Copyright statement and speaker’s release for video publishing

The author consents to the photographic, audio and video recording of this lecture at the CERN Accelerator School. The term “lecture” includes any material incorporated therein including but not limited to text, images and references.

The author hereby grants CERN a royalty-free license to use his image and name as well as the recordings mentioned above, in order to post them on the CAS website.

The material is used for the sole purpose of illustration for teaching or scientific research. The author hereby confirms that to his best knowledge the content of the lecture does not infringe the copyright, intellectual property or privacy rights of any third party. The author has cited and credited any third-party contribution in accordance with applicable professional standards and legislation in matters of attribution.
Why vacuum in accelerators?

- maximize beam lifetime
- minimize emittance growth (hadrons)
- minimize component activation
- minimize impact on detectors, electronic components
Vacuum - Outline

1. Vacuum Basics
   pressure, density, gas equation, pumping speed, flow regimes, conductance, pressure profile calculation

2. Accelerator Vacuum
   requirements: bremsstrahlung, elastic scattering, emittance growth beam induced desorption: SR, ions
   examples of vacuum chambers

3. Components for Vacuum Systems
   pumps: turbo, ion sputter, NEG, cryo-pump
   flange systems
Pressure

\[
p = \frac{\text{force}}{\text{area}}
\]

- \( 1 \text{ Pa} = 1 \text{ N/m}^2 = 0.01 \text{mbar} \)
- \( 1 \text{ atm} = 10^5 \text{ Pa} \)
- \( \rightarrow \) weight of \( 1 \text{kg/cm}^2 \)

average velocity

\[
\bar{v} = \sqrt{\frac{8 k_b T}{\pi m_0}}
\]

number of molecules impinging per time and area

\[
\frac{dN}{dA \, dt} = \frac{1}{4} n_v \bar{v}
\]

- \( n_v \) volume density of molecules
- \( k_b \) Boltzmann constant, \( 1.38 \times 10^{-23} \text{ J/K} \)

cyclotron resonator: continuous tuning required due to air pressure variation
Vacuum Pressure – Orders of Magnitude

- Ambient pressure
  - $2.50 \times 10^{19} \text{ cm}^{-3}$
  - Mean free path $N_2$: 60 nm

- High vacuum
  - $2.50 \times 10^{13} \text{ cm}^{-3}$
  - Mean free path: 60 mm

- Ultra high vacuum
  - $2.50 \times 10^{10} \text{ cm}^{-3}$
  - Mean free path: 60 m

- Ultra high vacuum
  - $2.50 \times 10^{7} \text{ cm}^{-3}$
  - Mean free path: 60 km

Application:

- Sputter processes
- Insulating vacuum
- Proton cyclotron
- Electron storage ring
- „Cold“ beam vacuum

Units:
- 1 mbar = 0.75 Torr
- 1 mbar = 100 Pa
Gas Equation and „amount of gas“

\[ PV = N k_b T = nRT \]

R = 8.314 Nm / mole K
\( k_b = 1.38 \times 10^{-23} \text{ J/K} \)

N = number of molecules
n = number of moles

to specify a leak rate:
\[ x \ [\text{mbar l / s}] \]

\[ \text{example bicycle tire:} \]
\[ P = 2.5 \text{bar}, V = 1l, \text{leak } Q = 2 \times 10^{-4} \text{ mbar l / s} \]
\[ \text{after 1 Month (2.5 million sec): } p = 2.0 \text{ bar} \]

\[ \text{accelerator section, no pumping, no outgassing:} \]
\[ P = 10^{-10} \text{ mbar}, V = 1000l, \text{leak } Q = 10^{-9} \text{ mbar l / s} \]
\[ \text{after 1 Month (2.5 million sec): } p = 2.5 \times 10^{-6} \text{ mbar} \]
Pumping

Pump = device that absorbs gas molecules

Pumping speed
\[ S \text{ [l/s]} = \frac{Q}{P} \text{ at pump interface} \]

S varies for gas species

For example:
- Typ. ion getter pump: 60 l/s
- Turbo pump: 100 l/s
- Cryo pump: 500 l/s

Gas load \( Q = 10^{-9} \text{ mbar l/s} \)

\[ S = 100 \text{ l/s} \rightarrow P \approx 10^{-11} \text{ mbar} \]
Flow Regimes

mean free path of gas molecules:

\[ \lambda = \frac{k_b T}{\sqrt{2} \sigma P} \]

see also Knudsen Number:

\[ Kn = \frac{\lambda}{d} \]

for example:

\[ N_2, \ P = 10^{-6}\text{mbar}, \ \lambda \approx 60\text{m} \]

\[ \rightarrow \text{molecular flow} \]

viscous flow: \( \lambda \ll d, \ Kn \ll 1 \)

\[ C_{\text{visc}} \propto d^4 \overline{P} \Delta P \]

molecular flow: \( \lambda \gg d, \ Kn \gg 1 \)

\[ C_{\text{molec}} \propto d^3 \Delta P \]

heart attack!

d /≠ 2 → C /≠ 8!
Conductance

**conductance** is defined as the ratio of the molecular flux $Q$ to the pressure drop $\Delta P$ along a vacuum vessel

- function of the shape (e.g. diam.) of the vessel
- the type of the gas
- it’s temperature

\[
C = \frac{Q}{\Delta P}
\]

- orifice: \( C = \sqrt{\frac{k_B T}{2\pi M}} A \), \( C_{\text{air}} = 11.6 \text{[l/s]} \cdot \text{A[cm}^2\text{]} \)
- tube: \( C = \sqrt{\frac{2\pi k_B T}{M} \frac{d^3}{l}} \), \( C_{\text{air}} = 12.1 \text{[l/s]} \cdot \frac{d^3\text{[cm]}}{l\text{[cm]}} \)

**example:**
- tube d=8 cm, l=30 cm: 200 l/s
- tube d=1 cm, l=30 cm: 0.4 l/s

$M$ = molecular mass
$A$ = area
$d$ = diameter
$l$ = length
Conductance - Combining Vessels

\[ C_{\text{total}} = \left( \frac{1}{C_1} + \frac{1}{C_2} \right)^{-1} \]

\[ C_{\text{total}} \approx C_2 \quad \text{for} \quad C_2 \ll C_1 \]

**example:**
ion getter pump 400 l/s connected by
\( d=8\text{cm}, l=30\text{cm} \) tube: \( S_{\text{eff}} = 136 \text{ l/s} \)
Sources of gas

main sources of gas in accelerator vacuum:
• thermal desorption
• beam induced desorption (synchrotron radiation, beam impact, electron cloud ...)
  → dynamic pressure, discussed later
• diffusion out of bulk materials
• permeation through materials
• virtual and real leaks

in practice, outgassing of water:
q(t) ≈ 3×10^{-9} \text{ mbar l / s cm}^2 / t \text{ [h]}
baking! exponential dependence on T

thermal desorption
chem./phys. binding char. time = sojourn time
e.g. \( E_d = 1 \text{eV}, T = 293K \)
\( \tau = 5h \)
\[
q(t) \propto \frac{1}{t}
\]
\[
\tau \propto \exp \left( \frac{E_d}{k_b T} \right)
\]

bulk diffusion
diffusion coefficient D mainly H\(_2\) relevant
\[
q(t) \propto \sqrt{D(T)/t}
\]
\[
D(T) \propto \exp \left( -\frac{E_{\text{diff}}}{k_b T} \right)
\]
Pump Down Processes

volume: \( p \propto \exp(-\alpha t) \)

surface: \( p \propto 1/t \)

bulk, diffusion: \( p \propto 1/\sqrt{t} \)

permeation: \( p = \text{const} \)

log. scale: different effects dominate after varying times
Pressure Computation for 1-dimensional Systems

starting from definition of conductance $C = Q / \Delta P$
introduce correct sign and specific conductance:

continuity equation, change of flow by pumping and outgassing:

$$Q = -C \Delta s \frac{\Delta P}{\Delta s}$$

$$Q(s) = -C \cdot \partial P(s)/\partial s$$

$$\partial Q(s)/\partial s = q - S P(s)$$

1-dim diffusion equation:

$$\frac{\partial}{\partial s} C \frac{\partial}{\partial s} P(s) - S P(s) + q = 0$$

compare conductance of circular tube:

$$C' = \sqrt{\frac{2\pi k T}{M}} \frac{d^3}{l}$$

specific conductance

specific pumping speed

specific outgassing rate
Quadratic Solution for lumped Pumps

\[ P(s) = \frac{ql}{S} + \frac{q}{8c} \left( l^2 - 4s^2 \right) \]

the parabolic profile results in following average and maximum pressure:

\[ P_{\text{avg}} = ql \left( \frac{1}{S} + \frac{l}{12c} \right), \quad P_{\text{max}} = ql \left( \frac{1}{S} + \frac{l}{8c} \right) \]

choose distance and pumping speed to achieve desired pressure and to reasonably balance both terms

\[ S \neq 0 \quad S = 0, \text{ length } l \quad S \neq 0 \]

example:
7cm tube, \( q_o = 5 \times 10^{-12} \text{ mbar l / s cm}^2 \), \( S=100 \text{l/s} \)
\rightarrow \( l=5 \text{m}, \ P_{\text{avg}} = 1 \times 10^{-9} \text{ mbar} \)
\rightarrow \( l=3 \text{m}, \ P_{\text{avg}} = 5 \times 10^{-10} \text{ mbar} \)
General Solution by Matrix Transport of $Q$, $P$

$$
\begin{pmatrix}
P(s) \\
Q(s)
\end{pmatrix}
= 
\begin{pmatrix}
\cosh(\alpha s) & -\frac{1}{\alpha c} \sinh(\alpha s) \\
-\alpha c \sinh(\alpha s) & \cosh(\alpha s)
\end{pmatrix}
\begin{pmatrix}
P(0) \\
Q(0)
\end{pmatrix}
+ \frac{q}{\alpha}
\begin{pmatrix}
\frac{1}{\alpha c} (1 - \cosh(\alpha s)) \\
\sinh(\alpha s)
\end{pmatrix}
\alpha = \sqrt{\frac{S}{c}}
$$

$$
\lim_{\alpha \to 0}:
\begin{pmatrix}
P(s) \\
Q(s)
\end{pmatrix}
= 
\begin{pmatrix}
1 & -s/c \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
P(0) \\
Q(0)
\end{pmatrix}
+ q s
\begin{pmatrix}
-s/2c \\
1
\end{pmatrix}
$$

[V. Ziemann, SLAC/Pub/5962]

example calculation:
lumped pumps: $S = 100$ l/s
distrib. pumps: $S = 60$ l/s m
outgassing: $q_0 = 5 \times 10^{-12}$ mbar l / s cm$^2$
Time Dependent Diffusion Equation

\[ \mathcal{V} \frac{\partial}{\partial t} P(s, t) = \frac{\partial}{\partial s} C \frac{\partial}{\partial s} P(s, t) - \mathcal{S} P(s, t) + q \]

specific volume [l/m]

compare classical diffusion eq.:

\[ \frac{\partial}{\partial t} f(x, t) = \frac{\partial}{\partial x} D \frac{\partial}{\partial x} f(x, t) \]

\[ \mathcal{D} = \frac{\langle \Delta x^2 \rangle}{\langle \Delta t \rangle} = \frac{C}{V} \]

example:

tube 7cm, diffusion time over 5m:
N₂: 2.3 s; He: 0.9 s

tube 2cm, diffusion time over 5m:
N₂: 8 s; He: 3 s
Monte Carlo Code Molflow+ (2008)

C++ code, OpenSource since 2018
J-L. Pons (ESRF), M. Ady, R. Kersevan (CERN)

Web site for info and downloads:

example calculation:
100k molecules tracked, computation time:
few seconds, pressure profile
Synrad+ for calculation of synchrotron radiation

• Monte Carlo code computes photons generated by the beam and projects them onto the vacuum chamber surface
• in a second step the molecular outgassing is computed
• the result serves as input for Molflow+ to compute the pressure distribution

A 10-minute introduction to

SynRad+

A test-particle Monte Carlo simulator for synchrotron radiation

• SR spectrum + flux
• calculates beam orbit from lattice file (MAD-X)
• dipole approximation only, no undulator interference effects

https://molflow.web.cern.ch/content/synrad-documentation
Next:
Accelerator Vacuum

requirements: bremsstrahlung, elastic scattering, emittance growth
beam induced desorption: SR, ions
Generic Beam Lifetime due to Beam-Gas Interaction

$$\Delta N_{b,\text{lost}} = -N_b \frac{\text{area of molecules}}{\text{total area}}$$

$$= -N_b \frac{nV\sigma}{V/\Delta l}$$

$$= -N_bn\sigma \Delta l$$

$$= -N_bn\sigma \beta c \Delta t$$

results in differential equation:

$$\frac{dN_b}{dt} = -N_b \sigma \beta cn$$

solution:

$$N_b(t) = N_0 \exp\left(-\sigma \beta cn t\right) , \tau \approx \frac{1}{\sigma cn}$$

specific loss processes by gas scattering

- bremsstrahlung (electrons)
- elastic scattering (Coulomb, nuclear)
- inelastic scattering (nuclear)
- multiple Coulomb: p-emittance growth
Electrons: Bremsstrahlung Lifetime

**Bremsstrahlung**
particle loses energy in Coulomb field of gas molecule;
is lost if leaving energy acceptance

$$\sigma_{\text{inel}} \approx -\frac{4}{3} \frac{V_n}{N_A} \frac{1}{X_0} \ln \delta_E$$

resulting lifetime:

$$\tau_{\text{brems}} [h] = \frac{-0.695}{\ln(\delta_E)} \left( \sum_i P_i [\text{pbar}] \frac{X_{0,i} [\text{m}]}{X_0} \right)^{-1}$$

**radiation length:**
(normal condition)

|       | H₂ | He | CH₄ | H₂O | CO | Ar | Air |
|-------|----|----|-----|-----|----|----|-----|
| X₀ [m]| 7530 | 5670 | 696 | 477 | 321 | 117 | 304 |

$$V_n = 22.4 \text{l}, \text{ molar Volume}$$
$$N_A \text{ Avogadro Number}$$
$$\delta_E = \Delta E / E, \text{ energy acceptance}$$
$$X_0 \text{ gas specific radiation length}$$

**example HERA-e:**
$$\delta_E = 8 \times 10^{-3}; P_{\text{tot}} = 10^{-8} \text{ mbar}$$
composition: 75% H₂, 25% CO
$$\tau_{\text{brems}} = 16 \text{ h}$$

[e.g. particle data booklet]
Electrons: Elastic Coulomb Scattering

**Rutherford Scatting**

diff. cross section for occurrence of scattering angle $\theta$:

$$\frac{d\sigma_i}{d\Omega} = \frac{Z_i^2 r_e^2}{4\gamma^2} \frac{1}{\sin^4(\theta/2)}$$

consider total cross-section for loss of electron, i.e. scattering beyond aperture $A_y$:

$$\sigma_{i,el} \approx \frac{2\pi Z_i^2 r_e^2}{\gamma^2} \frac{1}{\theta_0^2}, \quad \theta_0 = A_y/\beta_y$$

resulting lifetime:

$$\tau_{el} [h] = 2839 \frac{E^2 [\text{GeV}^2]}{\beta_y^2 [\text{m}^2]} \left( \sum_i P_i [\text{pbar}] \sum_j k_{ij} Z_j^2 \right)^{-1}$$

**example HERA-e:**

- pressure: $P_{\text{tot}} = 10^{-8}$ mbar
- composition: 75% H$_2$, 25% CO
- $Z_{\text{eff}} = \text{rms}(Z) = 3.6$
- $A_y = 20$ mm, $\beta_{y,\text{avg}} = 25$ m
- $\tau_{\text{elastic}} = 5.200$ h → insignificant
Hadron Beam Emittance Growth

multiple elastic scattering in the absence of radiation damping leads to diffusive emittance growth.

definition of emittance growth time:

\[ \tau_{\varepsilon} = \left( \frac{1}{\varepsilon_x} \frac{d\varepsilon_x}{dt} \right)^{-1} \]

growth rate:

\[ \frac{d\varepsilon}{dt} = \frac{\bar{\beta}_y d\theta_0^2}{dt} = \frac{\bar{\beta}_y}{(cp)^2 \text{[MeV]}^2} \frac{c}{P_0} \sum_i \frac{P_i}{X_{0,i}} \]

example HERA-\( p \varepsilon \) growth rate:

\( E_k = 920 \text{ GeV}, \beta_{y,\text{avg}} = 50 \text{ m} \)

\( P_{\text{tot}} = 5 \times 10^{-11} \text{ mbar @ 4.2 Kelvin, } H_2 \)

emittance: \( \varepsilon_x = 5 \times 10^{-9} \text{ m}\cdot\text{rad} \)

\( \tau_{\varepsilon} = 2.000 \text{ h} \)
Synchrotron Radiation induced Desorption

dynamic vacuum
• SR photons generate photoelectrons, these desorb gas molecules from the surface
• desorption yield $\eta$ per photon is reduced with integrated dose (conditioning)

SR photons per length and time:
$$\frac{dN_\gamma}{dtds} = 1.28 \cdot 10^{17} \frac{I \text{ [mA]} E \text{ [GeV]}}{\rho \text{ [m]}}$$
resulting specific outgassing:
$$q = \eta_\gamma k_b T \frac{dN_\gamma}{dtds}$$

measured desorption yield for different gases [G.Vorlaufer]

measured dynamic pressure rise as a function of integrated current [PETRA-III, DESY]
Reduced desorption by NEG Coating

NEG coating reduces SR desorption immediately

Conditioning is slower afterwards

However, NEG coated chambers lead to good conditions in practice

Synchrotron Radiation-Induced Desorption from a NEG-Coated Vacuum Chamber, P. Chiggiato, R. Kersevan (1999)
Heavy Ion induced Gas Desorption

demonstration of transmission breakdown by gas desorption

[measurements & simulations in AGOR cyclotron, KVI-Groningen, S.Brandenburg et al]

- transmission of $^{40}\text{Ar}^{5+}$ 8 MeV per nucleon
- base vacuum $3 \times 10^{-7}$ mbar
- injected intensity up to $6 \times 10^{12}$ pps
- Beam-power: $\leq 320$ W

$\rightarrow$ release of $10^5$ (!) gas molecules per lost ion is compatible with data
Dynamic effect in LHC: Electron Cloud Effect

• photoelectrons can start avalanche effect resulting in intense electron clouds
• crucial: secondary electron yield (SEY), i.e. how many e\(^{-}\) released per incoming e\(^{-}\)
• results in pressure bump, heat load in cold systems (problem at LHC)
• may affect beam stability
• depends on bunch spacing and beam intensity

mitigations:
• wall coating, e.g. graphite, TiN (low SEY)
• weak magnetic solenoid field

\[ E(e^-) \approx 1\text{..}100\text{eV} \]
Specialized Chambers: LHC & FCC with Beam Screens

LHC(left), FCC comparison

courtesy images: M.Jimenez et al F.Perez, M.Morrone, I.Bellafont et al

- At the expense of a higher complexity (translated into a higher, but still affordable, cost) the beam induced vacuum effects are mitigated and the pumping speed and cooling capacity have been considerably increased
Vacuum Chambers for Electron Synchrotron

Profile extruded aluminum, milled and bent ($\rho=196\text{m}$); NEG strip (St707) for pumping

Low cost per meter, however: difficult interface to stainless steel flanges

Solution: explosion bondings SS/Al with 4cm Al thickness
Next:
Components for Vacuum Systems

pumps: overview, turbo, ion sputter, NEG, cryo-pump
flange systems, collimators, residual gas analysis (RGA)
Overview Pumps and Gauges

PUMPS
- roughing pump
- turbomolecular pump
- sputter ion pump
- titanium sublimation pump
- non-evaporable getter pump
- cryopump

GAUGES
- membrane gauge
- Pirani gauge
- Penning gauge
- cold cathode gauge (Magnetron)
- hot-cathode ionisation gauge (Bayard-Alpert, extractor gauge)

can be used as „Penning gauge“

discussed next slides
Turbo Molecular Pump

- pumps all gases
- blade speed similar molecule speed(!)
- 30,000 ... 60,000 RPM
- works down to $10^{-10}$ mbar

![Turbo Molecular Pump Image](Wikipedia)

\[
\text{blades at speed } v = 2\pi f \\
e.g. \text{30,000 rpm} = 300 \text{ m/s}
\]

| molecule | avg speed @ 293K [m/s] | compression ratio |
|----------|------------------------|-------------------|
| H₂       | 1800                   | $10^3$            |
| He       | 1250                   | $10^4$            |
| CO       | 470                    | $10^9$            |
Sputter Ion Pump

single penning cell
electric and magnetic field
gas ionization, acceleration

pumping mechanism
implantation, chemisorption
and burying of gas molecules

[Diagram of sputter ion pump with labels for cathode, anode, high voltage (HV 3...7kV), and magnetic field (B).]

chemisorption
implanted and buried (only method for noble gases)
sputtered material
implanted

current is proportional to P
→ can be used as pressure gauge
Ion Sputter Pumps

pumping speed: 2 l/s ... 500 l/s
weight: 0.3 kg ... 120 kg

courtesy Agilent catalog

example: modern Agilent 200 pump

pumping port
penning cells
permanent magnet
NEG – Non Evaporable Getter Pumps

• NEG captures gases by chemical reaction, e.g. H$_2$O, CO, N$_2$ permanently, H$_2$ is dissolved in bulk material

• no pumping of noble gases – combination with sputter ion pumps required

• NEG must be activated by heating; e.g. St707™ @180°C..350°C

oxidized surface

activation

fresh metallic surface

Zr-V-Fe alloy

constantan strip for electric heating

SAES Getters
NEG Pump Designs

NEG + Ion sputter combined
NEG cartridge
NEG wafer
pills, disks, rings

images: SAES Getters
Cryo Pump

- high pumping speed for all gases
- cryo-condensation of N₂, O₂ and Ar on cold surface
- cold surface partly covered with charcoal: cryosorption for H₂, He, Ne
- periodic regeneration by warmup

[Lothar Schulz]
Metal sealed Flange Systems

- low leak rate, UHV compatible
- radiation proof
- safe mounting
- easy leak search

Helicoflex: Technetics Group

Conflat Flange (CF)

VAT Flange, flat seal
Inflatable Seals

- leak rate \( \sim 10^{-6} \text{ mbar l / s} \)
- quick and simple mounting
- at positions with limited access or high activation

Inflatable seals installed between resonators

O-ring grooves

Evacuated intermittent volume
Collimators

- collimators are parts of the vacuum system with multi-physics aspects
- some materials are not optimal for vacuum, e.g. graphite or graphite with MoGr coating (porosity, outgassing, dust)
- straightness, thermal shock resistance, heat load and heat conductivity, efficient cooling, thermal outgassing, electrical conductivity, mechanical precision and reproducibility, radio-activation and handling
Residual Gas Analysis (RGA)

- quadrupole mass spectrometers to analyze the composition of residual gases
- allows to assess the cleanliness of components and to diagnose problems

[R.Gaiffi, PSI]
Accelerator Vacuum - Summary

- e: bremsstrahlung
- p: emittance growth

**Beam Vacuum**

- outgassing, permeation/leaks
- beam induced: SR, ions, e-cloud

**Gas Sources**

- e.g. 10^{-11} mbar l/s cm^2
- e.g. SR: $\eta = 10^{-5}$

**Pumping**

- lumped: turbo, ion sputter, cryo
- NEG strips, NEG coating

- e.g. e-synchrotron: 10^{-8} mbar
- e.g. p-cyclotron: 10^{-6} mbar

- e.g. Turbo S = 100 l/s
- e.g. Cryo: S = 800 l/s

**vacuum engineering:**
materials & materials preparation, mechanical stability, thermo-mechanical problems

Pumps, Gauges, Flange Systems, Valves
References

• dedicated CERN accelerator school on vacuum: [https://cas.web.cern.ch/schools/glumslov-2017](https://cas.web.cern.ch/schools/glumslov-2017)

• The physical basis of ultra-high vacuum, P.A. Redhead, J.P. Hobson, E.V. Kornelsen. AVS.

• Particle Data Group: [Atomic and Nuclear Properties of Materials](https://pdg.lbl.gov/2023/radioactive-lifetimes.html) (radiation length $X_0$, interaction length etc)