Accelerator Vacuum

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CERN Accelerator School – Introductory Course

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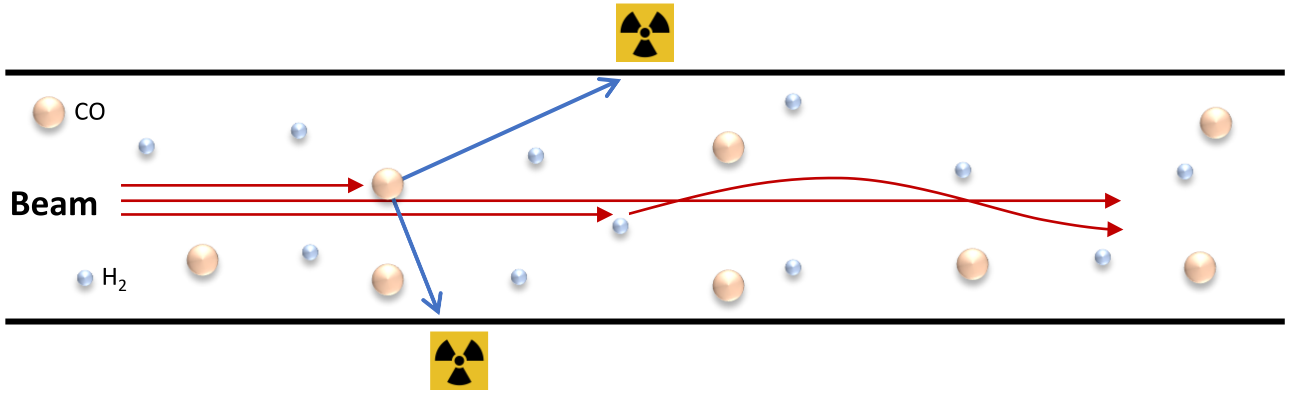
Why vacuum in accelerators ?

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

beam-gas scattering



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

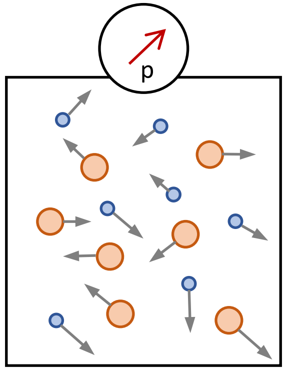
3. Components for Vacuum Systems

pumps: turbo, ion sputter, NEG, cryo-pump

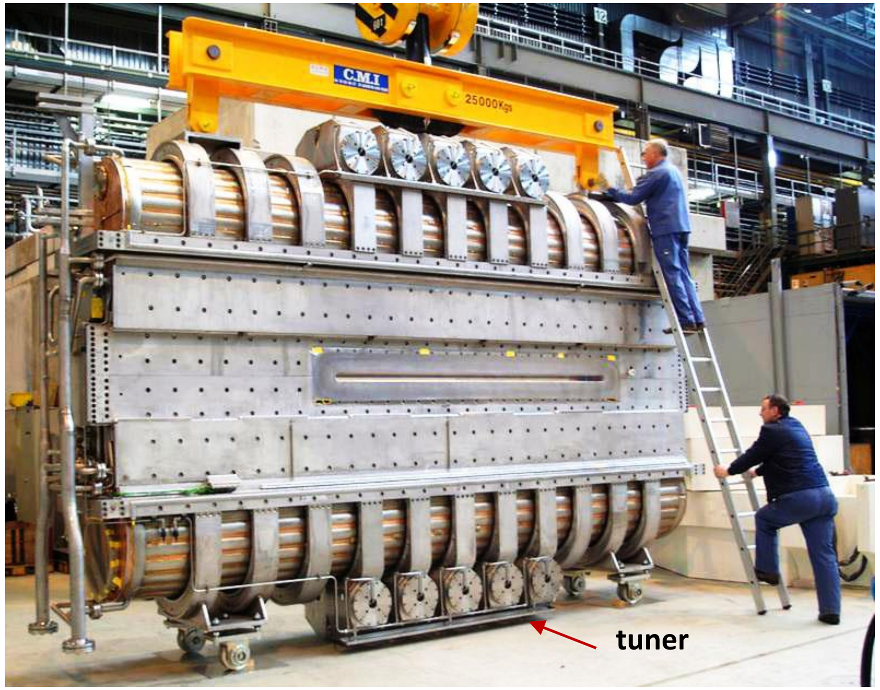
flange systems

Pressure

pressure = force / area
1 Pa = 1 N/m^2 = 0.01mbar
1 atm = 10^5 Pa
$\rightarrow$ weight of 1kg/cm^2



cyclotron resonator: continuous tuning required due to air pressure variation

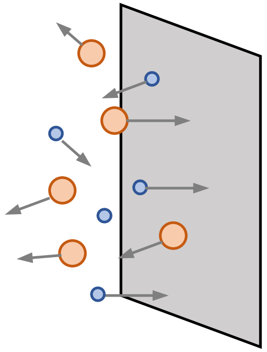


average velocity

$$\overline{v} = \sqrt{\frac{8k_b}{\pi m_0}T}$$

number of molecules impinging per time and area

$$\frac{dN}{dA\,dt} = \frac{1}{4} n_v \overline{v}$$



n_v volume density of molecules
k_b Boltzmann constant, 1.38×10^{-23} J/K

Vacuum Pressure – Orders of Magnitude

[mbar]		volume density	mean free path N_2	application
10^3	ambient pressure	2.50×10^{19} cm^{-3}	60 nm	
10^2				
10^1				
10^0				
10^{-1}				
10^{-2}				sputter processes
10^{-3}	high vacuum ↓	2.50×10^{13} cm^{-3}	60 mm	
10^{-4}				
10^{-5}				insulating vacuum ↓
10^{-6}		2.50×10^{10} cm^{-3}	60 m	proton cyclotron ↓
10^{-7}				
10^{-8}				
10^{-9}	ultra high vacuum ↓	2.50×10^{7} cm^{-3}	60 km	electron storage ring ↓
10^{-10}				„cold“ beam vacuum ↓

(low P) Units:

1mbar = 0.75 Torr

1mbar = 100 Pa

Gas Equation and „amount of gas“

$$PV = Nk_bT = nRT$$

R = 8.314 Nm / mole K
k_b = 1.38×10^{-23} J/K

N = number of molecules
n = number of moles

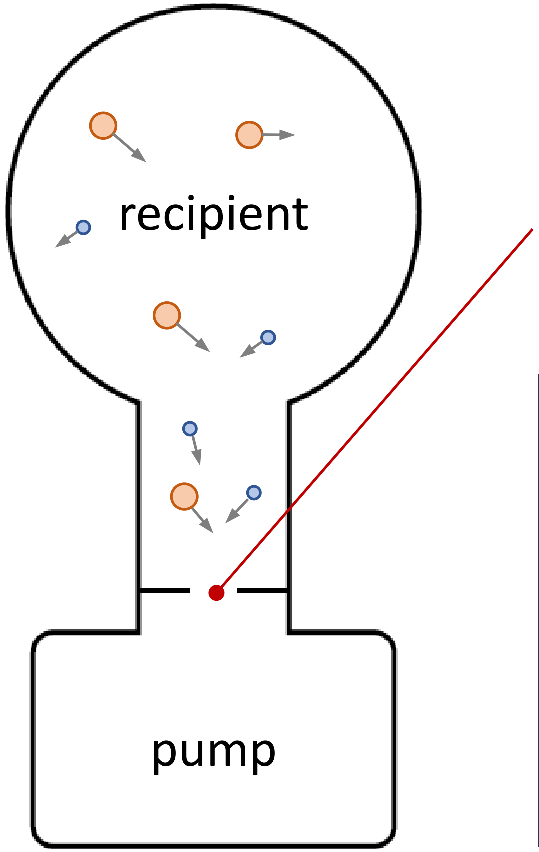
thus ***PV* [mbar l]** is a measure of the amount of gas (for a given temperature)
also: molar volume = 22.4 l / mol
(1atm = 101325 Pa, 273K)

to specify a leak rate:
x [mbar l / s]

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

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

Pumping



pumping speed
***S* [l/s]** = Q/P at pump interface
S varies for gas species

pump = device that absorbs gas molecules

for example:

typ. ion getter pump:	60 l/s
turbo pump:	100 l/s
cryo pump:	500 l/s

gas load $Q = 10^{-9}$ mbar l / s
$S = 100$ l/s $\rightarrow P \approx 10^{-11}$ mbar

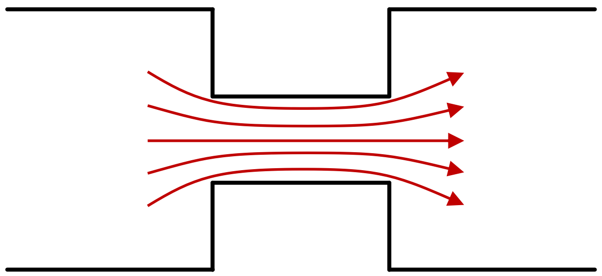
Flow Regimes

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}mbar, $\lambda \approx$ 60m
→ molecular flow

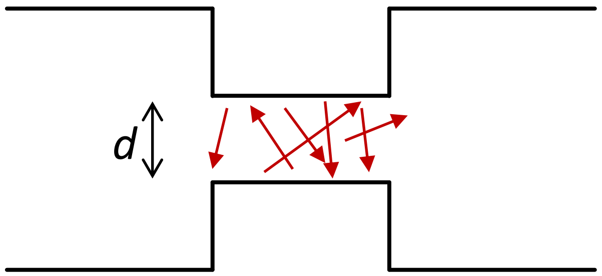
viscous flow: λ << d, *Kn* << 1



$$C_{\mathrm{visc}} \propto d^4\, \overline{P}\, \Delta P$$

heart attack!

molecular flow: λ >≈ d, *Kn* >≈ 1



$$C_{\mathrm{molec}} \propto d^3\, \Delta P$$

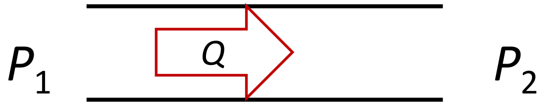
d /= 2 → *C* /= 8!

Conductance

conductance is defined as the ratio of the molecular flux *Q* to the pressure drop ΔP along a vacuum vessel

- function of the shape (eg. diam.) of the vessel
- the type of the gas
- it´s temperature

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



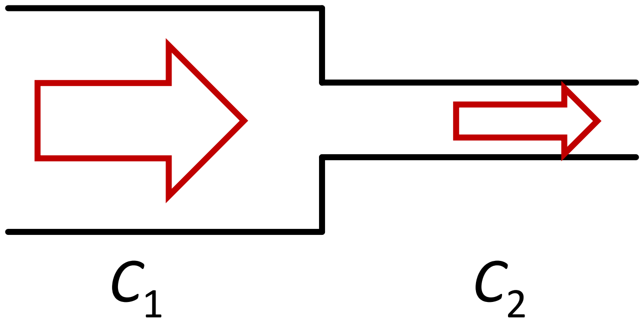
orifice: $$C = \sqrt{\frac{k_b T}{2\pi M}} A \, , \quad C_{\text{air}} = 11.6[\text{l/s}] \; A[\text{cm}^2]$$

tube: $$C = \sqrt{\frac{2\pi k_b T}{M}} \frac{d^3}{l} \, , \; C_{\text{air}} = 12.1[\text{l/s}] \frac{d^3[\text{cm}]}{l[\text{cm}]}$$

M = molecular mass
A = area
d = diameter
l = length

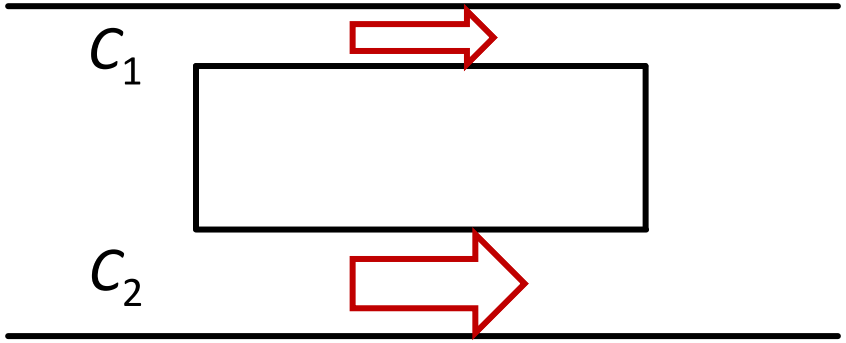
example:
tube d=8 cm, l=30 cm: 200 l/s
tube d=1 cm, l=30 cm: 0,4 l/s

Conductance - Combining Vessels

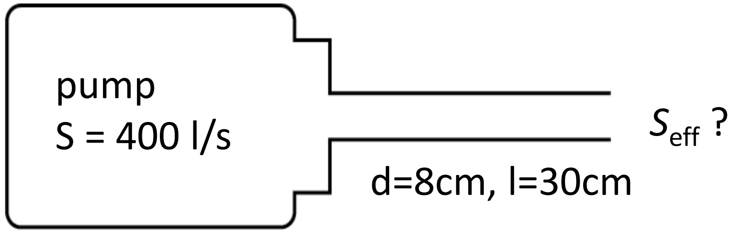


$$C_{\text{total}} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

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



$$C_{\text{total}} = C_1 + C_2$$



example:
ion getter pump 400l/s connected by d=8cm, l=30cm tube: S_{eff} = 136 l/s

Sources of gas

main sources of gas in accelerator vacuum:

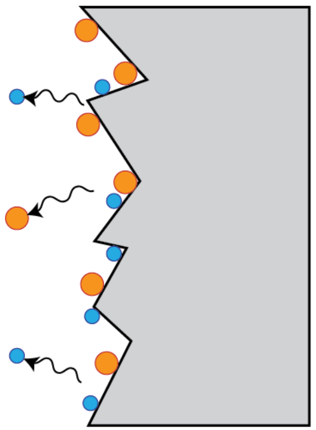
- thermal desorption
- beam induced desorption (synchrotron radiation, beam impact, electron cloud …) → dynamic pressure, discussed later
- diffusion out of bulk materials
- permeation through materials
- virtual and real leaks

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

thermal desorption
chem./phys. binding
char. time = sojourn time
e.g. E_d=1eV, T=293K
τ = 5h

$$q(t) \propto \frac{1}{t}$$

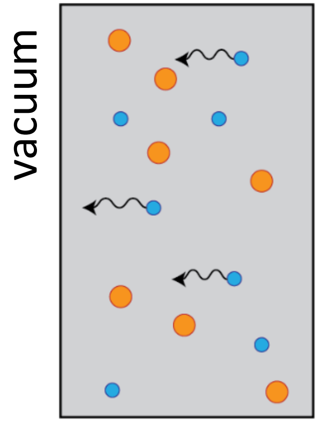
$$\tau \propto \exp\left(\frac{E_d}{k_b T}\right)$$



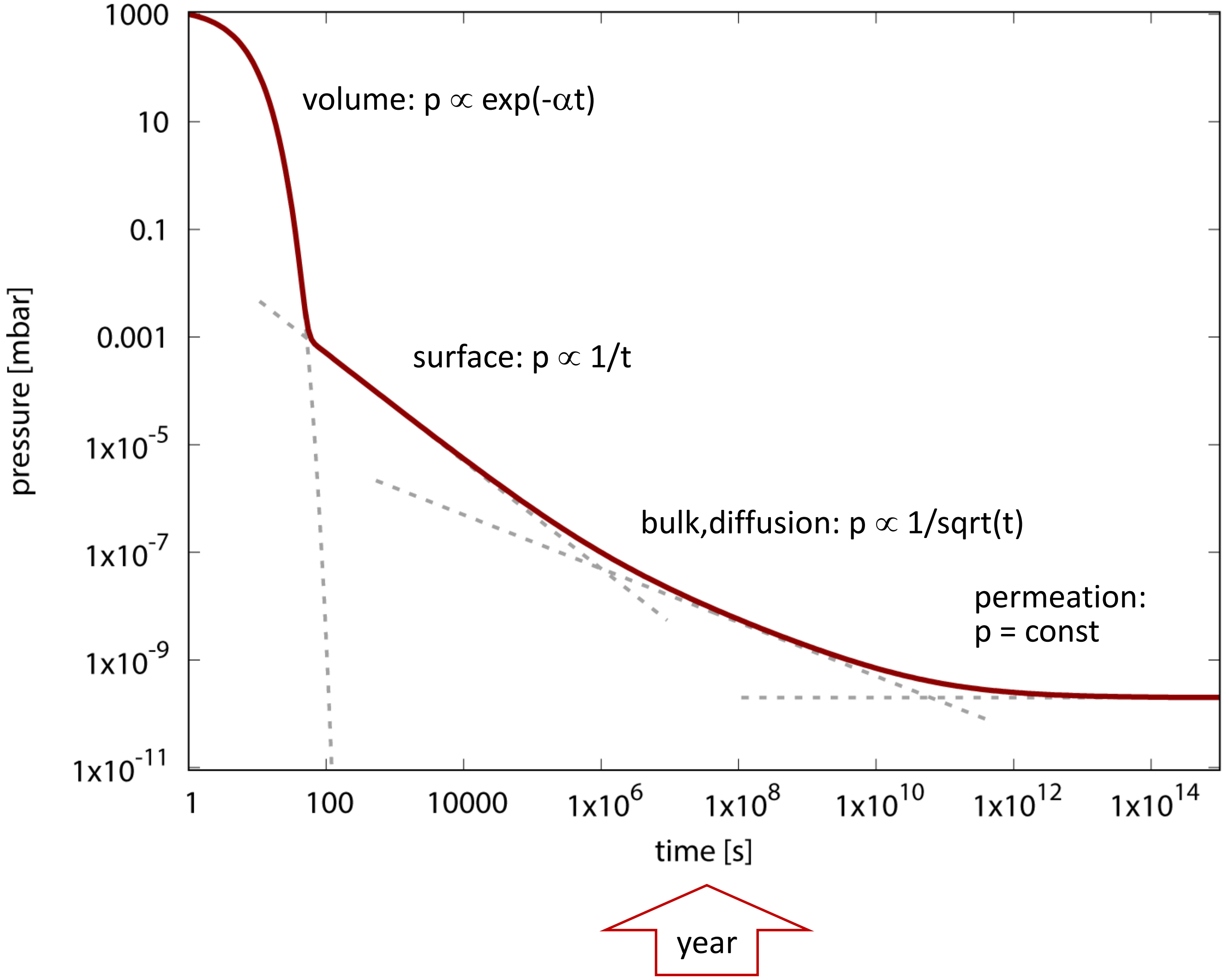
bulk diffusion
diffusion coefficient D
mainly H_2 relevant

$$q(t) \propto \sqrt{D(T)/t}$$

$$D(T) \propto \exp\left(-\frac{E_{\text{diff}}}{k_b T}\right)$$



Pump Down Processes



log. scale:
different effects dominate
after varying times

Pressure Computation for 1-dimensional Systems

starting from definition of conductance
C = Q / ΔP
introduce correct sign and specific conductance:

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

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

compare conductance of circular tube:

$$C = \underbrace{\sqrt{\frac{2\pi k_b T}{M}}\, d^3}_{\mathcal{C}} \underbrace{\frac{1}{l}}_{\uparrow}$$

gas&tube specific   length

continuity equation, change of flow by pumping and outgassing:

$$\partial Q(s)/\partial s = q - \mathcal{S}\,P(s)$$

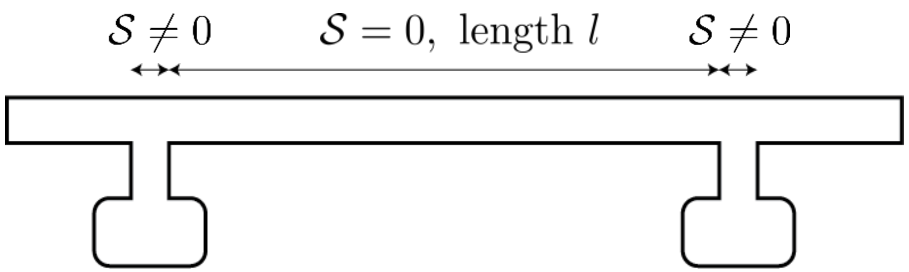
1-dim diffusion equation:

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

$\mathcal{C}$	$\left[\frac{\mathrm{l\,m}}{\mathrm{s}}\right]$	specific conductance
$\mathcal{S}$	$\left[\frac{\mathrm{l}}{\mathrm{s\,m}}\right]$	specific pumping speed
q	$\left[\frac{\mathrm{mbar\,l}}{\mathrm{s\,m}}\right]$	specific outgassing rate

Quadratic Solution for lumped Pumps

$$P(s) = \frac{ql}{S} + \frac{q}{8\mathcal{C}}\left(l^2 - 4s^2\right)$$



the parabolic profile results in following average and maximum pressure:

$$P_{\text{avg}} = ql\left(\frac{1}{S} + \frac{l}{12\,\mathcal{C}}\right), \quad P_{\max} = ql\left(\frac{1}{S} + \frac{l}{8\,\mathcal{C}}\right)$$

pumping speed

conductance limited

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

example:
7cm tube, $q_0 = 5\times10^{-12}$ mbar l / s cm², S=100l/s
→ l=5m, $P_{avg} = 1\times10^{-9}$ mbar
→ l=3m, $P_{avg} = 5\times10^{-10}$ mbar

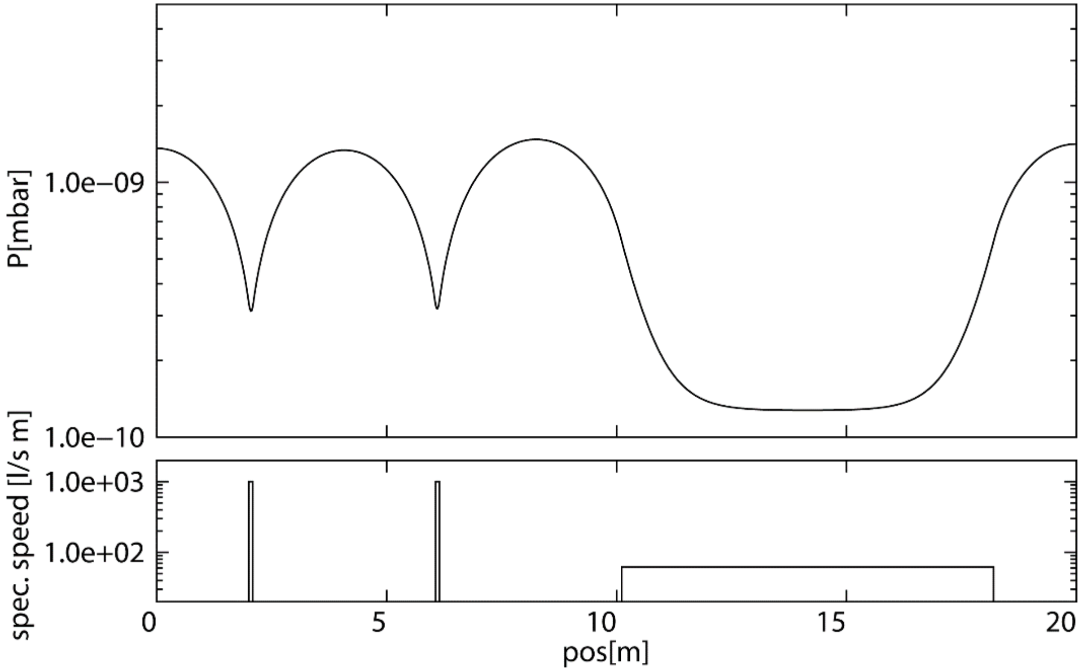
General Solution by Matrix Transport of Q, P

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

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

[V. Ziemann, SLAC/Pub/5962]

example calculation:
lumped pumps: S = 100 l/s
distrib. pumps: S = 60 l/s m
outgassing: $q_0 = 5\times10^{-12}$ mbar l / s cm²



Time Dependent Diffusion Equation

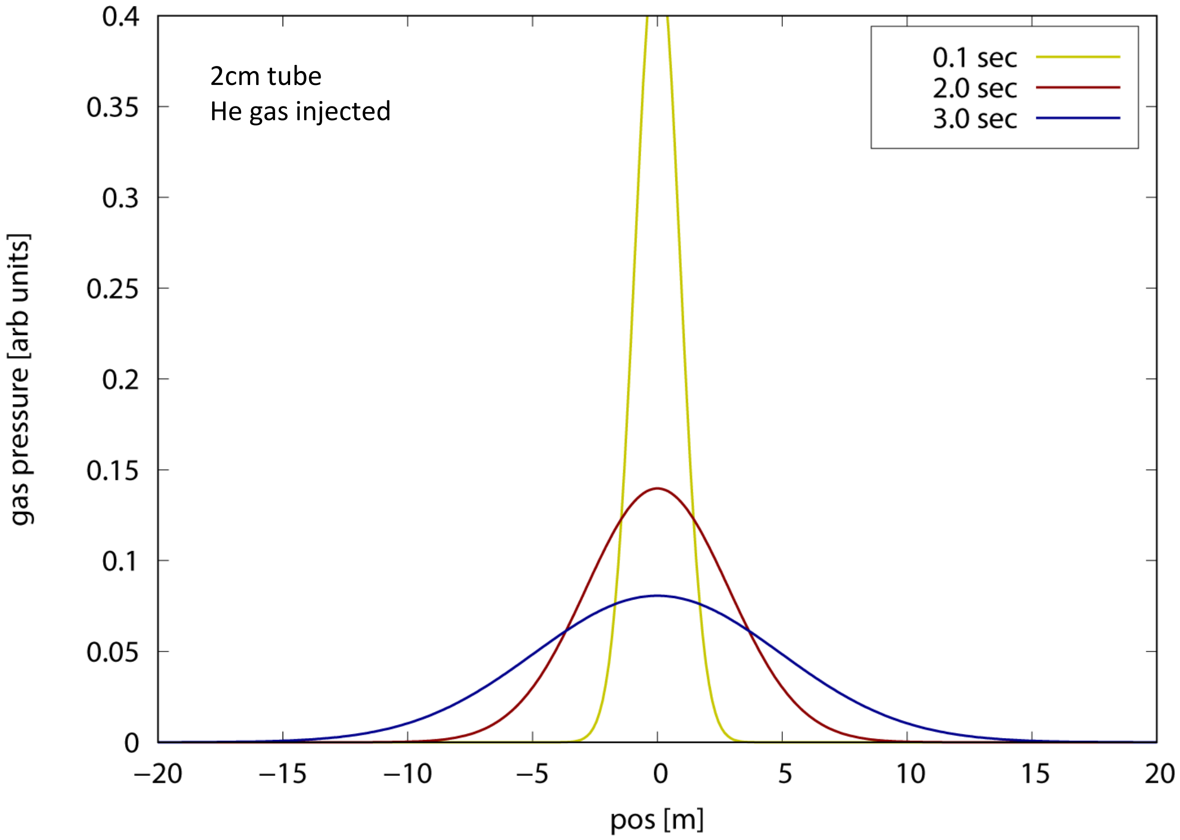
$$\mathcal{V}\frac{\partial}{\partial t}P(s,t) = \frac{\partial}{\partial s}\,\mathcal{C}\,\frac{\partial}{\partial s}P(s,t) - \mathcal{S}P(s,t) + q$$

specific volume [l/m]

compare classical diffusion eq.:

$$\frac{\partial}{\partial t}f(x,t) = \frac{\partial}{\partial x}\,\mathcal{D}\,\frac{\partial}{\partial x}f(x,t)$$

$$\rightarrow \mathcal{D} = \frac{<\Delta x^2>}{<\Delta t>} = \frac{\mathcal{C}}{\mathcal{V}}$$



example:

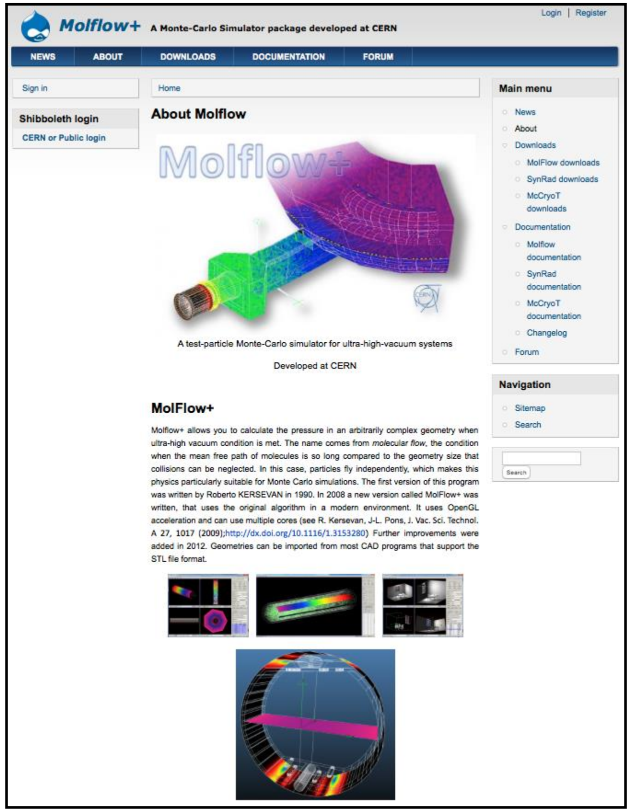
tube 7cm, diffusion time over 5m:
N_2: 2.3 s; He: 0.9 s

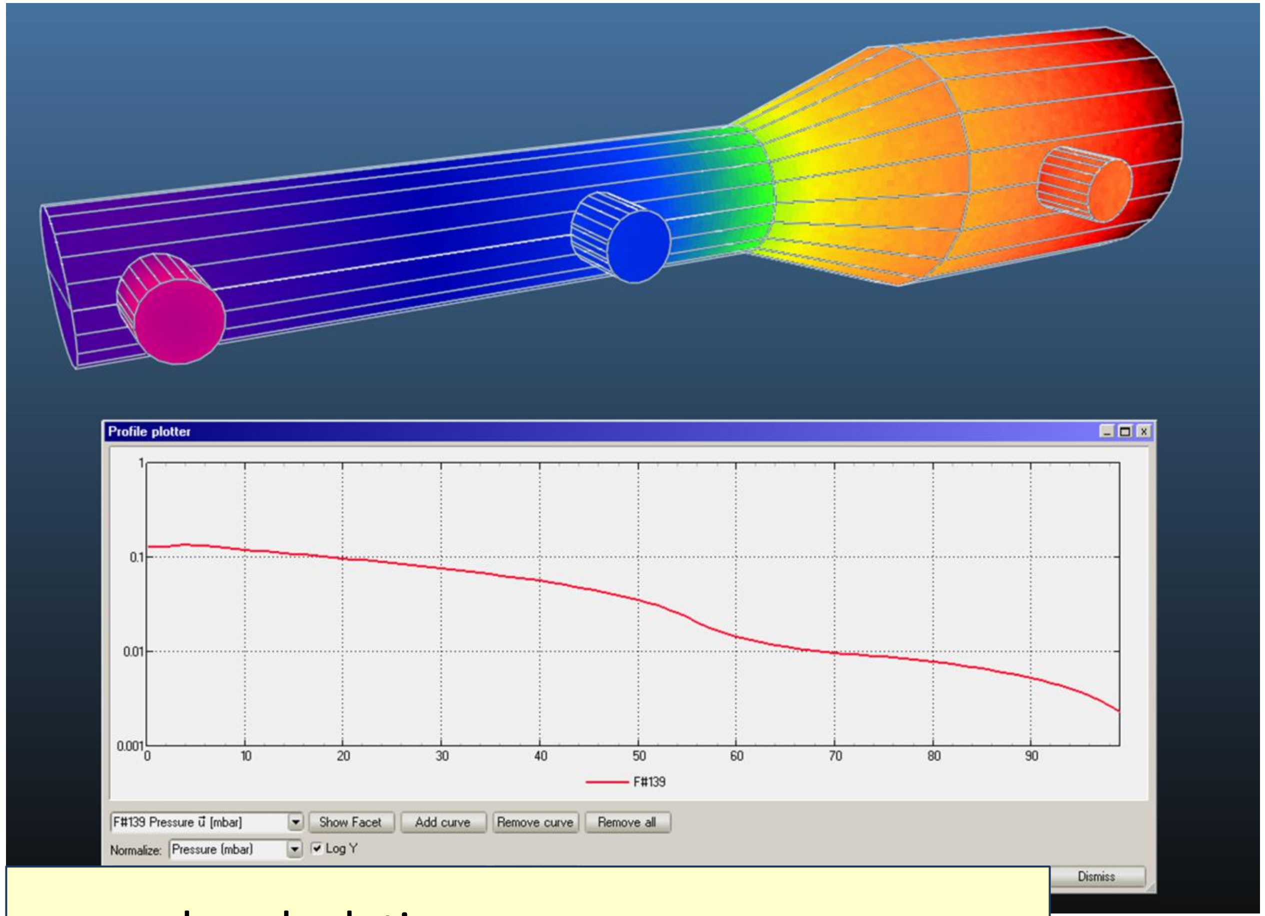
tube 2cm, diffusion time over 5m:
N_2: 8 s; He: 3 s

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:

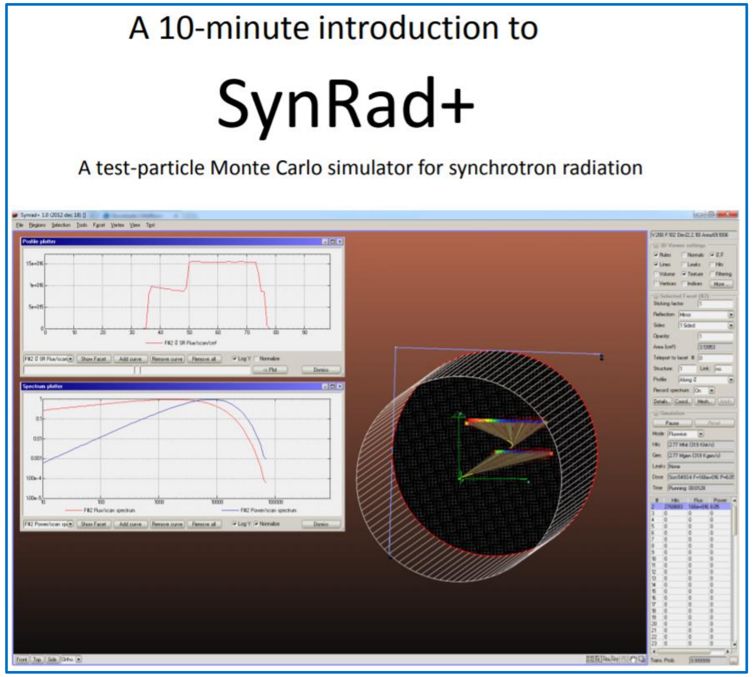




example calculation:
100k molecules tracked, computation time: few seconds, pressure profile

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



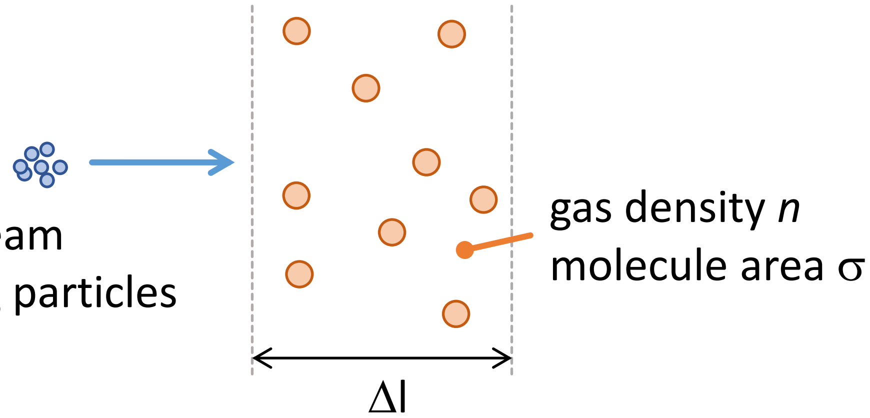
- SR spectrum + flux
- calculates beam orbit from lattice file (MAD-X)
- dipole approximation only, no undulator interference effects

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



$$\begin{aligned}
\Delta N_{b,\mathrm{lost}} &= -N_b \times \frac{\text{area of molecules}}{\text{total area}} \\
&= -N_b \times \frac{nV\sigma}{V/\Delta l} \\
&= -N_b n \sigma \Delta l \\
&= -N_b n \sigma \beta c \Delta t
\end{aligned}$$

probability of collision

results in differential equation: $$\frac{dN_b}{dt} = -N_b \sigma \beta c n$$

σ = cross section for generic „loss process“

solution: $$N_b(t) = N_0 \exp\left(-\sigma \beta c n\, t\right), \;\; \tau \approx \frac{1}{\sigma c\, n}$$

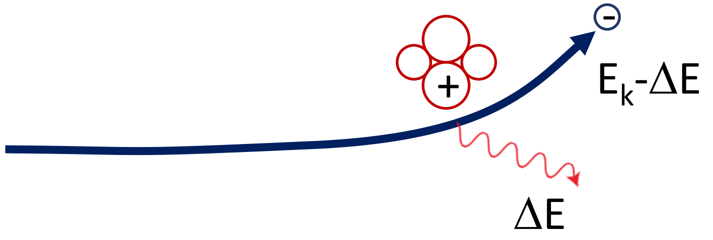
specific loss processes by gas scattering

- <u>bremsstrahlung</u> (electrons)
- <u>elastic scattering</u> (Coulomb, nuclear)
- inelastic scattering (nuclear)
- multiple Coulomb: <u>p-emittance growth</u>

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:

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

V_n = 22.4l, molar Volume
N_A Avogadro Number
δ_E = ΔE/E, energy acceptance
X_0 gas specific radiation length

radiation length:
(normal condition)

	H_2	He	CH_4	H_2O	CO	Ar	Air
X_0 [m]	7530	5670	696	477	321	117	304

[e.g. particle data booklet]

example HERA-e:
δ_E = 8×10^{-3}; P_{tot} = 10^{-8} mbar
composition: 75% H_2, 25% CO
$\boldsymbol{\tau_{brems}}$ **= 16 h**

Electrons: Elastic Coulomb Scattering

Rutherford Scatting

diff. cross section for occurrence of scattering angle θ:

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

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

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

resulting lifetime:

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

example HERA-e:
pressure: P_{tot} = 10^{-8} mbar
composition: 75% H_2, 25% CO
Z_{eff} = rms(Z_i) = 3.6
A_y = 20 mm, $\beta_{y,avg}$ = 25 m
$\tau_{elastic}$ = 5.200 h → insignificant

sum over gas types and atoms per molecule

Hadron Beam Emittance Growth

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

definition of emittance growth time:

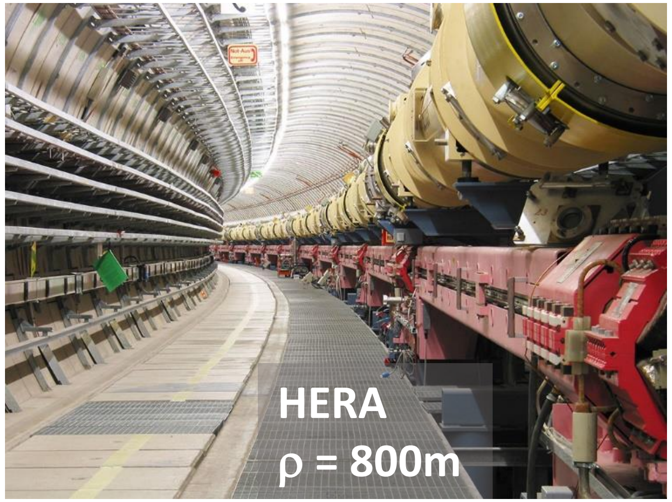
$$\tau_\varepsilon = \left(\frac{1}{\varepsilon_x} \frac{d\varepsilon_x}{dt} \right)^{-1}$$

growth rate:

$$\frac{d\varepsilon}{dt} = \overline{\beta_y} \frac{d(\theta_0^2)}{dt} = \overline{\beta_y} \frac{(13.6)^2}{(cp)^2\,[\mathrm{MeV}^2]} \frac{c}{P_0} \sum_i \frac{P_i}{X_{0,i}}$$

example HERA-p ε growth rate:
E_k = 920 GeV, $\beta_{y,avg}$ = 50 m
P_{tot} = 5×10^{-11} mbar @ 4.2 Kelvin, H_2
emittance: ε_x = 5×10^{-9} m·rad

τ_ε = 2.000 h



protons

electrons

Synchrotron Radiation induced Desorption

dynamic vacuum

- SR photons generate photoelectrons, these desorb gas molecules from the surface
- desorption yield η per photon is reduced with integrated dose (conditioning)

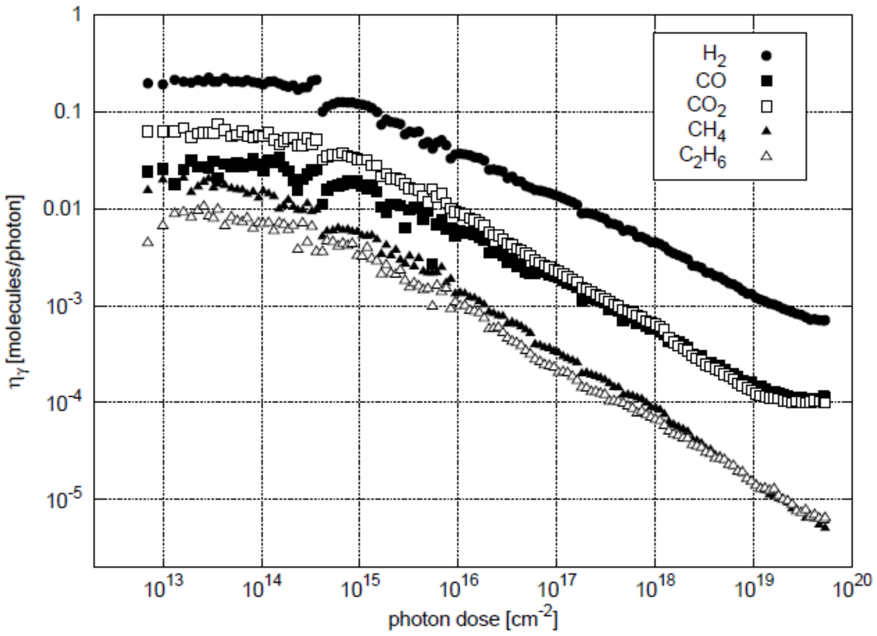
SR photons per length and time:

$$\frac{dN_\gamma}{dtds} = 1.28 \cdot 10^{17} \frac{I\,[\mathrm{mA}]\,E\,[\mathrm{GeV}]}{\rho\,[\mathrm{m}]}$$

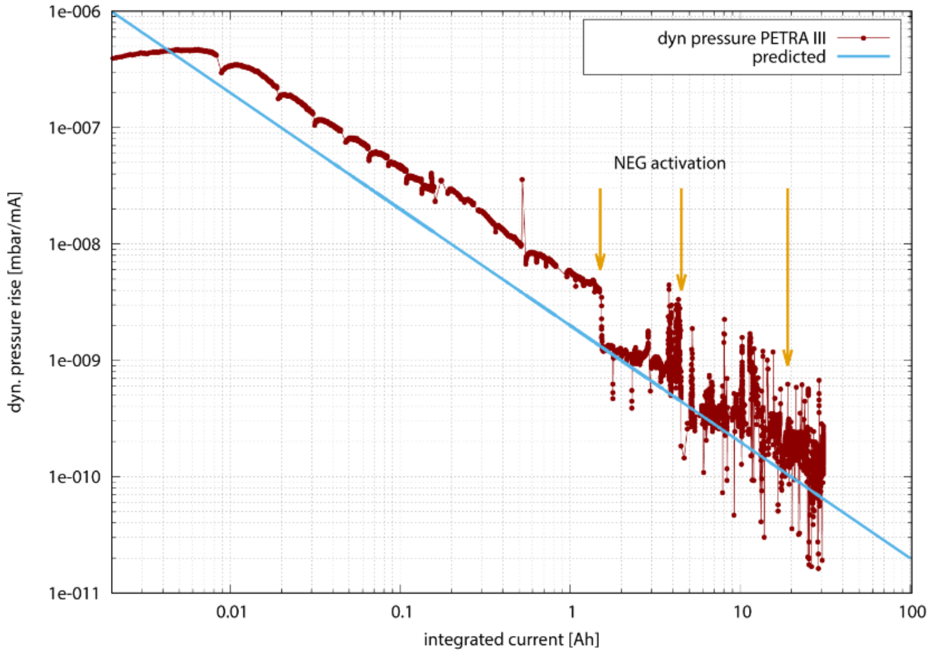
resulting specific outgassing:

$$q = \eta_\gamma\, k_b\, T\, \frac{dN_\gamma}{dtds}$$

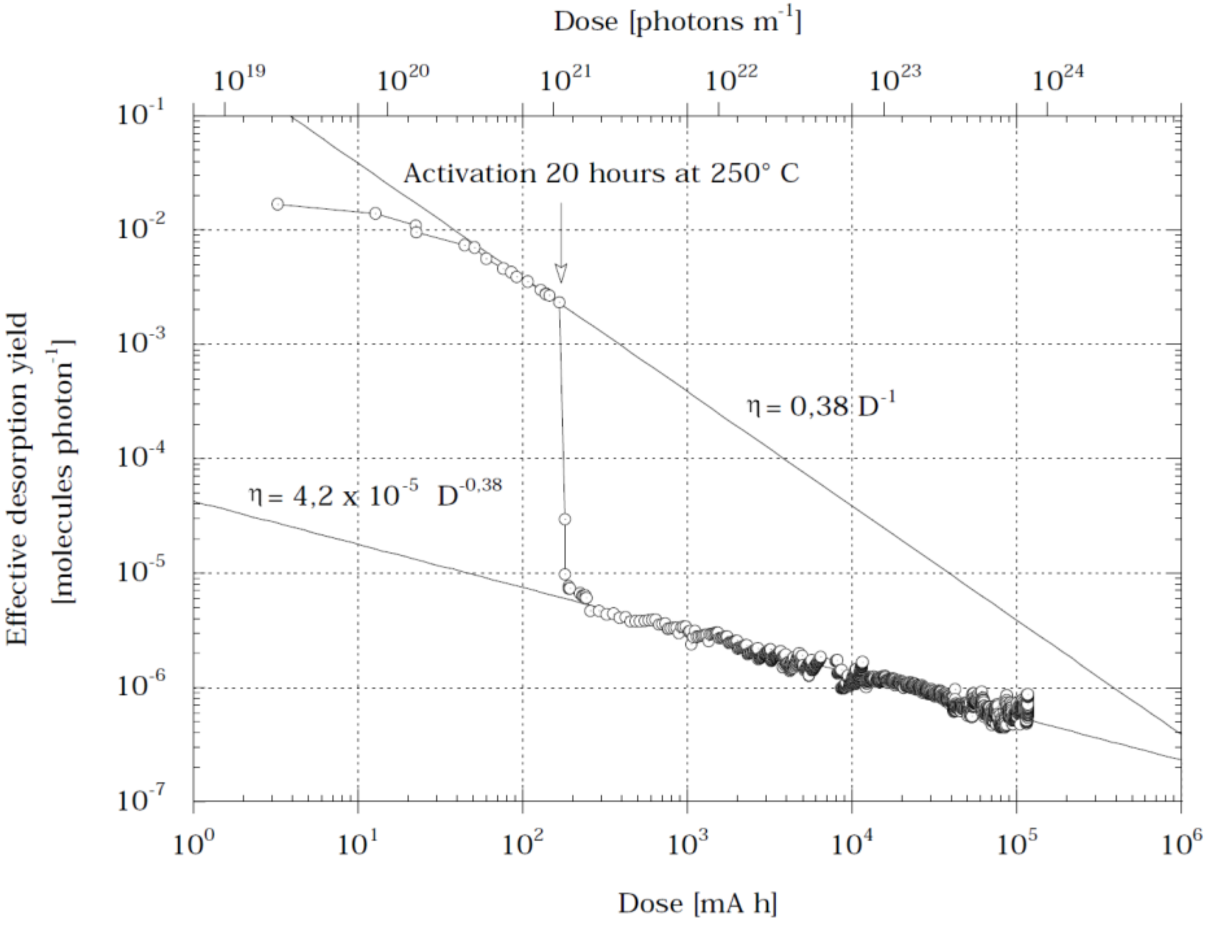
measured desorption yield for different gases [G.Vorlaufer]



measured dynamic pressure rise as a function of integrated current [PETRA-III, DESY]



Reduced desorption by NEG Coating



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

→ NEG coating reduces SR desorption immediately

→ conditioning is slower afterwards

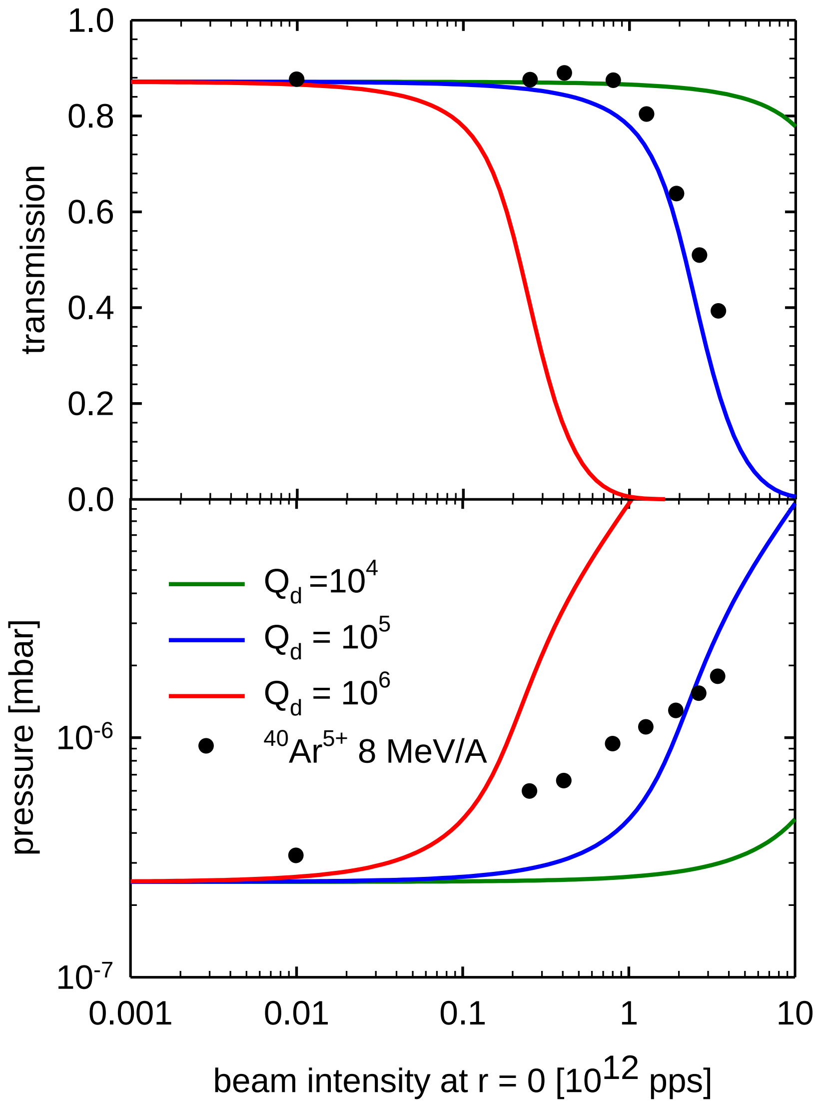
→ however, NEG coated chambers lead to good conditions in practice

Heavy Ion induced Gas Desorption

demonstration of transmission breakdown by gas desorption

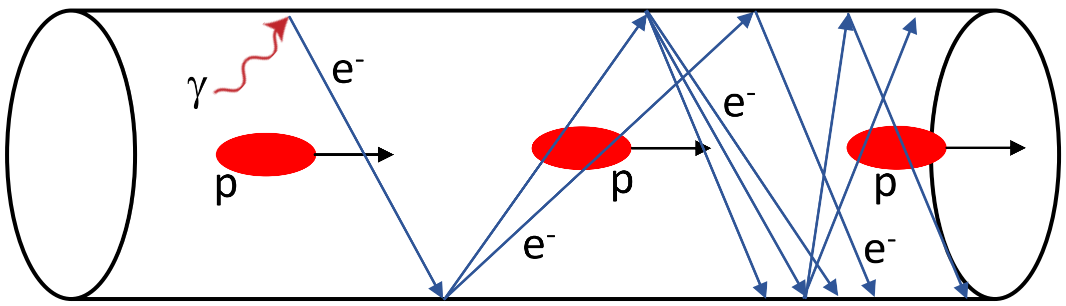
[measurements & simulations in AGOR cyclotron, KVI-Groningen, S.Brandenburg et al]

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



→ release of 10^5 (!) gas molecules per lost ion is compatible with data

Dynamic effect in LHC: Electron Cloud Effect



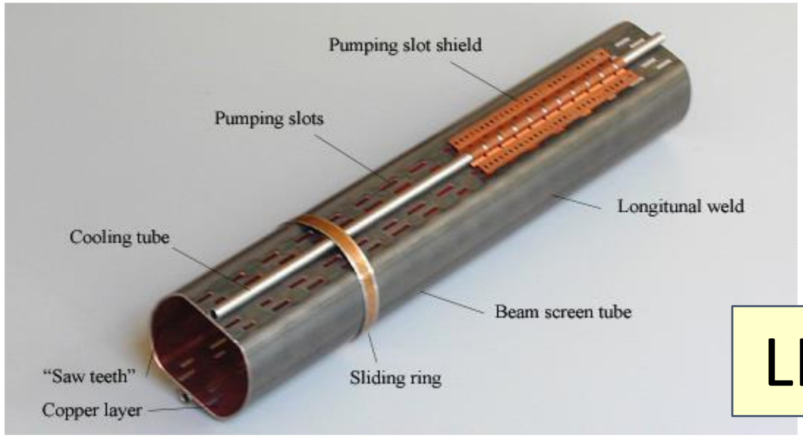
$E(e^-) \approx 1..100eV$

- 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:

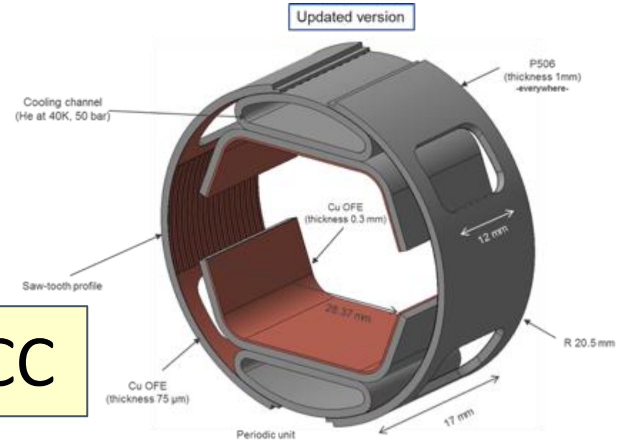
- wall coating, e.g. graphite, TiN (low SEY)
- weak magnetic solenoid field

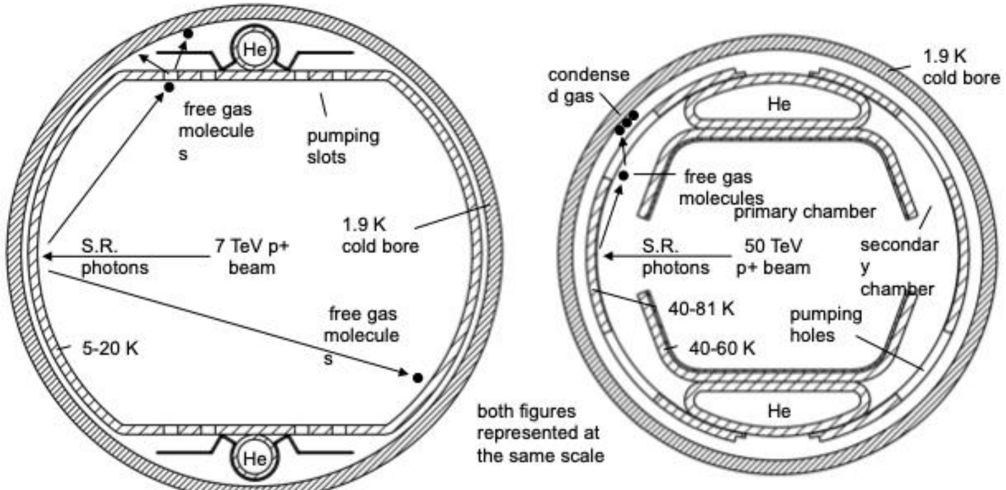
Specialized Chambers: LHC & FCC with Beam Screens



LHC

FCC





LHC - 173 l/(s·m) for H_2 at 5 K
0.22 W/m emitted SR

FCC-hh - 898 l/(s·m) for H_2 at 40 K
35.4 W/m emitted SR

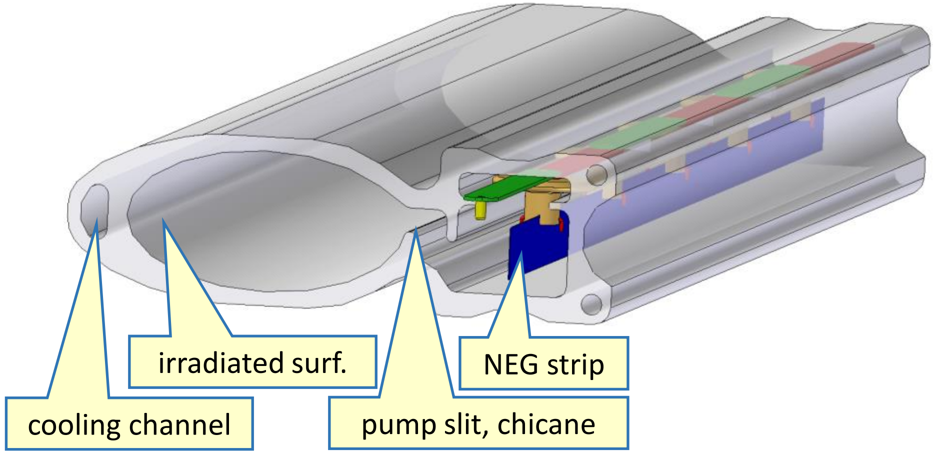
- At the expense of a **higher complexity** (translated into a higher, but still affordable, cost) the beam induced vacuum effects are mitigated and the **pumping speed** and cooling capacity have been **considerably increased**

LHC(left), FCC comparison

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

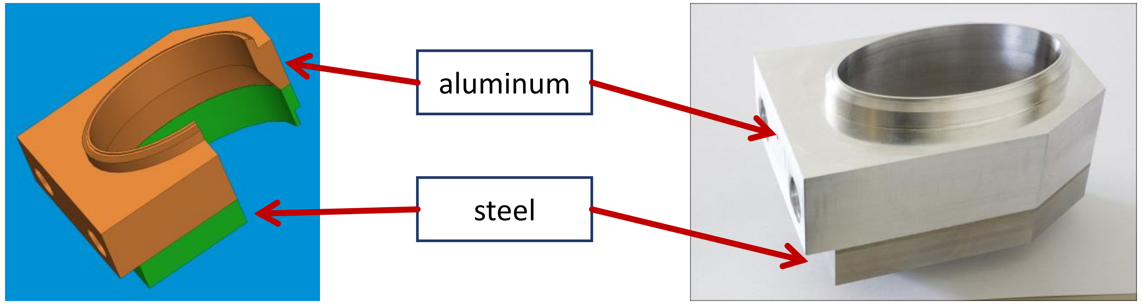
Vacuum Chambers for Electron Synchrotron

profile extruded aluminum, milled and bent (ρ=196m); NEG strip (St707) for pumping



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

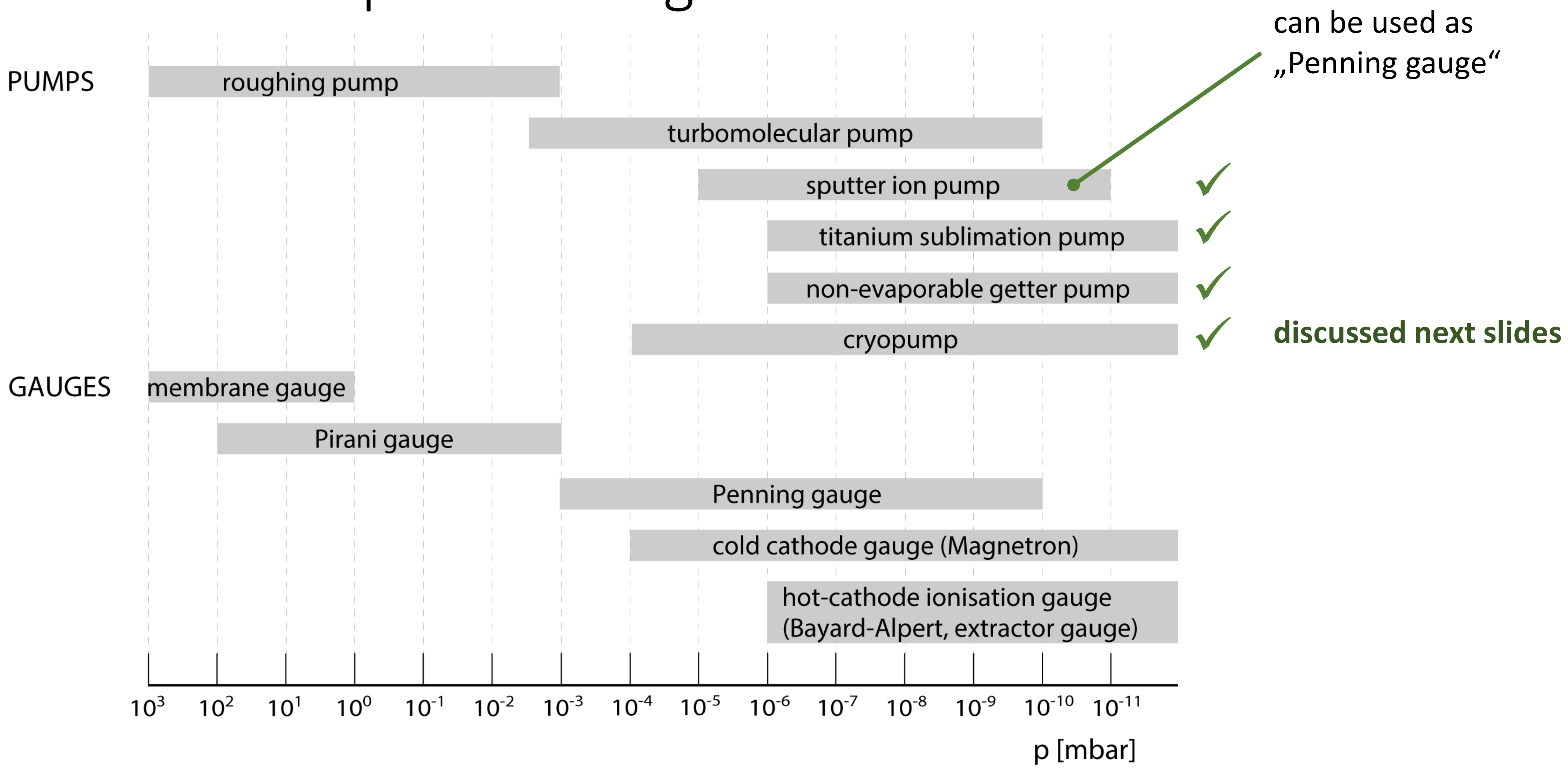
<u>solution</u>:
explosion bondings SS/Al
with 4cm Al thickness



Next:
Components for Vacuum Systems

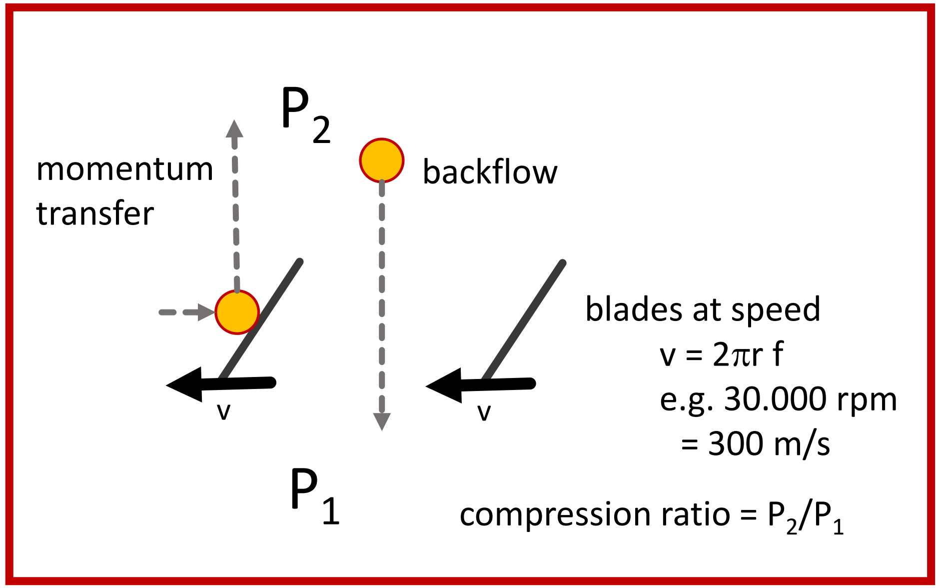
pumps: overview, turbo, ion sputter, NEG, cryo-pump
flange systems, collimators, residual gas analysis (RGA)

Overview Pumps and Gauges



Turbo Molecular Pump

Wikipedia

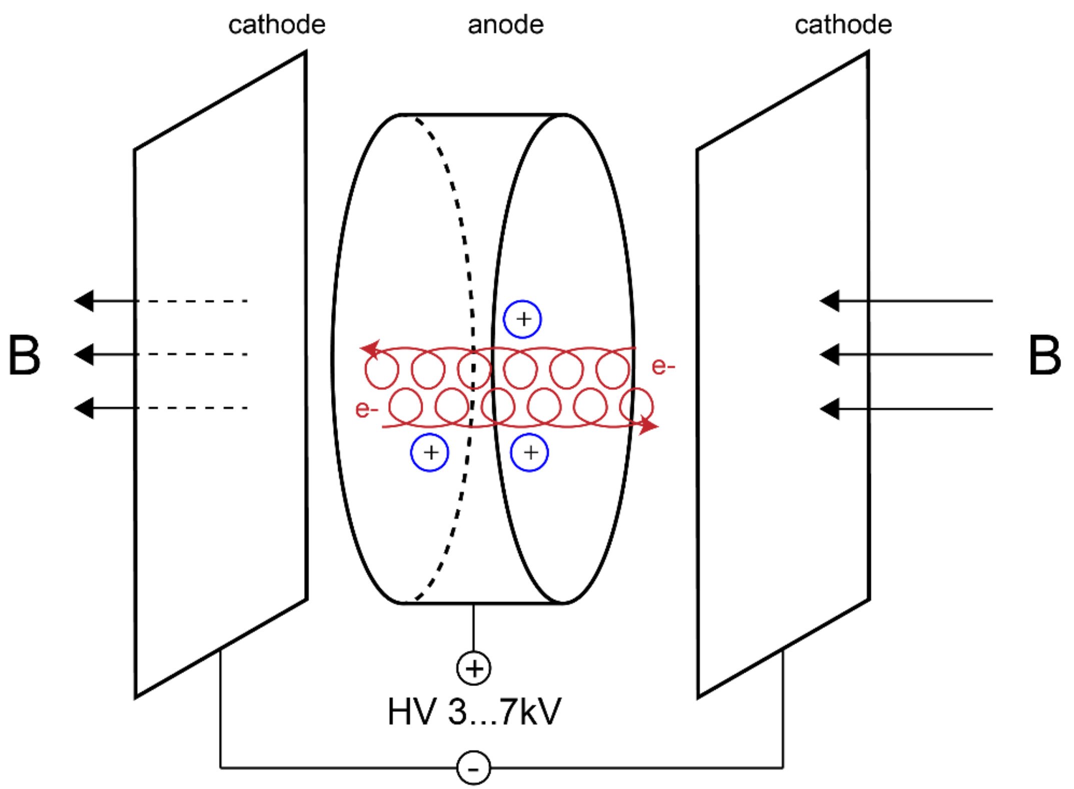


- pumps all gases
- blade speed similar molecule speed(!)
- 30.000 … 60.000 RPM
- works down to 10^{-10} mbar

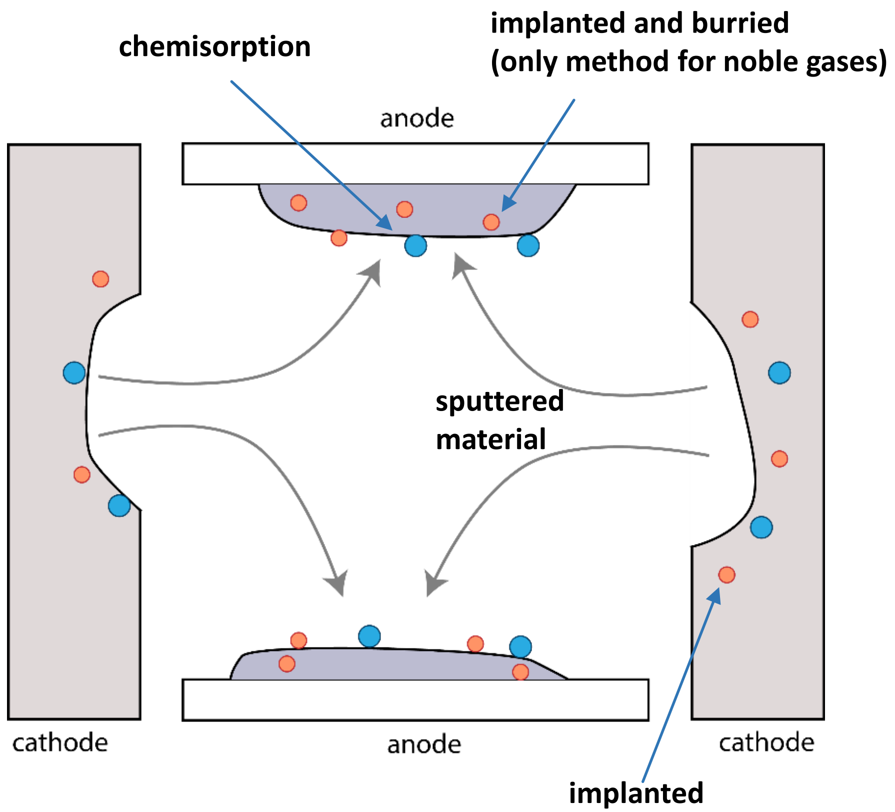
molecule	avg speed @ 293K [m/s]	compression ratio
H_2	1800	10^3
He	1250	10^4
CO	470	10^9

Sputter Ion Pump

single penning cell
electric and magnetic field
gas ionization, acceleration



pumping mechanism
implantation, chemisorption
and burying of gas molecules



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

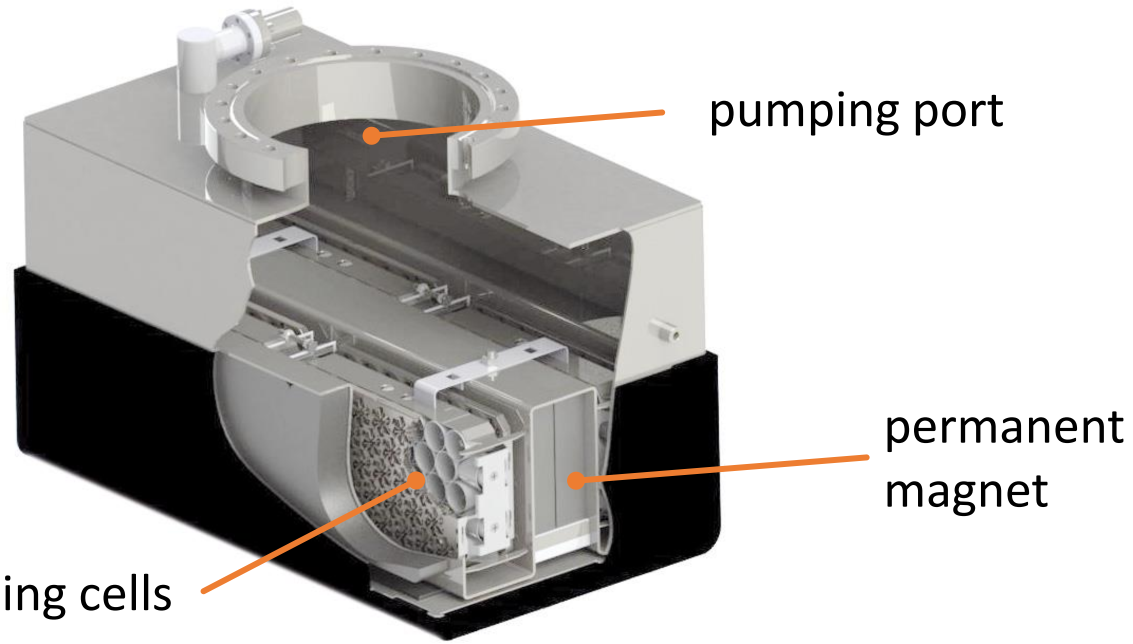
Ion Sputter Pumps

courtesy Agilent catalog

pumping speed:
2 l/s … 500l/s

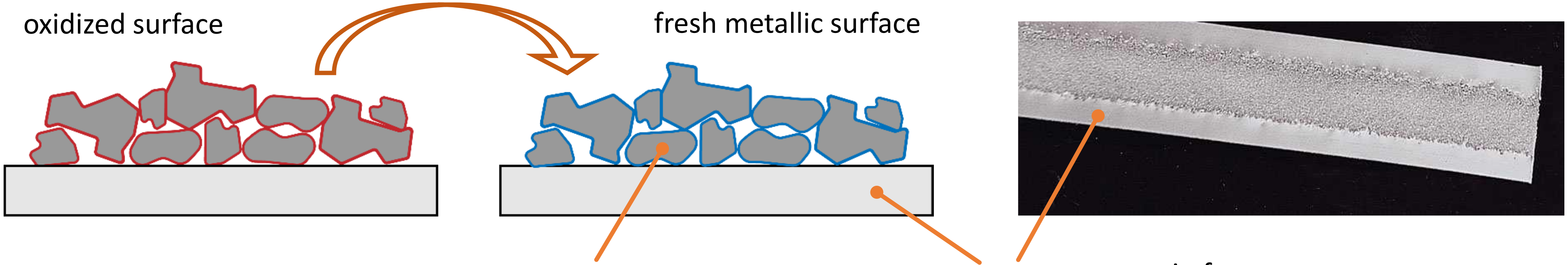
weight:
0.3kg … 120kg

example:
modern Agilent
200 pump



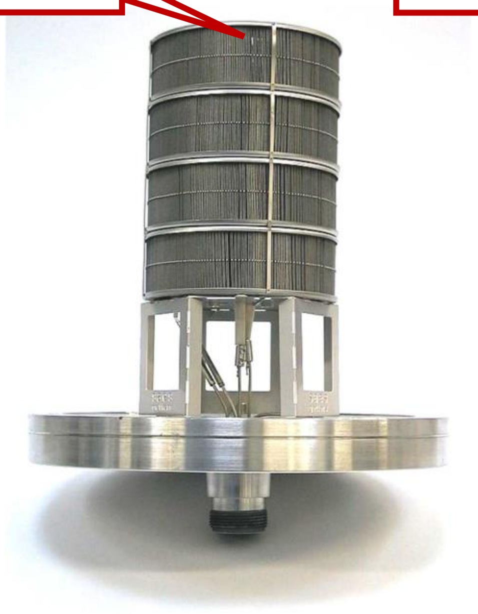
NEG – Non Evaporable Getter Pumps

- NEG captures gases by chemical reaction, e.g. H_2O, 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

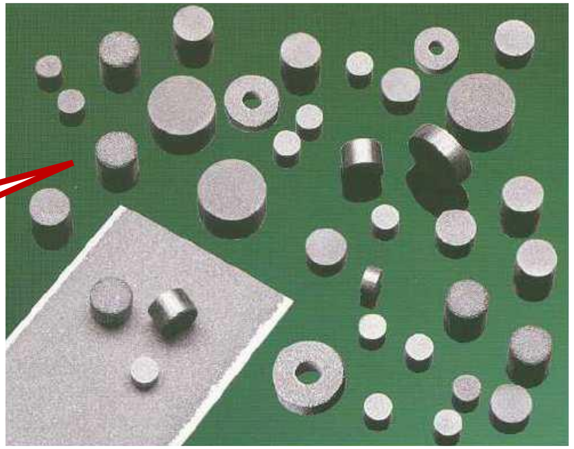


NEG Pump Designs

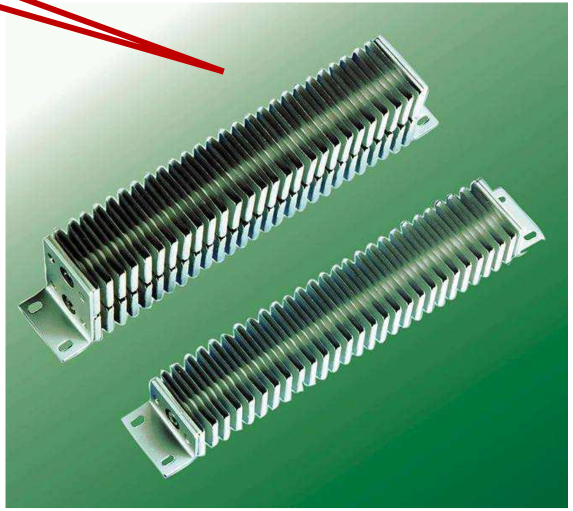
NEG + Ion sputter combined



NEG cartridge



pills, disks, rings

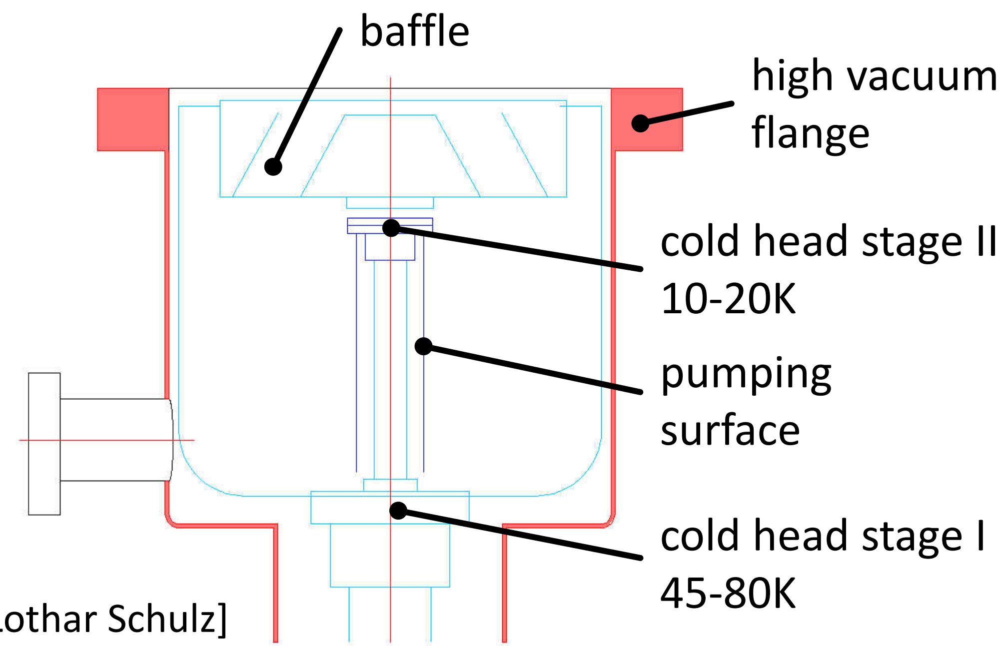


NEG wafer

images: SAES Getters

Cryo Pump

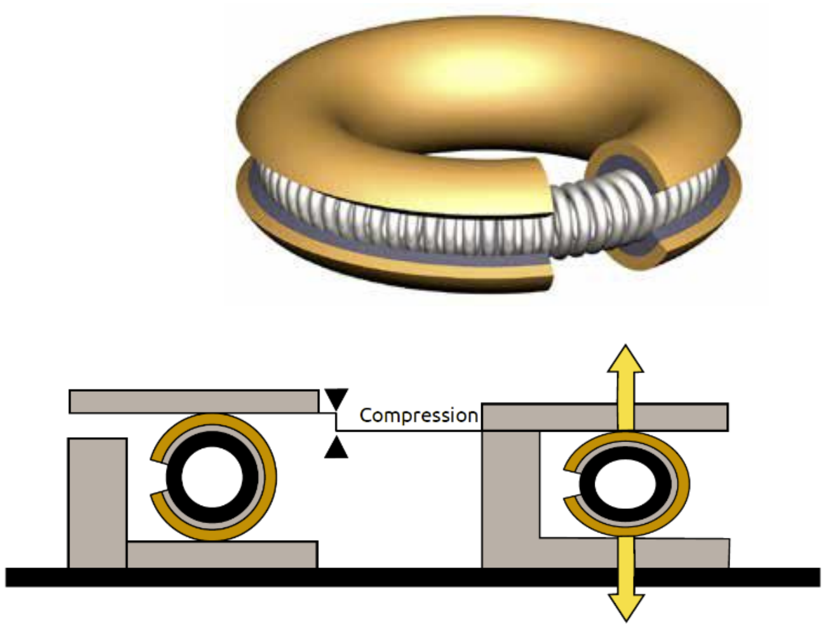
- high pumping speed for <u>all</u> gases
- cryo-condensation of N_2, O_2 and Ar on cold surface
- cold surface partly covered with charcoal: cryosorption for H_2, He, Ne
- periodic regeneration by warmup



[Lothar Schulz]

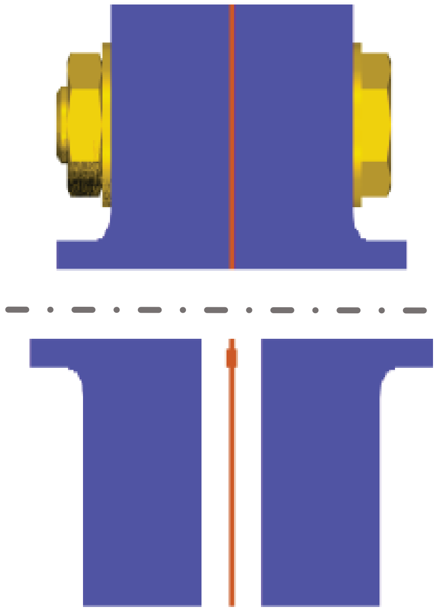
Metal sealed Flange Systems

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



Helicoflex: Technetics Group

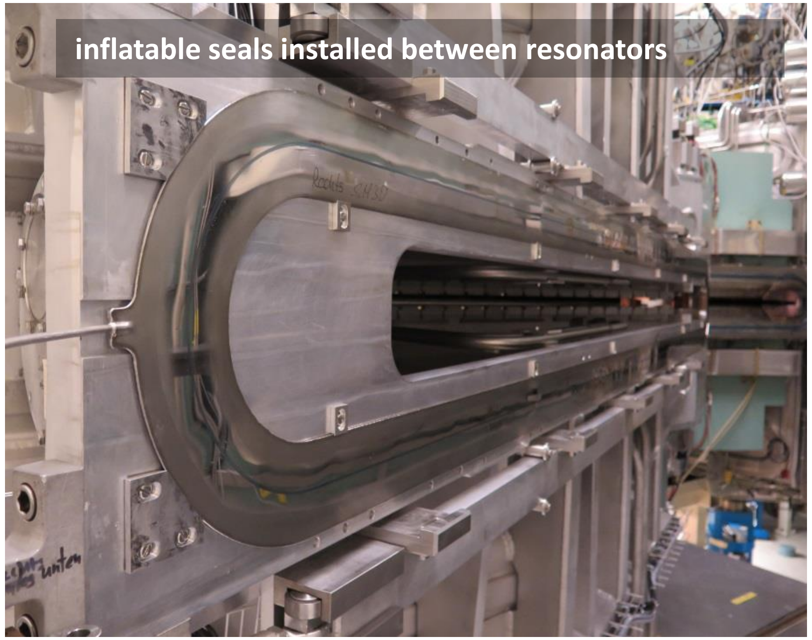
Conflat Flange (CF)

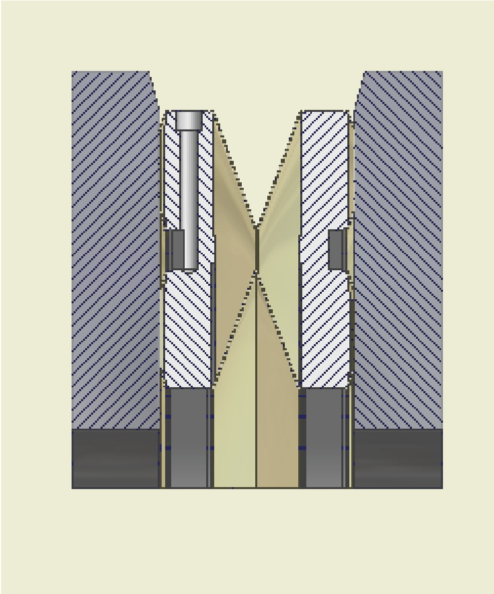


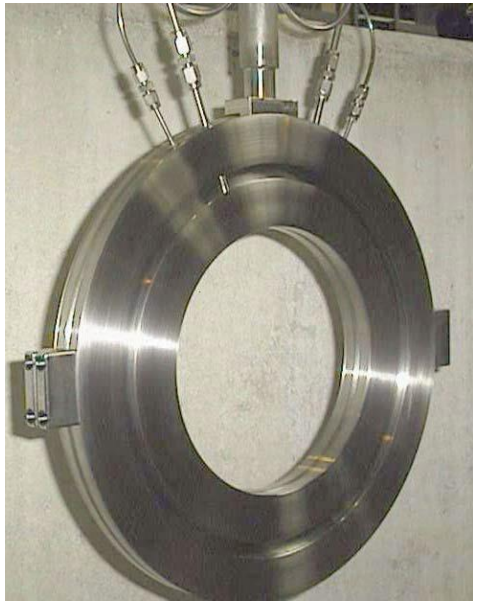
VAT Flange, flat seal

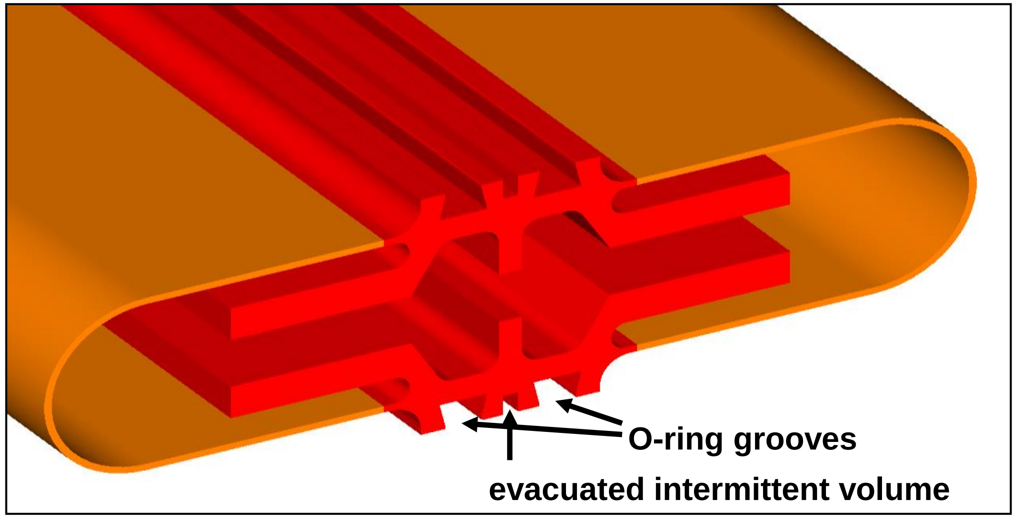
Inflatable Seals

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



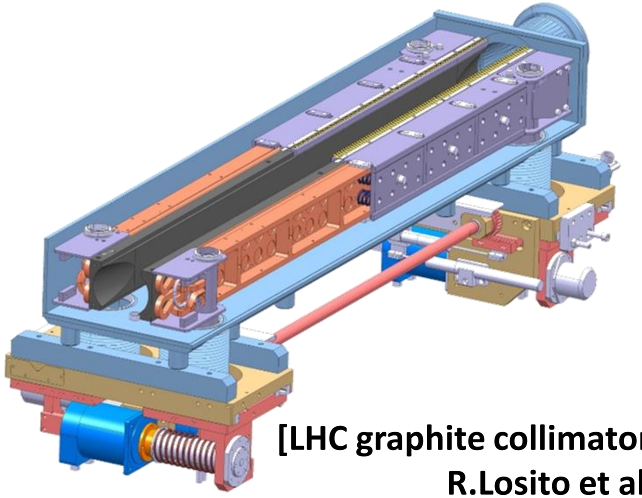




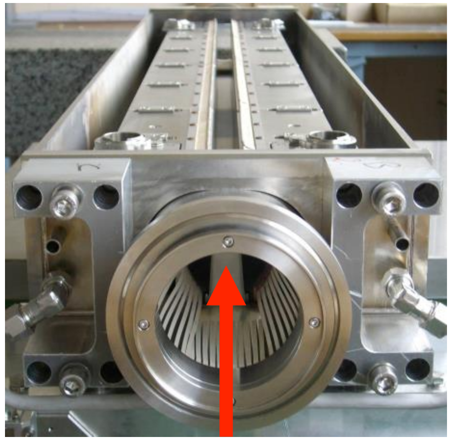


Collimators

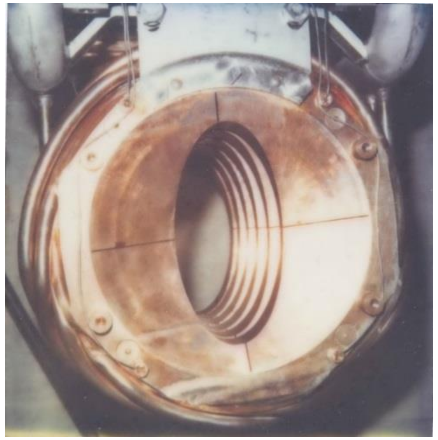
- collimators are parts of the vacuum system with multi-physics aspects
- some materials are not optimal for vacuum, e.g. graphite or graphite with MoGr coating (porosity, outgassing, dust)
- straightness, thermal shock resistance, heat load and heat conductivity, efficient cooling, thermal outgassing,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



[LHC graphite collimator, R.Losito et al]



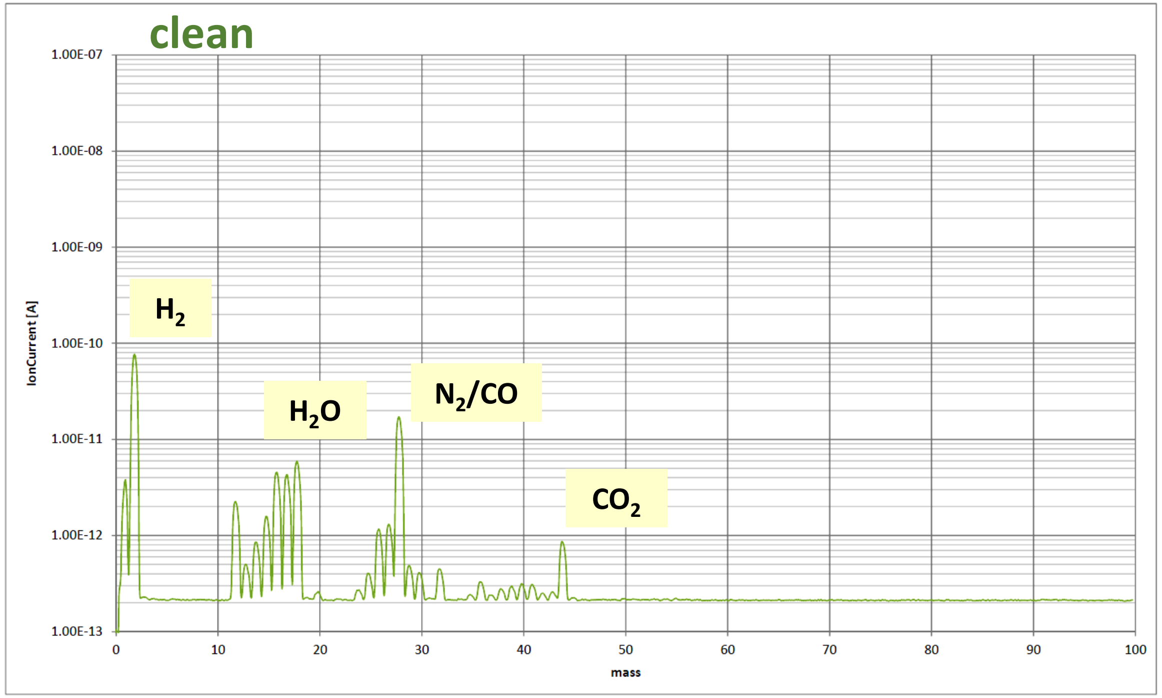
[LHC collimator, S.Radaelli et al]

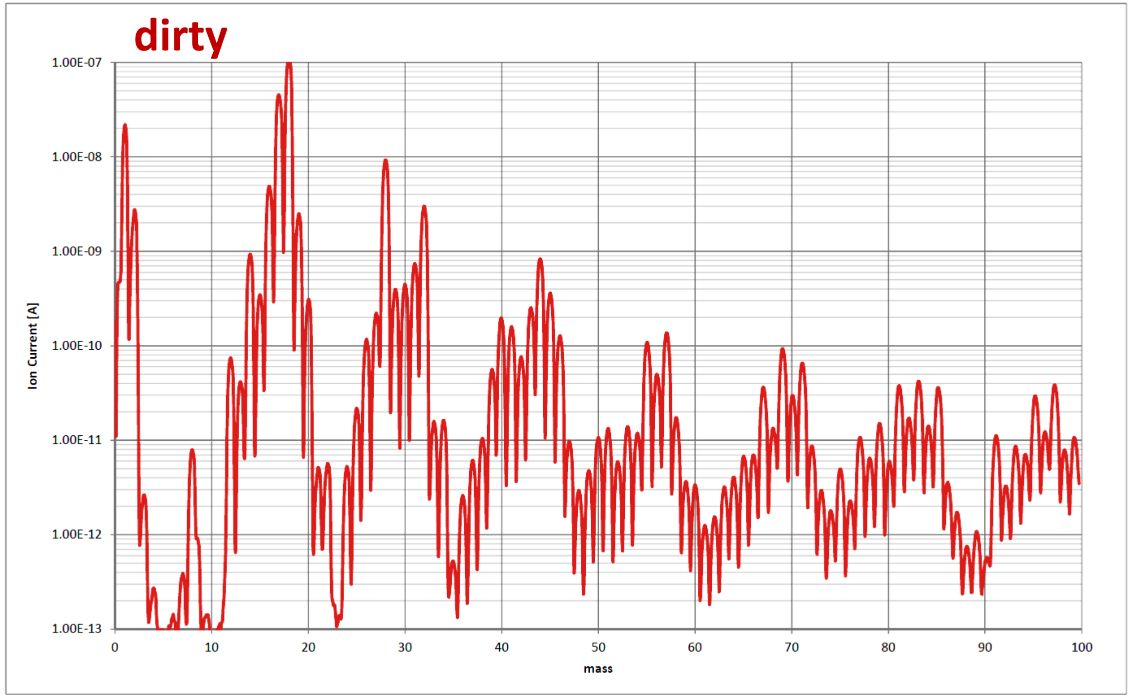


[PSI-HIPA >100kW avg power, D.Kiselev et al]

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: breamsstrahlung
- p: emittance growth

Beam Vacuum

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

Gas Sources

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

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

Pumping

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

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

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
- 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 (radiation length X_0, interaction length etc)