

Vacuum for accelerators

6th ARD ST3 workshop

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Outline

- Why vacuum in accelerators?
- Basic theory of gases
- Gas flow
- Gas sources
- Gas removal
- Residual gas analysis

Why vacuum in accelerators?

- Avoid high voltage break downs in accelerating structures (and high intensity lasers)
- Thermal isolation of cryogenic equipment
- Increase lifetime of photocathodes
- Stabilization of laser transport
- Contamination protection of optics

Why vacuum in accelerators?

- Collision of beam particles with residual gas have to be minimized, or
 - Loss of particles
 - Shorter lifetime
 - Damage of beamline components
 - Higher background in detectors
 - Higher activation of beamline components → risk of personal safety
 - Degradation of beam quality
 - Emittance growth
 - Reduced luminosity
 - Higher Bremsstrahlung
 - Energy loss of primary particles
 - Damage of components
 - Risk of personal safety
- Some examples discussed on the next slides

Why vacuum in accelerators?

Elastic (coulomb) scattering from residual gas

- Based on Rutherford scattering cross section (in cgs units)

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi\epsilon_0} \left(\frac{z \cdot Z \cdot e^2}{\beta \cdot c \cdot p} \right)^2 \cdot \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$$

$z \cdot e$:= charge of the incident particle

$Z \cdot e$:= charge of the target

θ := scattering angle

Why vacuum in accelerators?

Elastic (coulomb) scattering from residual gas

- Beam lifetime (for storage rings) τ_{es}
- Particles will be lost if the scattering angle exceeds the physical acceptance (apertures of vacuum chambers)
- to increase beam lifetime
 - Increase energy
 - Increase aperture
 - Decrease pressure
 - Avoid heavy nuclei
 - Avoid long chain molecules

$$\tau_{es}[h] = 2839 \frac{E^2[GeV^2] A_y^2[mm^2]}{\langle \beta_y \rangle^2 [m^2]} \frac{1}{\sum_i p_i [pbar] \sum_j k_{ij} Z_j^2}$$

aperture
Average β -function
pressure
Number of atoms with Z in the molecule

„Vacuum Electronics“, Springer-Verlag Berlin Heidelberg, 2008.

Why vacuum in accelerators?

Inelastic scattering (Bremsstrahlung)

- Beam particles lose energy by emission of radiation in collisions with nuclei and electrons
- If energy loss is larger than acceptance ($\delta_E = \Delta E/E_0$) the particle will be lost
- Inelastic cross section σ_{is}

$$\sigma_{is} \approx -\frac{4}{3} \frac{V_n}{N_A} \frac{1}{X_0} \ln(\delta_E)$$

- $V_n := 22.4 \text{ l/mol}$
- $X_0 := \text{radiation length}$

$$\frac{1}{X_0} = \frac{r_e^2 Z^2}{137} n \left(4 \ln \left(\frac{183}{Z^{1/3}} \right) + \frac{2}{9} \right)$$

„Particle accelerator physics“, H. Wiedemann, Springer-Verlag Berlin Heidelberg, 2007

	H ₂	He	CH ₄	H ₂ O	CO	N ₂	C ₂ H ₆	Ar	CO ₂	air
A	2	4	16	18	28	28	30	40	44	
X ₀ (m)	7530	5670	696	477	321	326	364	117	196	304

- Beam lifetime:

„Vacuum Electronics“, Springer-Verlag Berlin Heidelberg, 2008.

$$\tau_{is} = \frac{-0.695}{\ln(\delta_E)} \left(\sum_i \frac{p_i [\text{pbar}]}{X_{0,i} [\text{m}]} \right)^{-1}$$

- Watch out for pressure and Z!

Basic theory of gases

Basic theory of gases

What is vacuum?

- ISO 3529/1
 - „A commonly used term to describe the state of a rarefied gas or the environment corresponding to such a state, associated with a pressure or a mass density below the prevailing atmospheric level.“
- DIN 28400/1
 - If the pressure of a gas is smaller than 300 mbar and so smaller as the lowest atmospheric pressure on the surface of the earth.

- Pressure = force per area

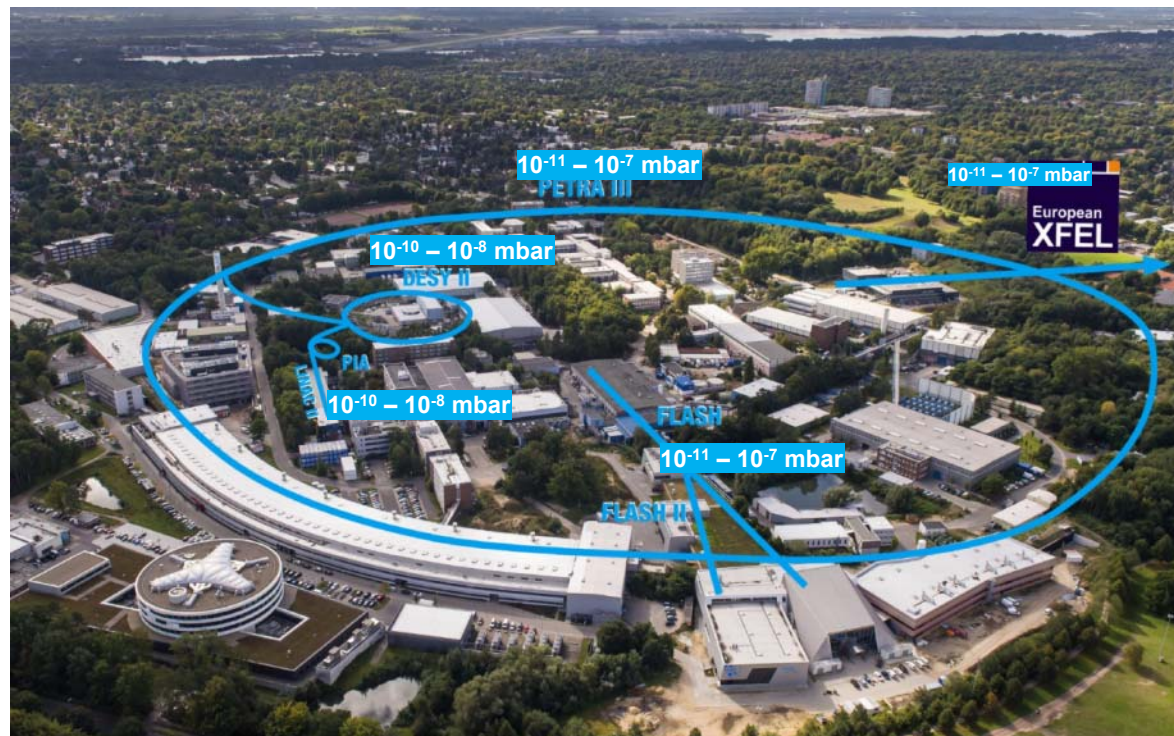
- $p = \frac{F}{A}$

- SI unit: Pa = N·m⁻²
- Common in accelerator technique
mbar and *Torr*

	Pa	bar	mbar	Torr
Pa	1	10 ⁻⁵	10 ⁻²	7.5·10 ⁻³
bar	10 ⁵	1	1000	750
mbar	100	10 ⁻³	1	0.75
Torr	133	1.33·10 ⁻³	1.33	1

Basic theory of gases

- Pressure ranges for the main accelerators at DESY (SRF-modules excluded)



Basic theory of gases

- Properties of gases
 - Pressure (p), temperature (T), mass (m), number of particles (N)
 - Boltzmann constant

$$k_B = 1.38064852 \cdot 10^{-23} \frac{m^2 kg}{s^2 K}$$

- Assumptions for following basics
 - The gas volume under consideration contains a large number of molecules
 - Adjacent molecules are separated by a distance larger than their diameter
 - All molecules are in a state of movement
 - No forces between molecules except during collisions

Basic theory of gases

- Boyle's Law

Pressure varies inversely with volume

$$p_1 \cdot V_1 = p_2 \cdot V_2 \quad (N \text{ and } T \text{ constant})$$

- Amonton's Law

Pressure varies with temperature

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} \quad (N \text{ and } V \text{ const.})$$

- Charles' Law

Volume varies with temperature

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad (N \text{ and } P \text{ const.})$$

- Dalton's law

In a gas mixture the pressure is the same as the sum of all partial pressures

$$p = p_1 + p_2 + p_3 + p_3 + \dots$$

- Avogadro's law

Pressure proportional to number of molecules

$$\frac{p_1}{N_1} = \frac{p_2}{N_2} \quad (T \text{ and } V \text{ const.})$$

Basic theory of gases

- Combining Boyle's and Charle's law yields general gas law

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

- Ideal gas law

$$p \cdot V = N \cdot k_B \cdot T$$

- Relates gas quantity units

- N := number of molecules, pV := pressure volume units, e.g. *mbar·l*

- $N = \frac{pV}{k_B T}$

- $k_B = 1.38064852 \cdot 10^{-23} \frac{m^2 kg}{s^2 T} = 1.38064852 \cdot 10^{-23} \frac{Pa \cdot m^3}{K} = 1.38064852 \cdot 10^{-22} \frac{mbar \cdot l}{K}$

- At room temperature (296 K): $\frac{1}{k_B T} \approx 2.4 \cdot 10^{19} [mbar \cdot l]^{-1}$

Basic theory of gases

Velocity distribution

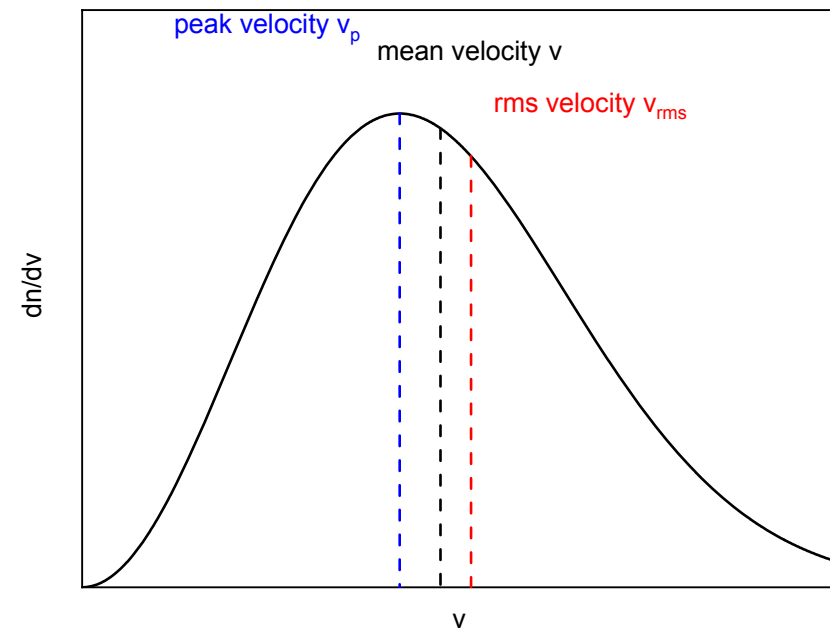
- Molecules underlay the Maxwell-Boltzmann distribution

- $\frac{dn}{dv} = \frac{2N}{\sqrt{\pi}} \left(\frac{m}{2k_B T} \right)^{3/2} v^2 \exp \left[-\frac{m \cdot v^2}{2k_B T} \right]$

- Peak velocity: $v_p = \sqrt{\frac{2k_B T}{m}}$

- Mean velocity: $v = \sqrt{\frac{8k_B T}{\pi \cdot m}}$

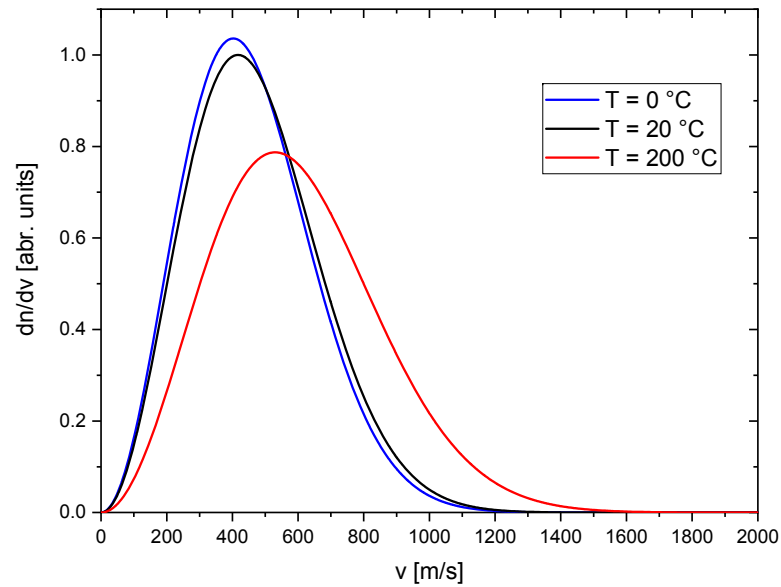
- rms velocity: $v_{rms} = \sqrt{\frac{3k_B T}{m}}$



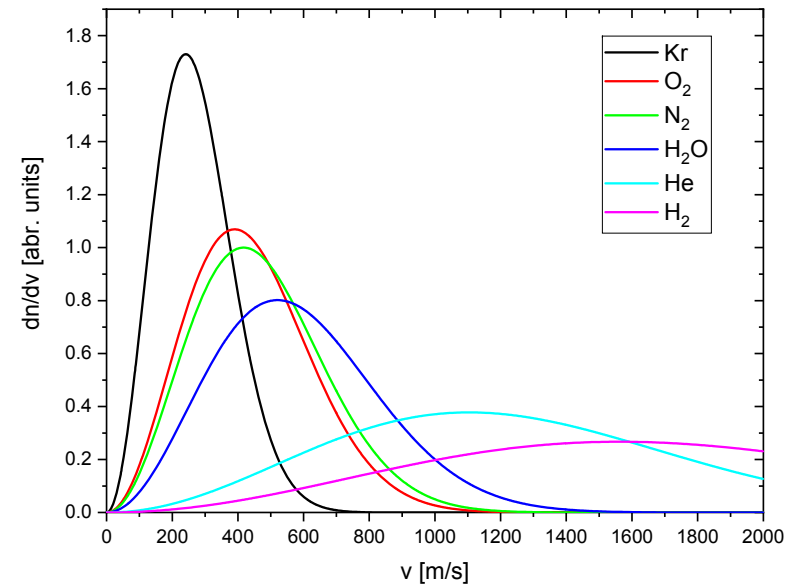
Basic theory of gases

Velocity distribution

- Air for different temperatures



- Different molecules at 20°C



Basic theory of gases

Mean free path

- Mean path before a gas particle collides with another one

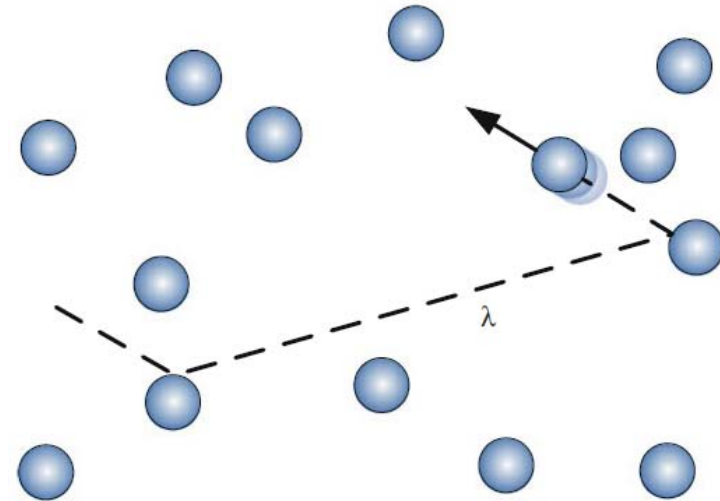
$$\lambda = \frac{1}{\sqrt{2} \cdot \pi} \cdot \frac{1}{d_{mol}^2} \cdot \frac{1}{n}$$

- d_{mol} := diameter of the molecule [m]
- n := gas density = $p/k_B T$

$$\rightarrow \lambda = \frac{k_B \cdot T}{\sqrt{2} \cdot \pi \cdot d_{mol}^2 \cdot p}$$

- For air @ 20°C: $\lambda = 0.0067 / p [\text{mbar}]$

p [mbar]	1000	1	1E-3	1E-6	1E-9
λ	67 nm	67 μm	67 mm	67 m	67 km



“Micro and Nano Fabrication”, H.H. Gatzert et al., Springer-Verlag Berlin Heidelberg 2015

Flow of gases

Flow of gases

Flow regimes

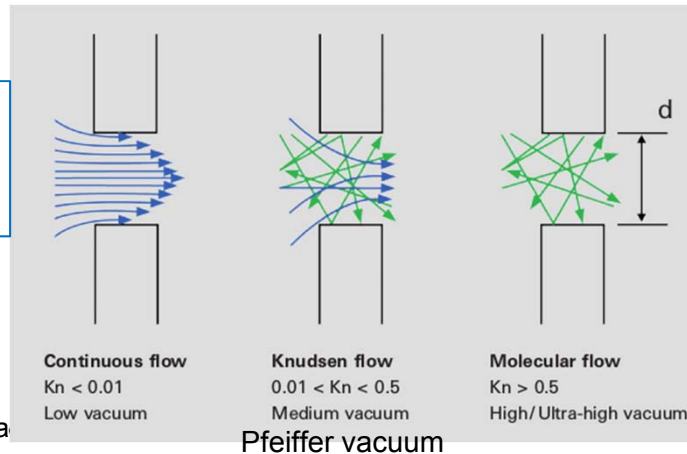
- Flow of gases in a vacuum system divided into three regimes which are defined by a dimensionless number – Knudsen number K_n

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

λ : = mean free path

d : = characteristic dimension of the channel (e.g. pipe diameter)

Continuous / viscous flow:
Characterized by molecule-
molecule collisions



Molecular flow:
Characterized by molecule-wall
collisions

Flow of gases

Flow regimes

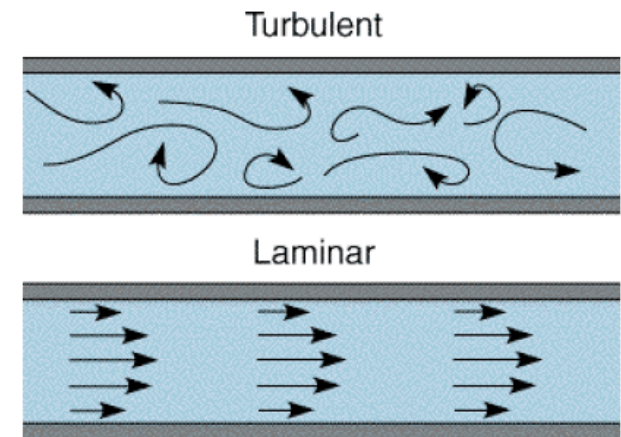
- Continuous / viscous flow can be either turbulent or laminar
 - Defined by dimensionless number – Reynolds' number, R

$$R = \frac{U \cdot \rho \cdot d}{\eta}$$

U := stream velocity; ρ := gas density

d := pipe diameter; η := viscosity

- $R < 1200$: laminar flow (zero flow velocity at wall)
- $R > 2200$: turbulent flow



Flow of gases

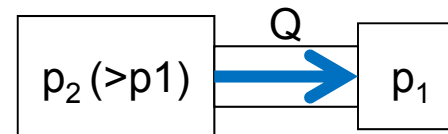
Throughput (Q), Conductance (C), Pumping speed (S)

- Throughput is the quantity of gas, so the volume of gas at known pressure, passing a plane in a known time

$$Q = \frac{d}{dt}(pV) \left[\frac{\text{Pa} \cdot \text{m}^3}{\text{s}} \right]$$

- The flow of gas in a pipe (or duct) depends on the pressure difference as well as the connection geometry.
- Throughput divided by pressure difference at constant temperature yields conductance C

$$C = \frac{Q}{P_2 - P_1} \left[\frac{\text{m}^3}{\text{s}} \right]$$



Flow of gases

Throughput (Q), Conductance (C), Pumping speed (S)

- Pumping speed (S) of a vacuum pump is defined as the volumetric displacement rate

$$S = \frac{dV}{dt} \left[\frac{m^3}{s} \right]$$

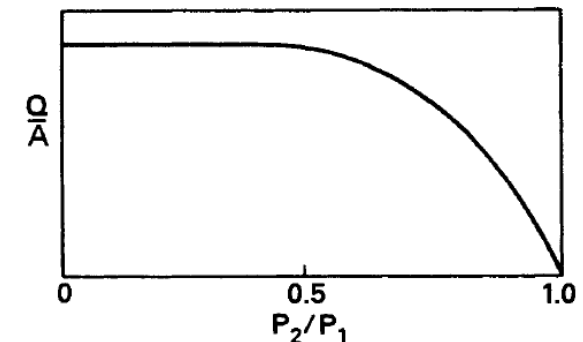
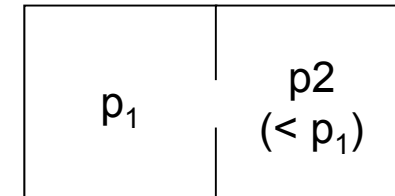
- Relation between throughput, pumping speed and pressure (at the inlet of the pump)

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

Flow of gases

Conductance - Continuum flow

- Orifices
 - Extremely complicated
 - Depends usually on inlet (p_1) and outlet (p_2) pressure and geometry
 - Throughput increases with decreasing outlet pressure
 - Exception: critical or choked flow
 - Gas stream speed exceeds speed of sound
 - Further reduction of the outlet pressure does not further increase the flow
 - For air at 22 °C the choked-flow limit is $\frac{p_2}{p_1} \leq 0.52$
 - Choked-flow important when describing flow restrictors or small leaks to atmosphere



"A User's Guide to Vacuum Technology", J. F. O'Hanlon, John Wiley & Sons, Inc., 2003.

Flow of gases

Conductance - Molecular flow

- Orifices (with area A)

$$C_{or} = \frac{Q}{p_1 - p_2} = \frac{v}{4} A$$

- With $v = \sqrt{\frac{8k_B T}{\pi \cdot m}}$ as we know, we get

$$C_{or} \left[\frac{m^3}{s} \right] = 36.24 \sqrt{\frac{T[K]}{M[amu]}} A[m^2]$$

- For example N_2 at 22 °C:

$$C_{or} \left[\frac{m^3}{s} \right] \approx 118 \cdot A[m^2]$$

$$C_{or} \left[\frac{l}{s} \right] \approx 11.8 \cdot A[cm^2]$$

- Long round tubes (diameter d , length l , $l \gg d$)

$$C_{lt} = \frac{\pi}{12} v \frac{d^3}{l}$$

- With $v = \sqrt{\frac{8k_B T}{\pi \cdot m}}$ as we know, we get

$$C_{lt} = 37.94 \sqrt{\frac{T[K]}{M[amu]}} \frac{d^3[m^3]}{l[m]}$$

- For example N_2 at 22 °C:

$$C_{lt} \left[\frac{m^3}{s} \right] \approx 123 \cdot \frac{d^3[m^3]}{l[m]}$$

$$C_{lt} \left[\frac{l}{s} \right] \approx 12.3 \cdot \frac{d^3[cm^3]}{l[cm]}$$

Flow of gases

Conductance - Molecular flow

- Short round tube
 - Taking the conductance for long round tubes $C_{lt} = \frac{\pi}{12} v \frac{d^3}{l}$ and decreasing the length to zero would yield an infinite conductance
 - On the other hand $C_{or} = \frac{v}{4} A$ for an orifice, which in fact is a tube with zero length
 - Solution by Clausing
 - $C = \alpha \frac{v}{4} A$, with α being the transition probability that a molecule entering the pipe will leave it at the other end

- For orifices: $\alpha = 1$
- For long round tubes: $\alpha = \frac{4d}{3l}$ yielding $C_{lt} = \frac{4d}{3l} \frac{v}{4} \frac{\pi d^2}{4} = \frac{\pi}{12} v \frac{d^3}{l}$
- Tabulated values for α :

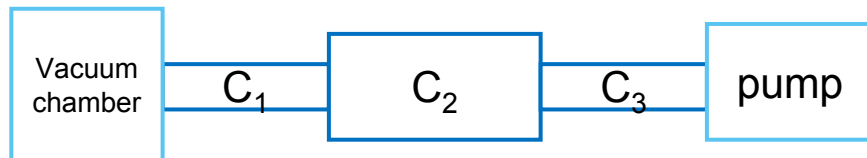
Table 3.1 Transmission Probability α for Round Pipes

l/d	α	l/d	α
0.00	1.00000	1.6	0.40548
0.05	0.95240	1.7	0.39195
0.10	0.90922	1.8	0.37935
0.15	0.86993	1.9	0.36759
0.20	0.83408	2.0	0.35658
0.25	0.80127	2.5	0.31054
0.30	0.77115	3.0	0.27546
0.35	0.74341	3.5	0.24776
0.40	0.71779	4.0	0.22530
0.45	0.69404	4.5	0.20669
0.50	0.67198	5.0	0.19099
0.55	0.65143	6.0	0.16596
0.60	0.63223	7.0	0.14684
0.65	0.61425	8.0	0.13175
0.70	0.59737	9.0	0.11951
0.75	0.58148	10.0	0.10938
0.80	0.56655	15.0	0.07699
0.85	0.55236	20.0	0.05949
0.90	0.53898	25.0	0.04851
0.95	0.52625	30.0	0.04097
1.00	0.51400	40.0	0.03546
1.10	0.49500	50.0	0.03127
1.20	0.47800	60.0	0.02829
1.30	0.46200	80.0	0.02529
1.40	0.44700	100.0	0.02329
1.50	0.43200	150.0	0.02029
1.60	0.41800	200.0	0.01829
1.70	0.40400	300.0	0.01629
1.80	0.39100	400.0	0.01529
1.90	0.37800	500.0	0.01429
2.00	0.36600	600.0	0.01329
2.50	0.32200	800.0	0.01129
3.00	0.28800	1000.0	0.01029
4.00	0.22200	1500.0	0.00829
5.00	0.17800	2000.0	0.00729
6.00	0.14800	3000.0	0.00629
8.00	0.10800	4000.0	0.00529
10.00	0.08800	5000.0	0.00429
15.00	0.05800	6000.0	0.00329
20.00	0.04300	8000.0	0.00229
30.00	0.02800	10000.0	0.00129
40.00	0.01800	15000.0	0.00029
50.00	0.01200	20000.0	0.00029
60.00	0.00900	30000.0	0.00029
80.00	0.00500	40000.0	0.00029
100.00	0.00300	50000.0	0.00029
150.00	0.00100	60000.0	0.00029
200.00	0.00050	80000.0	0.00029
300.00	0.00020	100000.0	0.00029
400.00	0.00010	150000.0	0.00029
500.00	0.00005	200000.0	0.00029
600.00	0.00003	300000.0	0.00029
800.00	0.00001	400000.0	0.00029
1000.00	0.00000	500000.0	0.00029
1500.00	0.00000	600000.0	0.00029
2000.00	0.00000	800000.0	0.00029
3000.00	0.00000	1000000.0	0.00029
4000.00	0.00000	1500000.0	0.00029
5000.00	0.00000	2000000.0	0.00029
6000.00	0.00000	3000000.0	0.00029
8000.00	0.00000	4000000.0	0.00029
10000.00	0.00000	5000000.0	0.00029
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100000.00	0.00000	50000000.0	0.00029
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400000.00	0.00000	150000000.0	0.00029
500000.00	0.00000	200000000.0	0.00029
600000.00	0.00000	300000000.0	0.00029
800000.00	0.00000	400000000.0	0.00029
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6000000000.00	0.00000	3000000000000.0	0.00029
8000000000.00	0.00000	4000000000000.0	0.00029
10000000000.00	0.00000	5000000000000.0	0.00029
15000000000.00	0.00000	6000000000000.0	0.00029
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30000000000.00	0.00000	10000000000000.0	0.00029
40000000000.00	0.00000	15000000000000.0	0.00029
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100000000000.00	0.00000	50000000000000.0	0.00029
150000000000.00	0.00000	60000000000000.0	0.00029
200000000000.00	0.00000	80000000000000.0	0.00029
300000000000.00	0.00000	100000000000000.0	0.00029
400000000000.00	0.00000	150000000000000.0	0.00029
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3000000000000.00	0.00000	1000000000000000.0	0.00029
4000000000000.00	0.00000	1500000000000000.0	0.00029
5000000000000.00	0.00000	2000000000000000.0	0.00029
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60000000000000.00	0.00000	30000000000000000.0	0.00029
80000000000000.00	0.00000	40000000000000000.0	0.00029
100000000000000.00	0.00000	50000000000000000.0	0.00029
150000000000000.00	0.00000	60000000000000000.0	0.00029
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5000000000000000.00	0.00000	2000000000000000000.0	0.00029
6000000000000000.00	0.00000	3000000000000000000.0	0.00029
8000000000000000.00	0.00000	4000000000000000000.0	0.00029
10000000000000000.00	0.00000	5000000000000000000.0	0.00029
15000000000000000.00	0.00000	6000000000000000000.0	0.00029
20000000000000000.00	0.00000	8000000000000000000.0	0.00029
30000000000000000.00	0.00000	10000000000000000000.0	0.00029
40000000000000000.00	0.00000	15000000000000000000.0	0.00029
50000000000000000.00	0.00000	20000000000000000000.0	0.00029
60000000000000000.00	0.00000	30000000000000000000.0	0.00029
80000000000000000.00	0.00000	40000000000000000000.0	0.00029
100000000000000000.00	0.00000	50000000000000000000.0	0.00029
150000000000000000.00	0.00000	60000000000000000000.0	0.00029
200000000000000000.00	0.00000	80000000000000000000.0	0.00029
300000000000000000.00	0.00000	100000000000000000000.0	0.00029
400000000000000000.00	0.00000	150000000000000000000.0	0.00029
500000000000000000.00	0.00000	200000000000000000000.0	0.00029
600000000000000000.00	0.00000	300000000000000000000.0	0.00029
800000000000000000.00	0.00000	400000000000000000000.0	0.00029
1000000000000000000.00	0.00000	500000000000000000000.0	0.00029
1500000000000000000.00	0.00000	600000000000000000000.0	0.00029
2000000000000000000.00	0.00000	800000000000000000000.0	0.00029
3000000000000000000.00	0.00000	1000000000000000000000.0	0.00029
4000000000000000000.00	0.00000	1500000000000000000000.0	0.00029
5000000000000000000.00	0.00000	2000000000000000000000.0	0.00029
6000000000000000000.00	0.00000	3000000000000000000000.0	0.00029
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30000000000000000000.00	0.00000	10000000000000000000000.0	0.00029
40000000000000000000.00	0.00000	15000000000000000000000.0	0.00029
50000000000000000000.00	0.00000	20000000000000000000000.0	0.00029
60000000000000000000.00	0.00000	30000000000000000000000.0	0.00029
80000000000000000000.00	0.00000	40000000000000000000000.0	0.00029
100000000000000000000.00	0.00000	50000000000000000000000.0	0.00029
150000000000000000000.00	0.00000	60000000000000000000000.0	0.00029
200000000000000000000.00	0.00000	80000000000000000000000.0	0.00029
300000000000000000000.00	0.00000	100000000000000000000000.0	0.00029

Flow of gases

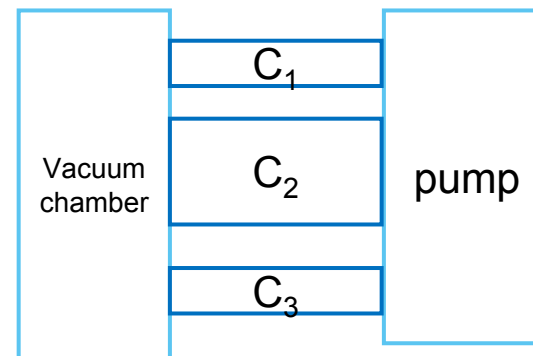
Conductance combination

- Conductances in series
- For example:



$$\frac{1}{C_{total}} = \sum_i \frac{1}{C_i}$$

- Conductances in parallel
- For example:

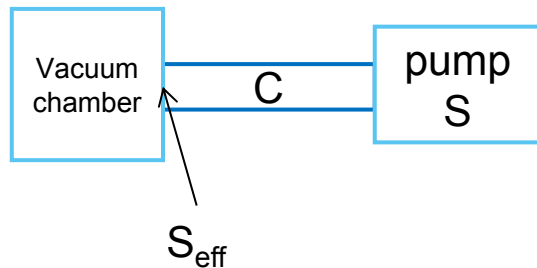


$$C_{total} = \sum_i C_i$$

Flow of gases

Conductance combination

- Effective pumping speed
 - Connecting a pump via a pipe to the vacuum chamber



$$\frac{1}{S_{eff}} = \frac{1}{C} + \frac{1}{S}$$

- Example: A pump with $S=100$ l/s for N_2 is connected via a pipe with $d=6$ cm and $l=12$ cm to a vacuum chamber.

- $C = \alpha \frac{v}{4} A \approx 11.8 \cdot \alpha \cdot \frac{\pi}{4} 6^2 \text{ l/s}$
- $l/d = 2 \rightarrow \alpha = 0.35658$
- $S_{eff} \approx 54 \text{ l/s}$

Gas sources

Gas sources

- Residual gas from atmosphere
 - Does not play a role for UHV systems
- Gas injection
 - Is usually well controlled
- Leaks, virtual and real ones
 - Have to be avoided
- Main gas sources in UHV accelerator vacuum systems:
 - Thermal outgassing
 - Photon, electron, ion stimulated desorption
 - Permeation

Gas sources

Leaks

- Real leaks – open connection between inside of vacuum vessel to outside → composition of the residual gas as air
- Leak rate Q_L
- Measured by special devices (leak detectors, mass spectrometer) and a tracer gas, which usually is helium

Diameter cm	Leak rate $\frac{\text{mbar} \cdot \ell}{\text{s}}$
10^{-2} m = 1.0 cm	10^{14}
10^{-3} m = 1.0 mm	10^{12}
10^{-4} m = 0.1 mm	10^9 (= 1)
10^{-5} m = 0.01 mm	10^{-2}
10^{-6} m = 1.0 μm	10^{-4}
10^{-7} m = 0.1 μm	10^{-6}
10^{-8} m = 0.01 μm	10^{-8}
10^{-9} m = 1.0 nm	10^{-10}
10^{-10} m = 1.0 Angstrom	10^{-12} (Detection limit, He leak detector)

Leybold, „Fundamentals of vacuum technology“

Concept / criterion	Comment	Q_L [mbar · l/s]	Relevant particle size
Water-tight*)	Droplets	$Q_L < 10^{-2}$	
Vapor-tight	“Sweating”	$Q_L < 10^{-3}$	
Bacteria-tight*)			
(cocci)		$Q_L < 10^{-4}$	Avg. $\approx 1 \mu\text{m}$
(rod-shaped)			Avg. $\approx 0.5\text{--}1 \mu\text{m}$, 2–10 μm long
Oil-tight		$Q_L < 10^{-5}$	
Virus-tight*)			
(vaccines such as pox)		$Q_L < 10^{-6}$	$\varnothing \approx 3 \cdot 10^{-7} \text{ m}$
(smallest viruses, bacteriophages)		$Q_L < 10^{-8}$	$\varnothing \approx 3 \cdot 10^{-8} \text{ m}$
(viroids, RNA)		$Q_L < 10^{-10}$	$\varnothing \approx 1 \cdot 10^{-9} \text{ m}$ (thread-like)
Gas-tight		$Q_L < 10^{-7}$	
“Absolutely tight”	Technical	$Q_L < 10^{-10}$	

What we aim for

*) As opposed to vapor, it is necessary to differentiate between hydrophilic and hydrophobic solids. This also applies to bacteria and viruses since they are transported primarily in solutions.

Gas sources

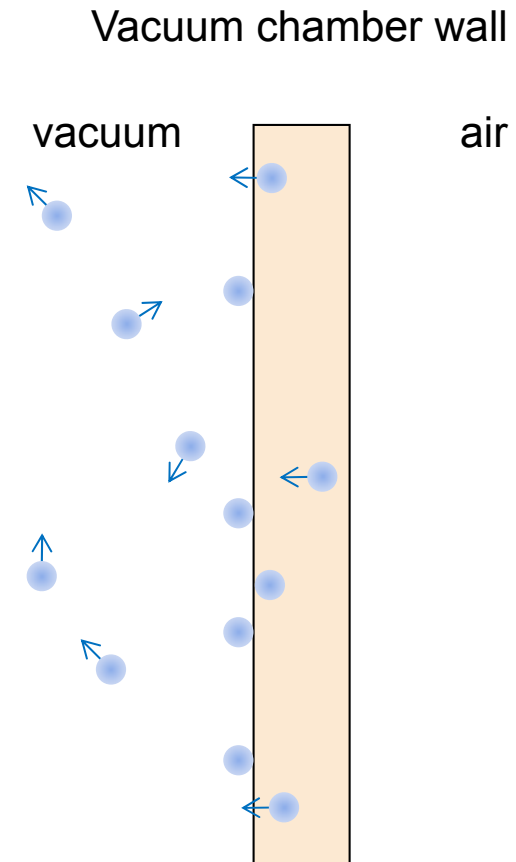
Leaks

- Virtual leaks
 - No open connection between inside of vacuum vessel to outside
 - But residual gas composition comparable to air
 - Trapped volume inside the vacuum vessel with only a tiny (low conductance) connection to the inside
- Reasons are often
 - Improper weld seams
 - Screw connections inside vacuum
- To be avoided already in the design phase
 - If possible welding at the inside of the vacuum vessel. If this is not possible weld seam has to go through the whole material. Never welding from both sides.
 - Only vented screws inside of vacuum, e.g. a whole through the screw or thread flattened slightly on one side
 - ...

Gas sources

Thermal desorption

- Thermal desorption or thermal outgassing means
 - Molecules adsorbed on the surface (initially or after venting the vacuum system) desorbing when chamber is pumped
 - Molecules diffuse from the bulk of the vacuum chamber material towards the surface and desorb there
- Thermal outgassing rate depends on several factors
 - Material, surface finish, cleaning procedure, history of the material, temperature, pump time, venting gas,...



Gas sources

Thermal desorption

- UHV-compatible and –incompatible materials, from the DESY vacuum specification

	UHV-compatible materials	UHV-incompatible materials
Pure Materials	aluminum indium copper molybdenum silicon tantalum titanium tungsten	zinc cadmium lead
Stainless Steel	preferred types: 1.4429 1.4435 1.4404 (see also DESY material specifications Vacuum/002/2008, Vacuum/003/2008 and Vacuum 006/2009))	
Alloys	appropriate aluminum alloys AMPCO® 18 copper-beryllium DENSIMET® INCONEL® 600 or 718 Mu-Metal tin-bronze (e.g. CuSn 8) GLIDCOP®	alloys containing: zinc (e.g. brass) lead
Insulators	preferred types: aluminum ceramics macor* sapphire	organic materials (with a few exceptions)

- Besides the outgassing properties in accelerators a second property is important: radiation hardness!
- For instance Teflon is vacuum compatible but not radiation hard and therefore forbidden in accelerator vacuum systems.

Gas sources

Thermal desorption

- Specific desorption rate $q = \frac{Q}{A} \left[\frac{\text{mbar} \cdot \text{l}}{\text{s} \cdot \text{cm}^2} \right]$
- Methods to reduce thermal desorption rate
 - Only use vacuum compatible materials
 - Polishing of surfaces → reduction of surface
 - Cleaning, clean handling (never touch a vacuum surface without gloves)
 - Typical outgassing rate of a fingerprint is 10^{-5} mbar·l/s
 - In-vacuum bakeout → drastically reduces H₂O outgassing, removes hydrocarbons
 - ...

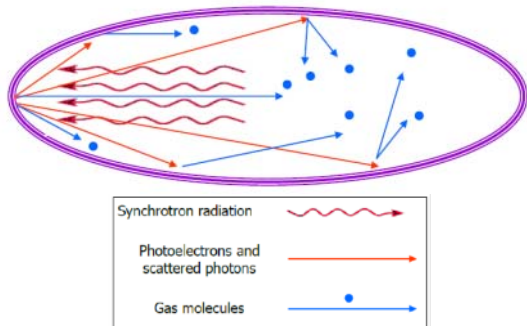
- Examples of thermal outgassing rates at room temperature after 1 hour in vacuum

Material	$q \left[\frac{\text{mbar} \cdot \text{l}}{\text{s} \cdot \text{cm}^2} \right]$
Aluminium (fresh)	$9 \cdot 10^{-9}$
Aluminium (after bakeout 20 h @ 100 °C)	$5 \cdot 10^{-14}$
Stainless steel 304	$2 \cdot 10^{-8}$
Stainless steel 304 (electropolished)	$6 \cdot 10^{-9}$
Stainless steel 304 (electropolished, 30 h @ 250 °C)	$4 \cdot 10^{-12}$

Gas sources

Photon stimulated desorption (PSD)

- One of the most important gas sources in the presence of synchrotron radiation (SR)



Courtesy E. Al-Dmour, CAS, 2017.

- When and where photoelectrons leave or arrive surfaces they may desorb molecules
- As thermal desorption PSD depends on:
 - Material, cleaning procedure, history of the material, temperature, pumping time
- In addition it depends on
 - Energy of the impinging photons
 - Photon flux
 - Integral photon dose

Gas sources

Photon stimulated desorption (PSD)

- Photon desorption yield

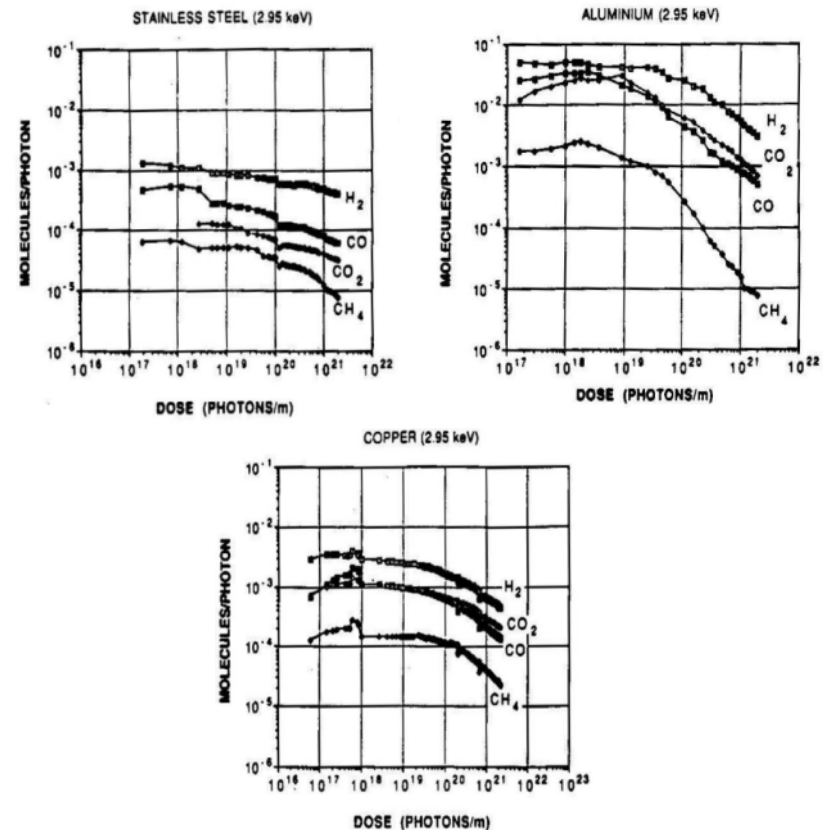
$$\eta_{ph} = \frac{\text{number of desorbed molecules}}{\text{number of photons impinging the surface}}$$

- Conditioning: photon desorption yield decreases with accumulated dose D

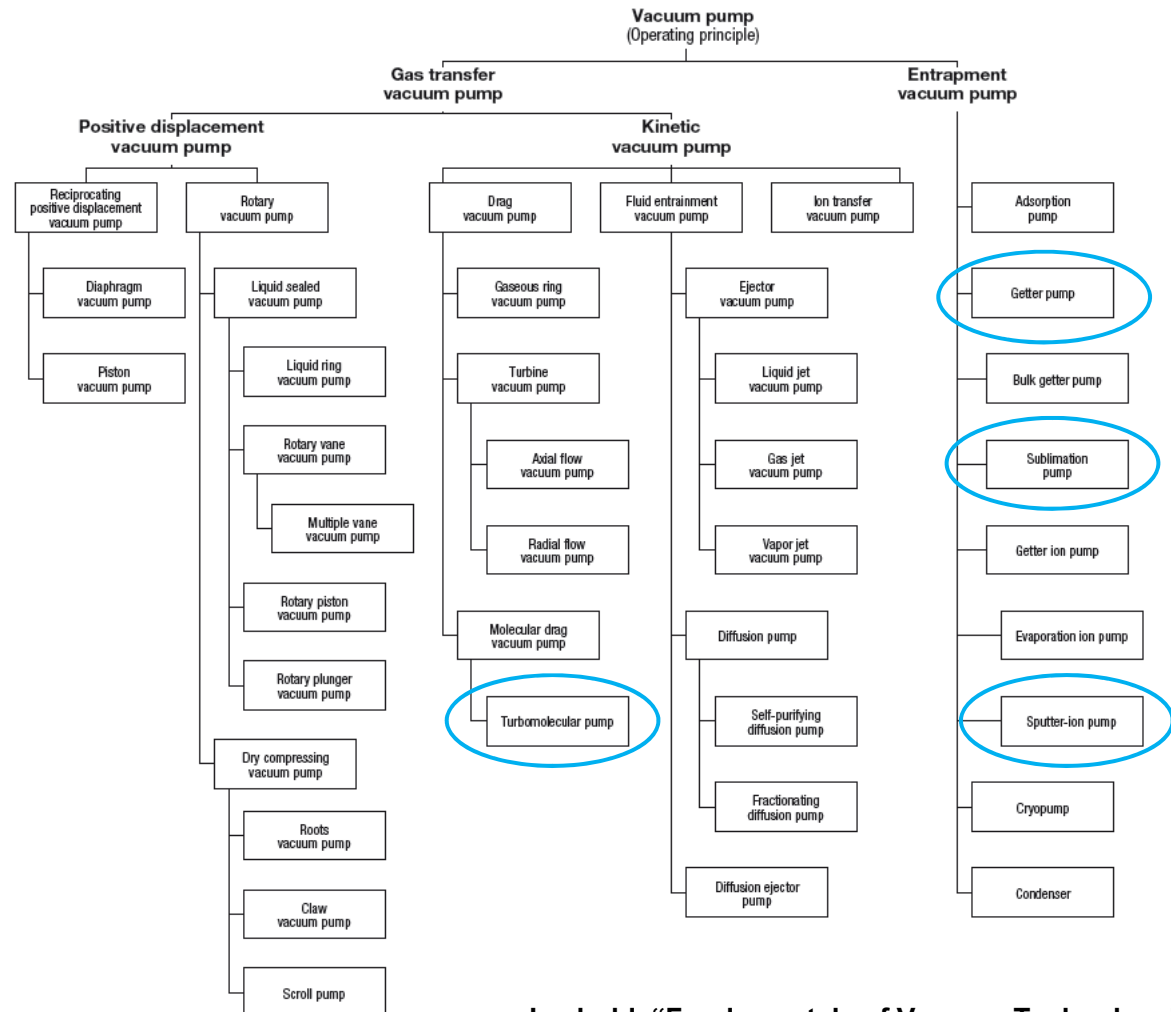
$$\eta_{ph} = \eta_{ph,0} D^{-\alpha}$$

- sometimes the conditioning is called “bakeout with beam”
- Conditioning is required after each venting in storage rings because PSD usually prevents from full beam current operation

A. Mathewson, AIP Conf. Proc. 236(1), 313, 1991.



Gas removal (Pumps)

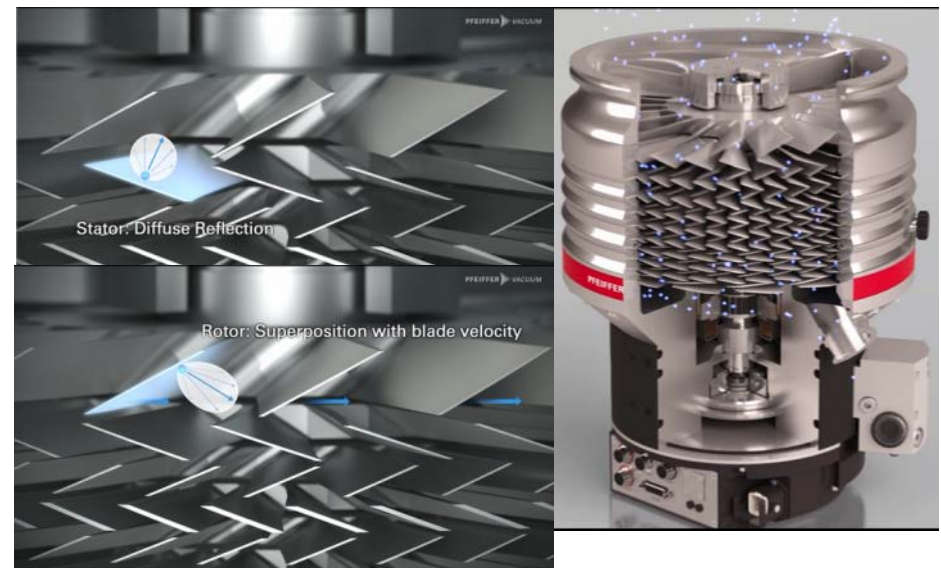


Gas removal (pumps)

Turbo molecular pumps (TMP)

- Momentum transfer pump
- Compresses gas from the inlet to the outlet
- Pumping speed
 - constant over wider pressure range
 - Mainly independent of molecular mass
- Can evacuate large amounts of gas
- Requires backing (fore-vacuum pump)
- Con's:
 - Not maintenance free
 - Moving parts → vibrations
 - Valves required to avoid venting in case of failure

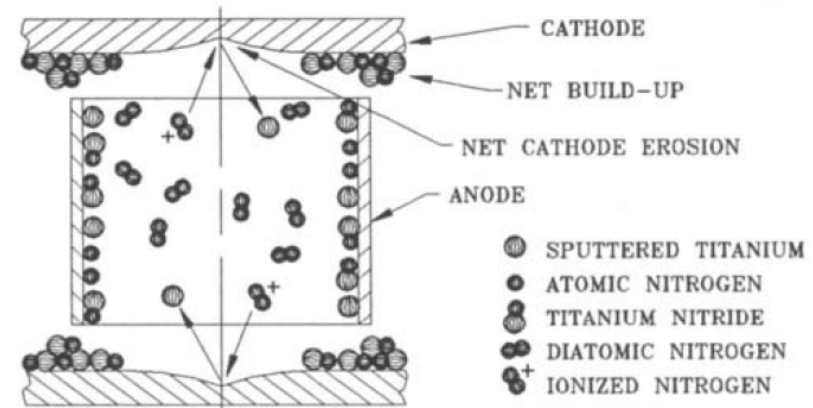
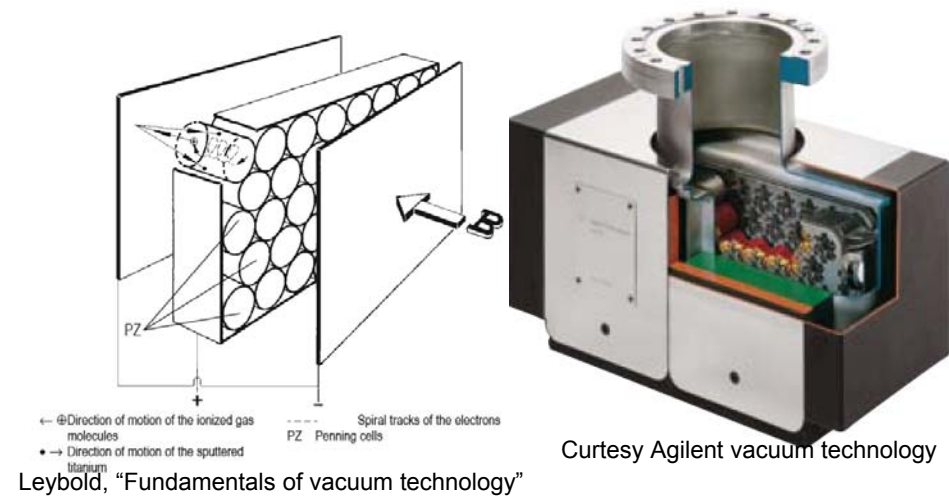
Pfeiffer vacuum



Gas removal (pumps)

Sputter ion pump (SIP)

- Gas molecules are ionized in one of the penning cells by electron impact ionization
- Ions are accelerated towards the cathode (usually titanium) and sputter the cathode material, which condenses on the anodes and second cathode
- Pumping mechanisms
 - Implantation
 - Chemical reaction of active gases with titanium
 - Burial by the sputtered material



Kimo M. Welch, "Capture Pumping Technology", 2nd fully revised edition

Gas removal (pumps)

Sputter ion pump (SIP)

- Pro's
 - Current generated by ions can be utilized for pressure readout
 - Very reliable – only high voltage needed for operation
 - Maintenance free
 - No moving parts – no vibrations
- Con's
 - Influence of the magnetic stray field has to be taken into account during design of the vacuum system
 - Problems with noble gases (lower pumping speed and noble gas instability)
 - Noble diode pumps (second cathode made of tantalum instead of titanium)
 - better pumping speed for noble gases but lower for active gases
 - Less affected by instability
 - Generate particles (dust) over time

Gas removal (pumps)

Titan sublimation pumps (TSP)

- Utilizes the high reactivity of titanium
 - Reactive gases are pumped by chemical reactions with the titanium
 - O: forms with titanium Ti_xO_y
 - N: forms with titanium Ti_xN_y
 - CO, CO₂, ...
 - Exception is hydrogen
 - Atomic hydrogen diffuses into the titanium
 - H₂ cracks at the surface into atomic hydrogen which then diffuses into the titanium
 - No pumping of inactive gases like noble gases, methane CH₄ very slowly

- Big titanium area yields high pumping speed
- Titanium wires are heated to evaporate titanium which condenses on surfaces

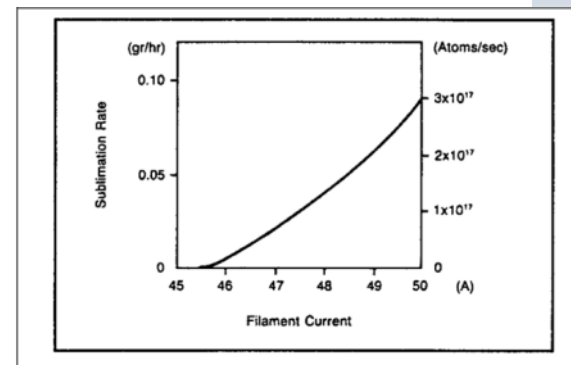
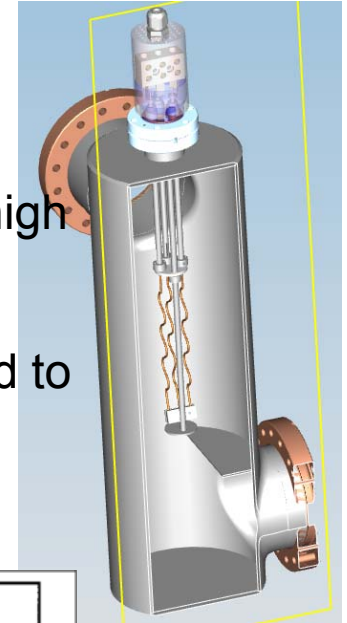


Figure 4 Typical Titanium Sublimation Rate Versus Filament Current
Titanium sublimation cartridge user manual; Agilent Technologies

Gas removal (pumps)

Titan sublimation pumps (TSP)

- Pumping speed $S[l/s] = 1000 \cdot A \frac{v}{4} s$
 - A := area, v := speed of molecules, s := sticking coefficient

Gas	Initial Sticking Coefficient		Quantity Sorbed ^a ($\times 10^{15}$ molecules/cm ²)	
	(300 K)	(78 K)	(300 K)	(78K)
H ₂	0.06	0.4	8–230 ^b	7–70
D ₂	0.1	0.2	6–11 ^b	—
H ₂ O	0.5	—	30	—
CO	0.7	0.95	5–23	50–160
N ₂	0.3	0.7	0.3–12	3–60
O ₂	0.8	1.0	24	—
CO ₂	0.5	—	4–24	—
He	0	0		
Ar	0	0		
CH ₄	0	0.05		

Source. Reprinted with permission from *J. Vac. Sci. Technol.*, 13, p. 471, D. J. Harra. Copyright 1976, The American Vacuum Society.

^a For fresh film thickness of 10^{15} Ti atoms/cm².

“A User’s Guide to Vacuum Technology”, J. F. O’Hanlon, John Wiley & Sons, Inc., 2003.

John F. O’Hanlon, J. F. O’Hanlon, John Wiley & Sons, Inc., 2003.

Pro’s

- High pumping speed for active gases
- After activation no media required for operation, until saturation
- Usually at DESY accelerators weeks or months in-between activations

Con’s

- During activation high pressure rises which usually prevent from machine operation
- No pumping of inactive gases
- During activation creation of methane
- Require backing pump (usually sputter ion pumps)

Gas removal (pumps)

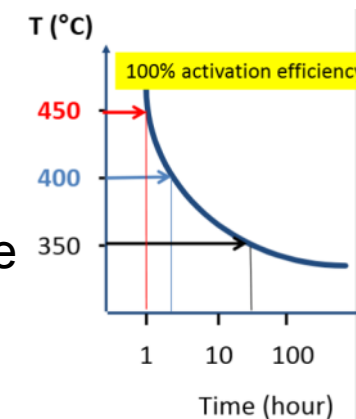
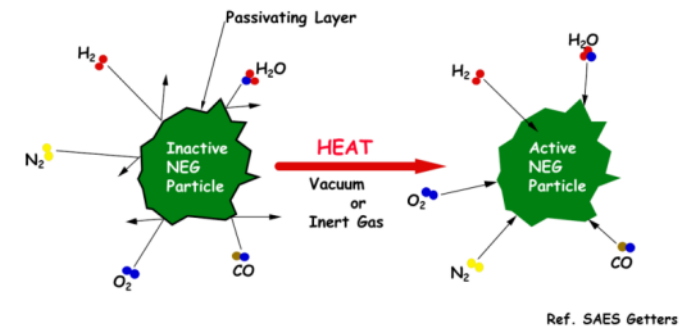
Non-evaporable getter pumps (NEG)

- Sorb active gases by chemical reaction
- Porous alloys with very large active metallic (Ti, Zr,) surface after activation
- Pumping principles
 - Reactive gases like O_2 , N_2 , CO , CO_2 – adsorbed irreversibly, formation of oxides, nitrides, carbides,...
 - H_2 – adsorbed reversibly, diffusion into bulk
 - H_2O , hydrocarbons – adsorbed in a combination of irreversibly and reversibly
 - Hydrocarbons adsorbed very slowly
 - Noble gases – not pumped at all

Gas removal (pumps)

Non-evaporable getter pumps (NEG)

- Activation of the NEG
- If no active sites on the surface are left the NEG has to be activated
- Activation at high temperatures (depending on the NEG alloy)
 - Oxides, nitrides and carbides do not crack but diffuse into the bulk
- Since the activation is a diffusion process it depends:
 - exponentially on temperature
 - Square root of time
- Lower temperature can be compensated by increases time
 - E.g. 1 h @ 450 °C \approx 4 h @ 400 °C \approx 24 h @ 350 °C

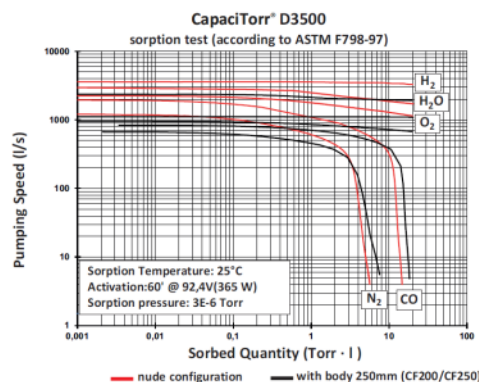
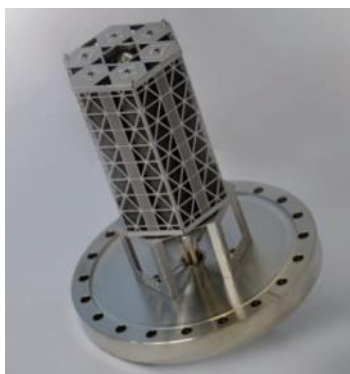


Courtesy SAES getters

Gas removal (pumps)

Non-evaporable getter pumps (NEG)

Ready to use plain NEG pumps up to 3500 l/s

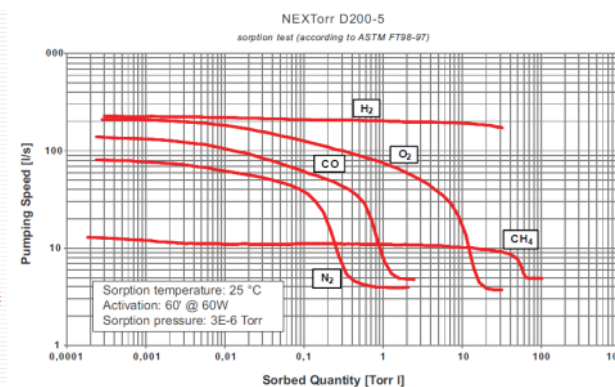
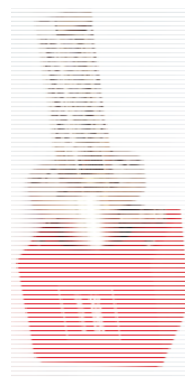


Cartridges or even only pellets to build your own pump

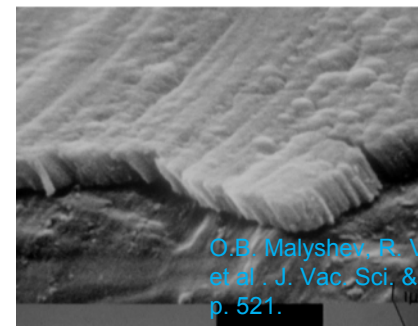


DESY. |6th ARD ST3 workshop| S. Lederer "Vacuum for accelerators"

Ready to use in combination with SIP



As thin film on a vacuum chamber

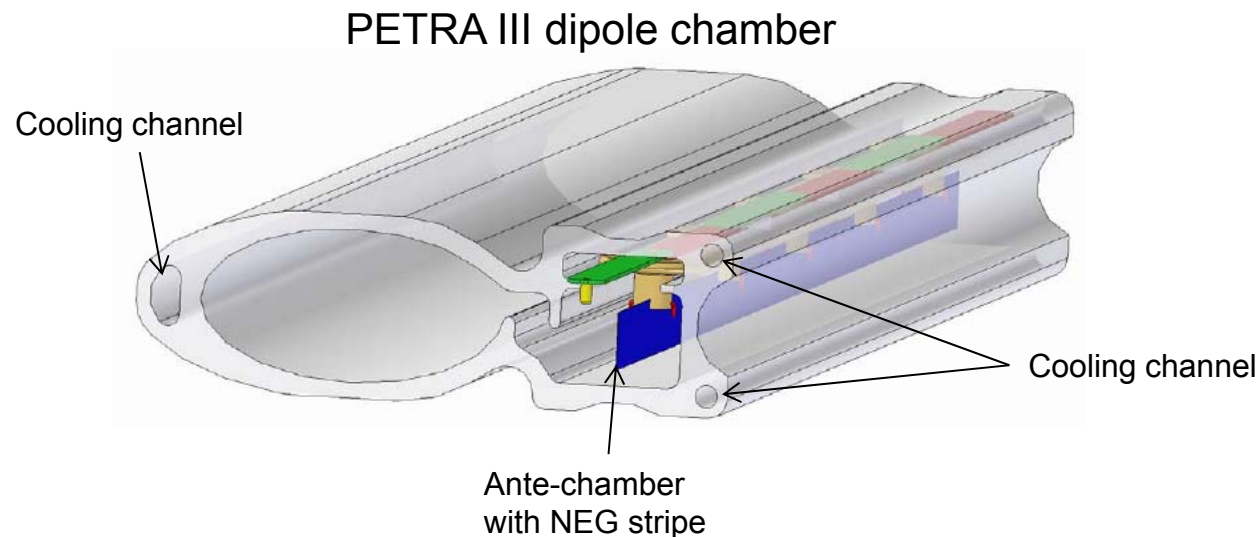


O.B. Malyshev, R. Valizadeh, J.S. Colligon et al. / J. Vac. Sci. & Technol. A 27 (2009), p. 521.

Gas removal (pumps)

Non-evaporable getter pumps (NEG)

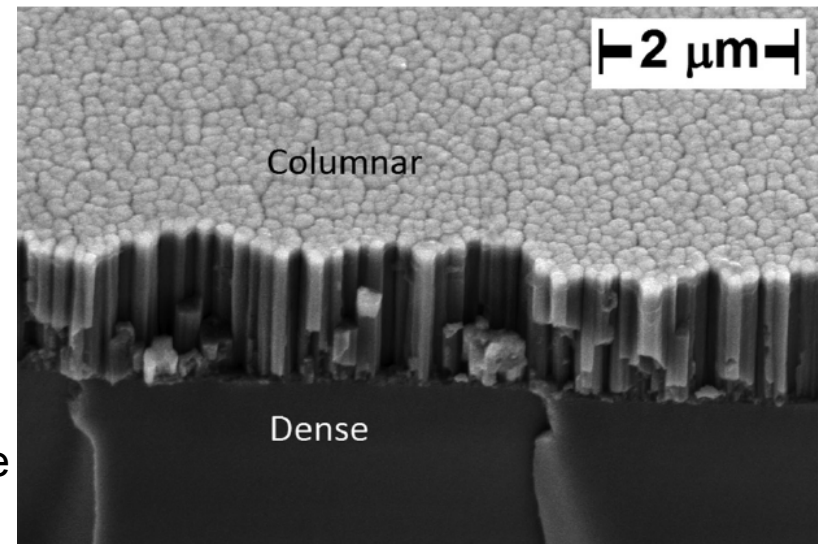
- The flexibility in cartridge designs gives great possibilities in accelerators with high magnet density (storage rings), so small space for pumps – the antechamber concept



Gas removal (pumps)

Non-evaporable getter pumps (NEG)

- Thin films
 - Whole chamber is coated by NEG ($\approx 1\mu\text{m}$)
 - Activation by heating the chamber for 24 h @ 190 degC (NEG = TiZrV)
 - Easy for a vacuum chamber but really hard for a magnet!
 - Highest pumping if film is columnar (big surface area), but
 - NEG acts also as barrier and best if film is dense
 - So, from simple vacuum point of view a combination of dense and columnar NEG should be best



O.B. Malyshev, R. Valizadeh, A.N. Hannah, J. Vac. Sci. & Technol. A 34 (2016), p. 061602.

Gas removal (pumps)

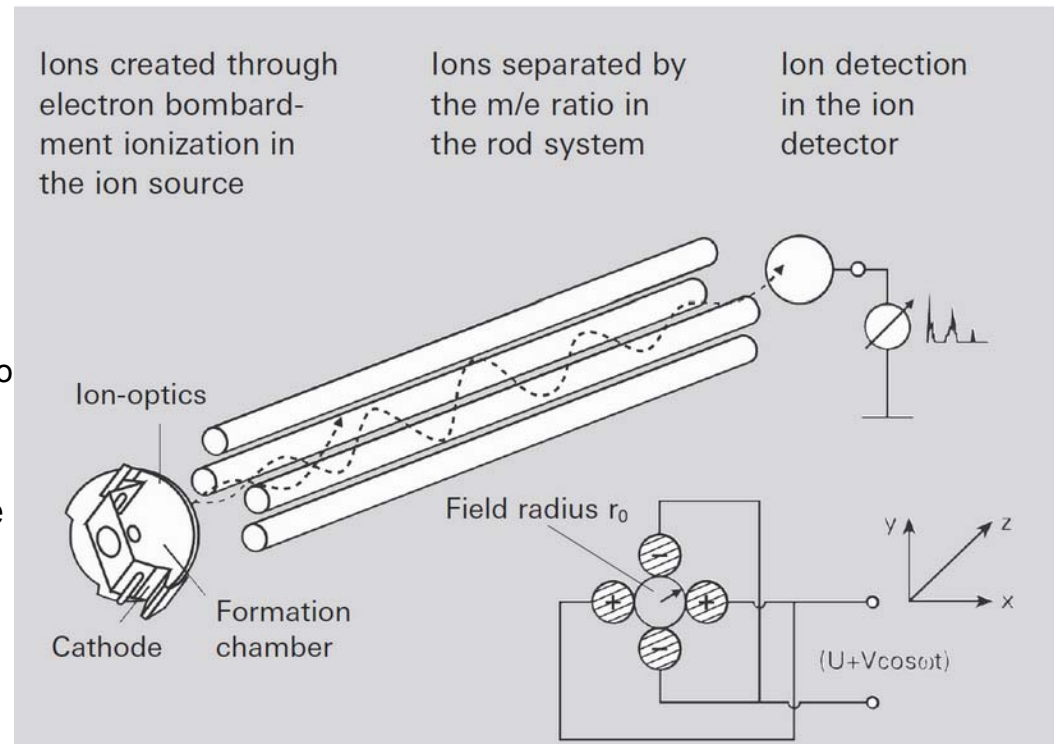
Non-evaporable getter pumps (NEG)

- Thin films
 - Extremely elegant method for reducing the pressure in the accelerator, but
 - Activation very complicated because of the usually close magnets
 - Application for FEL's like the European XFEL not possible because of beam dynamics requirement
 - Roughness and conductivity mess up impedance budget

Residual gas analysis

Residual gas analysis

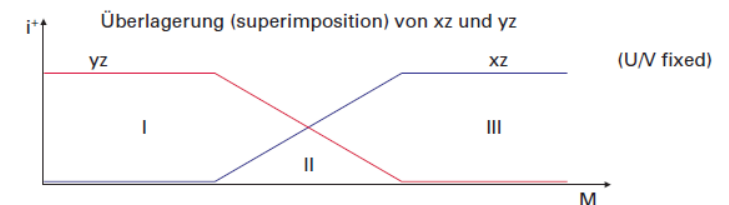
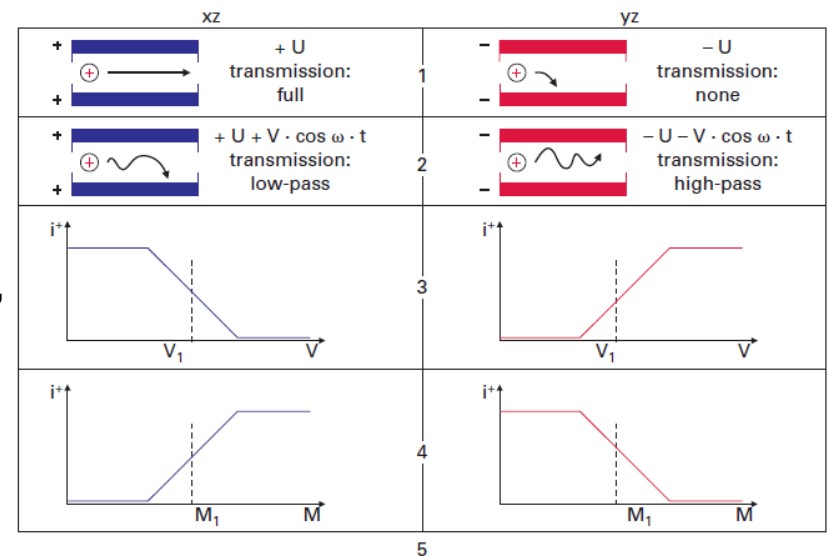
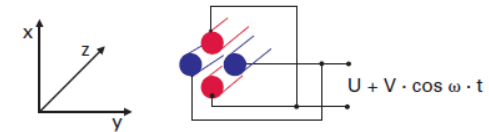
- Residual gas analysis
- Detector for helium leak checks
- Online monitor of vacuum systems, early leak detection during operation
 - If in an accelerator the pressure rises and the RGA shows an increased signal for Argon, w/o gas injection, most probable a leak to air occurred.
- Most commonly used in vacuum technique are quadrupole mass spectrometers
 - Inexpensive
 - Compact
 - But poor mass resolution



Residual gas analysis

Quadrupole mass spectrometer

- After ionization all ions travel through the same electric potentials
- On the quadrupole rods a voltage U is applied, which is superimposed by a alternating voltage with changeable amplitude V
- In simplest words one of the rod pairs acts as high pass the other as low pass filter for ions with a mass to charge ratio $M=m/q$
 - For each V only one M can pass through the quadrupole
 - By changing V a mass scan can be performed

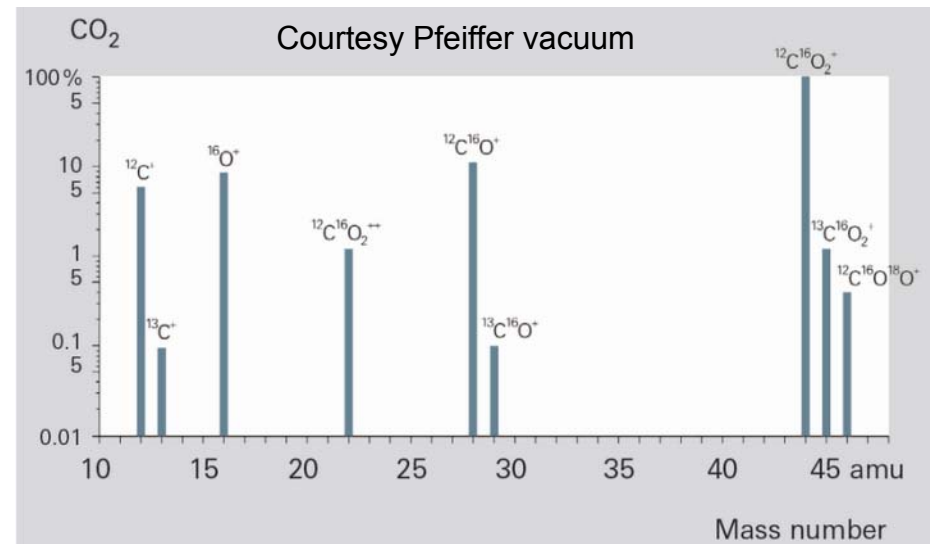


U/V Auflösung (resolution) ↔ Empfindlichkeit (sensitivity)

Residual gas analysis

Interpretation of mass spectra

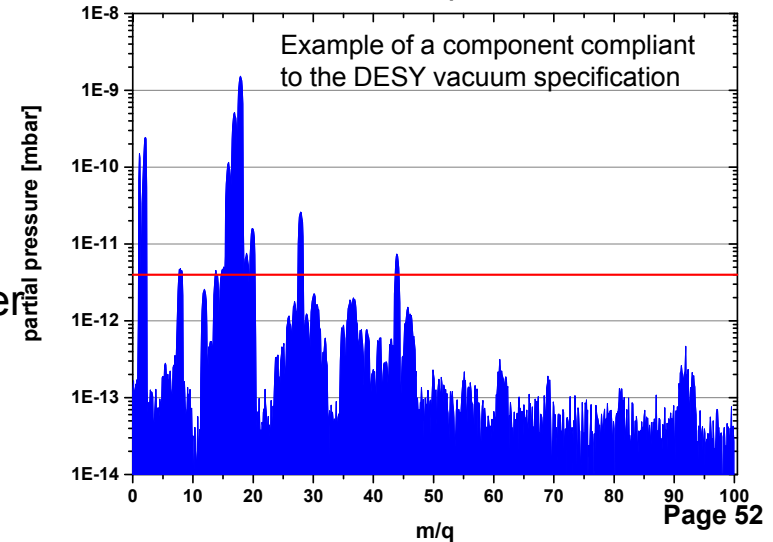
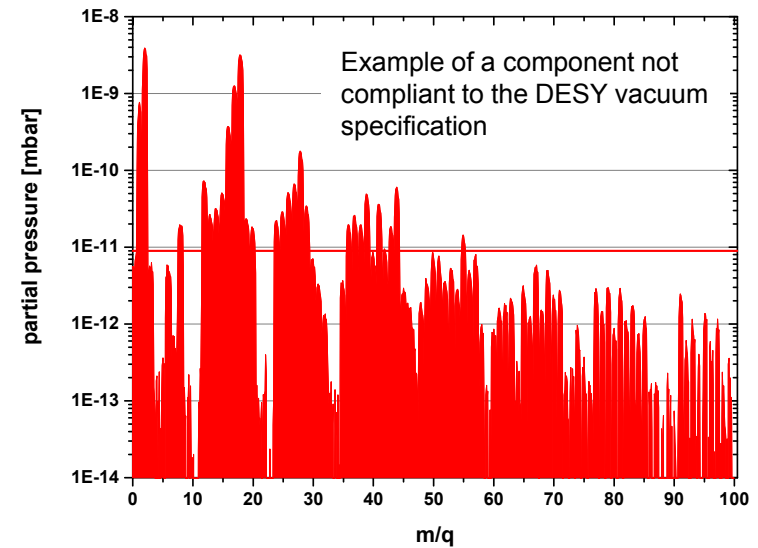
- Things that make life complicated but also can help
 - Cracking / fragmentation of molecules in the ion source (see example)
 - Very helpful to identify molecules with the same m/q, e.g. CO and N₂
 - Different ionization cross sections of the molecules
 - Multiple ionization in the ion source (see example)
 - Isotopes (e.g. ¹²C and ¹³C in the example)



Residual gas analysis

- Perfect tool for quality assurance of vacuum components
- As discussed in the beginning: try to avoid high Z and molecules with high number of atoms (e.g. long chain hydrocarbons)
- DESY vacuum specification for hydrocarbon cleanliness
 - At a pressure below $1 \cdot 10^{-7}$ mbar the sum of all partial pressures with $m/q > 44$ has to be smaller than 1 per mille of the total pressure.
 - Only components compliant to the specification will be installed

DESY. |6th ARD ST3 workshop| S. Lederer "Vacuum for accelerators"



Thanks for your attention