Accelerator Vacuum

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CERN Accelerator School – Introductory Course

October 6, 2021

The CERN Accelerator School

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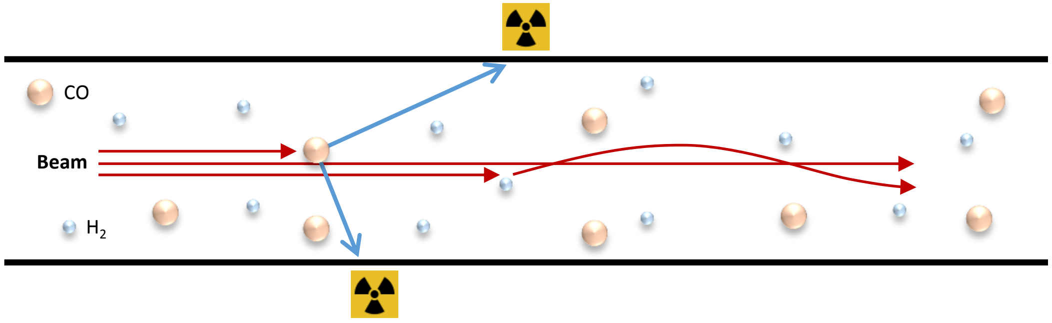
Why vacuum in accelerators ?

- 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

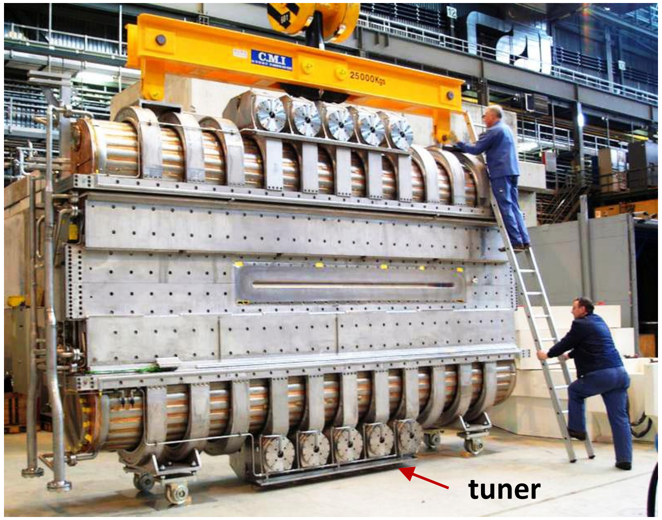
3. Components for Vacuum Systems

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

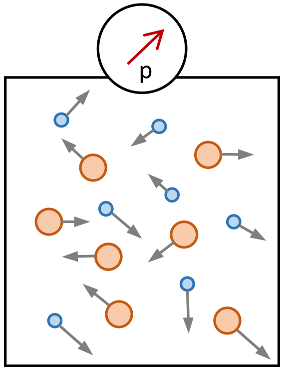
flange systems

Pressure

cyclotron resonator:
continuous tuning required
due to air pressure variation

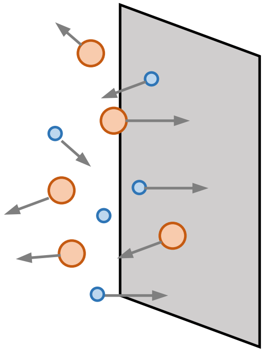


pressure = force / area
1 Pa = 1 N/m² = 0.01mbar
1 atm = 10^5 Pa
$\rightarrow$ weight of 1kg/cm²



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

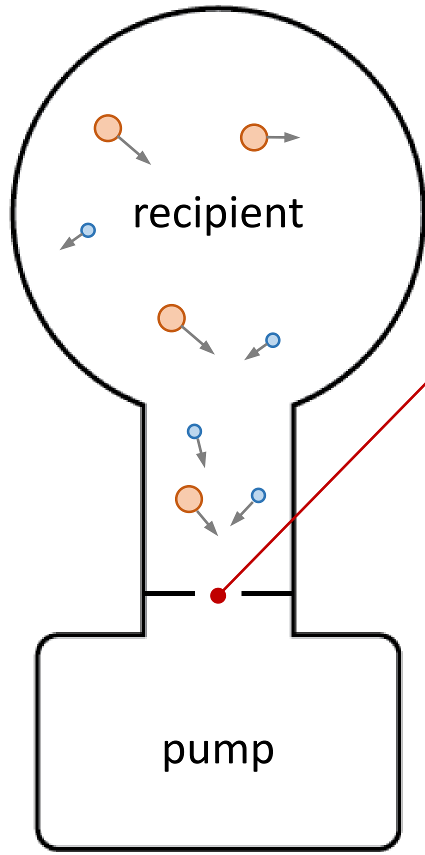
thus ***PV* [mbar l]** is a measure of the amount of gas (for a given temperature)
also: molar volume = 22.4 l / mol
(1atm = 101325 Pa, 273K)

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: $\lambda = \frac{k_b T}{\sqrt{2}\sigma P}$

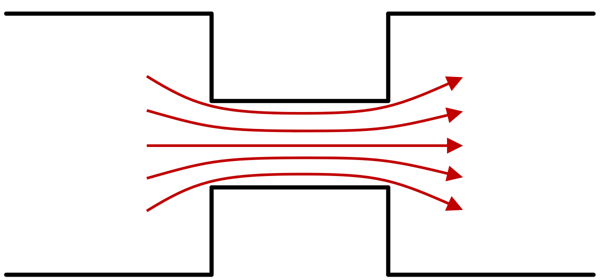
see also Knudsen Number: $Kn = \frac{\lambda}{d}$

for example:
N_2, P = 10^{-6}mbar, $\lambda \approx$ 60m
$\rightarrow$ molecular flow

viscous flow

λ << d

Kn << 1



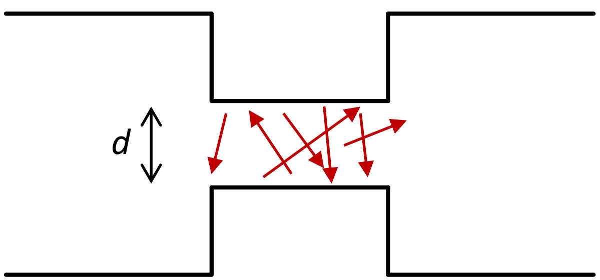
$$C_{\text{visc}} \propto d^4 \, \overline{P} \, \Delta P$$

heart attack!

molecular flow

λ >≈ d

Kn >≈ 1



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

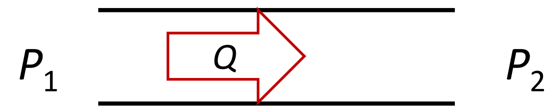
d /= 2 $\rightarrow$ *C* /= 8!

Conductance

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

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

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



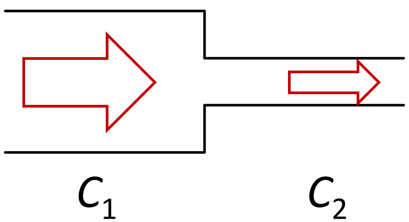
orifice: $$C = \sqrt{\frac{k_b T}{2\pi M}} A\,, \quad C_{\rm air} = 11.6[{\rm l/s}]\ A[{\rm cm}^2]$$

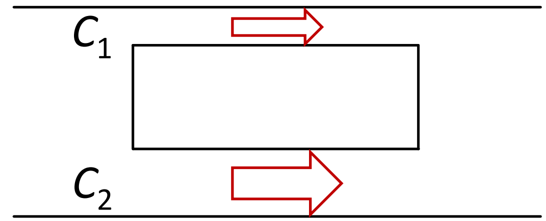
tube: $$C = \sqrt{\frac{2\pi k_b T}{M}}\,\frac{d^3}{l}\,,\ C_{\rm air} = 12.1[{\rm l/s}]\,\frac{d^3[{\rm cm}]}{l[{\rm cm}]}$$

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

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

Conductance - Combining Vessels

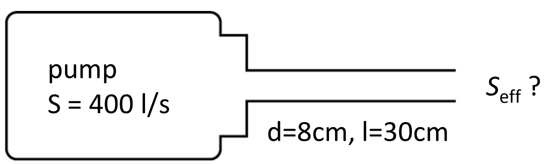




$$C_{\text{total}} = \left(\frac{1}{C_1} + \frac{1}{C_2}\right)^{-1}$$

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

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



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

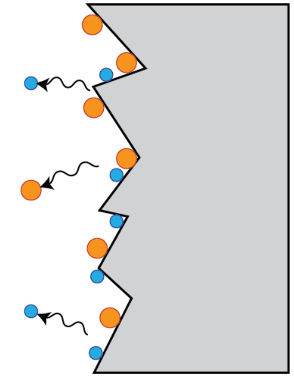
Sources of gas

main sources of gas in accelerator vacuum:

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

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

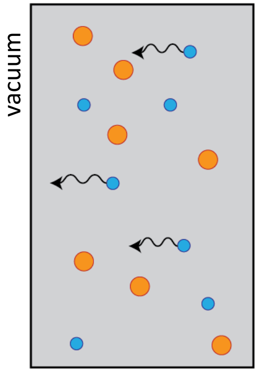
$$q(t) \propto \frac{1}{t}$$
$$\tau \propto \exp\left(\frac{E_d}{k_b T}\right)$$



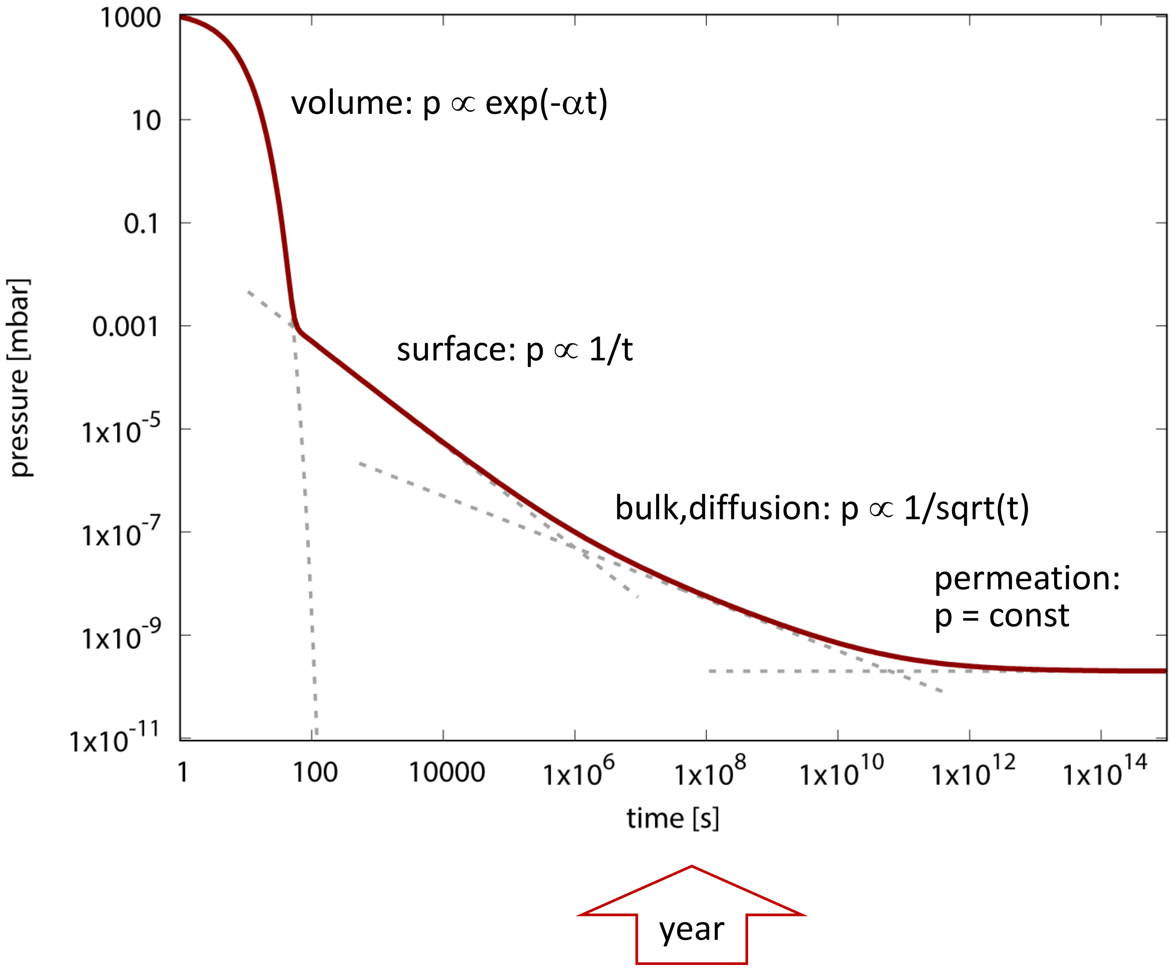
in practice, outgassing of water:
q(t) ≈ 3×10^{-9} mbar l / s cm^2 / t [h]
baking! exponential dependence on T

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:

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

$\mathcal{C}$: gas&tube specific; l: length

continuity equation, change of flow by pumping and outgassing:

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

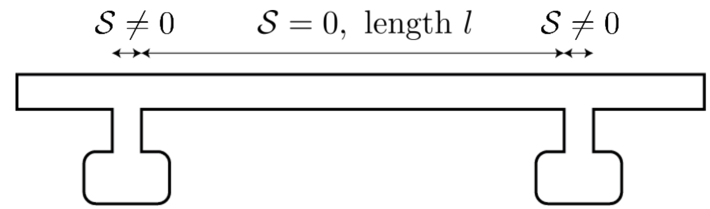
1-dim diffusion equation:

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

$\mathcal{C}$	$\left[\frac{\mathrm{l\,m}}{\mathrm{s}}\right]$	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:

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

conductance limited

pumping speed

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

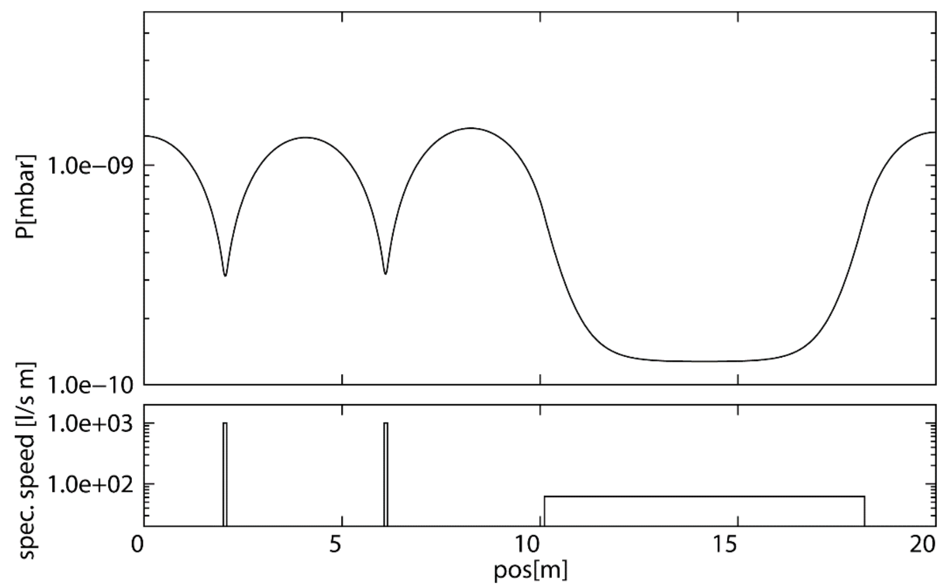
General Solution by Matrix Transport of Q, P

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

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

[V. Ziemann, SLAC/Pub/5962]

example calculation:
lumped pumps: S=100 l/s
distrib. pumps: $\mathcal{S}$ = 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.:

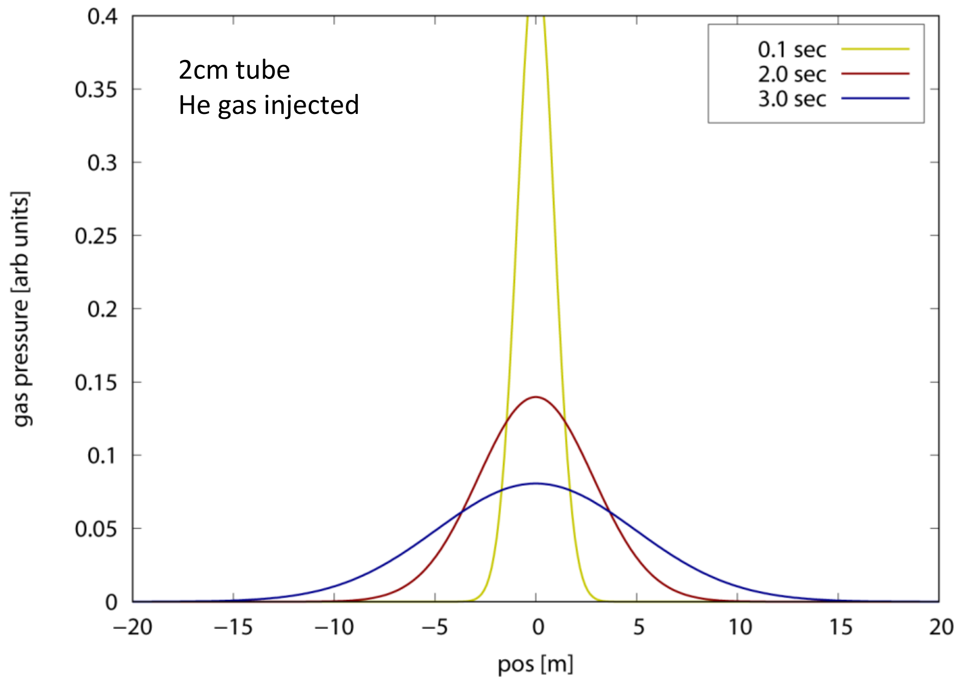
$$\frac{\partial}{\partial t}f(x,t) = \frac{\partial}{\partial x}\,\mathcal{D}\,\frac{\partial}{\partial x}f(x,t)$$

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

example:

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

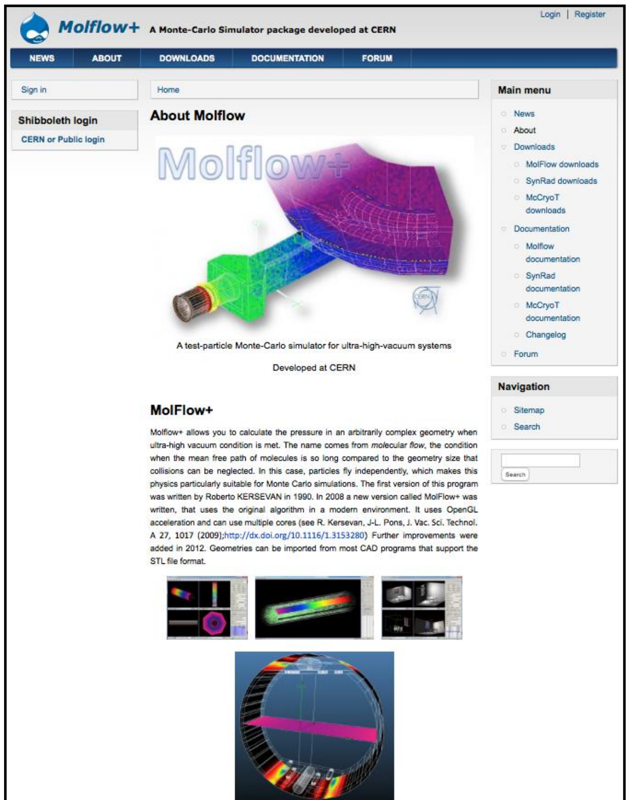
tube 2cm, diffusion time over 5m:
N_2: 8 s; He: 3 s

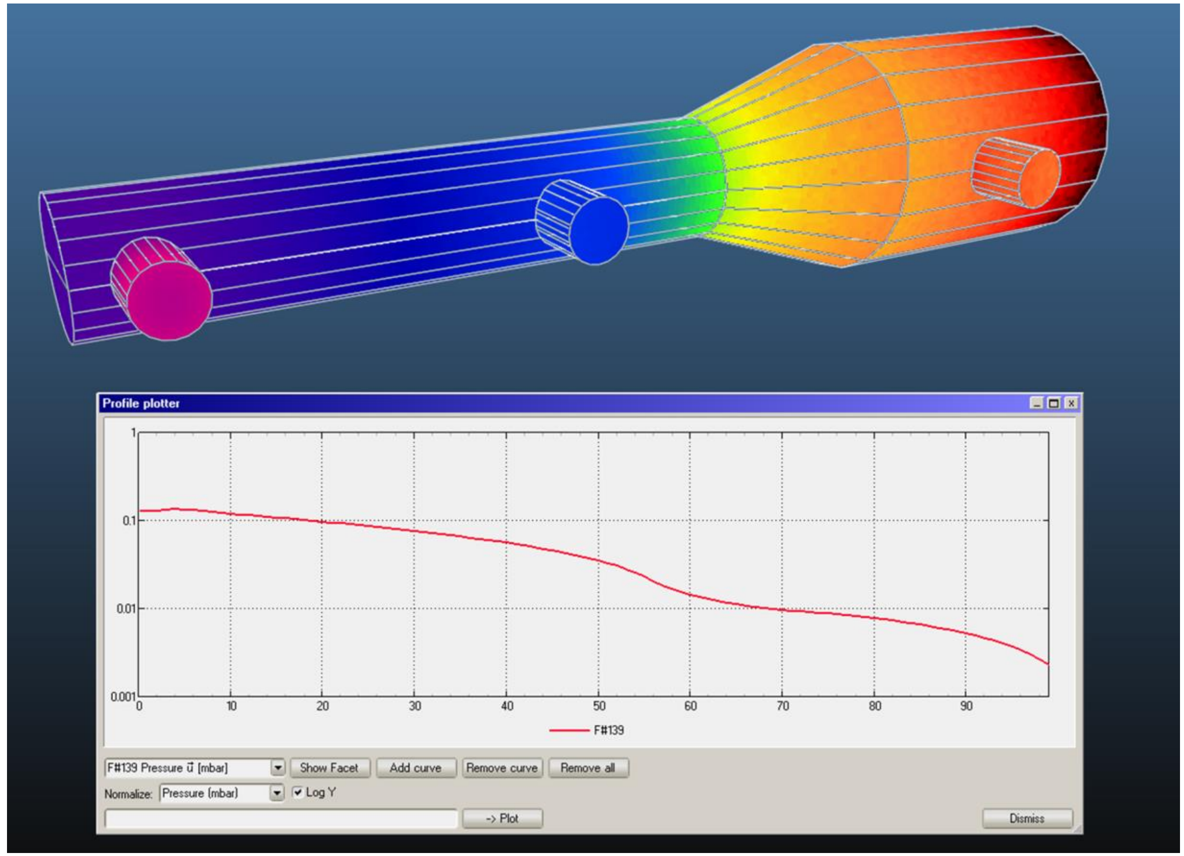


Monte Carlo Code Molflow+ (2008)

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

Web site for info and downloads:

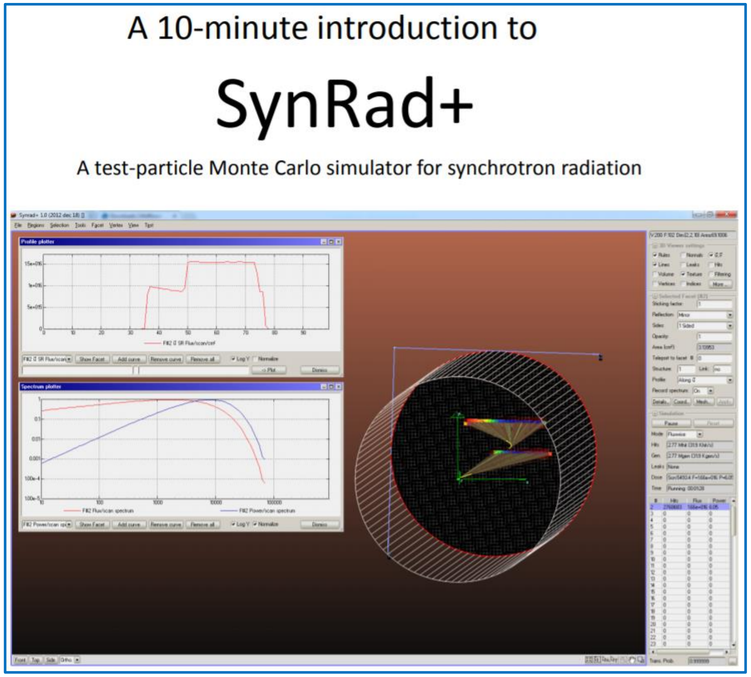




example calculation:
100k molecules tracked, computation time: few seconds, pressure profile

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



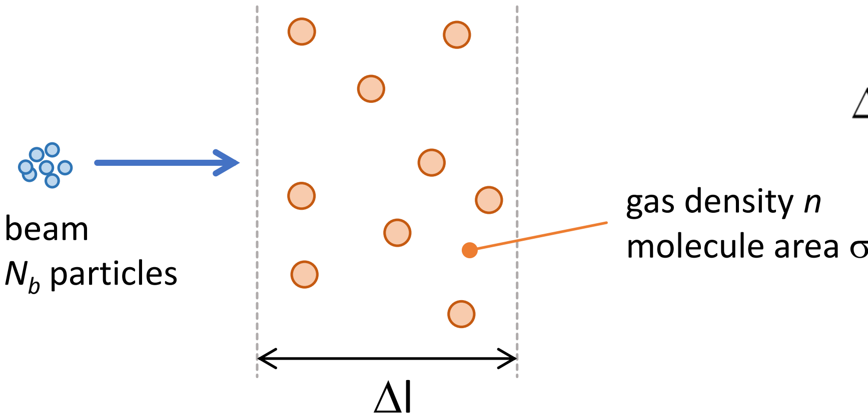
- SR spectrum + flux
- calculates beam orbit from lattice file (MAD-X)
- dipole approximation only, no undulator interference effects

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



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

probability of collision

results in differential equation:

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

σ = cross section for generic „loss process“

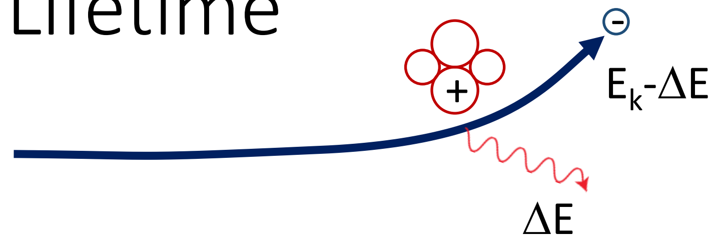
solution:

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

specific loss processes by gas scattering

- 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

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

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

resulting lifetime:

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

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
τ_{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:

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

sum over gas types and atoms per molecule

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

$\tau_{elastic}$ = 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:

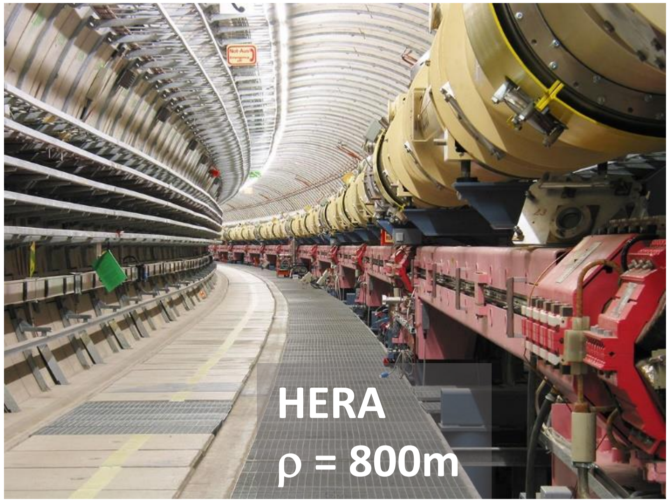
$$\tau_\varepsilon = \left(\frac{1}{\varepsilon_x} \; \frac{d\varepsilon_x}{dt} \right)^{-1}$$

growth rate:

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

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



p

e

Synchrotron Radiation induced Desorption

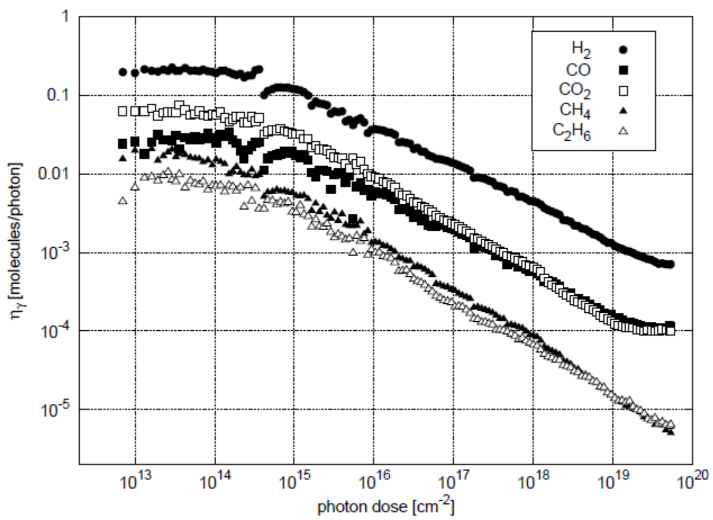
dynamic vacuum

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

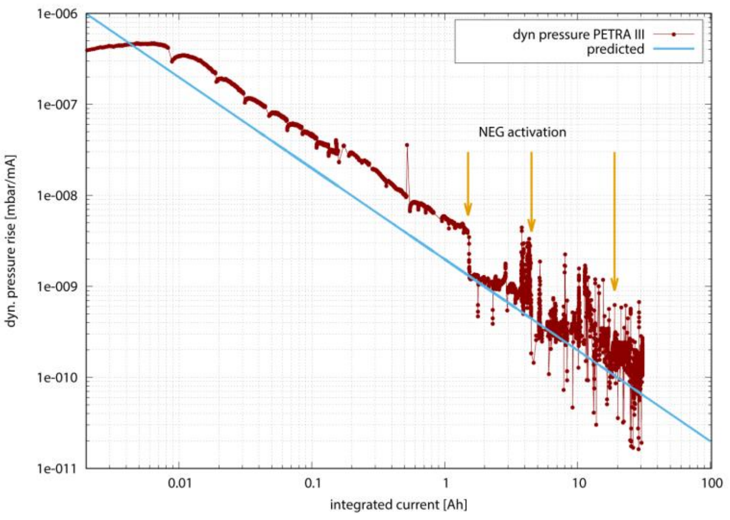
SR photons per length and time: $$\frac{dN_\gamma}{dtds} = 1.28 \cdot 10^{17} \frac{I\,[\mathrm{mA}]\;E\,[\mathrm{GeV}]}{\rho\,[\mathrm{m}]}$$

resulting specific outgassing: $$q = \eta_\gamma\, k_b\, T\, \frac{dN_\gamma}{dtds}$$

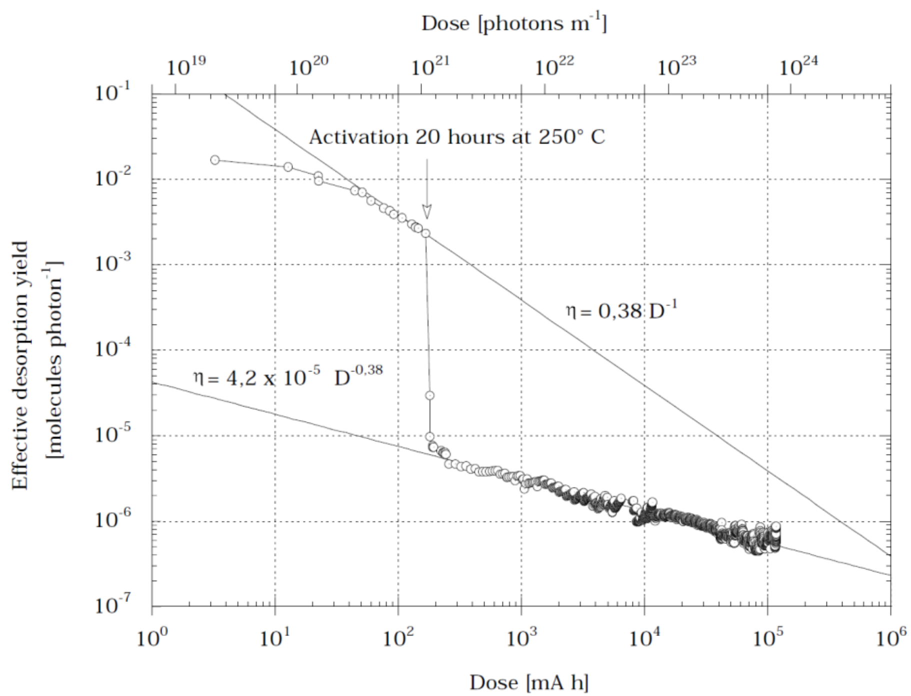
measured desorption yield for different gases [G.Vorlaufer]



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

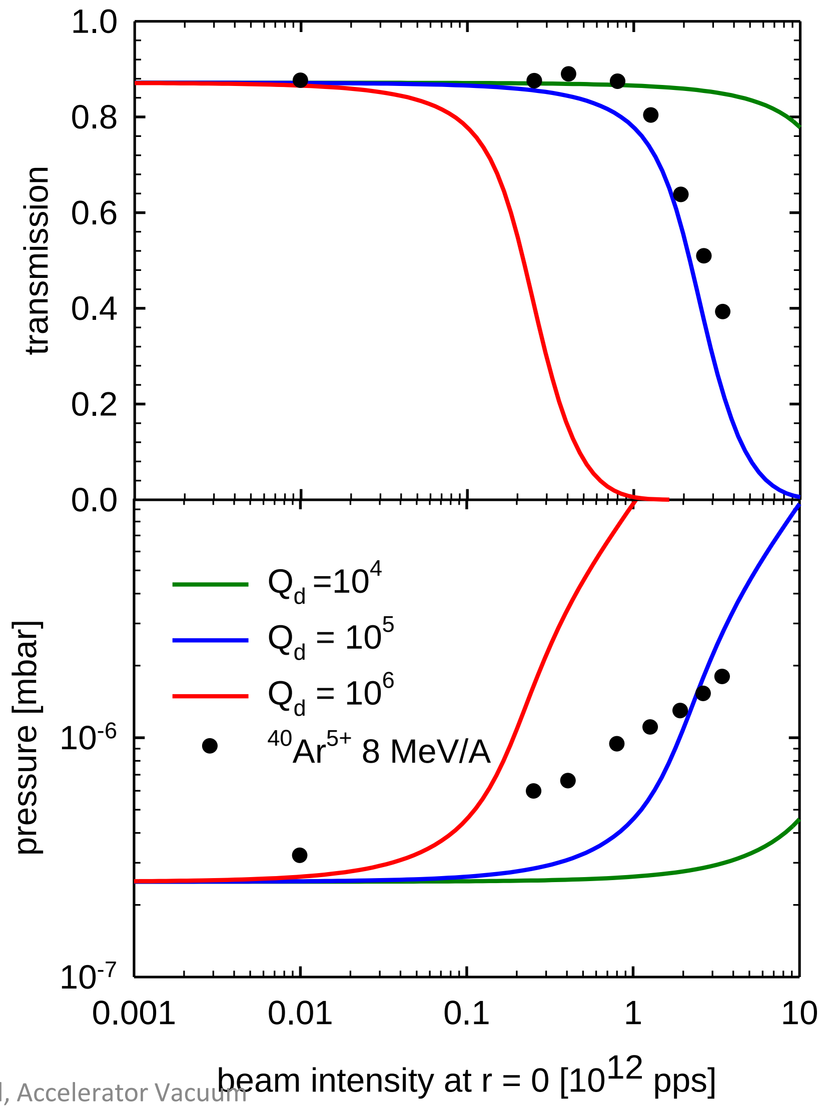
Heavy Ion induced Gas Desorption

demonstration of transmission breakdown by gas desorption

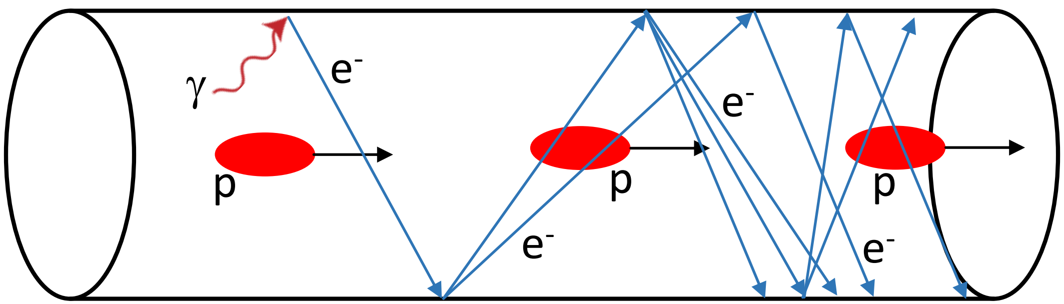
[measurements & simulations in AGOR cyclotron, KVI-Groningen, S.Brandenburg et al]

- 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
- beampower: $\leq$ 320 W

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



Dynamic effect in LHC: Electron Cloud Effect

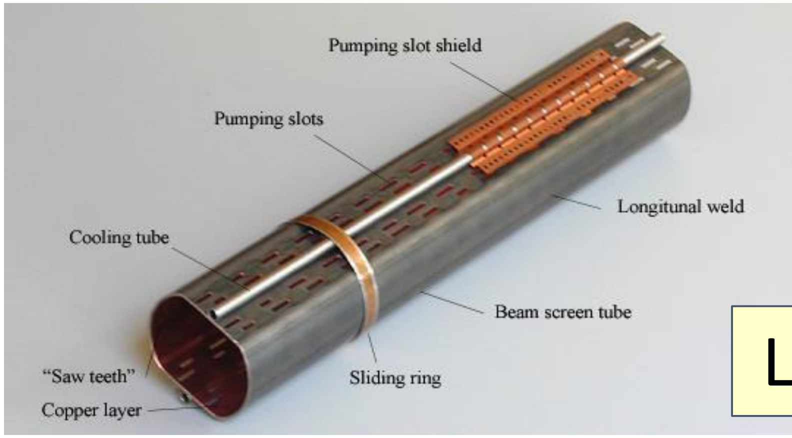


$E(e^-) \approx 1..100eV$

- 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

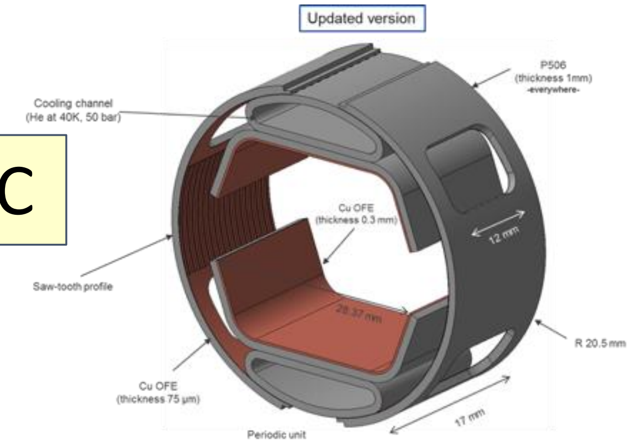
mitigations:
- wall coating, e.g. graphite, TiN (low SEY)
- weak magnetic solenoid field

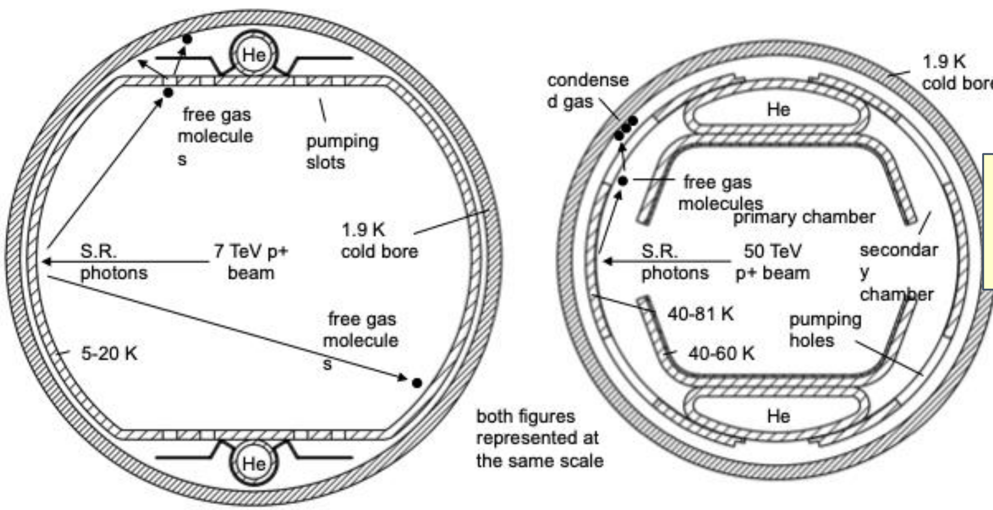
Specialized Chambers: LHC & FCC with Beam Screens



LHC

FCC





LHC(left), FCC comparison

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

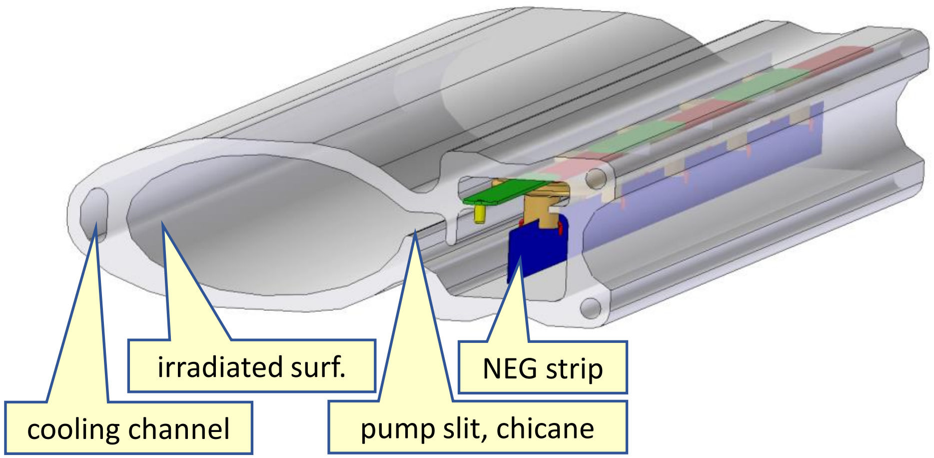
FCC-hh - 898 l/(s·m) for H_2 at 40 K
35.4 W/m emitted SR

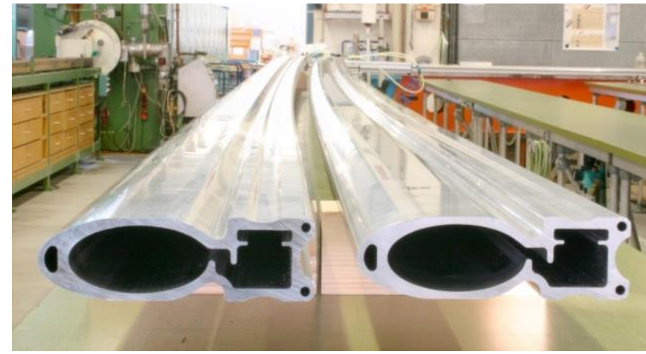
courtesy images:
M.Jimenez et al
F.Perez, M.Morrone, I.Bellafont et al

- 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**

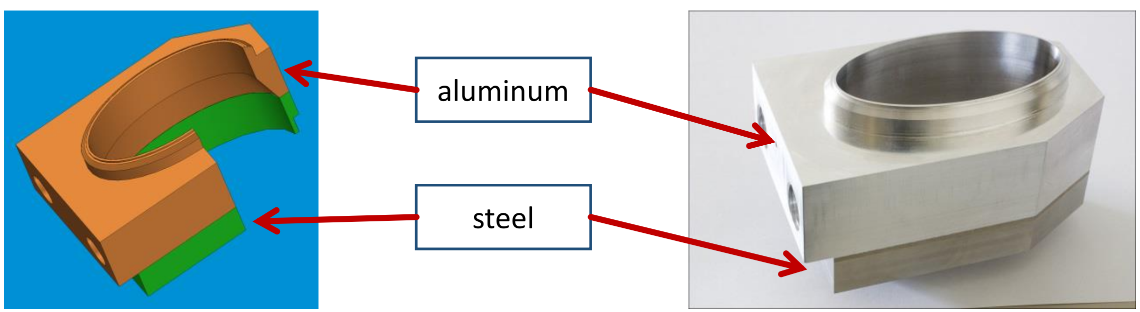
Vacuum Chambers for Electron Synchrotron

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





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

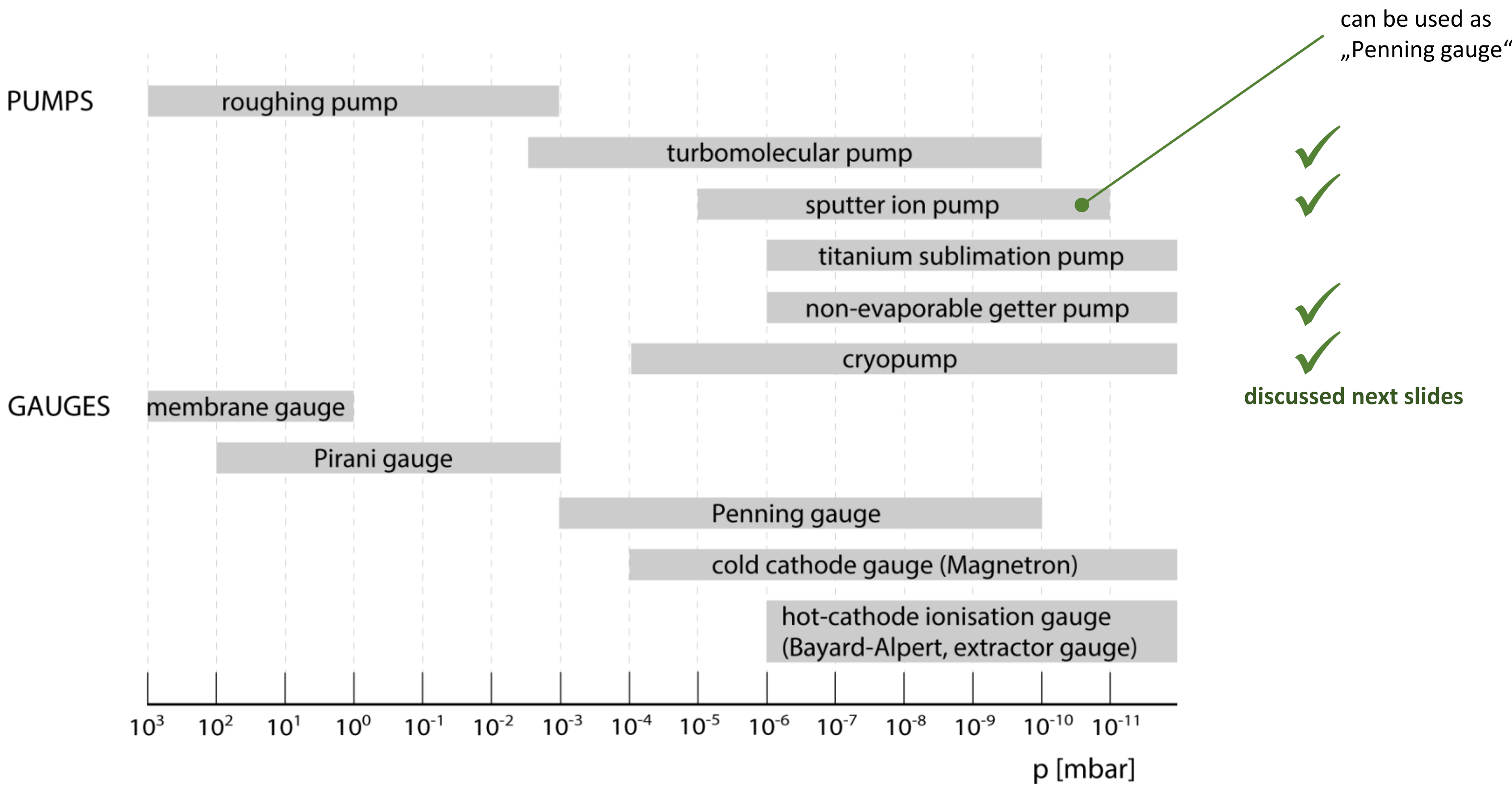


<u>solution</u>:
explosion bondings SS/Al with 4cm Al thickness

Next:
Components for Vacuum Systems

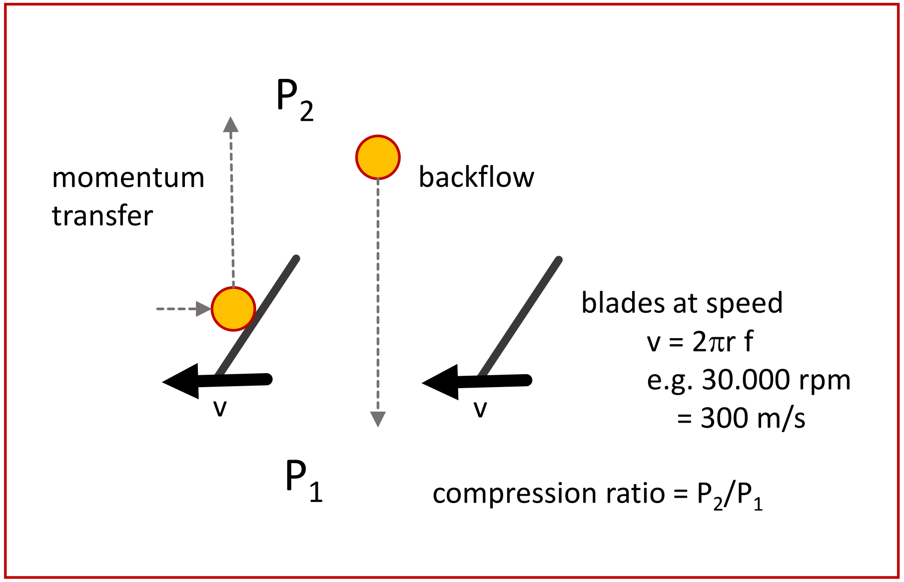
pumps: overview, turbo, ion sputter, NEG, cryo-pump
flange systems, collimators, residual gas analysis (RGA)

Overview Pumps and Gauges



Turbo Molecular Pump

Wikipedia

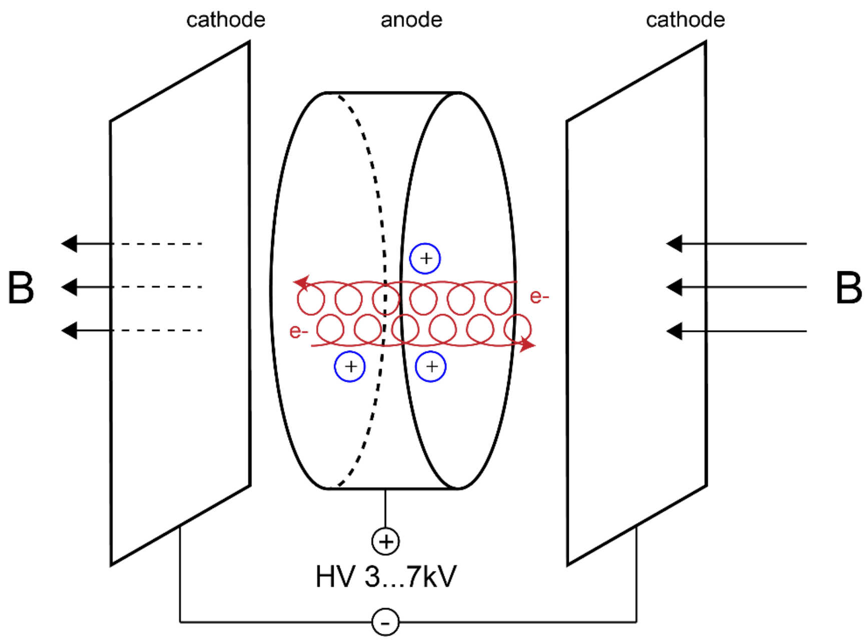


- pumps all gases
- blade speed similar molecule speed(!)
- 30.000 … 60.000 RPM
- works down to 10^{-10} mbar

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

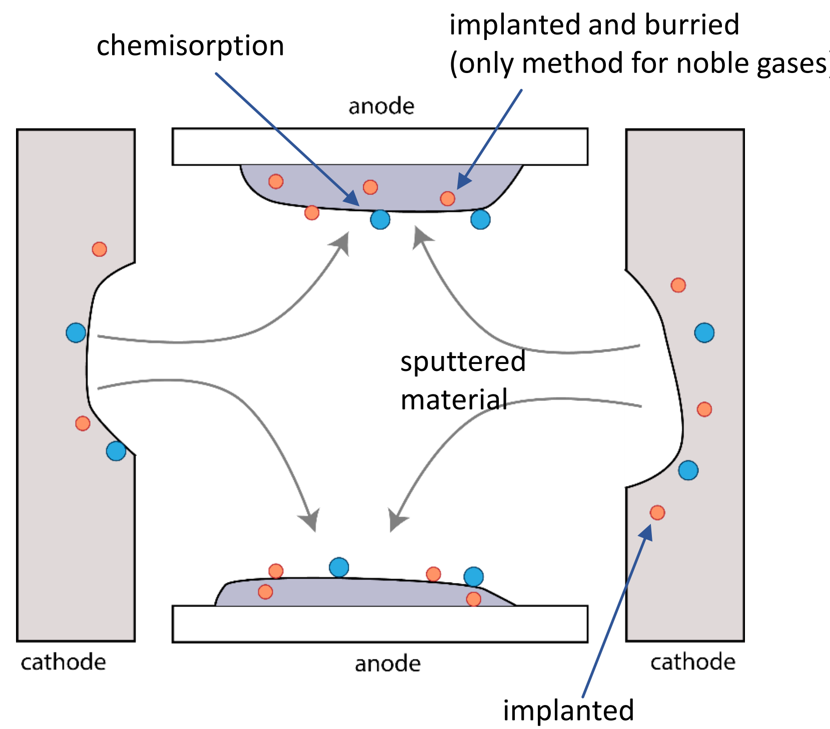
Sputter Ion Pump

single penning cell
electric and magnetic field
gas ionization, acceleration



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

pumping mechanism
implantation, chemisorption and
burying of gas molecules



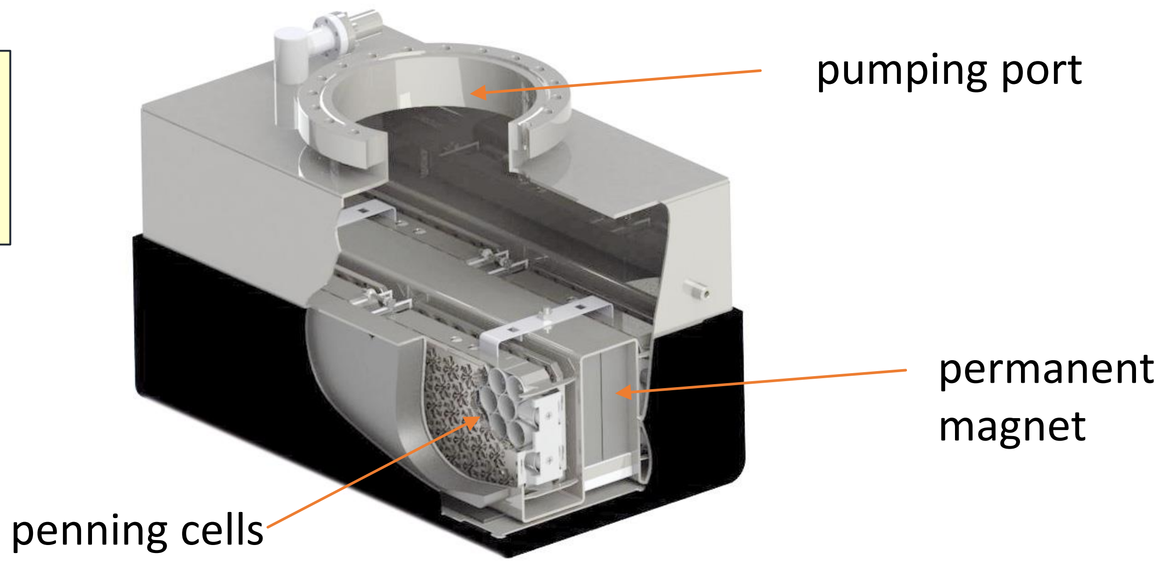
Ion Sputter Pumps

courtesy Agilent catalog

pumping speed:
2 l/s … 500l/s

weight:
0.3kg … 120kg

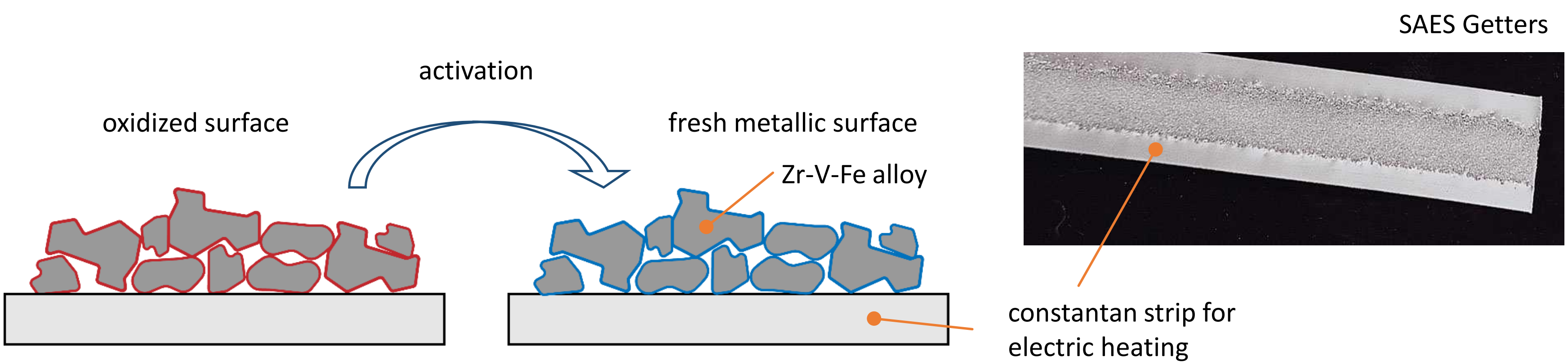
example:
modern Agilent 200 pump



NEG – Non Evaporable Getter Pumps

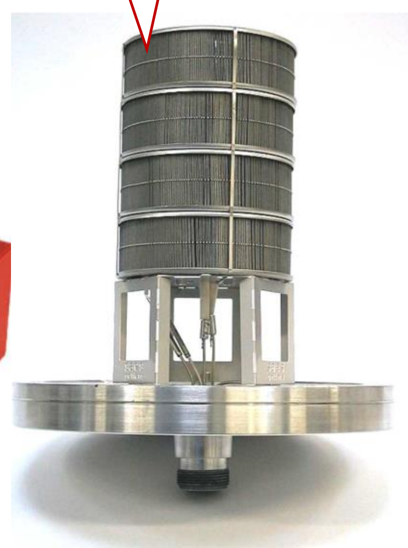
- NEG captures gases by chemical reaction, e.g. H_2O, CO, N_2 permanently, H_2 is dissolved in bulk material
- no pumping of noble gases – combination with sputter ion pumps required
- NEG must be activated by heating

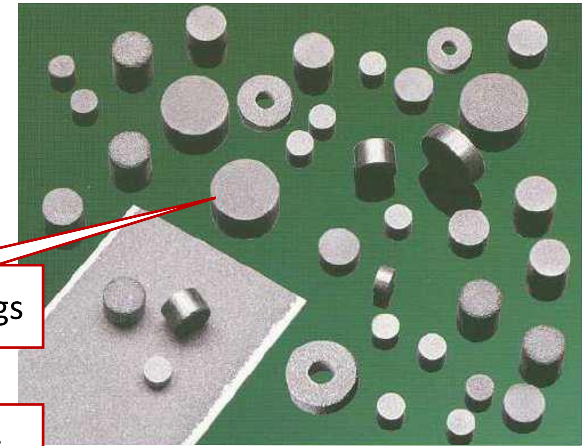
    e.g. St707™ @180°C..350°C

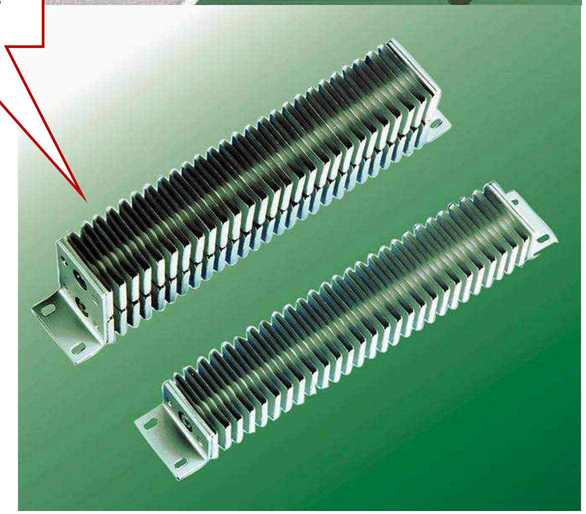


NEG Pump Designs

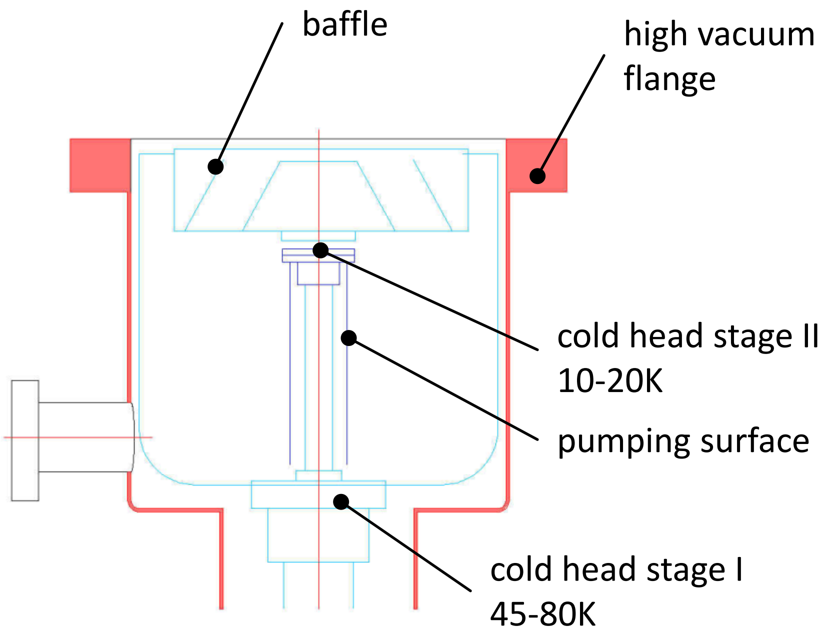
images: SAES Getters







Cryo Pump

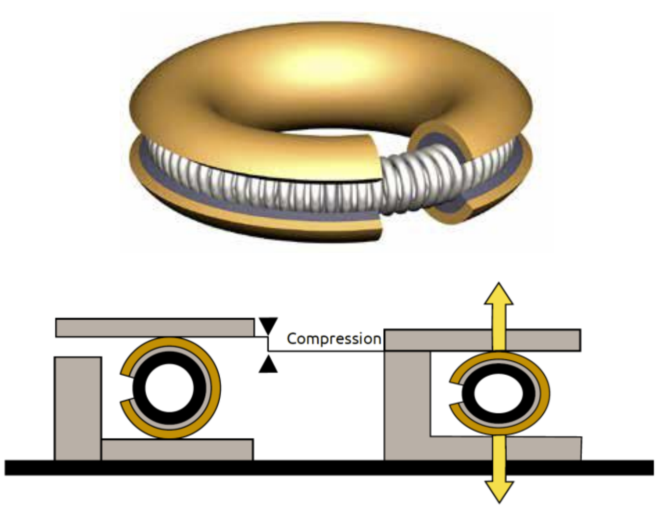


[Lothar Schulz]

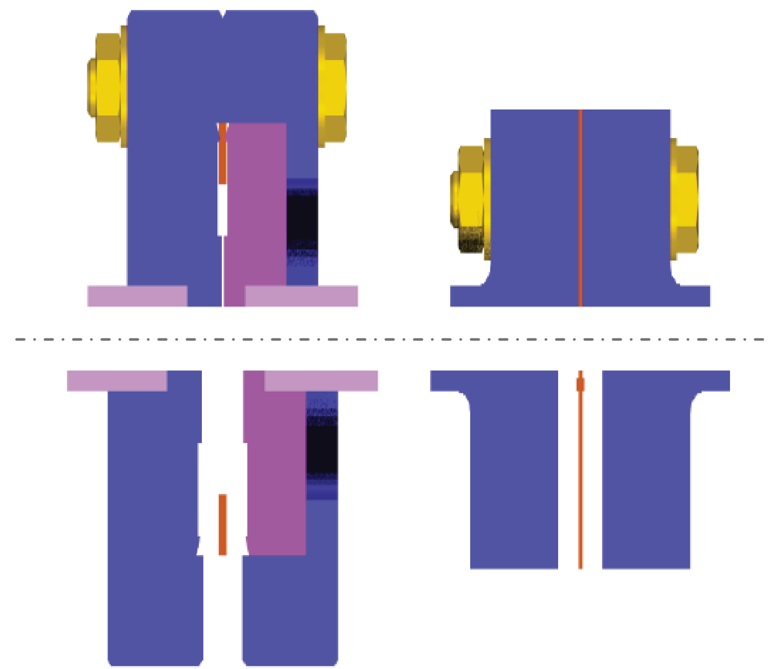
- high pumping speed for <u>all</u> gases
- cryo-condensation of N_2, O_2 and Ar on cold surface
- cold surface partly covered with charcoal: cryosorption for H_2, He, Ne
- periodic regeneration by warmup

Metal sealed Flange Systems

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



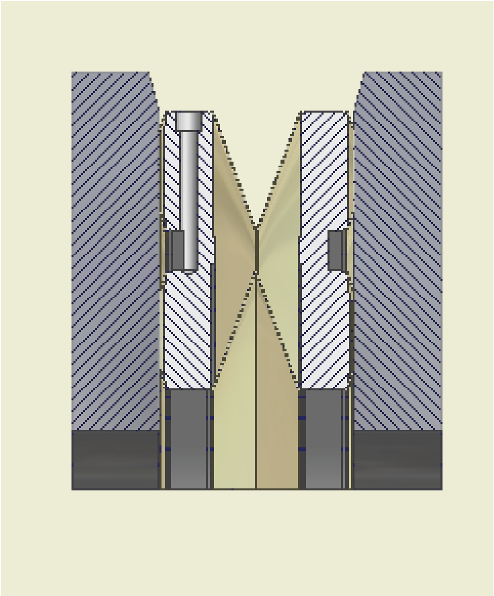
Helicoflex: Technetics Group

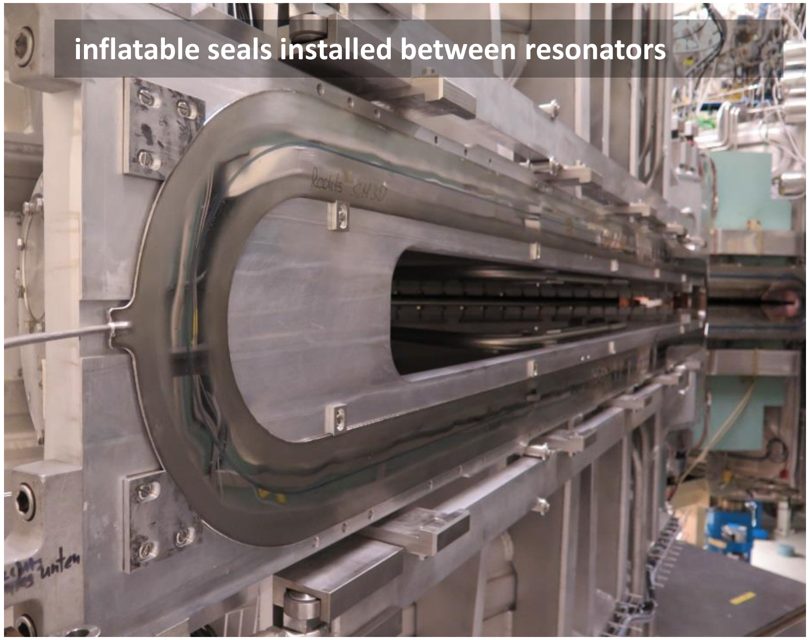


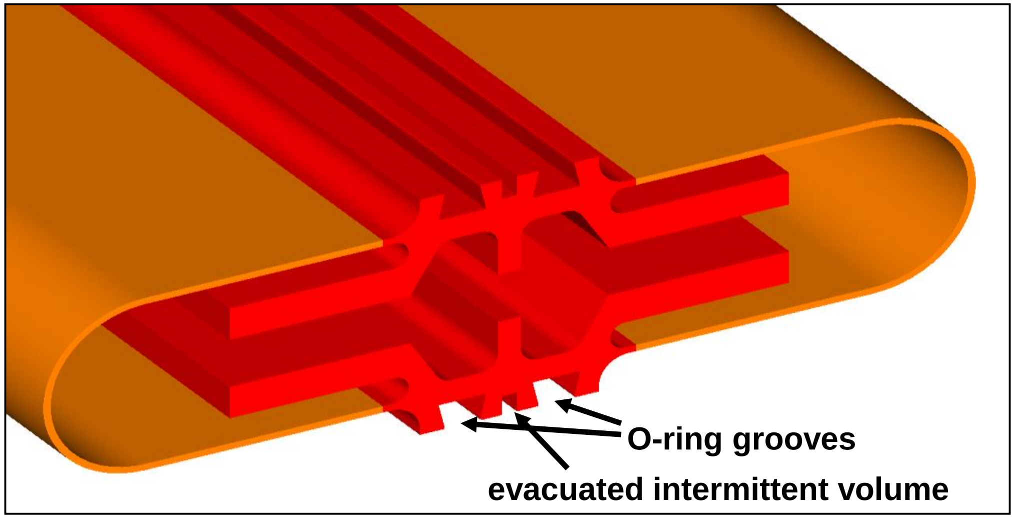
Conflat Flange (CF)   VAT Flange, flat seal

Inflatable Seals

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

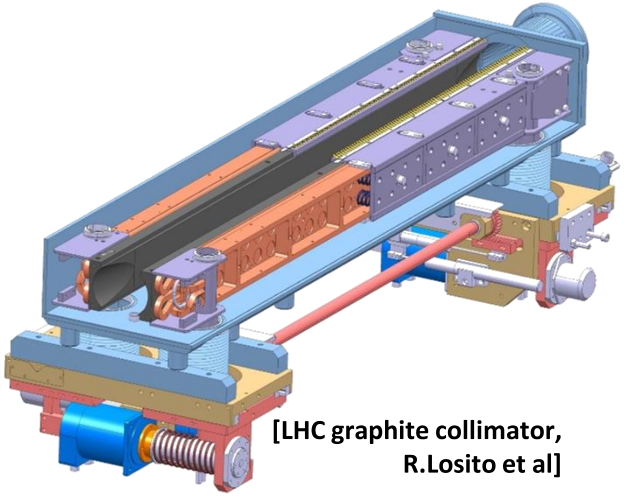






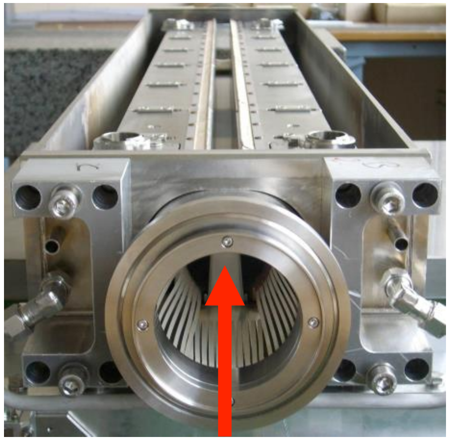
Collimators

- 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

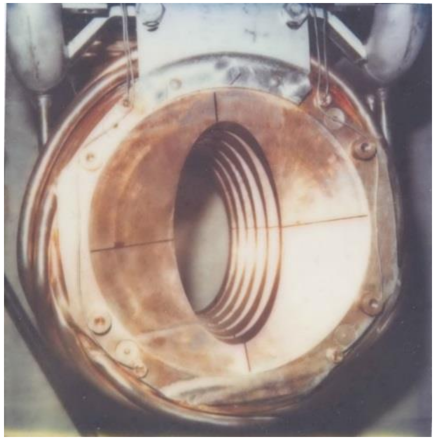


[LHC graphite collimator, R.Losito et al]

[LHC collimator, S.Radaelli et al]

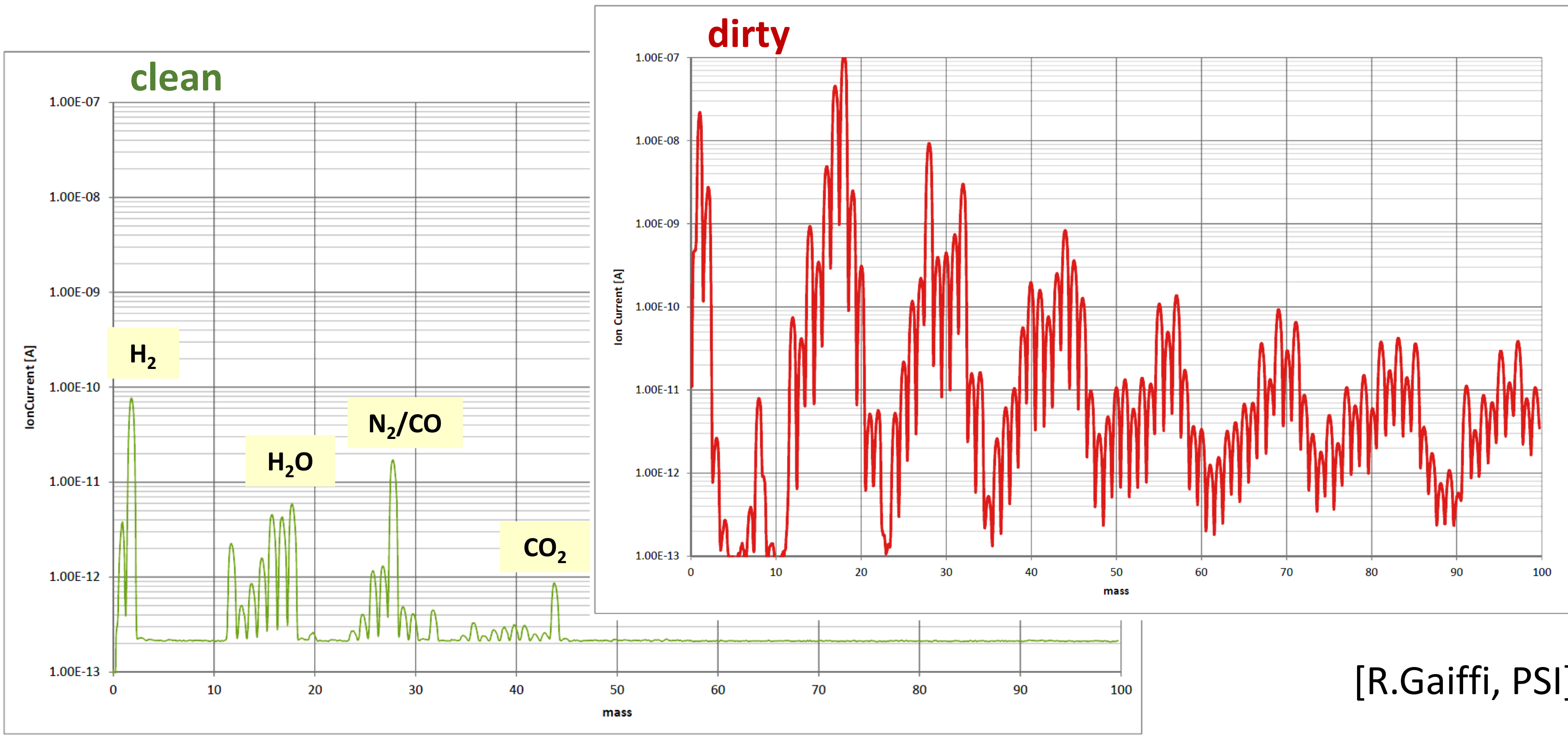


[PSI-HIPA >100kW avg power, D.Kiselev et al]



Residual Gas Analysis (RGA)

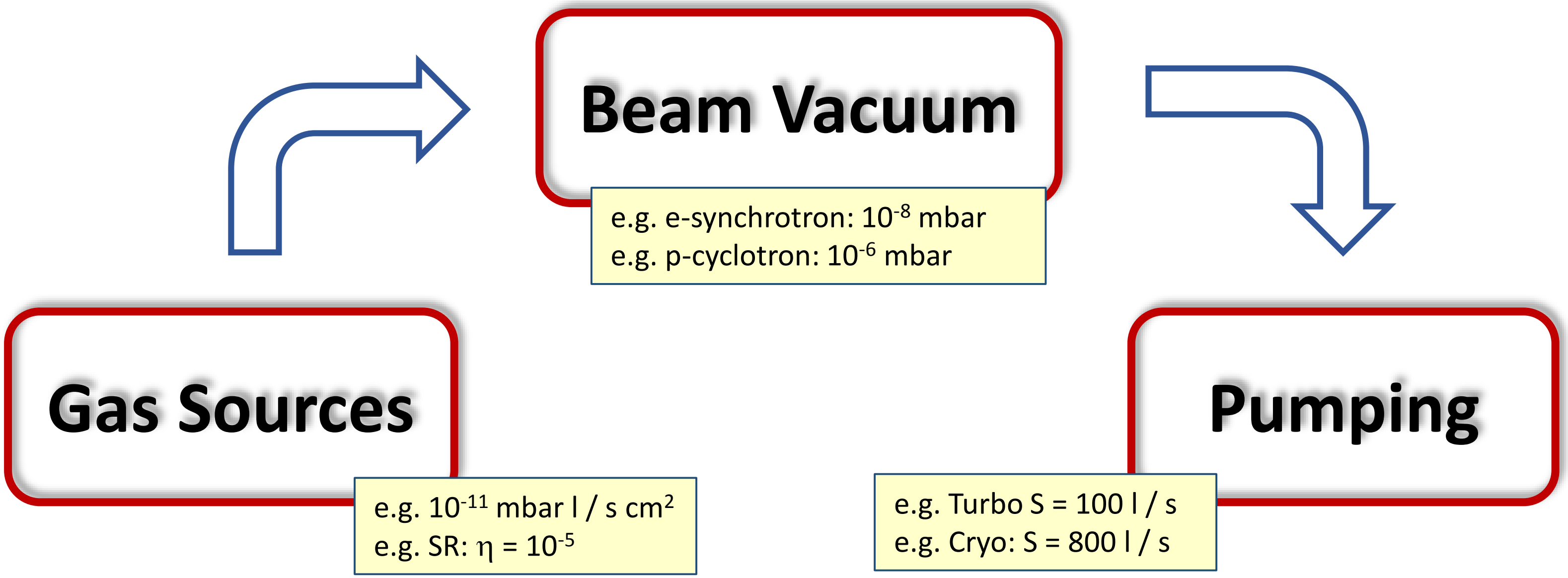
- quadrupole mass spectrometers to analyze the composition of residual gases
- allows to assess the cleanliness of components and to diagnose problems



[R.Gaiffi, PSI]

Accelerator Vacuum - Summary

- e: breamsstrahlung
- p: emittance growth



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

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

vacuum engineering:
materials & materials preparation, mechanical stability, thermomechanical 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)