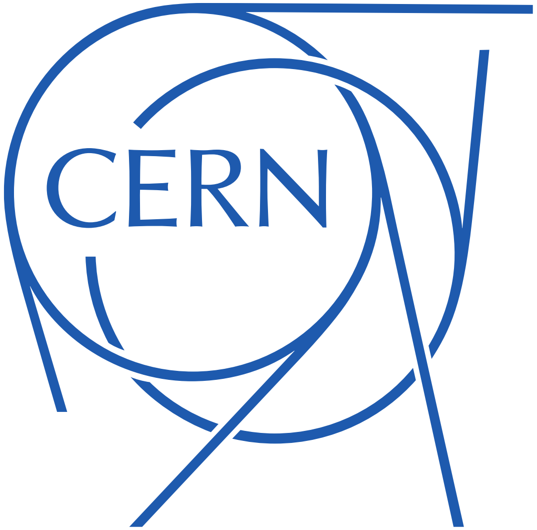

CERN

Vacuum Systems
Slot 2

V. Baglin

CERN TE-VSC, Geneva

Joint Universities Accelerator School

Outline

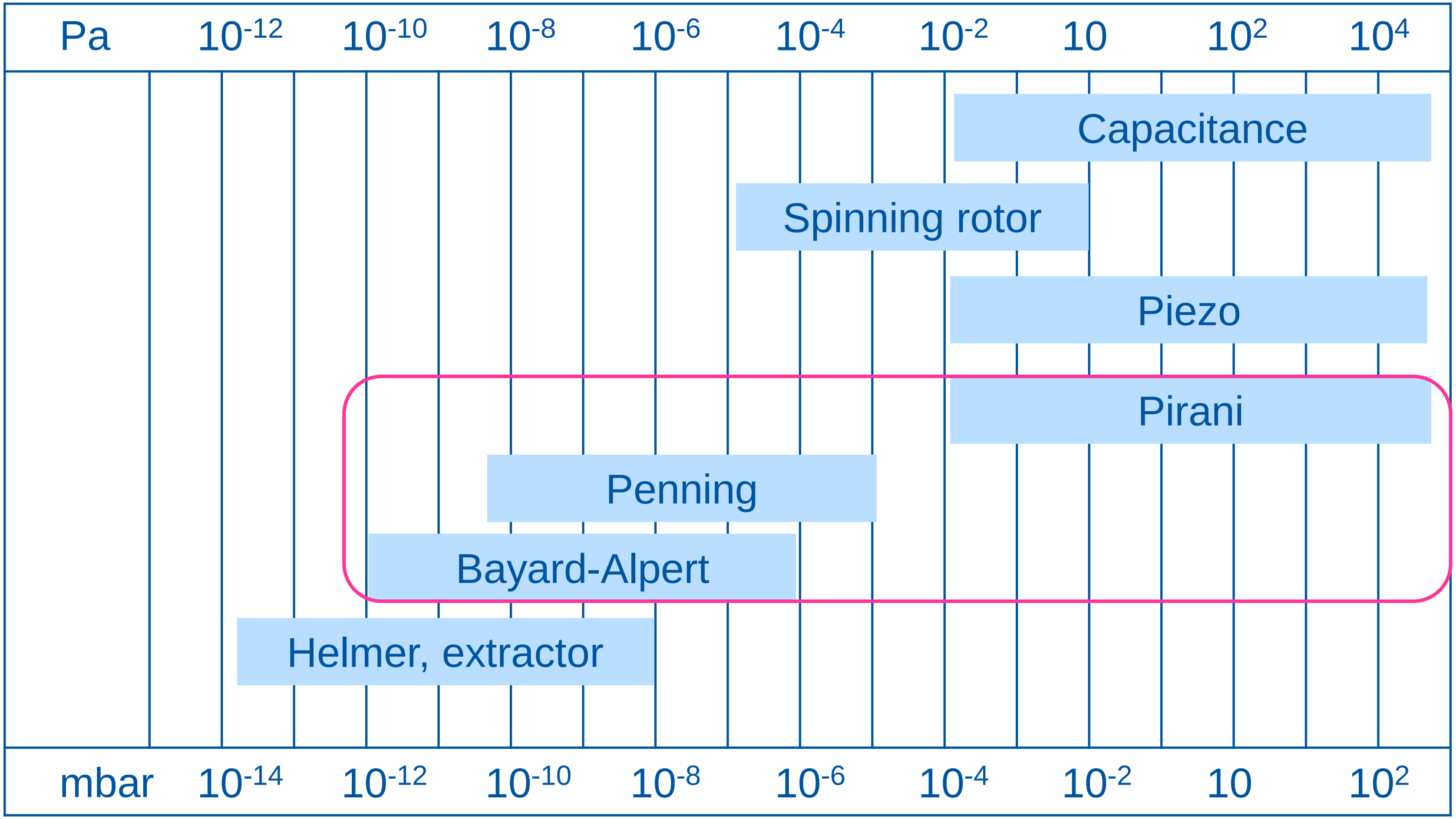
1. Measure of vacuum
2. Production of vacuum
3. Summary

1. Measure of vacuum

1.1 Vacuum gauges

Vacuum gauges pressure range

16 orders of magnitude !



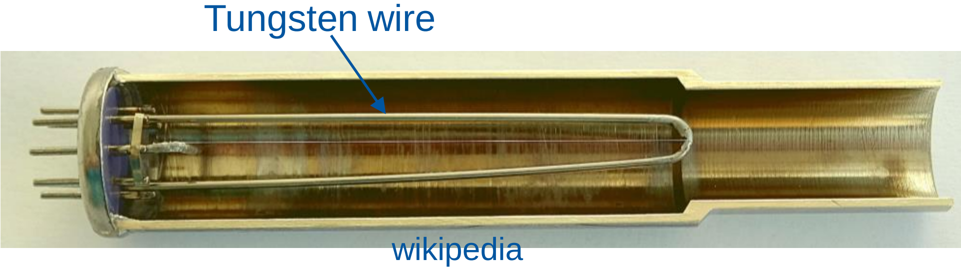
Pirani Gauge

- Pirani gauges are used in the range 1 atm -10^{-4} mbar to monitor the roughing of a vacuum system

- Robust, gas dependent, accuracy 10-100 %

- Operating principle based on the variation of the heat conductivity through a gas: balancing a Wheatstone bridge to keep power through filament constant

  ➔ pressure reading above 1 mbar are wrong



wikipedia

M. Pirani 1906

Inficon Pirani gauge

Pfeiffer Pirani gauge

Edwards Pirani gauge

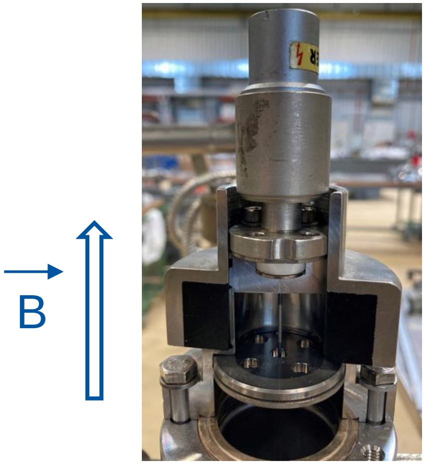
Penning gauge

- Penning gauges are commonly used in the range 10^{-5}-10^{-10} mbar. They are use for interlocking purposes

- Robust, gas dependent, accuracy ~ 20-50 %

- It is a cold cathode ionisation gauge *i.e.* there are no hot filament: electron are produced by field emission

- The operating principle is based on the measurement of a discharge current in a Penning cell which is a function of pressure : $I^+ = P^n$, n is close to 1



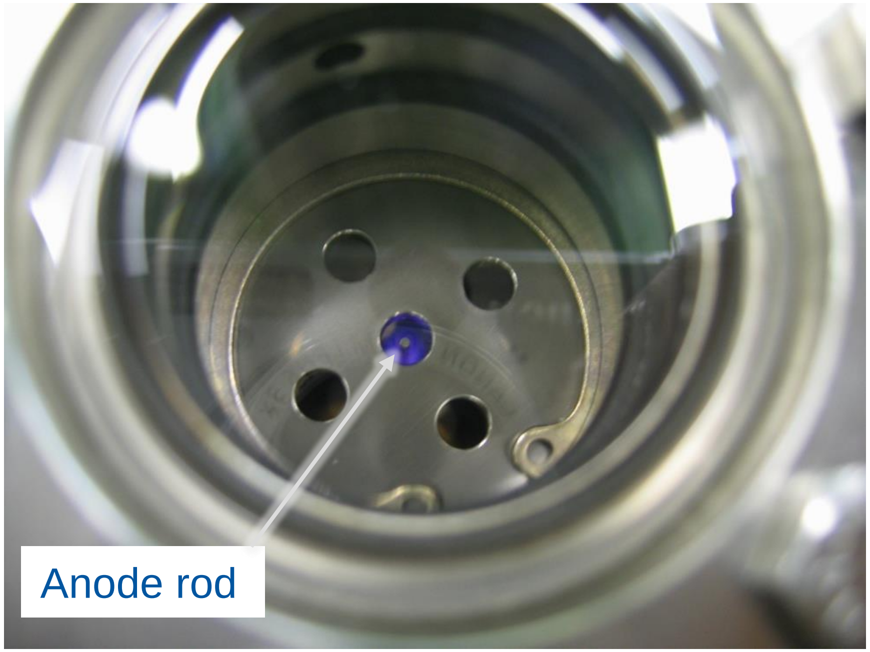

Pfeiffer Penning gauge


F. Penning 1937

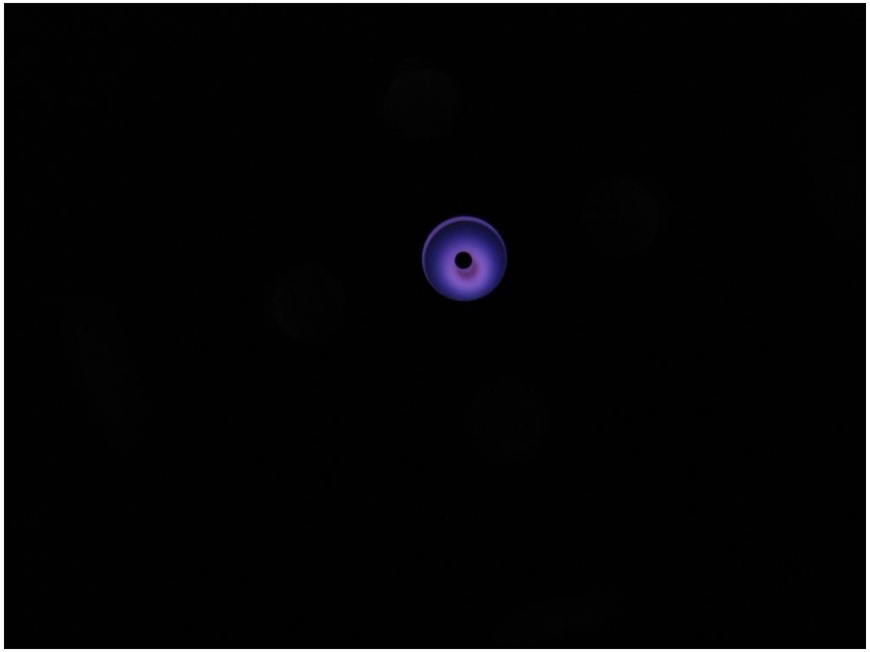
A discharge in a Penning gauge

- Penning gauge: a cloud of electrons is kept in place by a solenoidal magnetic field created by a permanent magnet ring

Penning gauge ON behind a glass window



In the dark, the discharge is seen: a plasma is created

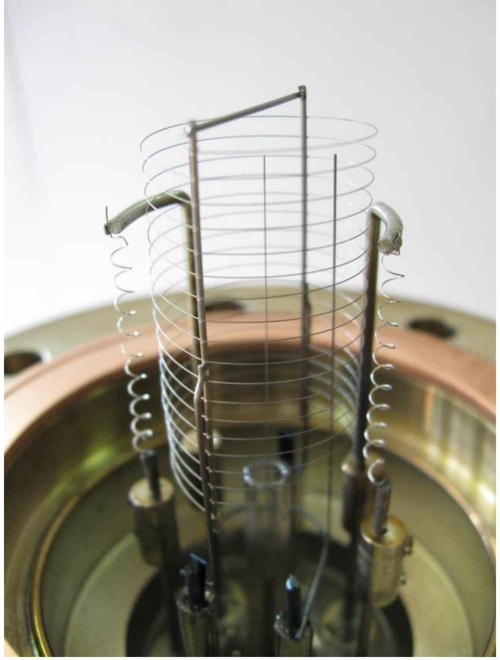


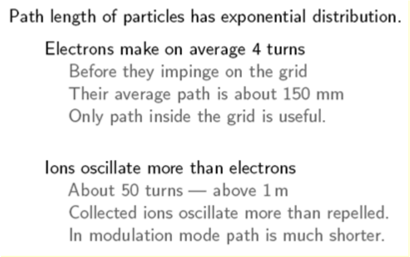
Pictures courtesy B. Henrist, TE-VSC

Bayard-Alpert Gauge

- Bayard-Alpert gauges are used for vacuum measurement purposes in the range 10^{-6} -10^{-12} mbar.

- It is a hot filament ionization gauge. Electrons emitted by the filament perform a few oscillations inside the grid and ionise the molecules of the residual gas. Ions are then collected by an electrode.



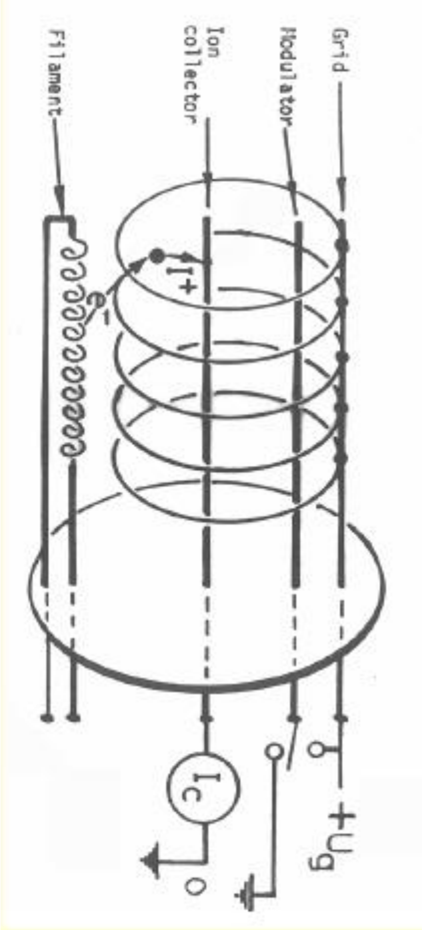


Path length of particles has exponential distribution.

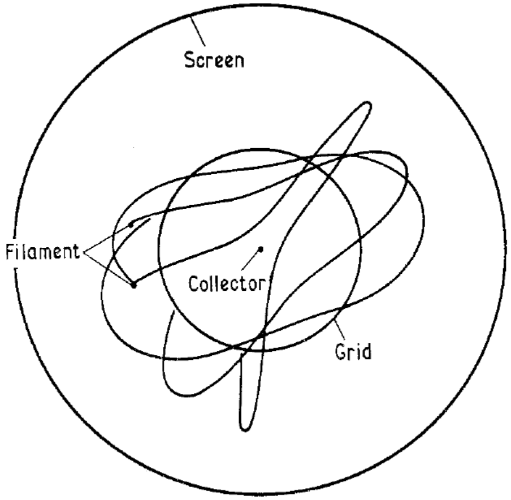
Electrons make on average 4 turns
  Before they impinge on the grid
  Their average path is about 150 mm
  Only path inside the grid is useful.

Ions oscillate more than electrons
  About 50 turns — above 1 m
  Collected ions oscillate more than repelled.
  In modulation mode path is much shorter.

Courtesy B. Jenninger, TE-VSC



Ion collector = 0 V
Filament = + 50 V
Grid = + 150 V
Modulator = + 150 V



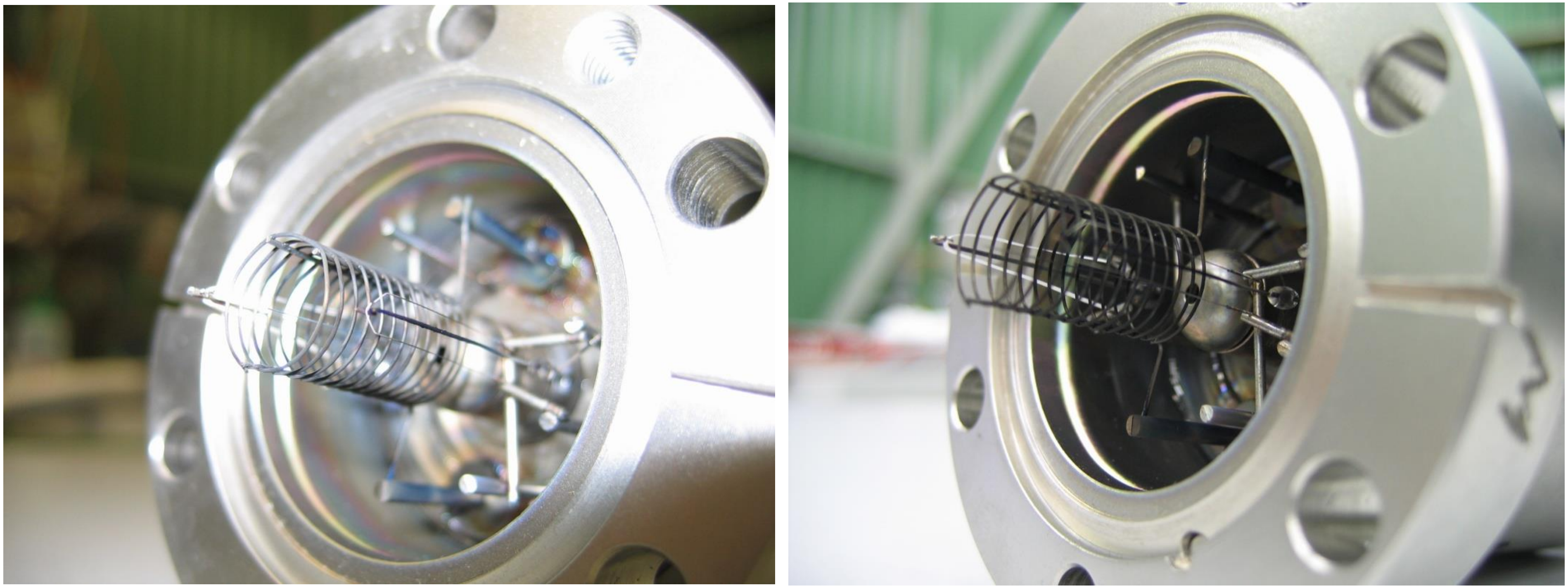
Electron trajectories for three different angles of incidence at the grid boundary, in a cross section of a Bayard-Alpert gauge

L.G. Pittaway. J. of Phys. D: Appl. Phys. 3, 1113-1121, 1970

A burned filament

- Obviously, even if there are 2 filaments, the gauge is polluted therefore the pressure measurement will not be correct !

- It is wise to exchange the vacuum gauge



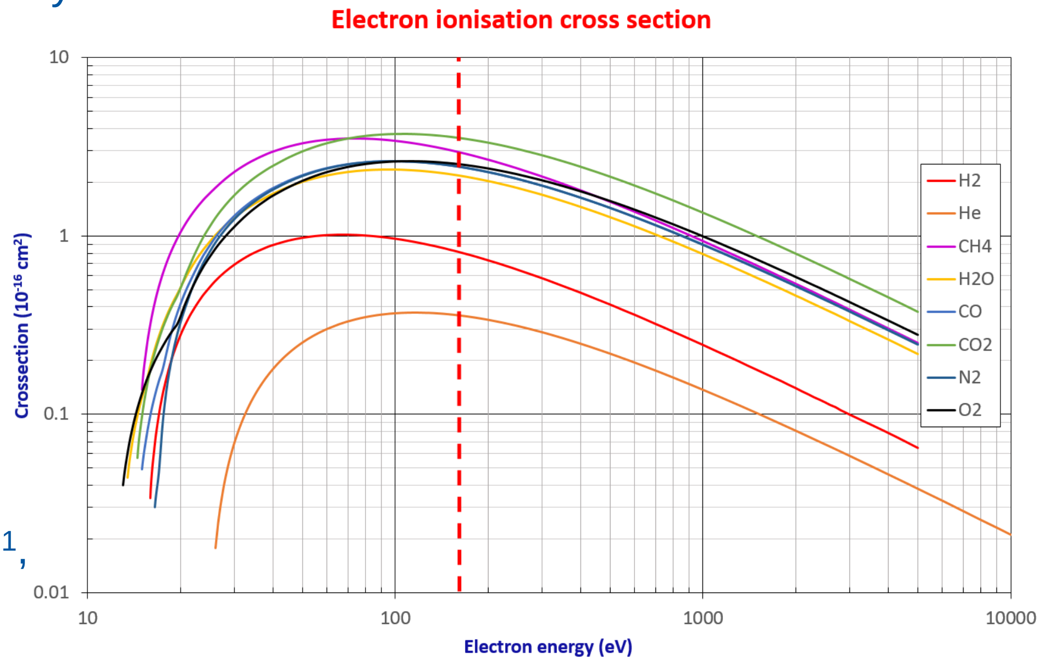
Pictures courtesy B. Henrist, TE-VSC

Bayard-Alpert Gauge: Sensitivity

- The ion current collection can be described by:

$$I^+ = I_e \sigma \, n \, L$$

Where :
I^+ is the ion current
I^- is the filament current
σ is the ionization cross section
n the gas density
L the electron path length



- The vacuum gauge sensitivity, S in mbar $^{-1}$, is defined by:

$$I^+ = I_e \, S \, P \qquad S = \frac{\sigma \, L}{k \, T}$$

I_e (mA)	P (mbar)	I^+ (pA)
4	10^{-10}	16
4	10^{-12}	0.16
0.1	10^{-10}	0.4
0.1	10^{-12}	0.004

- The gauge needs to be calibrated for several gases
- S_{N2} ~ 40 mbar $^{-1}$
- The pressure reading is expressed in nitrogen equivalent
- In UHV, typical collected currents are in the pA range

Bayard-Alpert Gauge: Sensitivity

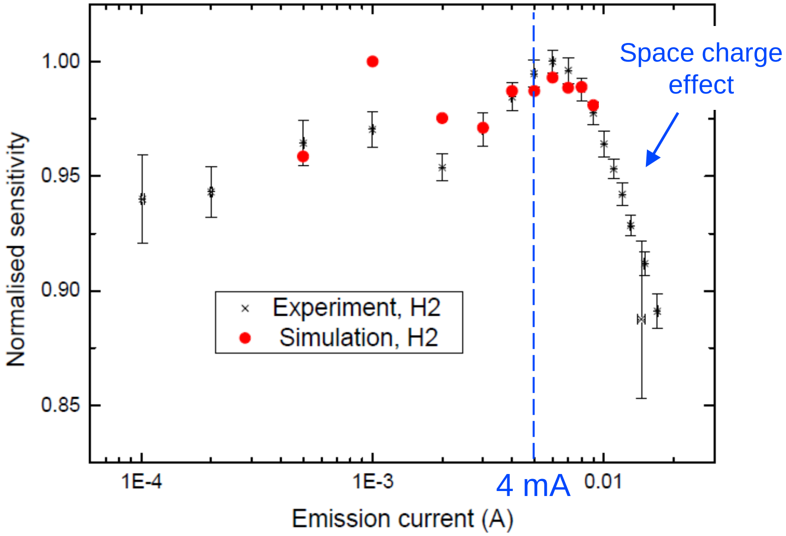
- The sensitivity can be measured and also computed from simulations

$$S_i = \frac{\sigma\, L}{k\, T}$$

- Relative sensitivity:

$$S_{rel,i} = \frac{S_{N2}}{S_i}$$

$$\boxed{P_i = S_{rel,i}\, P_{N2}}$$



B. Jenninger *et al*. Vacuum 138 (2017) 173-177

	H_2	He	CH_4	Ne	N_2	CO	C_2H_6	Ar	CO_2	Xe
S_i (mbar^{-1})	19.06	7.46	60.62	10.48	41.84	42.30	114.71	53.19	54.48	7.50
$S_{rel,i}$ (mbar,i/mbar,N_2)	2.20	5.61	0.69	3.41	**1.0**	0.99	0.36	0.79	0.77	4.83

- The sensitivity relative error equals ~ 10 %
- A pressure reading in N_2 equivalent is: $P_{read} = 2\ 10^{-10}$ mbar, in the case the main molecular species is H_2, the real pressure is: $P = S_{rel,H2} \times P_{read} = 4.4\ 10^{-10}$ mbar

1.2 Gas analysis

Residual gas composition

- Q: “Why do we need to know the gas composition in an accelerator?”
- As already mentioned, the beam circulating in the accelerator has a probability to collide with the residual gas.
- The beam can interact via elastic and inelastic processes (energy conserved or not), through many physical mechanisms.
- Here an example for the BESSY-II light source in Berlin (1.7 GeV, e- accelerator).

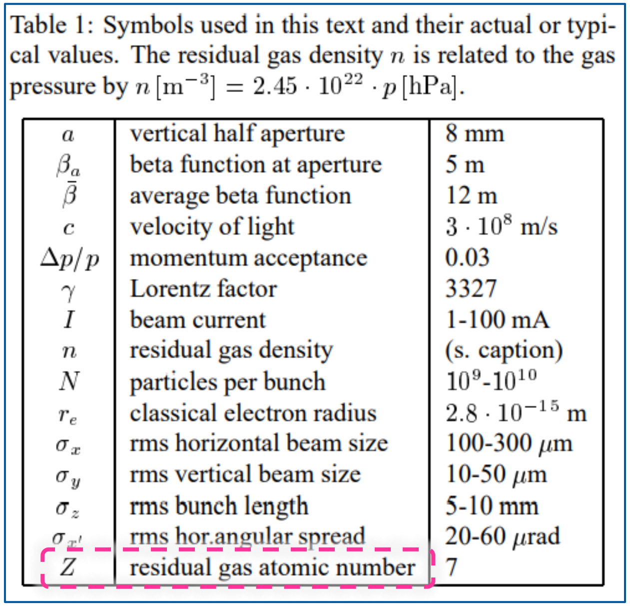
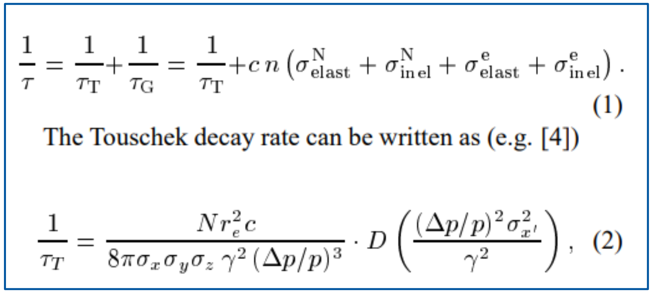


Table 1: Symbols used in this text and their actual or typical values. The residual gas density n is related to the gas pressure by $n\,[\mathrm{m}^{-3}] = 2.45 \cdot 10^{22} \cdot p\,[\mathrm{hPa}]$.

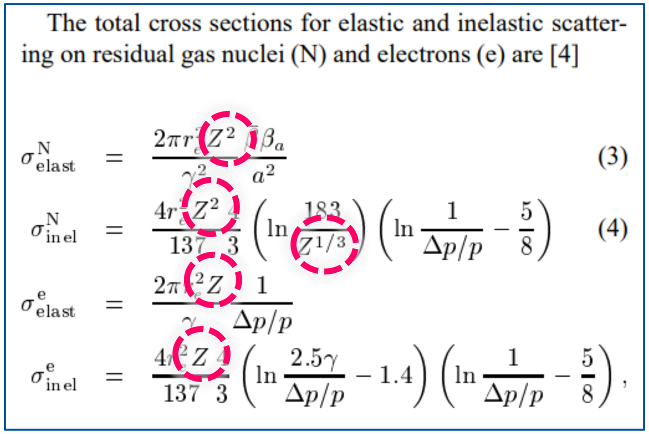
a	vertical half aperture	8 mm
β_a	beta function at aperture	5 m
$\bar{\beta}$	average beta function	12 m
c	velocity of light	$3 \cdot 10^8$ m/s
$\Delta p/p$	momentum acceptance	0.03
γ	Lorentz factor	3327
I	beam current	1-100 mA
n	residual gas density	(s. caption)
N	particles per bunch	10^9-10^{10}
r_e	classical electron radius	$2.8 \cdot 10^{-15}$ m
σ_x	rms horizontal beam size	100-300 μm
σ_y	rms vertical beam size	10-50 μm
σ_z	rms bunch length	5-10 mm
$\sigma_{x'}$	rms hor.angular spread	20-60 μrad
Z	residual gas atomic number	7



$$\frac{1}{\tau} = \frac{1}{\tau_\mathrm{T}} + \frac{1}{\tau_\mathrm{G}} = \frac{1}{\tau_\mathrm{T}} + c\,n\left(\sigma^\mathrm{N}_\mathrm{elast} + \sigma^\mathrm{N}_\mathrm{in\,el} + \sigma^\mathrm{e}_\mathrm{elast} + \sigma^\mathrm{e}_\mathrm{in\,el}\right). \qquad (1)$$

The Touschek decay rate can be written as (e.g. [4])

$$\frac{1}{\tau_T} = \frac{N r_e^2 c}{8\pi\sigma_x\sigma_y\sigma_z\,\gamma^2\,(\Delta p/p)^3} \cdot D\left(\frac{(\Delta p/p)^2\sigma_{x'}^2}{\gamma^2}\right), \qquad (2)$$



The total cross sections for elastic and inelastic scattering on residual gas nuclei (N) and electrons (e) are [4]

$$\sigma^\mathrm{N}_\mathrm{elast} = \frac{2\pi r_e^2 Z^2 \bar{\beta}\beta_a}{\gamma^2\, a^2} \qquad (3)$$

$$\sigma^\mathrm{N}_\mathrm{in\,el} = \frac{4 r_e^2 Z^2}{137}\frac{4}{3}\left(\ln\frac{183}{Z^{1/3}}\right)\left(\ln\frac{1}{\Delta p/p} - \frac{5}{8}\right) \qquad (4)$$

$$\sigma^\mathrm{e}_\mathrm{elast} = \frac{2\pi r_e^2 Z}{\gamma}\frac{1}{\Delta p/p}$$

$$\sigma^\mathrm{e}_\mathrm{in\,el} = \frac{4 r_e^2 Z}{137}\frac{4}{3}\left(\ln\frac{2.5\gamma}{\Delta p/p} - 1.4\right)\left(\ln\frac{1}{\Delta p/p} - \frac{5}{8}\right),$$

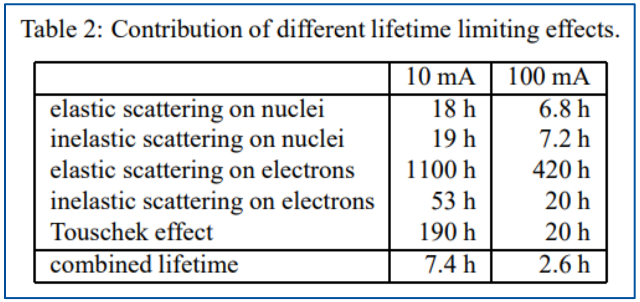


Table 2: Contribution of different lifetime limiting effects.

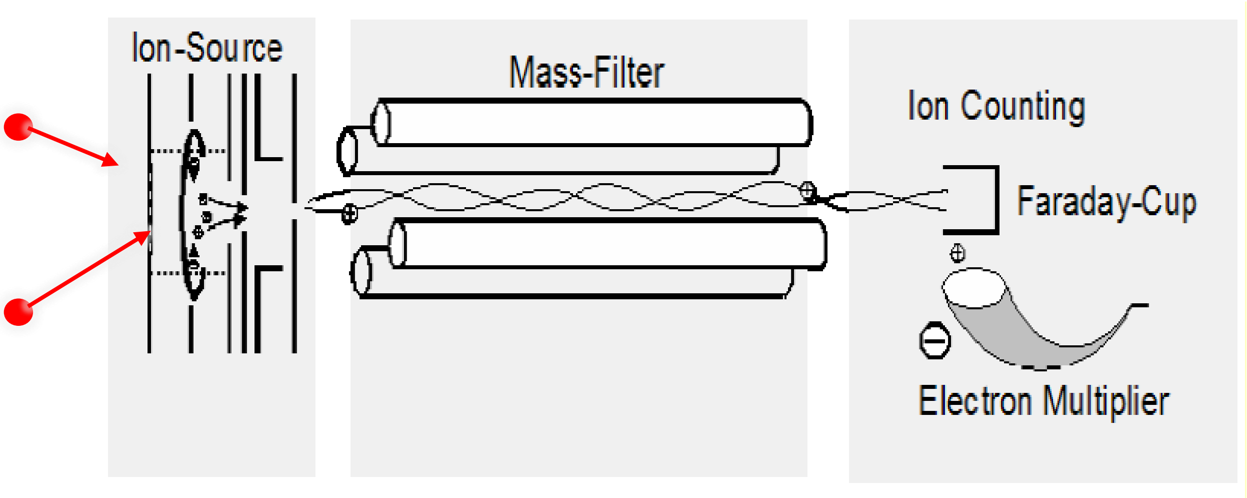
	10 mA	100 mA
elastic scattering on nuclei	18 h	6.8 h
inelastic scattering on nuclei	19 h	7.2 h
elastic scattering on electrons	1100 h	420 h
inelastic scattering on electrons	53 h	20 h
Touschek effect	190 h	20 h
combined lifetime	7.4 h	2.6 h

Ref. https://accelconf.web.cern.ch/p99/PAPERS/THA104.PDF

Residual Gas Analysers

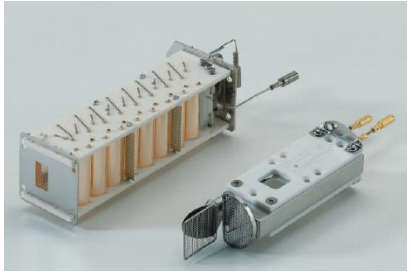
- Residual Gas Analysers are used in the range 10^{-4} -10^{-13} mbar. Their purpose is to do gas analysis to define the gas composition.
- A filament produces electrons which ionise the residual gas inside a grid.
- A mass filter is introduced between the grid and the ion collector.
- The ion current can be measured in Faraday mode or in secondary electron multiplier mode.

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



1 mA
Q ~ 2 10^{-9} mbar.l/s

ΔM at FHWM = 0.5 AMU



Range: 10^{-14} till 10^{-5} A
Gain ~ 10^{3} -10^{4} electrons/ion

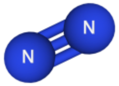
Picture Pfeiffer

RGA: Cracking pattern

- Ions produced inside the grid can be fragmented into sub-species by the collisions with electrons
- The table gives the percentage of the fragments with respect to the main peak

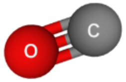
- Example Mass 28

- Nitrogen is traced by mass:



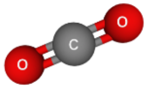
28 (N_2^+)
14 (N^+): $I_{14} = 0.14\ I_{28}$

- Carbon monoxide is traced by mass:

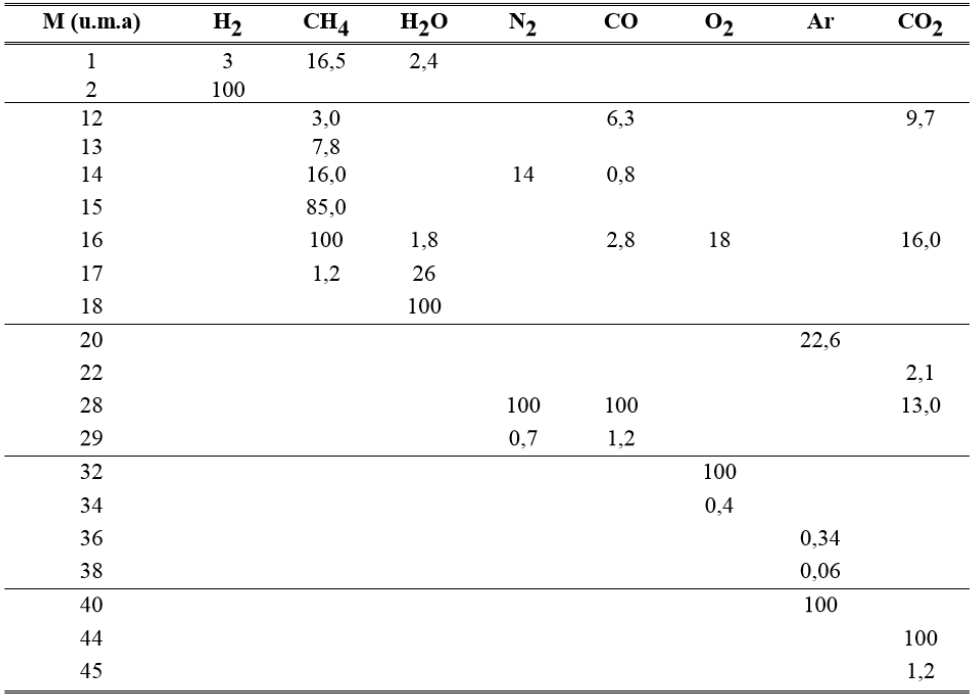


28 (CO^+)
12 (C^+): $I_{12} = 0.06\ I_{28}$

- Carbon dioxide is traced by mass:



44 (CO_2^+)
28 (CO^+): $I_{28} = 0.13\ I_{44}$
16 (O^+): $I_{16} = 0.16\ I_{44}$
12 (C^+): $I_{12} = 0.10\ I_{44}$



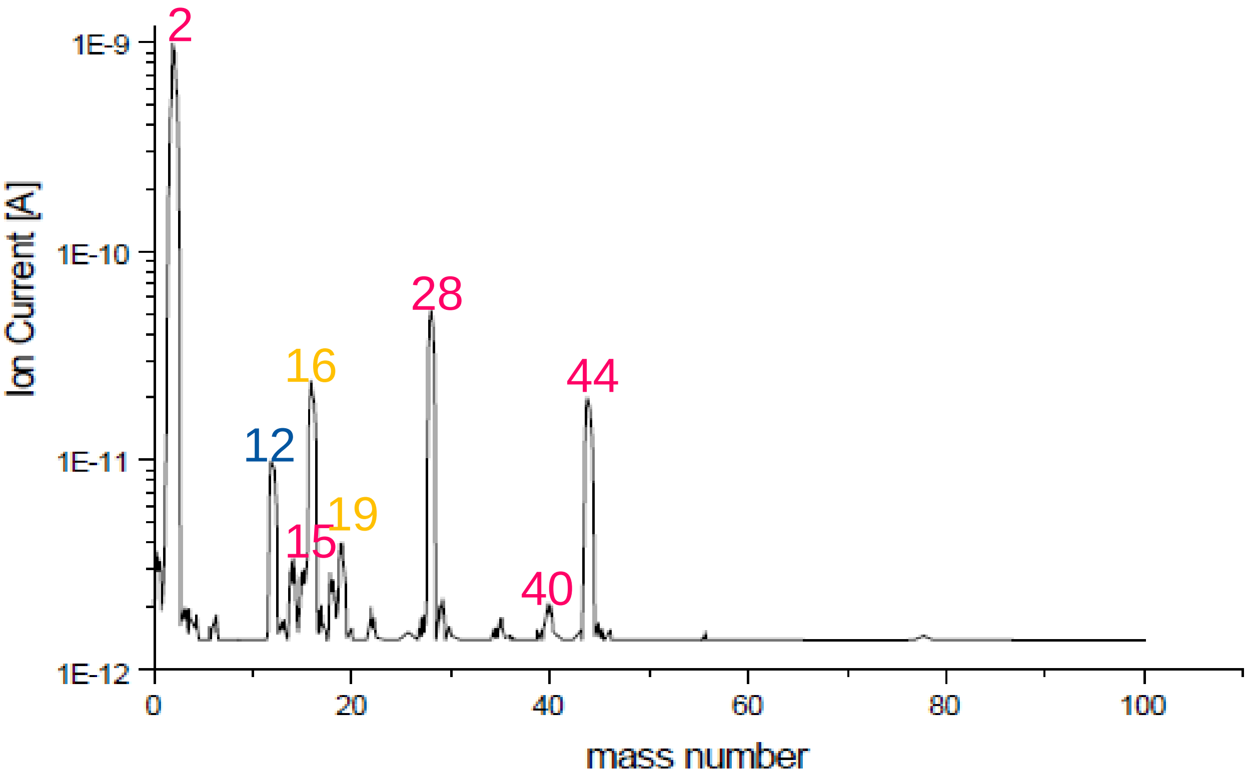
M (u.m.a)	H_2	CH_4	H_2O	N_2	CO	O_2	Ar	CO_2
1	3	16,5	2,4					
2	100							
12		3,0			6,3			9,7
13		7,8						
14		16,0		14	0,8			
15		85,0						
16		100	1,8		2,8	18		16,0
17		1,2	26					
18			100					
20							22,6	
22								2,1
28				100	100			13,0
29				0,7	1,2			
32						100		
34						0,4		
36							0,34	
38							0,06	
40							100	
44								100
45								1,2

RGA: Spectrum

- A typical spectrum of a baked* vacuum system: P = 10^{-10} mbar

* Baked vacuum system:
System which has received a thermal cycle above ~150 °C in order to remove H_2O vapor

M/e	Ion	Molecule
2	H_2^+	H_2
15	CH_3^+	CH_4
28	CO^+	CO
40	Ar^+	Ar
44	CO_2^+	CO_2
12	C^+	$CO+CO_2$
16	O^+	Filament artefacts
19	F^+	



H_2
Di-Hydrogen
M/e=2;1

CH_4
Methane
M/e=15;(16)

H_2O
Water
M/e=18;17;16

CO
Carbon monoxide
M/e=28;12

Ar
Argon
M/e=40;20

CO_2
Carbon dioxide
M/e=44;16;28;12

N_2
Nitrogen
M/e=28;14

O_2
Oxygen
M/e=32;16

RGA: Partial Pressure

- The RGA needs to be calibrated against a total pressure gauge for standard gases.
- To consider the RGA ageing, relative sensitives $S_{rel,i,RGA}$ are used and a **normalization factor**, K, is introduced

$$P_{i,N2} = K\, S_{abs,CO,RGA} \times S_{rel,i,RGA} \times I_i$$

- According to Dalton's law, the reading given by the total pressure gauge should be equal to the sum of the partial pressures, expressed in nitrogen equivalent:

$$P_{N2} = \sum_{j=1}^{n} P_{j,N2} = K\, S_{abs,CO,RGA} \sum_{j=1}^{n} \left(S_{rel,j,RGA} \times I_j\right)$$

- Therefore:

$$K = \frac{P_{N2}}{S_{abs,CO,RGA} \sum_{j=1}^{n} \left(S_{rel,j,RGA} \times I_j\right)}$$

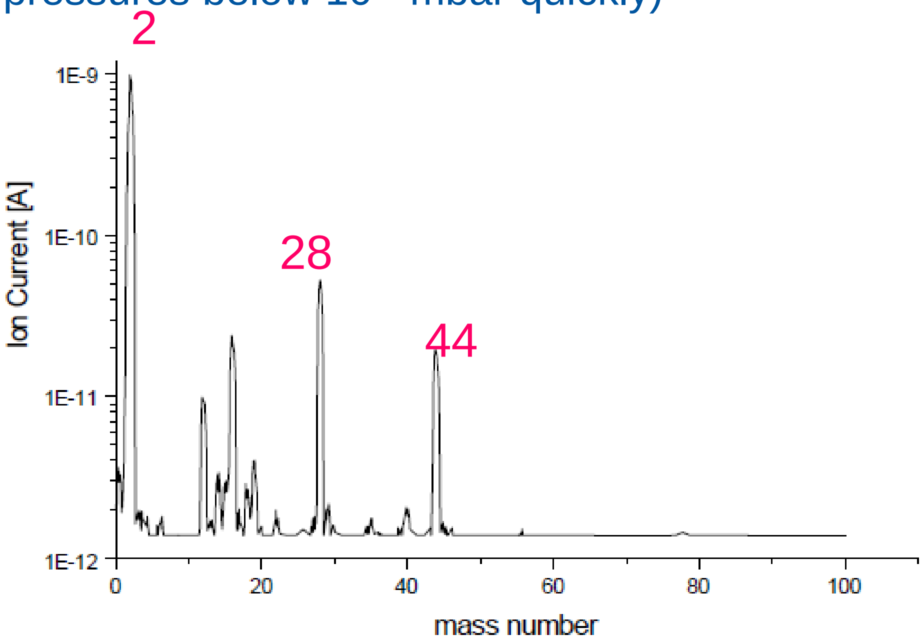
- So:

$$\boxed{P_i = S_{rel,i}\, P_{i,N2} = S_{rel,i} \frac{S_{rel,i,RGA}}{\sum_{j=1}^{n} S_{rel,j,RGA} \times I_j} P_{N2}\, I_i}$$

	H_2	CH_4	N_2	CO	Ar	CO_2
$S_{rel,i,RGA}$ (Torr N_2/Torr$_i$)	1.09	0.93	0.99	1	1.18	1.96

Typical spectrum of a baked vacuum system

- Baked system with P= 10^{-10} mbar N_{2}-eq
- “Baking” means heating under vacuum above 150 ºC for >24h, to remove water vapor; It is a pre-requisite to getting pressures below 10^{-8} mbar quickly)



	H_2	CH_4	CO	Ar	CO_2
I (A)	$1\cdot10^{-9}$	$2\cdot10^{-12}$	$7\cdot10^{-11}$	$5\cdot10^{-13}$	$2\cdot10^{-11}$
P (mbar)	$2\cdot10^{-10}$	$1\cdot10^{-13}$	$6\cdot10^{-12}$	$4\cdot10^{-14}$	$3\cdot10^{-12}$
% Pi	96	0	3	0	1

- Note: a simple estimation from the total pressure measurement would give P = $2.2\cdot10^{-10}$ mbar!

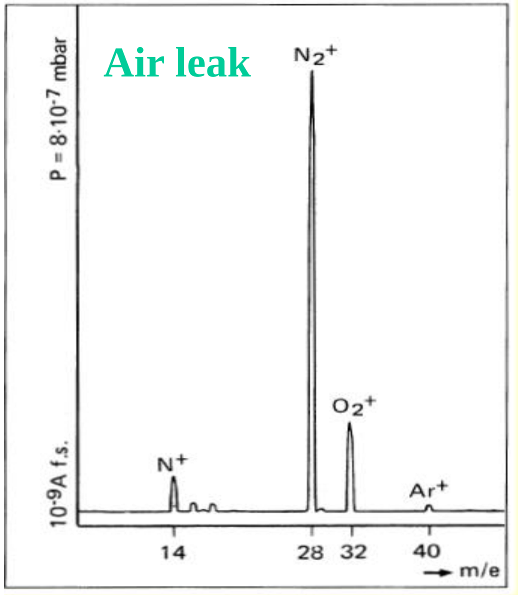
Typical spectrum in the presence of an air leak

- RGA are also useful to identify, trace and estimate air leaks

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	$5.2\ 10^{-4}$	$7\ 10^{-2}$

M/e	Ion	Molecule
14	N^+	N_2
28	N_2^+	N_2
32	O_2^+	O_2
40	Ar^+	Ar



- Assume an 8 cm diam. tube with specific conductance ~ 60 ℓ·m/s:
  - a leak detected 10 m away from the gauge (at P= $8\cdot10^{-7}$ mbar)
  - Hence, a pumping speed of 6 ℓ/s at the level of the leak gives a leak rate of:

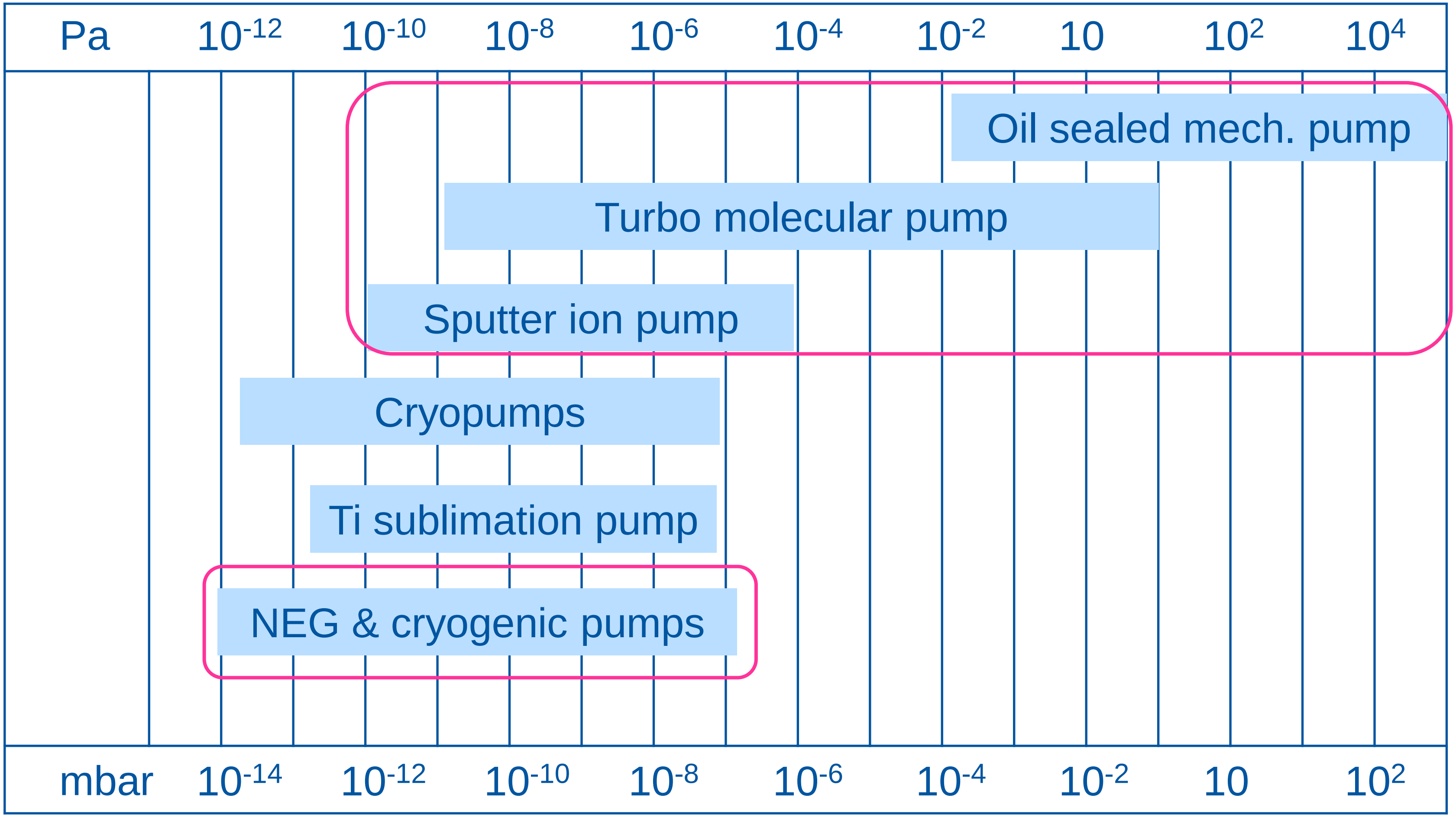
$$6 \times 8\cdot10^{-7} = 4.8\cdot10^{-6}\ \text{mbar}\cdot\ell/\text{s}$$

- Beware, oxygen being highly chemically reactive, its mass is not always present in the spectrum!

2. Production of vacuum

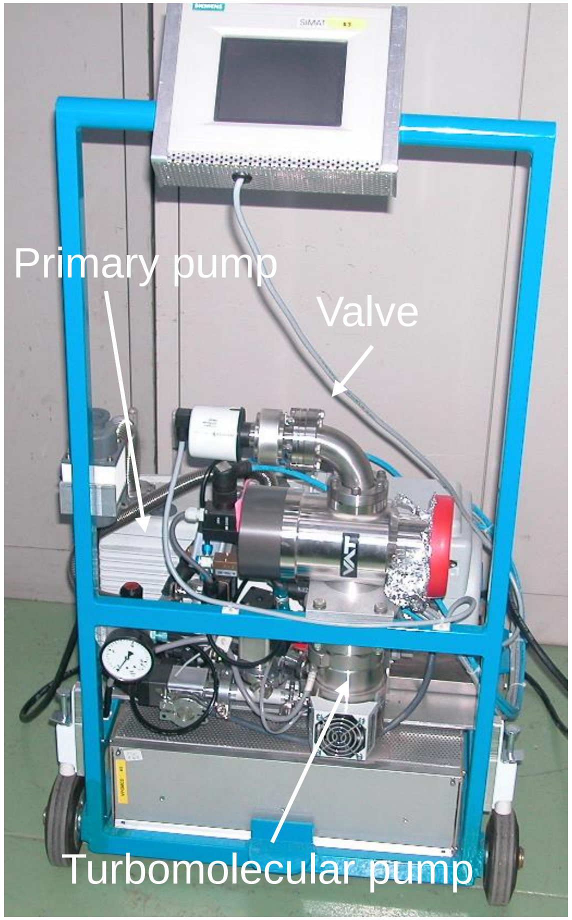
Vacuum pumps pressure range

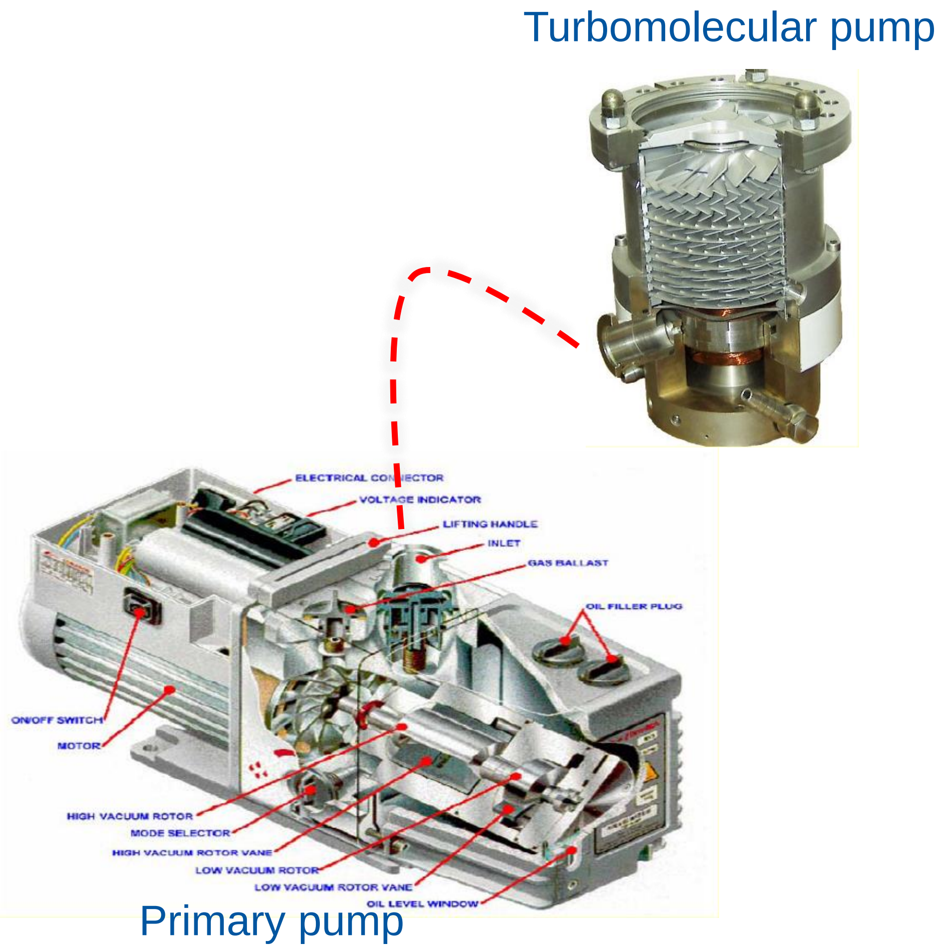
16 orders of magnitude !



Turbomolecular pumping group

- Used to pump down from atmosphere and commission vacuum sectors down to 10^{-11} mbar
- Mobile system based on rotary vane primary pump and turbomolecular pump

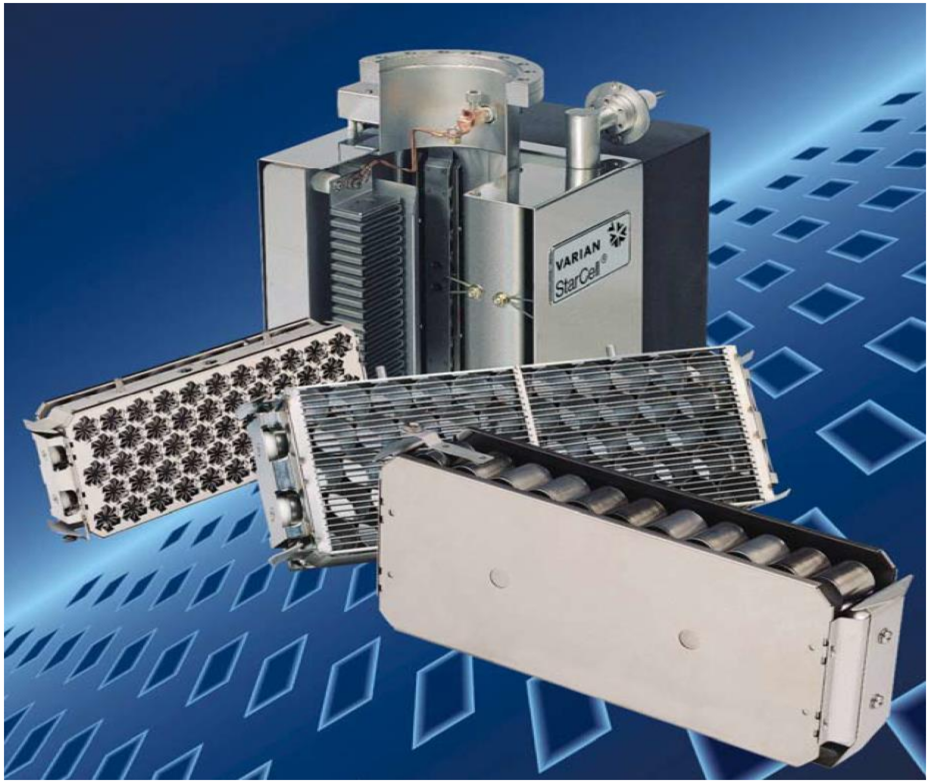




W. Becker, 1956
A. Pfeiffer GmbH

Sputter Ion Pump

- This pump operates in the range 10^{-5} -10^{-11} mbar. It is used to maintain the pressure in the vacuum chamber of an accelerator. It has NO exhaust, it traps the gas species.
- Typical pumping speed range from 1 to 500 l/s (but 1000-2000 l/s custom models exist)
- Titanium sputtered from the cathode bombarded by accelerated ions provides pumping.
- The ion current is proportional to pressure, hence these pumps are often used for interlocks, in place of gauges



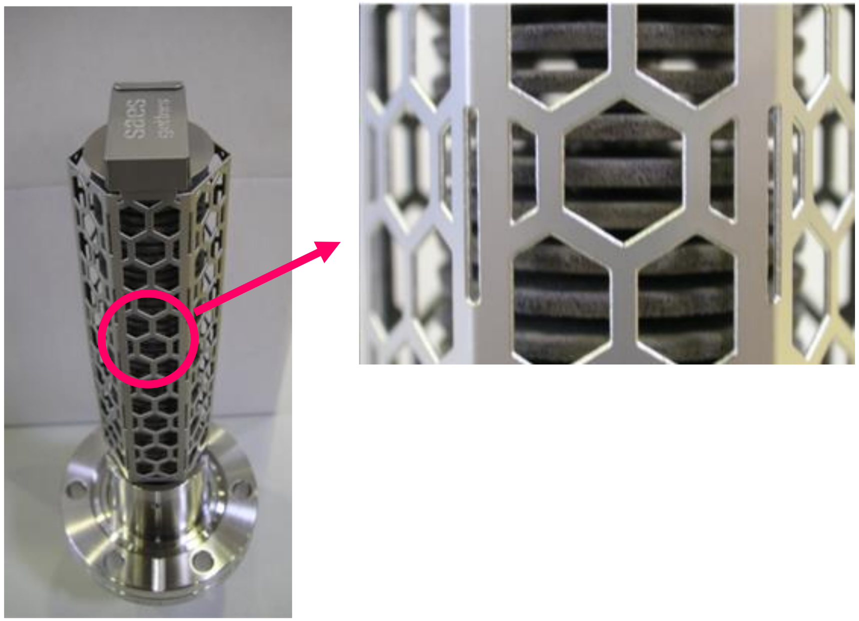
Pictures Agilent (Varian)

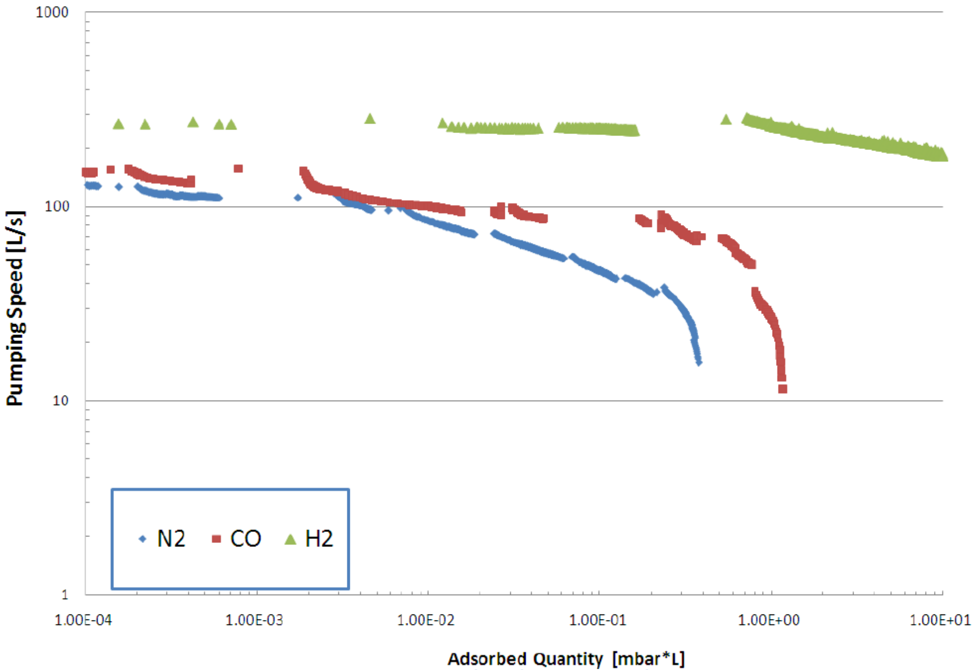
Hi-Voltage feed-thru
3-7 kV

NEG cartridge

- This pumps operates in the UHV regime in a range < 10^{-8} mbar
- It is used as a complementary pumping system to *e.g.* ion pumps.

- Zr based getter materials are sintered and form porous disks.
- After activation at ~ 500ºC for 1h, the pumping speed can be large: 100 – 2 000 l/s
- Large sorption capacity: >0.1 – 10 mbar.l for N_2, CO and > 10 mbar.l for H_2!
  - Reminder: 1 mbar.l = 4.3 10^{19} molecules, ~ 1 monolayers of a 10m long,Ø10 tube
- H_2 diffuse into the bulk, CO is adsorbed in 1 active site whereas N_2 requires 6.
- Gas mixture: CO adsorption inhibit H_2 and N_2 pumping

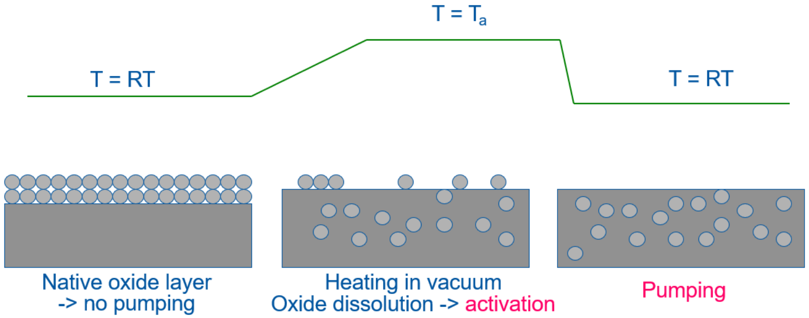




Courtesy G. Bregliozzi, J. Callagher, 2012

Non-Evaporable Getter (NEG)

- Getters (eg Ti) are materials capable of chemically adsorbing gas molecules. To do so their surface must be clean.
- For Non-Evaporable Getters (eg TiZrV films) a clean surface is obtained by heating to a temperature high enough to dissolve the native oxide layer into the bulk.
- NEGs pump most of the gas except rare gases and methane at room temperature



T = RT
$T = T_a$
T = RT

Native oxide layer
-> no pumping

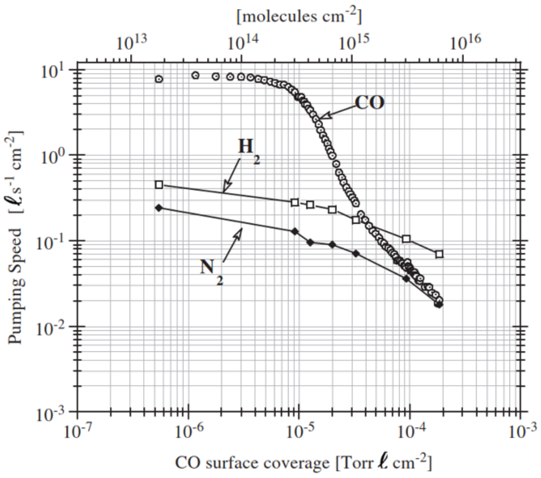
Heating in vacuum
Oxide dissolution -> activation

Pumping

- 1 µm thick film coated at 300˚C
- Very large pumping speed : ~ 250 l/s/m for H_2,

20 000 l/s/m for CO ➔ distributed pumping

- Very low outgassing rate (~200 CH_4/s/cm^2)
- But : limited capacity and fragile coating, sensitive to pollutant (hydrocarbons, Fluor …)



C. Benvenuti, 1996

P. Chiggiato and P. Costa Pinto, Thin Solid Films, 515 (2006) 382-388

Summary

- In order to measure the total pressure one has to use a combination of vacuum gauges, adopting different technologies (although new “integrated” gauges are on the market, where one instrument does it all, from ambient pressure down to UHV)
- Typical gauges are: Capacitance, Spinning Rotor, Piezoelectric, Pirani, Penning, Bayard-Alpert, Helmer, extractor;
- In addition to the total pressure one needs to know also the residual gas composition, since the stored particle beams interact in different ways and intensities in presence of different gas species: the elastic and inelastic cross-sections of interaction (residual gas nuclei and electrons) have a strong dependence on the atomic number of the residual gas molecules/atoms.
- Residual Gas Analyzers (RGAs) are typically used for the purpose of determining the gas composition; typically they are of the four-rod type, spanning 100-200 a.m.u.’s.
- For a well-baked vacuum system with no leaks, the typical gas composition is H_2, CH_4, CO, CO_2, with H_2 being the biggest component (good, as it has lowest Z)
- As for pumps, not a single pump can work in the full pressure range, from atmosphere (pumpdown phase) to UHV.
- Typical pumps used on particle accelerators are: turbopumps, ion-sputtering pump, NEG, cryogenic; NEG-coating is also very much used on modern accelerators (0.2~2 μm-thick layer of NEG material, deposited via physical vapor deposition techniques, sputtering; NEG: ternary alloy of Ti, Zr, V.)

Some References

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- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03
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- *The physical basis of ultra-high vacuum*, P.A. Redhead, J.P. Hobson, E.V. Kornelsen, American Vacuum Soc.
- *Scientific foundations of vacuum technique*, S. Dushman, J.M Lafferty. J. Wiley & sons.
- *Handbook of Vacuum Technology*, K. Jousten (ed.), Wiley VCH
- *Vacuum Technology*, A. Roth. Elsevier Science
- *Foundations of vacuum science and technology*, Ed by J.M. Lafferty. J. Wiley & sons.

Some Journals Related to Vacuum Technology for Particle Accelerators

- Journal of vacuum science and technology A and B
- Vacuum
- Nuclear Instruments and Technology (A and B)
- Review Modern Instruments
- Applied Physics
- Fusion Engineering and Design

Thank you for your attention !!!