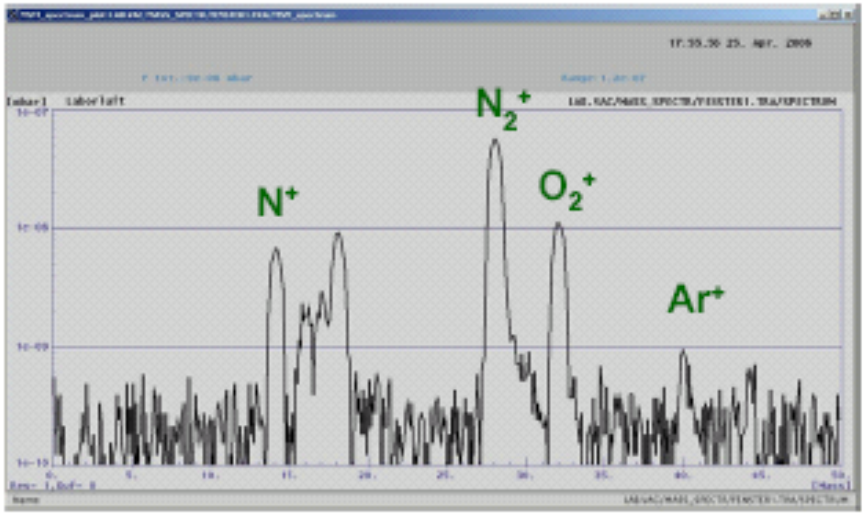
1. *Use very small helium flow*
2. *Tapping/bagging*
3. *N_2 counter-flow/purging*
4. *Plugging potential leaks by solvent*
5. *Positive pressure test*



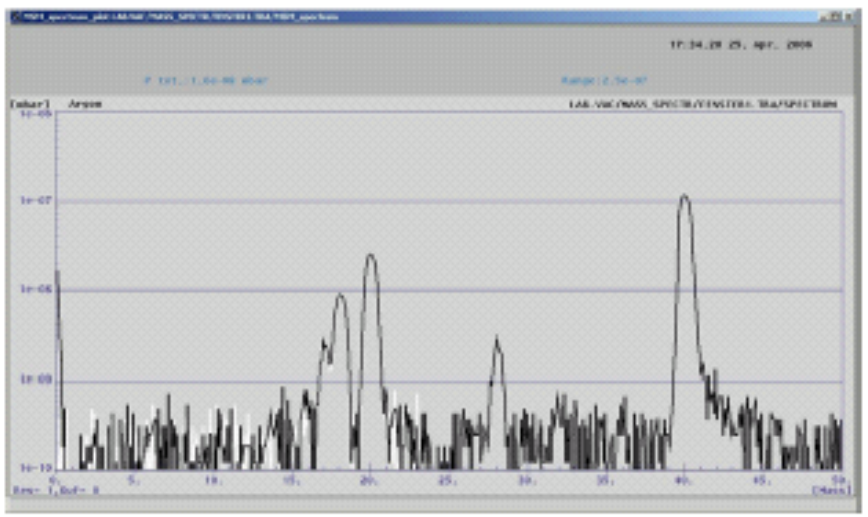
Leak Detection Methods

- **Mass of residual gas**
  - ➥ **tracer: He (Ar, air)**
  - ➥ **detector: mass spectrometer**
    - most sensitive method (10^{-12} mbar·l/s)

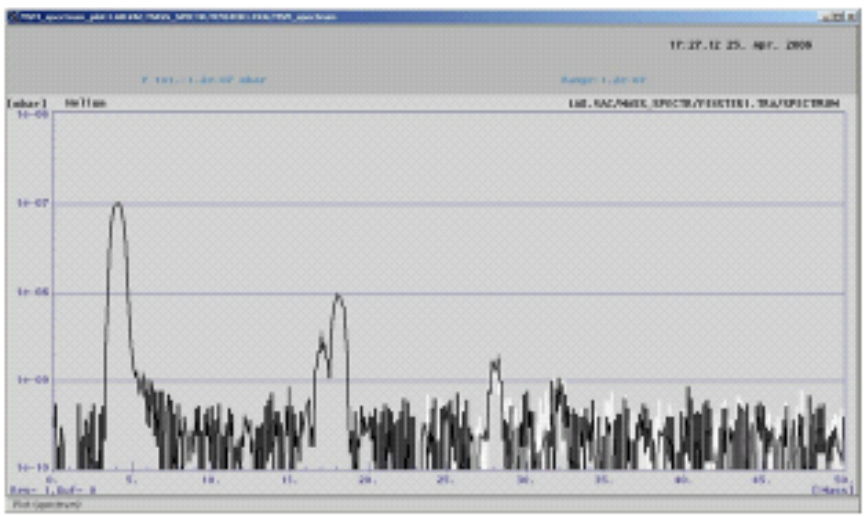
RGA Leak Checking



air



Ar



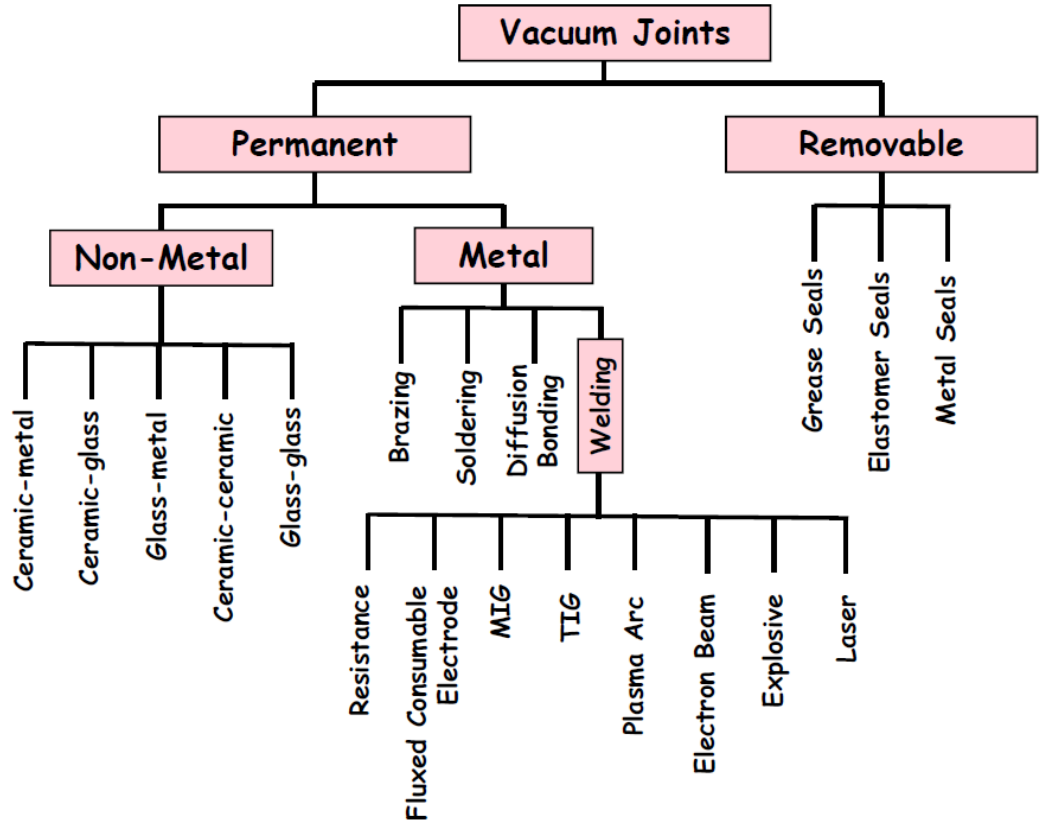
He

Vacuum Material and Cleaning

Vacuum Materials

- Metals
  - → Stainless Steels
  - → Aluminum and Alloys
  - → Copper and Alloys
  - → Other metals
- Non-metals
  - → Ceramics and Glasses
  - → Polymers

Methods of Making Vacuum Joints



Criteria influencing the Choice of Materials

Low outgassing rate
Low vapour pressure
Temperature resistant -> bakeout
Thermal and electrical conductivity -> beam interaction
Corrosion resistance -> leaks
Low induced radioactivity -> handling
High mechanical strength -> 1dN/cm^2 external atmospheric pressure!
Machining, welding
Low cost

Common choices:

Stainless steel
Aluminium
Copper
Ceramics for electric insulation
    Low porosity -> leaks
    Brazing to metal -> leaks
For particular applications: Be for detectors for high transparency
Organic materials (e.g. as composite materials (carbon-fibre & epoxy), polymers to be used in small quantities

Vacuum Materials Cleaning

- SST, AL,Cu Cleaning procedures
- Special treatment:

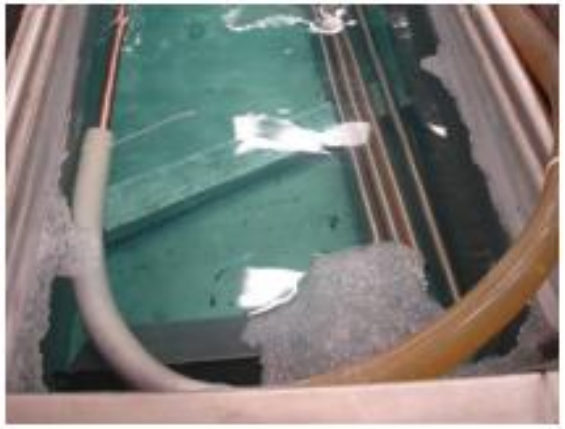
  *Ultrasonic wave Cleaning

  *Electrochemical Clearning

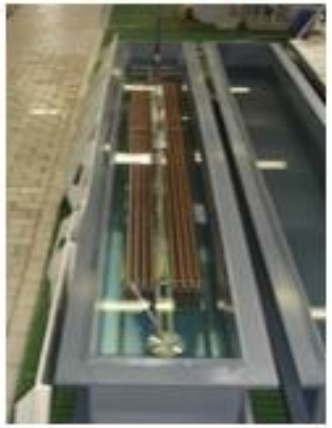
  *Electropolish

  *Glow Discharge

Degreasing:

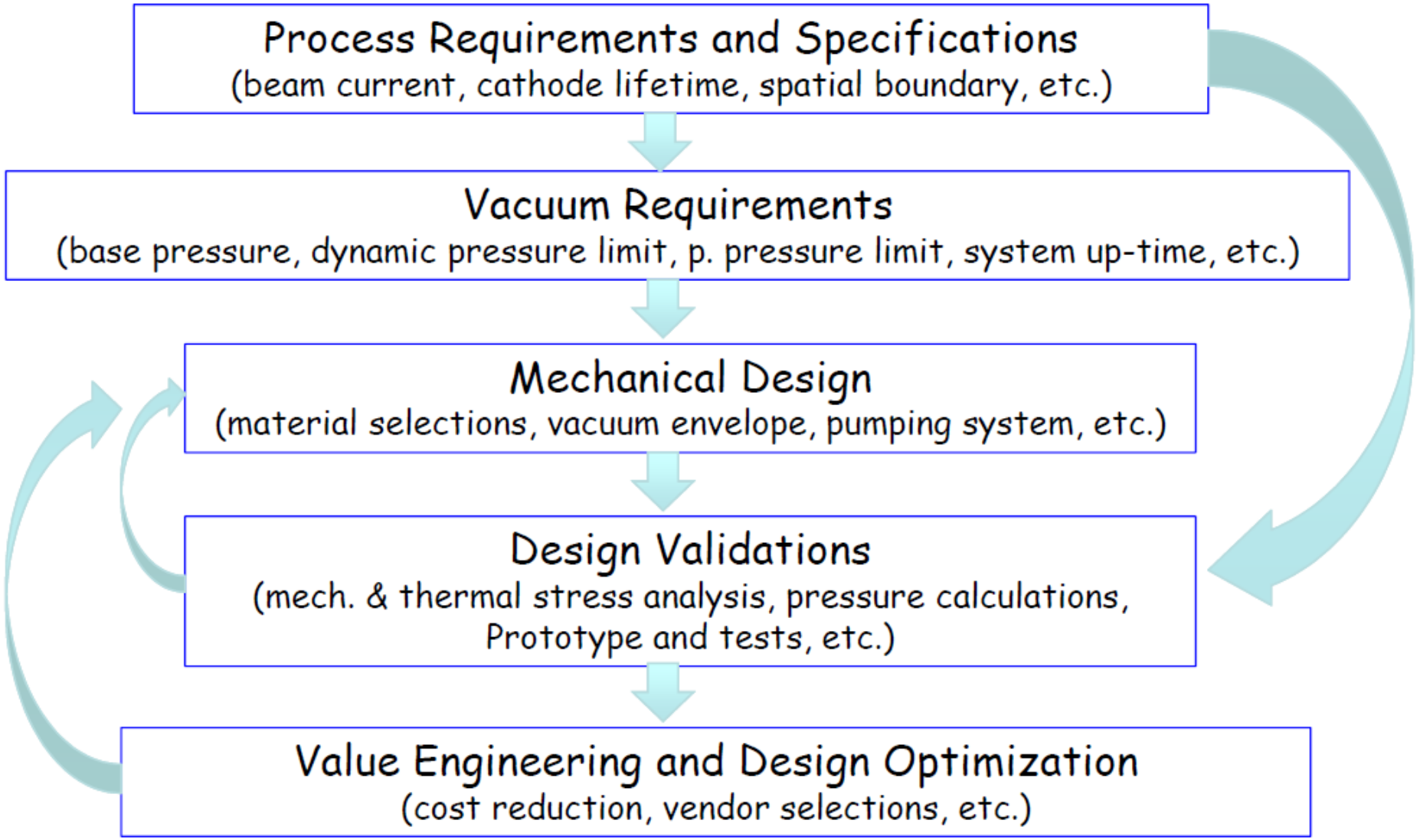


Etching and passivation:



Accelerator Vacuum System Integration

Particle Accelerator Vacuum System Design



Accelerator Vacuum Design Considerations

- Particle beam parameters
  - → Type of particles: e^-, e^+, p^+, ions, etc.
  - → Beam density
  - → Beam temporal and spatial properties, etc.
  - → …, …
- Magnets – Mainly spatial constraints
- Accelerating RF cavities
  - → Particulate control – ultra-clean vacuum systems
  - → 'Free' cryo-pumping for SRFs, but handling of warm-ups
  - → Cryo related issues (insolation vacuum, etc.)
- Key functional accelerator components
  - → SR generation insertion devices – in-vacuum and/or ex-vacuum
  - → Particle sources – electron and positron, protons, ions,
  - → Beam instrumentations – BPMs, beam size monitors, etc.

High Vacuum Systems

- *High vacuum system is dynamic pressure in range of 10^{-6} to 10^{-9} torr*
- *Examples of accelerator high vacuum systems:*
  → Low beam intensity LINACs
  → Low beam intensity energy booster rings for storage rings
  → Insolation vacuum for cryo-modules
- *For these systems, often discrete pumps are sufficient. Typical pumps used are ion pumps, diffusion pumps, cryo-pumps and turbo-molecular pumps.*
- *For cryo-module insolation vacuum, though with 'build-in' cryo-pumping from cryogenic surfaces, sufficient contingency pumping system must always included to deal with possible internal helium leaks.*
- *Material selection for high vacuum systems is usually dictated by cost and easiness of fabrications. Though cleanness is not as critical, a clean system will reduce cost of pumping system.*

Ultra-High Vacuum Systems

- *UHV system is dynamic pressure in range below 10^{-9} torr*
- *Examples of accelerator UHV systems:*
  → Electron storage rings for light sources and colliders
  → High intensity proton and ion machines
  → High intensity LINACs
- *For these systems, often distributed pumps are needed with gas conductance limited beam chambers, and distributed dynamic gas load. Only UHV-compatible pumps should be used, including ion pumps, NEGs and TiSPs.*
- *In most cases, only UHV compatible metals should be used for these systems. Stringent cleaning and UHV-compatible handling is paramount. Only all-metal joints are permitted.*
- *UHV ion gauges must be included in the UHV system. RGAs are strongly recommended for vacuum diagnostics.*
- *UHV system roughing and venting needs significant cares.*

Beam Lifetime in a Storage Ring

- Number of particle lost is proportional to the number of beam particles,

$$dN = -\sigma N(t)dt \qquad \text{where } \sigma = \text{constant}$$

- Define the beam lifetime as $\tau = 1/\sigma$; then beam current decays as:

$$I = I_0 e^{-t/\tau}$$

- There are three beam-loss processes: the quantum excitation (radiation dumping), intra-beam scattering (Touschek effect), and scattering off of residual gas molecules (elastic and inelastic). The individual loss mechanisms contribute the total lifetime as:

$$\frac{1}{\tau} = \frac{1}{\tau_{quantum}} + \frac{1}{\tau_{Touchek}} + \frac{1}{\tau_{elastic}} + \frac{1}{\tau_{inelastic}}$$

- In most cases, the quantum lifetime is significantly longer than all others. For electron beam with very small sizes, the Touschek lifetime may dominate. The goal of vacuum design is to achieve a pressure level as such that beam lifetime due to residual gas scattering is significantly below the Touschek lifetime.

Quantum Lifetime

The quantum fluctuations due to photon radiation may cause a particle to exceed the energy aperture or physical aperture of the machine. The resulting lifetime is called the "quantum lifetime".

$$\tau_q = \tau_x \frac{\sigma^2}{x_a^2} \exp\left[\frac{x_a^2}{2\sigma^2}\right] \qquad \Rightarrow x_a \approx 5\sigma$$

Usually one designs for *Xa* >=10 to provide adequate safety margin.

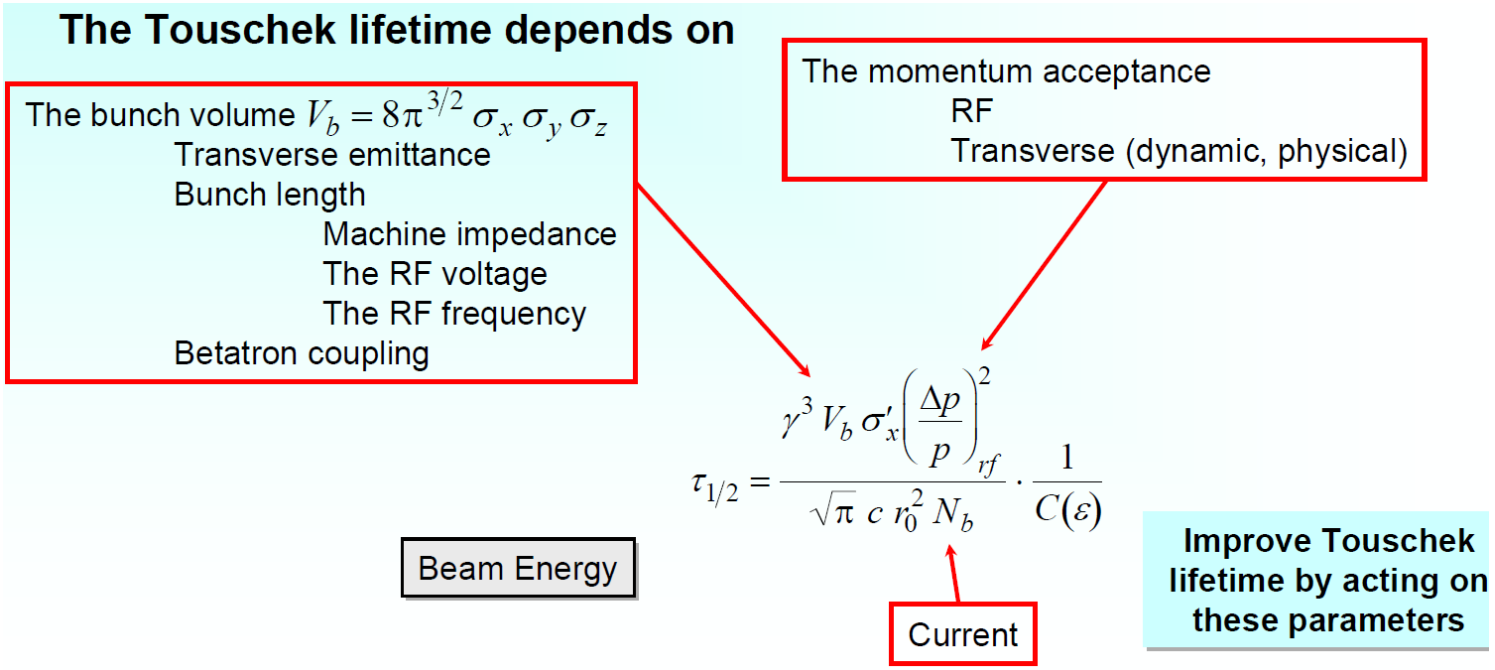
$$\tau_q = \tau_\varepsilon \frac{\sigma_E^2}{\Delta E_a^2} \exp\left[\frac{\Delta E_a^2}{2\sigma_E^2}\right]$$

One typically designs for $\Delta E_a \geq 10\sigma_E$

x_{max}/σ_x	5	5.5	6.0	6.5	7.0
τ_q	1.8 min	20.4 min	5.1 hrs	98.3 hrs	103 days

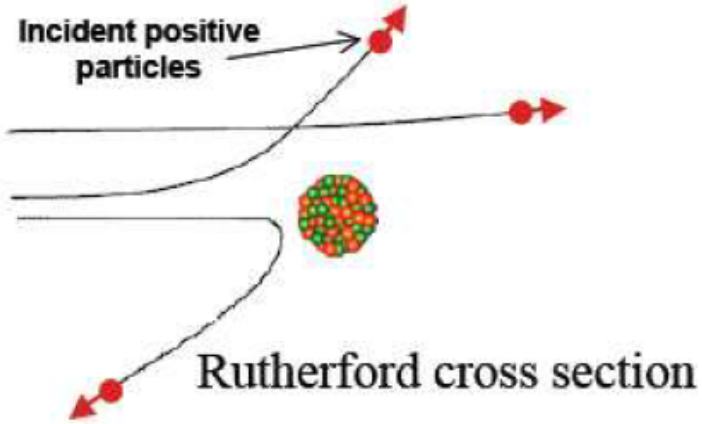
Touschek Lifetime

- Touschek scattering involves scattering of particles within the bunch, transferring energy among themselves. Such an energy transfer, if large enough, may eject the particle out of the bunch, thus causing it to be lost.

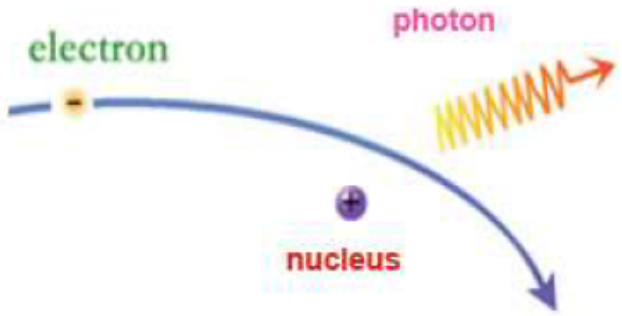


Beam Loss by Residual Gas Scattering

- Elastic (Coulomb scattering) from residual background gas
  → Scattered beam particle alters transverse motion, and undergoes betatron oscillations.
  → The particle will be lost when the oscillation amplitude exceeds physical acceptance aperture.
- Inelastic scattering (Bremsstrahlung) causes particles to loss energy. The particle will be lost if the energy loss exceeds the momentum acceptance of the ring.
- Inelastic scattering via atomic excitation has much smaller cross section, as compare to Bremsstrahlung.



Rutherford cross section

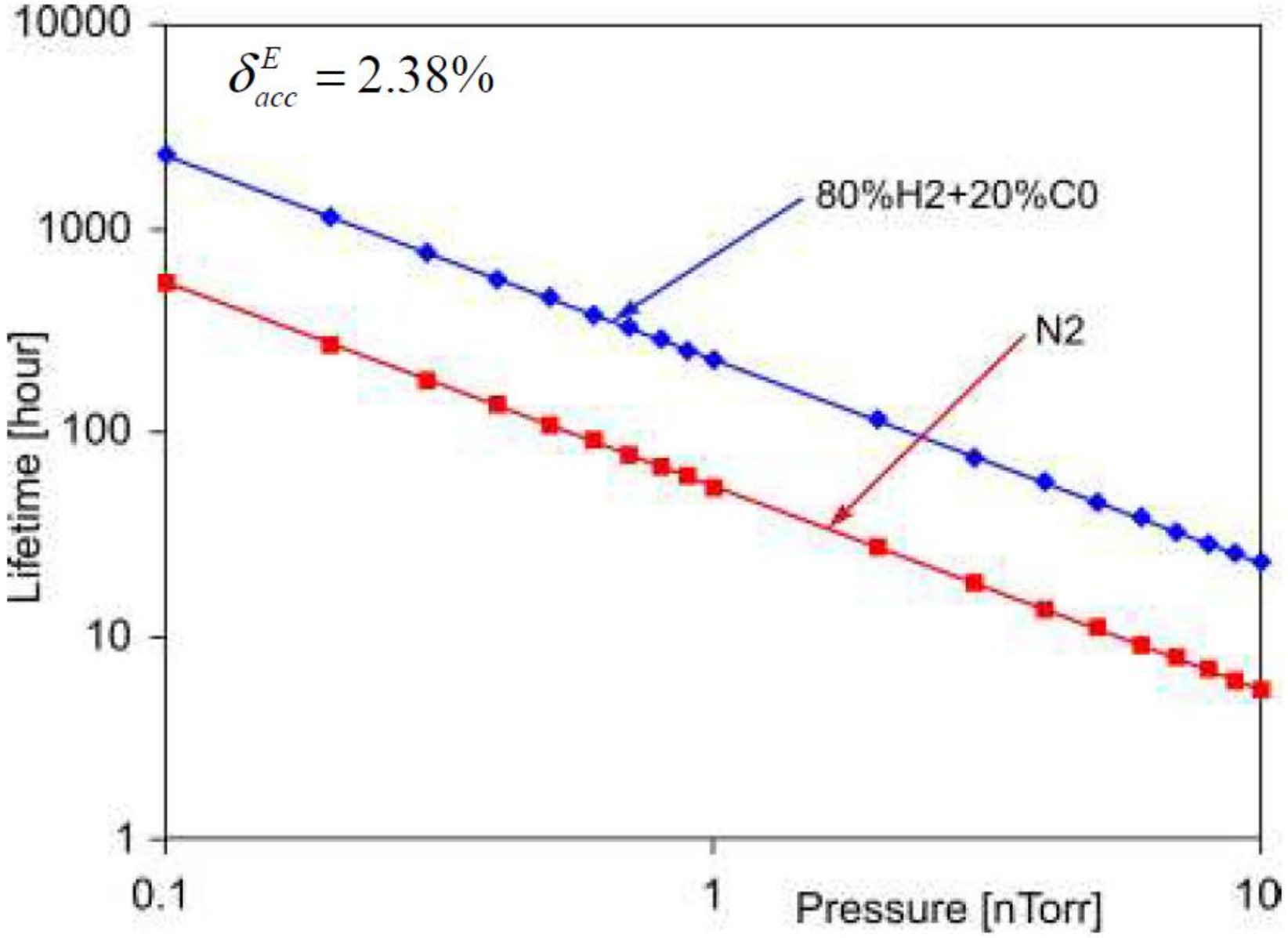


Bremsstrahlung cross section

Bremsstrahlung Scattering Lifetime

$$\tau = 2.82 \times 10^{-7} \frac{X_0}{MP}[h]$$

X0: Residual gas radiation length
M: Residual gas mass
P: Pressure[Pa]
Z:

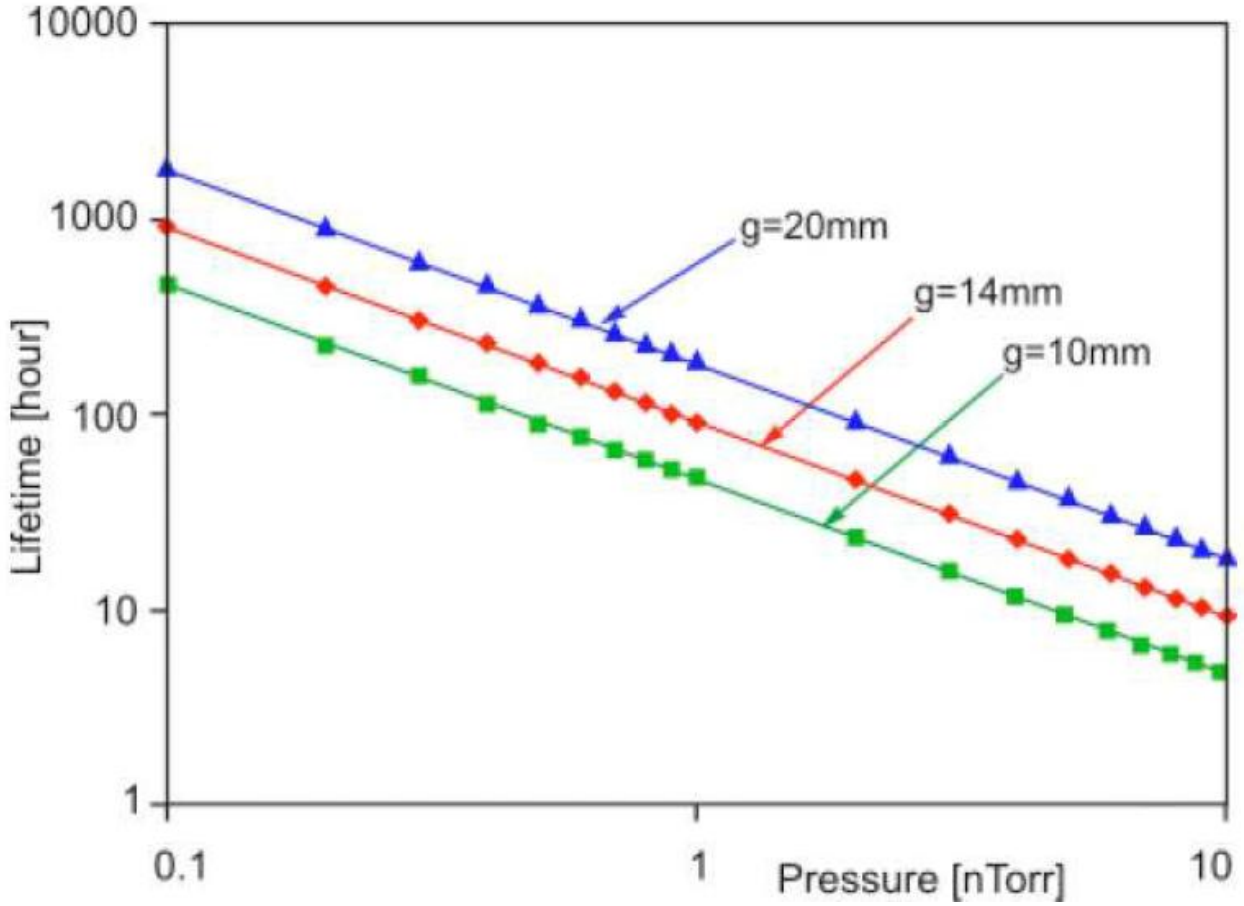


Elastic Scattering Lifetime

***Machine example**: Beam energy=3 GeV, $\langle\beta_y\rangle$=10m, smallest gap in the ring, g=10, 14 and 20 mm ($A_y=(g/2)^2/\beta_y$). The calculated lifetimes from elastic scattering of N_2 ($n=1$, $f_1=1$, $Z_1=7$, $N_1=2$) :*

$$\tau = 4.1\times10^{-10}\frac{b^2\gamma^2}{pZ^2\langle\beta_y\rangle}[s]$$

b: half height of vacuum chamber
γ: $\gamma = E/m_0c^2$;
P: residual gas pressure
Z: atomic number
<βy>: average of β function

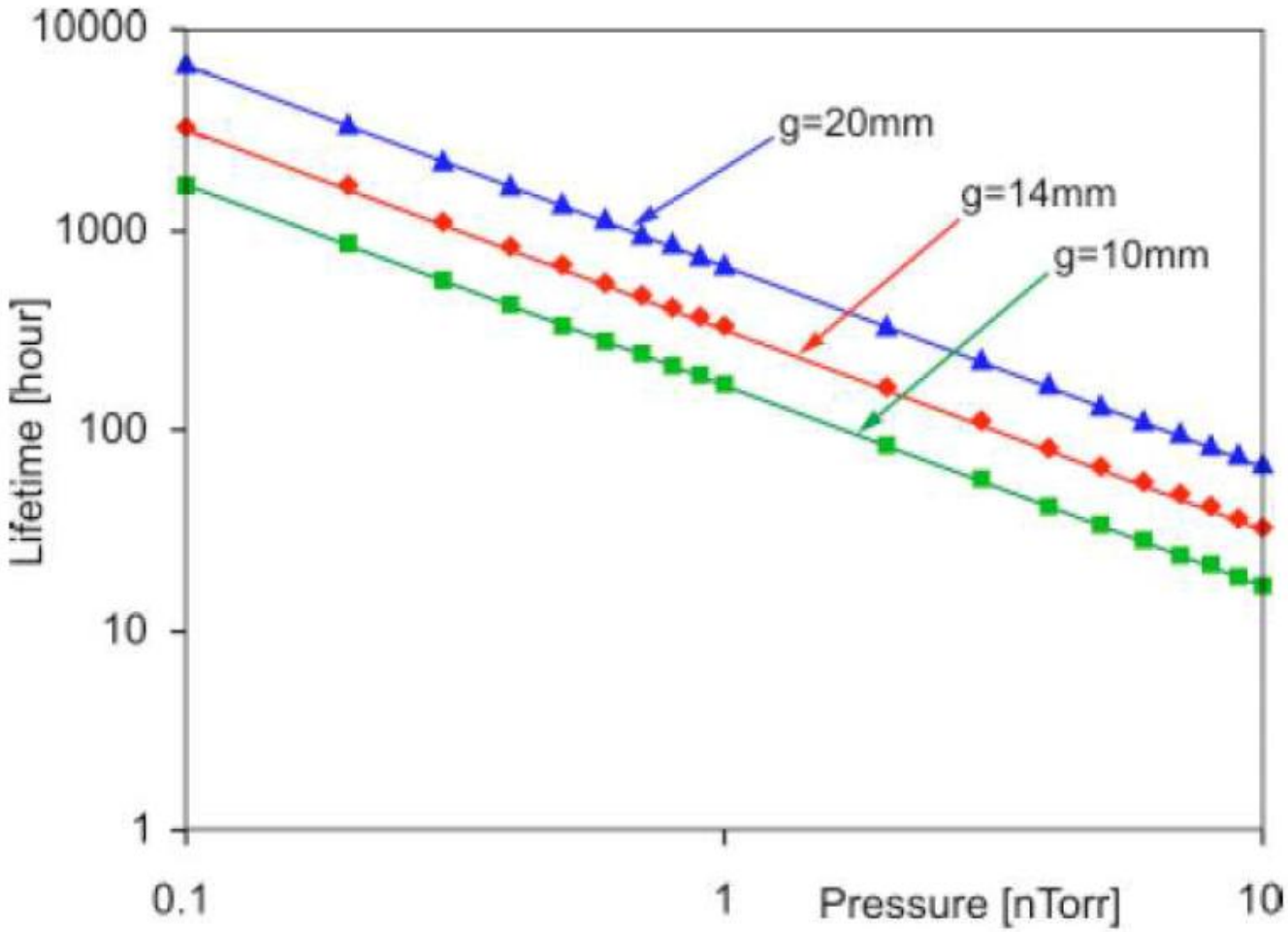


Elastic Scattering Lifetime

For the same machine parameters, but with 80% H2 and 20% CO ($n=2$, $f_1=0.8$, $Z_1=1$, $N_1=2$; $f_2=0.2$, $Z_2=7$, $N_2=2$), the elastic scattering lifetime:

$$\tau = 4.1\times10^{-10}\,\frac{b^2\gamma^2}{pZ^2\langle\beta_y\rangle}[s]$$

b: half height of vacuum chamber
γ: $\gamma = E/m_0c^2$
P: residual gas pressure
Z: atomic number
<βy>: average of β function



Beam Loss by Residual Gas Scattering

- *Elastic and inelastic scattering residual gas scattering have similar contribution to the electron beam losses in a storage rings.*
- *Both beam loss mechanisms have strong dependence on atomic numbers (Z-number) of the gases. Both are proportional to the size of the gas molecules (N). For example, Ar has a factor of* $(18^2*1/1^2*2)=162$ *higher scattering cross section than* H_2*. Contamination of long-chain hydrocarbons (large N) also induce more significant beam losses.*
- *For clean storage ring vacuum systems, average pressure ~ 1 nTorr is usually sufficiently low, so that beam losses due to the residual gas scattering processes are negligible, comparing to beam-beam effects.*
- *However, photon radiation from Bremsstrahlung scattering can generate background for HEP detectors. Thus vacuum level much better than 1 nTorr is usually required in the interaction region of a HEP collider.*

Gas Load

- Base Pressure

  -most depend on material outgassing rate

  (material selection, surface treatment,…)

- Dynamic Pressure

  -For e-/e+ storage rings, the dominating dynamic pressure rise is due to photon-induced desorption from intense SR.

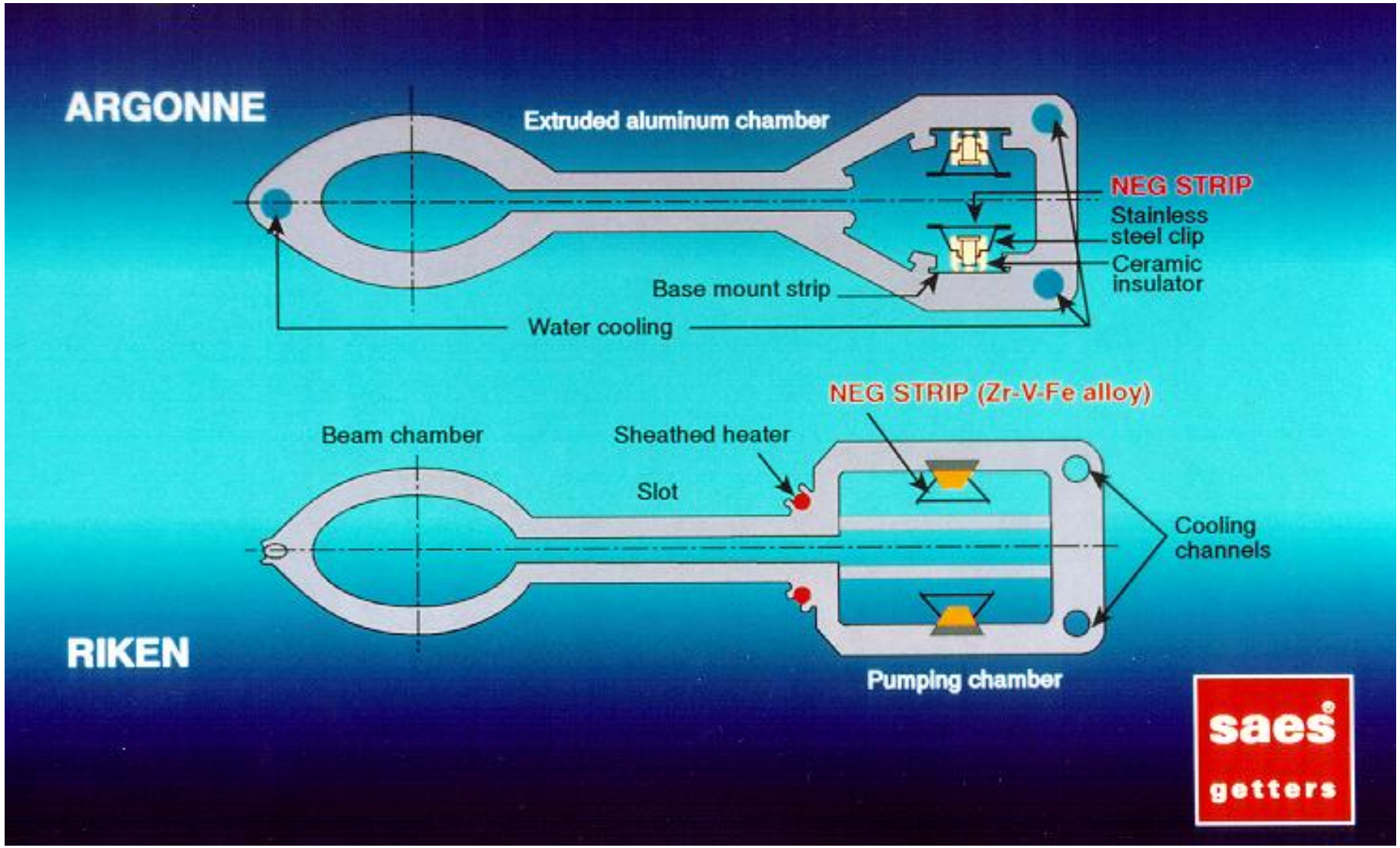
$$P_{SR} = \frac{88.5E^4 I}{\rho} \qquad P_L = \frac{P_{SR}}{2\pi\rho} = \frac{88.5E^4 I}{2\pi\rho^2} \qquad Q_{gas} = 24.2EI\eta \ \text{[Torr. L/s]}$$

  -For p+ and ion machines, SR usually negligible. The dynamic pressure rise is primarily due to lost particles. Though beam loss is small, proton/ion induced desorption is much higher than PSD.

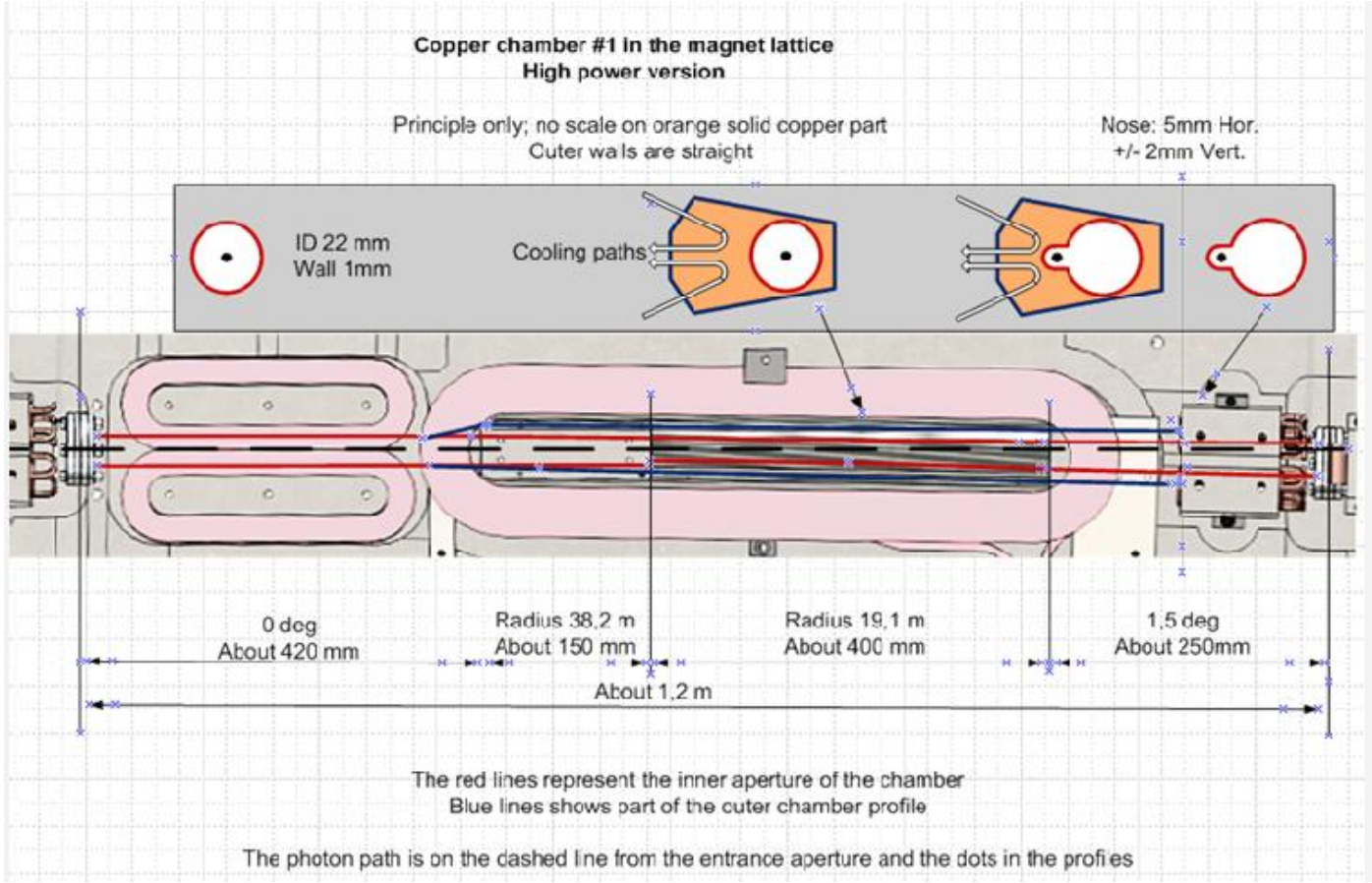
Beam Chamber Materials – Electric and Thermal

- *For high beam intensity accelerators, beam pipe material with high electric conductivity must be used for carrying image wall current.*
- *For beam chambers not subject to direct power deposition from synchrotron radiation or particle bombardment, stainless steel with copper coating/plating/lining is an option. The thickness of the copper coating only need to be a few factors of skin-depth at fundamental beam RF frequency.*
- *For beam chambers intercept SR power, or intense particle impingement, material with good bulk electric and thermal conductivities must be used. Aluminum alloys, copper or copper alloys are usually used.*

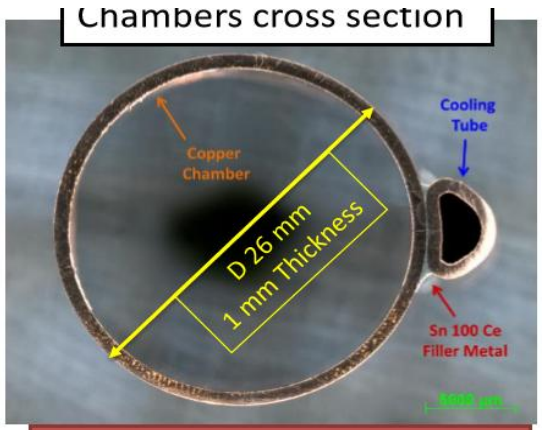
Vacuum Chamber Design

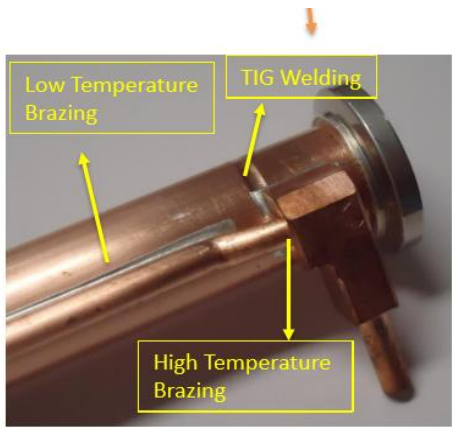


MAX-IV



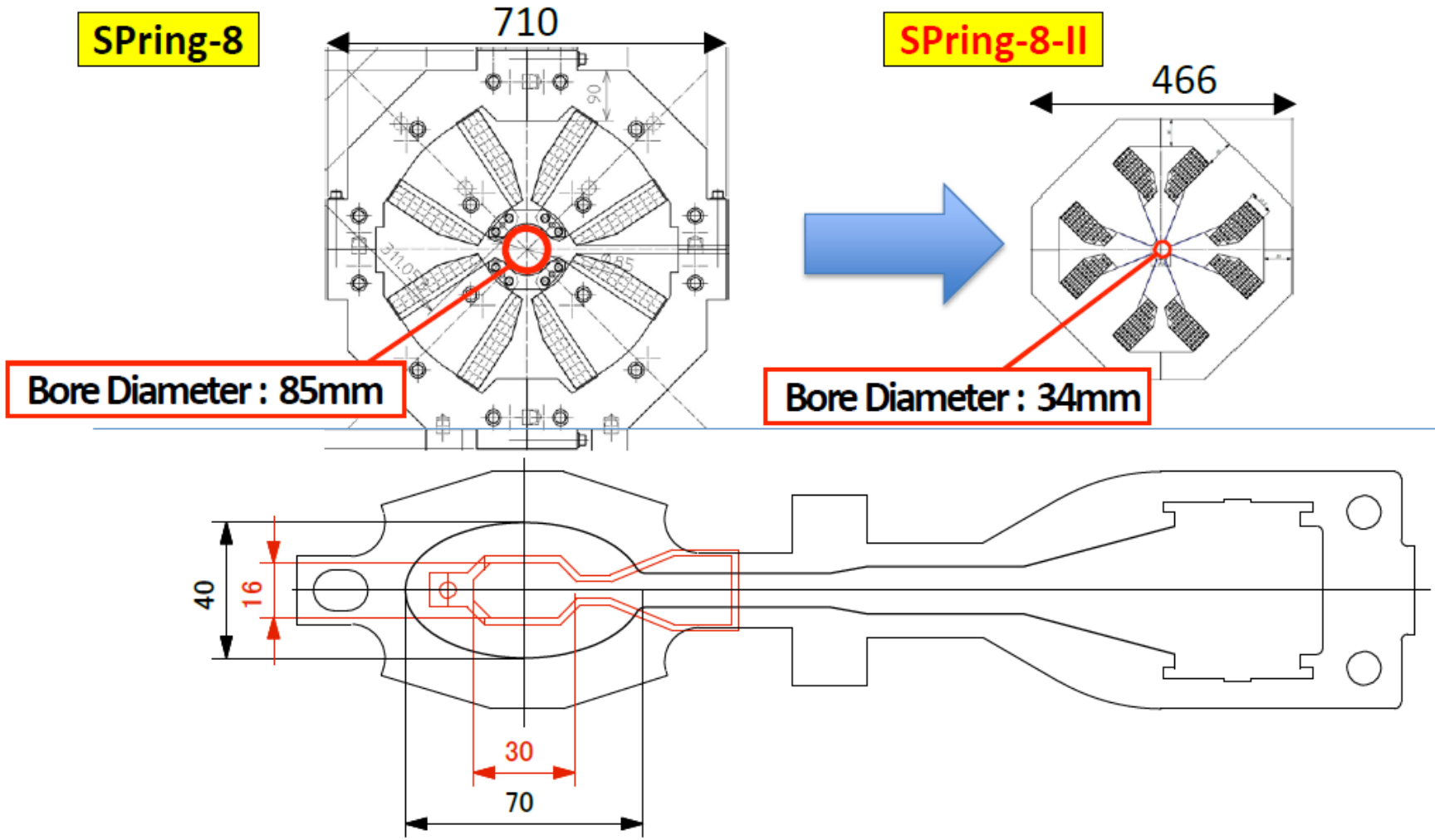
SIRIUS





Max. power density: 12 W/mm² (500 mA)
@ thin wall tubes

SPring-8-II from SPring-8

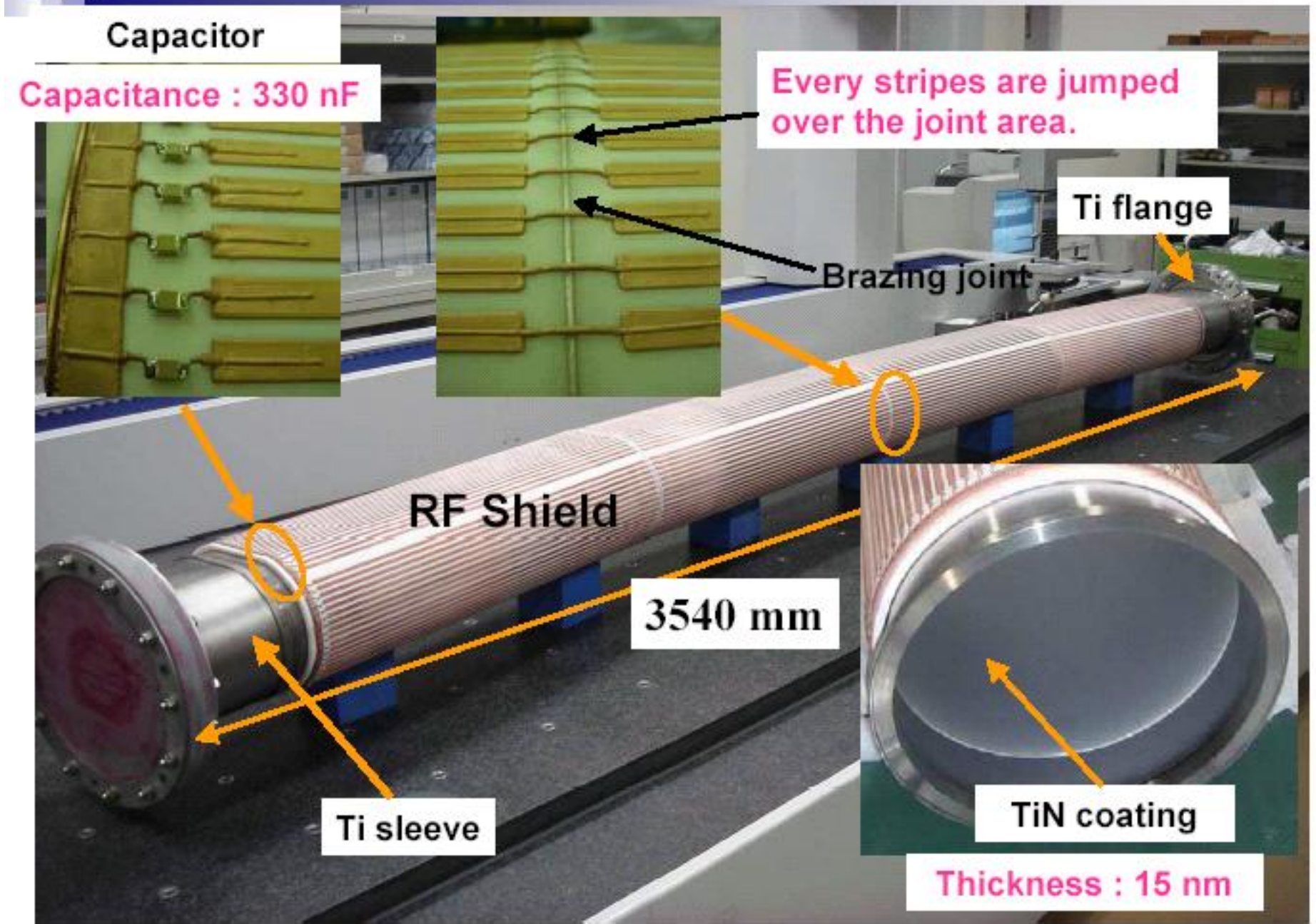


Black : Cross section of SPring-8 Aluminum Vacuum Chamber

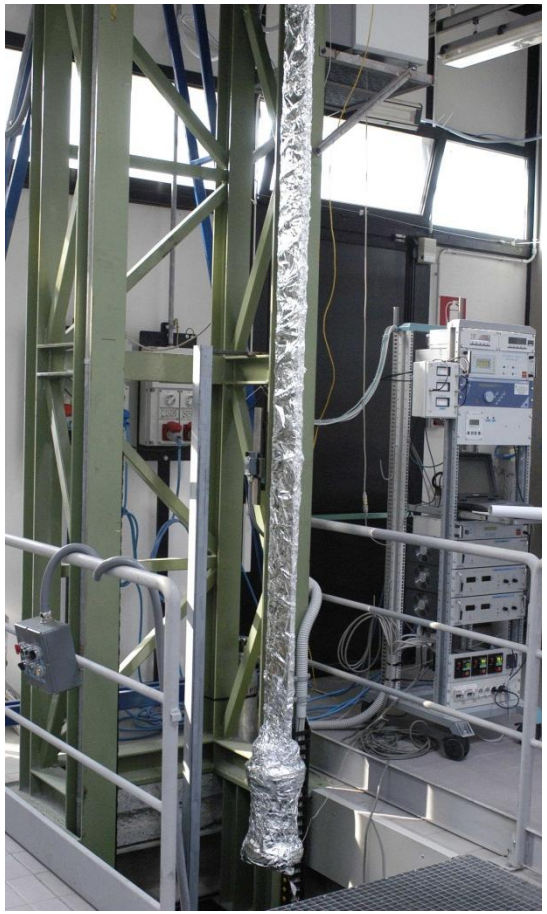
Red : Cross section of SPring-8-II Stainless Steel Vacuum Chamber

Ceramics chamber - picture -

J-PARC



NEG Coating Facility at SAES(Italy)

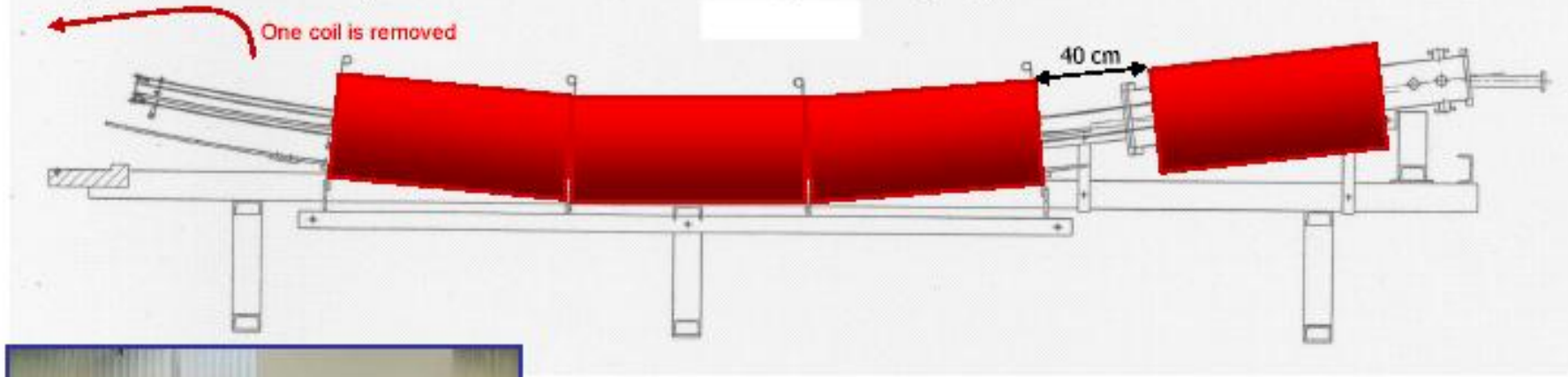


Detail of the SAES sputtering system used to apply the IntegraTorr SNEG coating, capable to process up to 7-meter long chambers.

Cathodes location - example

The SIS dipole chambers: sputtering facility

Integration of the dipole chamber into the sputtering system



The SIS dipole chambers: sputtering facility

Sputtering process

Coating parameters:

Cathode Voltage: [V]	500
Cathode current: [I]	0,4
Kr pressure: [mbar]	$7x10^{-3}$
Magnetic field: [Gauss]	150

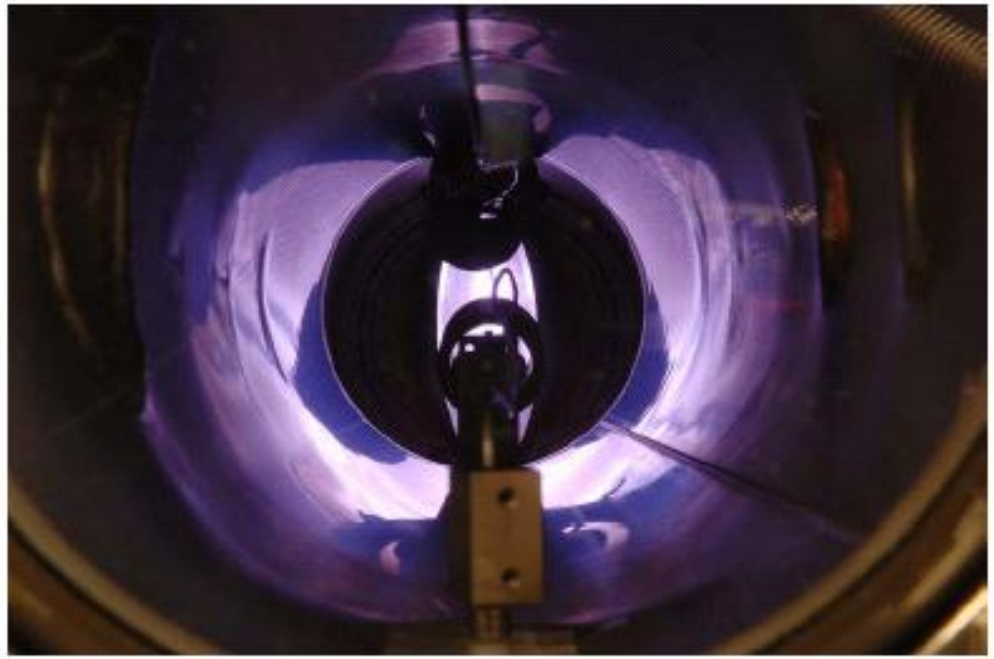
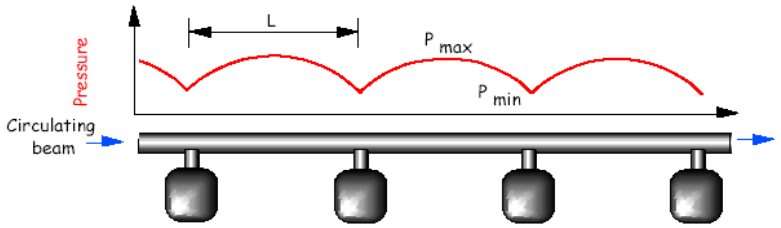
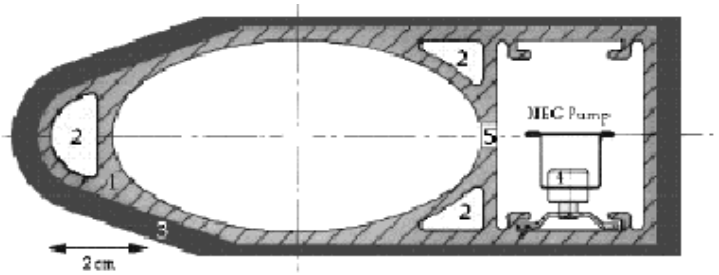


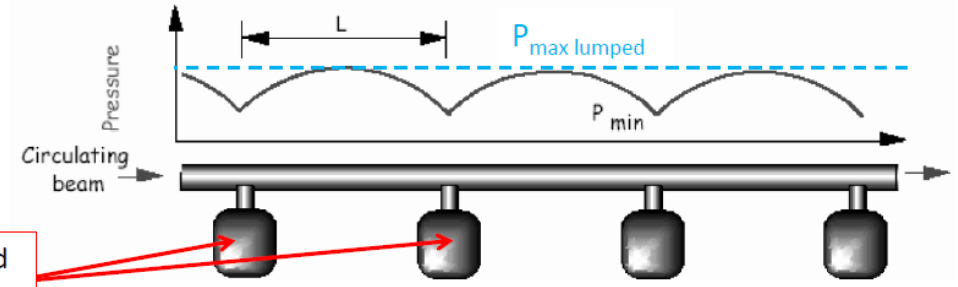
Foto G.Otto

From Lumped Pumps to Distributed Pumps



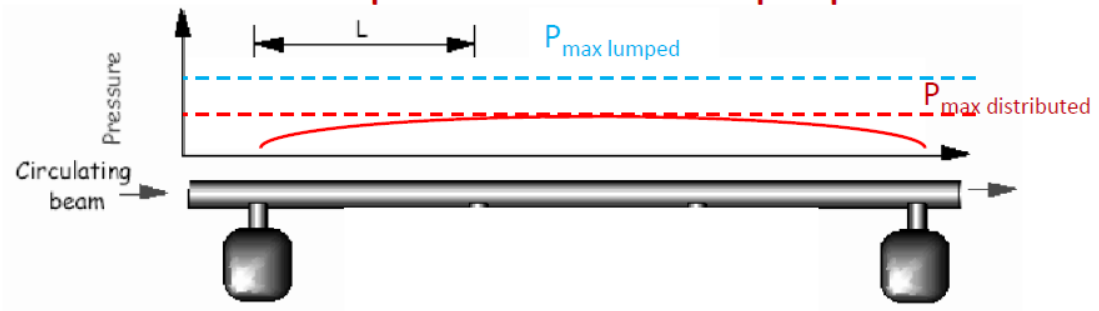


Pressure profile with lumped pumps

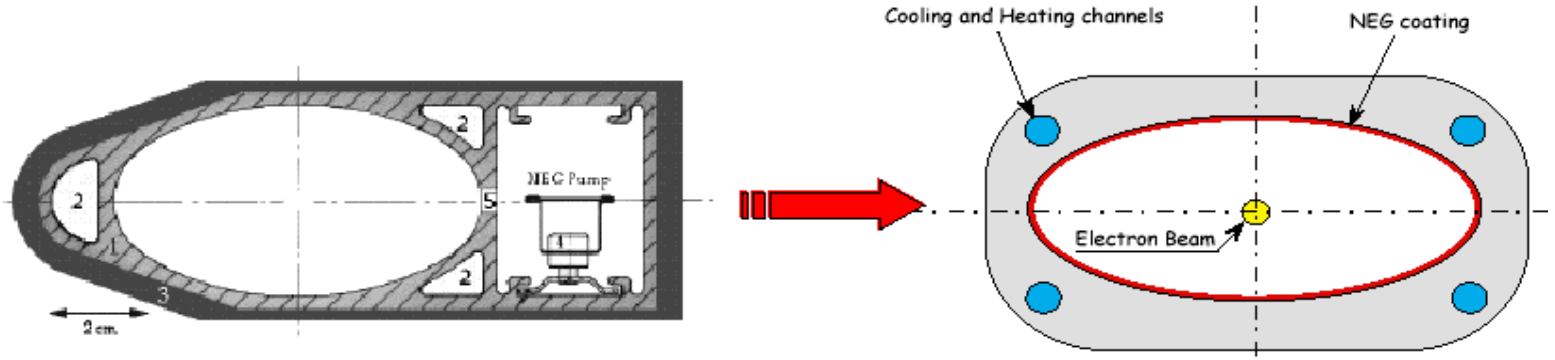


Lumped pumps

Pressure profile with distributed pumps



From Distributed Pumping to Integrated Pumping - NEG Coating

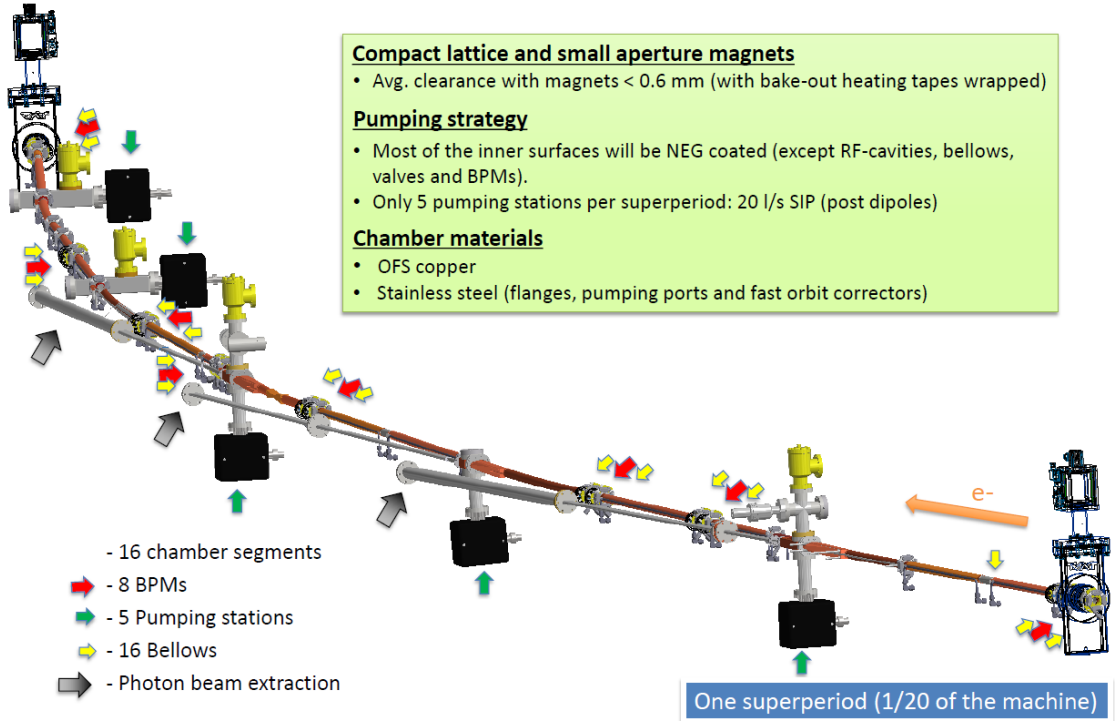


NEG-coating transforms a vacuum chamber from a gas source to a vacuum pump

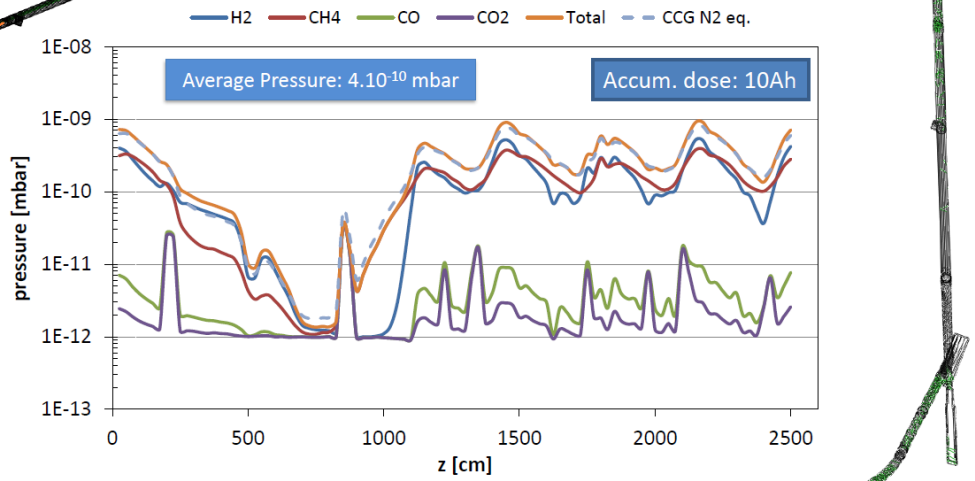
Compact lattice and small aperture magnets
- Avg. clearance with magnets < 0.6 mm (with bake-out heating tapes wrapped)

Pumping strategy
- Most of the inner surfaces will be NEG coated (except RF-cavities, bellows, valves and BPMs).
- Only 5 pumping stations per superperiod: 20 l/s SIP (post dipoles)

Chamber materials
- OFS copper
- Stainless steel (flanges, pumping ports and fast orbit correctors)



Synrad (R. Kersevan, CERN)



Used Sticking:
- H_2= 8.10^{-3}
- CH_4=3.6.10^{-3} ~ 10 l/s/m (only on SR absorbed facets) – *M. Ady, WEPME037, IPAC2014*
- CO= 5.10^{-1}
- CO_2=5.10^{-1}

Molflow+ (R. Kersevan, CERN)

Closing

- You may not need to deal with the vacuum fundamentals in your daily work, however, you still need to know how the different parameters in your system will affect your vacuum.
- Gas sources are important part which need to be under control at all stages, in order to achieve the required pressure.
- Relating outgassing, pressure, conductance and pumping speed together, will allow you to design a vacuum system
- Now you know the fundamentals of accelerator vacuum system, but as you know, “the devil is in the details”, so you need study hard to know all of them.

Good good study, Day day up!