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Vacuum Systems

V. Baglin

CERN TE-VSC, Geneva

The CERN Accelerator School

Outline

1. Vacuum Basis
2. Vacuum Components
3. Vacuum with Circulating Beams

1. Vacuum Basis

Pressure: Definition & Units

- The pressure is the force exerted by a molecule per unit of surface : 1 Pa = 1 N/m^2

→	Pa	kg/cm^2	Torr	mbar	bar	atm
1 Pa	1	$10.2\ 10^{-6}$	$7.5\ 10^{-3}$	10^{-2}	10^{-5}	$9.81\ 10^{-6}$
1 kg/cm^2	$98.1\ 10^{3}$	1	735.5	980	0.98	0.96
1 Torr	133	$1.35\ 10^{-3}$	1	1.33	$1.33\ 10^{-3}$	$1.31\ 10^{-3}$
1 mbar	101	$1.02\ 10^{-3}$	0.75	1	10^{-3}	$0.98\ 10^{-3}$
1 bar	$1.01\ 10^{5}$	1.02	750	10^{3}	1	0.98
1 atm	101 300	1.03	760	1 013	1.01	1

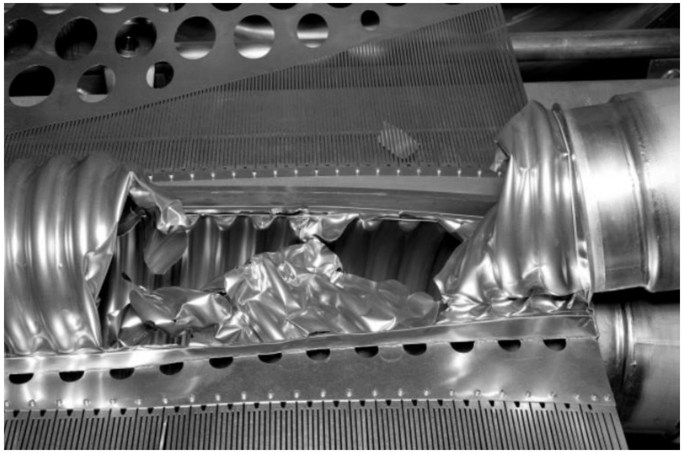
E. Torricelli, 1644

B. Pascal, 1647

As a consequence of the « vacuum force » …

O. Von Guericke, 1656

Some damages following pump-down or rupture



Ideal Gas Law

- Statistical treatment which concerns molecules submitted to thermal agitation (no interaction between molecules, random movement, the pressure is due to molecules hitting the surface)

- For such a gas, the pressure, P [Pa], is defined by the gas density, n [molecules.m^{-3}] , the temperature of the gas, T [K] and the Boltzman constant k , (1.38 10^{-23} J/K)

$$\boxed{P = n\,k\,T}$$

B. Clapeyron 1834

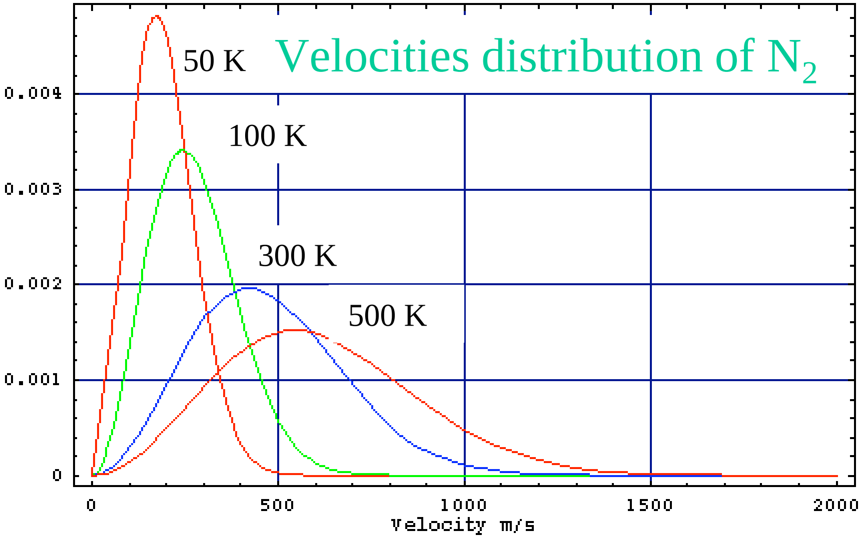
- The distribution of velocities, dn/dv, follows a Maxwell-Boltzmann function

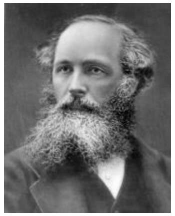
- The average velocity is :

$$\bar{v} = \sqrt{\frac{8kT}{\pi\, m}} = 146\sqrt{\frac{T}{M}}$$

- At room temperature (m/s) :

He	Air	Ar
1800	470	400





Maxwell 1860

Boltzmann 1870

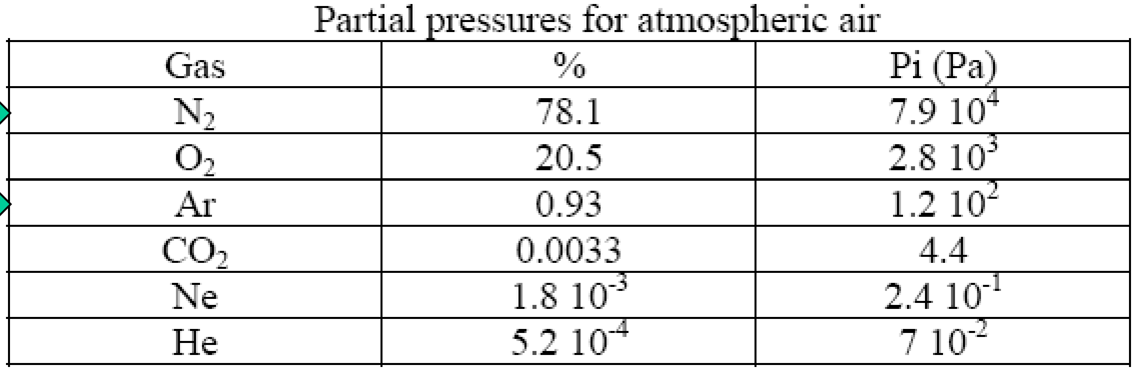
Total Pressure and Partial Pressure

- The gas is usually composed of several types of molecules (ex : air, residual gas in vacuum systems)

- The **total pressure,** P_{Tot}, is the sum of all the **partial pressure,** P_i (Dalton law)

$$\boxed{P_{Tot} = \sum P_i = k\,T \sum n_i}$$

John Dalton, 1801



Partial pressures for atmospheric air

Gas	%	Pi (Pa)
N_2	78.1	7.9 10^4
O_2	20.5	2.8 10^3
Ar	0.93	1.2 10^2
CO_2	0.0033	4.4
Ne	1.8 10^{-3}	2.4 10^{-1}
He	5.2 10^{-4}	7 10^{-2}

Molecule Mean Free Path

- It is the path length that a molecules traverse between two successive impacts with other molecules. It was derived by Clausius.

- It is a function of the pressure, *P*, of the temperature, *T*, and of the molecular diameter, σ.

$$\lambda = \frac{1}{\sqrt{2}\pi n \sigma^2} = \frac{1}{\sqrt{2}\pi} \frac{kT}{P} \frac{1}{\sigma^2}$$

$$\boxed{\lambda_{air}[cm] = \frac{5 10^{-3}}{P[Torr]}}$$

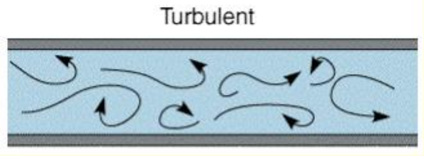
R. Clausius

➔ Increasing mean free path when decreasing pressure

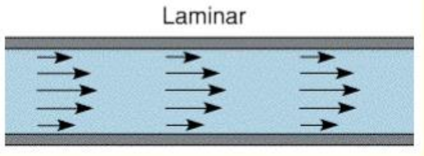
- Air at room temperature

P (Torr)	λ	Size	Regime
760	70 nm	Coronavirus	Atmosphere
1	50 µm	Human hair	Rough vacuum
10^{-3}	5 cm	Flower	Medium vacuum
10^{-7}	500 m	Stadium	High Vacuum
10^{-10}	500 km	Geneva-Paris	Ultra High Vacuum
10^{-12}	50,000 km	Earth circumference	Extreme High Vacuum

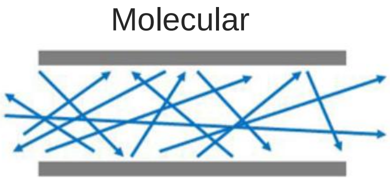
Type of Flows



- The turbulent flow is established around the atmospheric pressure



- In the low vacuum (10^{3}-1 mbar), the flow is viscous and laminar.



- In the high vacuum (10^{-3} – 10^{-7} mbar) and ultra-high vacuum (10^{-7}– 10^{-12} mbar), the flow is molecular. The mean free path is much larger than the vacuum chamber size. Molecules interact only with the vacuum chamber walls

Molecular flow is the main regime of flow to be used in vacuum technology

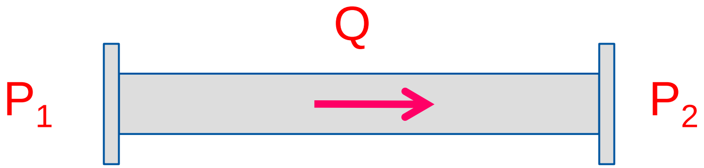
In this regime, the vacuum vessel has been evacuated from its volume.
The pressure inside the vessel is dominated by the nature of **the surface.**

Conductance

- It is defined by the ratio of the molecular flux, Q, to the pressure drop along a vacuum vessel. It is a function of the shape of the vessel, the nature of the gas and its temperature.

Saul Dushman
(1883–1954)

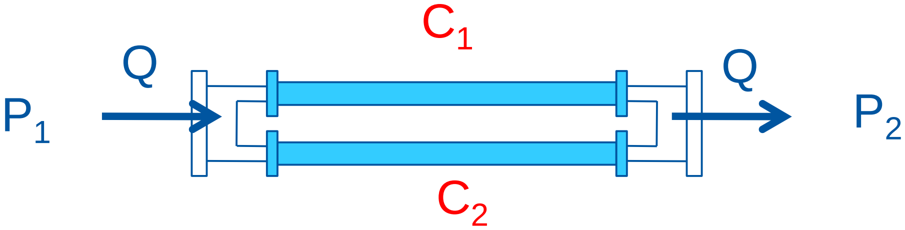
$$\boxed{C = \frac{Q}{(P_1 - P_2)}}$$



- Scales like: $C \sim \sqrt{\frac{T}{M}}$

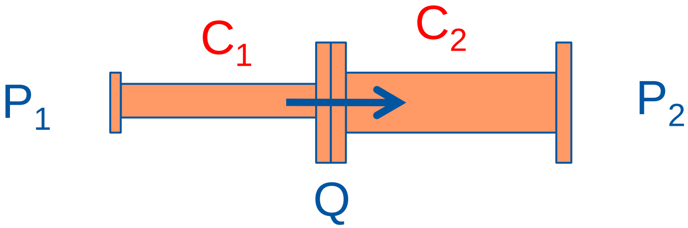
- Adding conductances in parallel

$$C = C_1 + C_2$$



- Adding conductances in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$



Conductance Calculus in Molecular Regime

- **For an orifice :**

$$C = \sqrt{\frac{kT}{2\pi\ \mathrm{m}}}A; \qquad C_{\mathrm{air},\,20^\circ}[l/s] = 11.6\ \mathrm{A}[cm^2]$$

The conductance of an orifice of 10 cm diameter is 900 ℓ/s

- **For a tube :**

$$C = \frac{1}{6}\sqrt{\frac{2\pi\ kT}{\mathrm{m}}}\frac{\mathrm{D}^3}{\mathrm{L}}; \qquad C_{\mathrm{air},\,20^\circ}[l/s] = 12.1\frac{\mathrm{D[cm]}^3}{\mathrm{L[cm]}}$$

The specific conductance of a tube of 10 cm diameter is 120 ℓ/s.m,

To increase the conductance of a vacuum system, it is better to have a vacuum chamber with large diameter and short lenght

Case of small tubes: LHC Beam Pipe

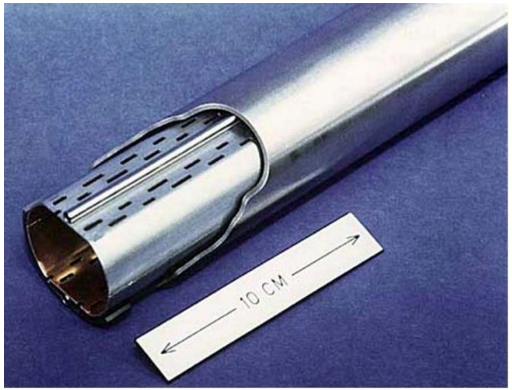
- Beam tube diameter 4.5 cm,
- Transparency 2.2 %,
- Slot size 8×1.5 mm^2

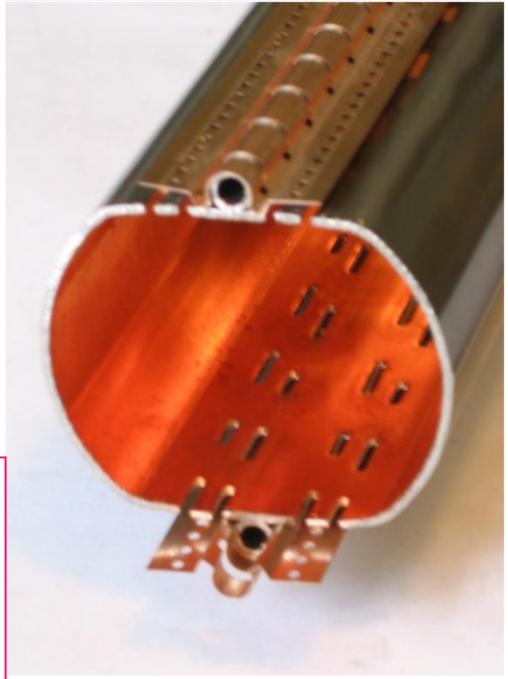
- Beam screen specific conductance = 11 ℓ/s.m

- Slot conductance = 1.4 ℓ/s

➔ This system is conductance limited and relies on the distributed pumping speed from the slots

➔ 260 holes per meter ensure a beam screen pumping speed of 360 ℓ/s





For small beam tube diameter, a distributed pumping system is required to compensate the reduced specific conductance

Pumping Speed

- The pumping speed, S, is the ratio of the flux, Q, of molecules pumped to the pressure, P

mbar.ℓ/s

$$\text{ℓ/s} \rightarrow \boxed{S = \frac{Q}{P}}$$

mbar

- S range from 10 to 20 000 ℓ/s

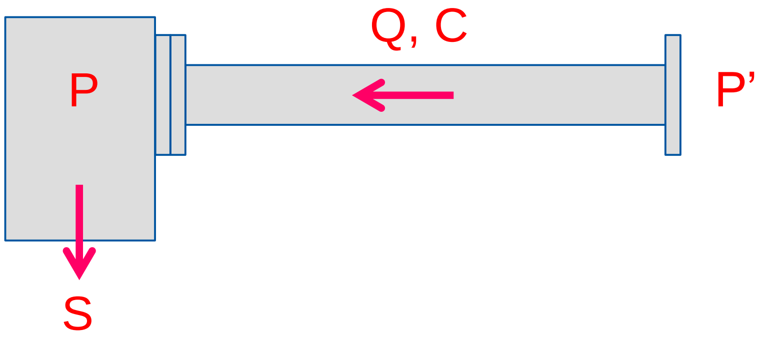
- Q range from 10^{-14} mbar.ℓ/s for metalic tubes to 10^{-5} – 10^{-4} mbar.ℓ/s for plastics

3 orders of magnitude for pumping
vs
10 orders of magnitude for outgassing

Outgassing MUST be optimised to achieve UHV

Effective pumping speed

- It is the pumping speed seen from P' trough the pipe of conductance, C



Pumping speed

$$\begin{cases} Q = P\,S \\ Q = C\,(P' - P) \end{cases} \Rightarrow Q = \frac{SC}{S+C}P' = S_{eff}P'$$

Conductance

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

- This is the result of adding in series the conductance C with the pumping speed S

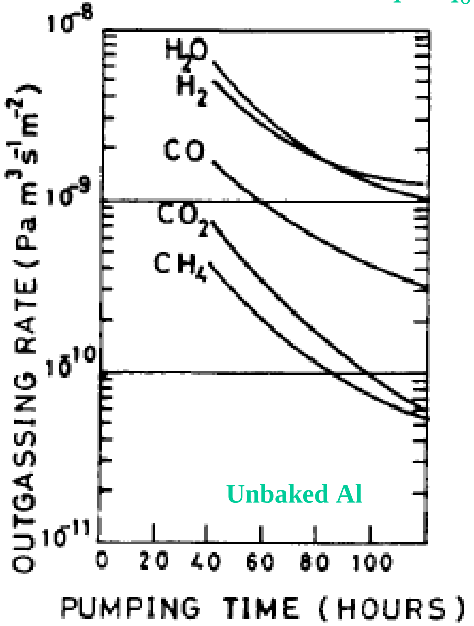
- If:
  1) C=S then S_{eff} = S/2
  2) C>> S then S_{eff} = S
  3) C<< S then S_{eff} = C, the system is "conductance limited"

Large conductances preserve the efficiency of the pumping system

Outgassing

- The outgassing rate, q, of a surface is the number of molecules desorbed from a surface per unit of surface and per unit of time
- It is a function of the surface nature, of its cleanliness, of its temperature and of the pump down time.
- In all vacuum systems, the final pressure is driven by the outgassing rate : $P_{final} = Q/S = q\ A / S$

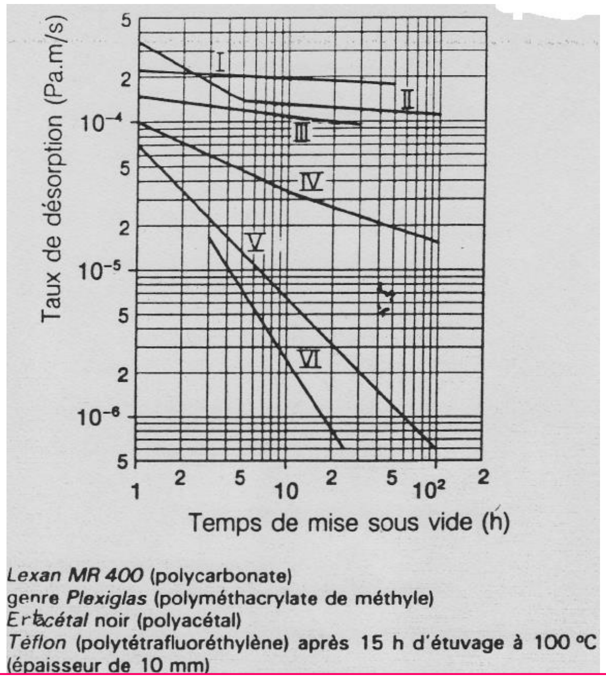
Metallic surfaces $q \sim q_0/t$



A.G. Mathewson *et al.*
J.Vac.Sci. 7(1), Jan/Fev 1989, 77-82

x 5 000

Plastic surfaces $q \sim q_0/\sqrt{t}$

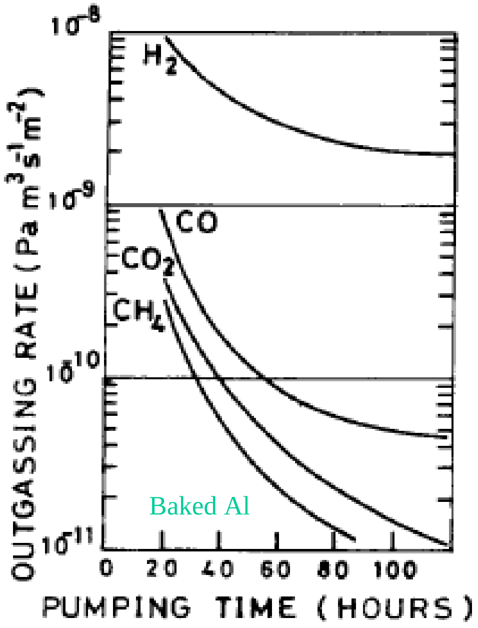


Good Vacuum Design :

Use ONLY metallic surfaces and reduce to ZERO the amount of plastics

In Situ Bake Out

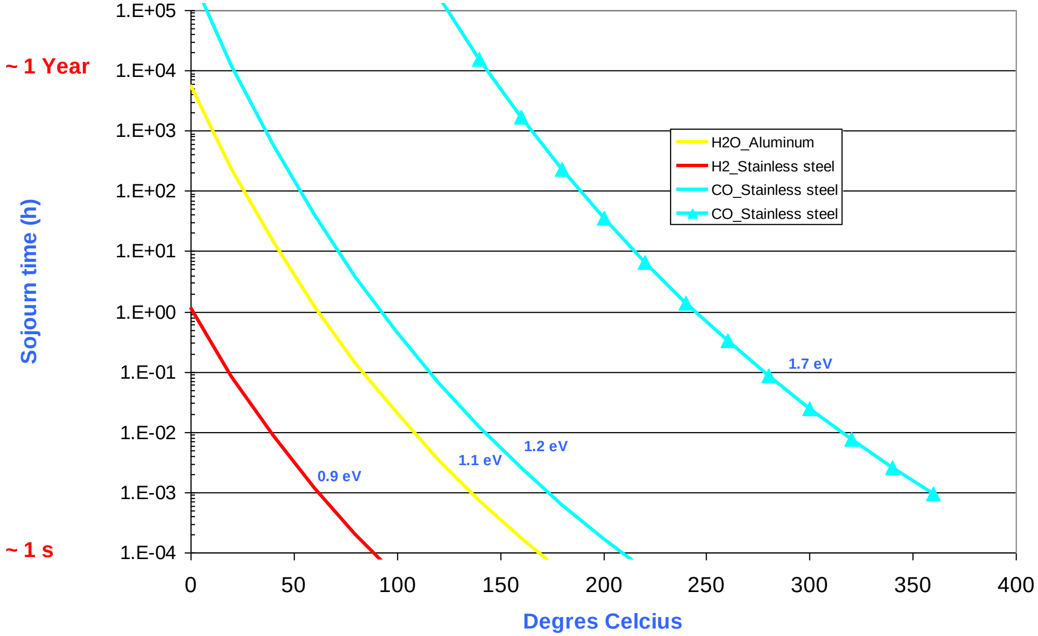
- The outgassing rate of unbaked surfaces is dominated by H_2O.
- A bake-out above 150°C increase the desorption rate of H_2O and reduce the H_2O sojourn time in such a way that H_2 become the dominant gas



A.G. Mathewson *et al.*
J.Vac.Sci. 7(1), Jan/Fev 1989, 77-82

$$\tau = \frac{e^{\frac{E}{kT}}}{\nu_0}$$

Sojourn time of a molecule as a function of temperature



Stainless steel after 10 h of pumping (Torr.ℓ/s/cm²)

	H2	CH4	H2O	CO	CO2
Unbaked	$7\ 10^{-12}$	$5\ 10^{-13}$	$\mathbf{3\ 10^{-10}}$	$5\ 10^{-12}$	$5\ 10^{-13}$
Baked	$\mathbf{5\ 10^{-13}}$	$5\ 10^{-15}$	$1\ 10^{-14}$	$1\ 10^{-14}$	$1\ 10^{-14}$

A.G. Mathewson *et al.* in Handbook of Accelerator Physics and Engineering, World Scientific, 1998

Cleaning Methods

- Several means are used in vacuum technology to reduce the outgassing rates

- Chemical cleaning is used to remove gross contamination such as grease, oil, finger prints.
- Example of CERN LHC beam screens :
  - Degreasing with an alkaline detergent at 50°C in an ultrasonic bath
  - Running tap water rinse
  - Cold demineralised water rinse by immersion
  - Rinse with alcohol
  - Dry with ambient air

cuves for beam screens

- Vacuum firing at 950°C is used to reduce the hydrogen content from stainless steel surface

Length: 6 m
Diameter: 1 m
Maximum charge weight: 1000 Kg
Ultimate pressure: 8 10^{-8}Torr
Pressure at the end of the treatment: high 10^{-6} Torr

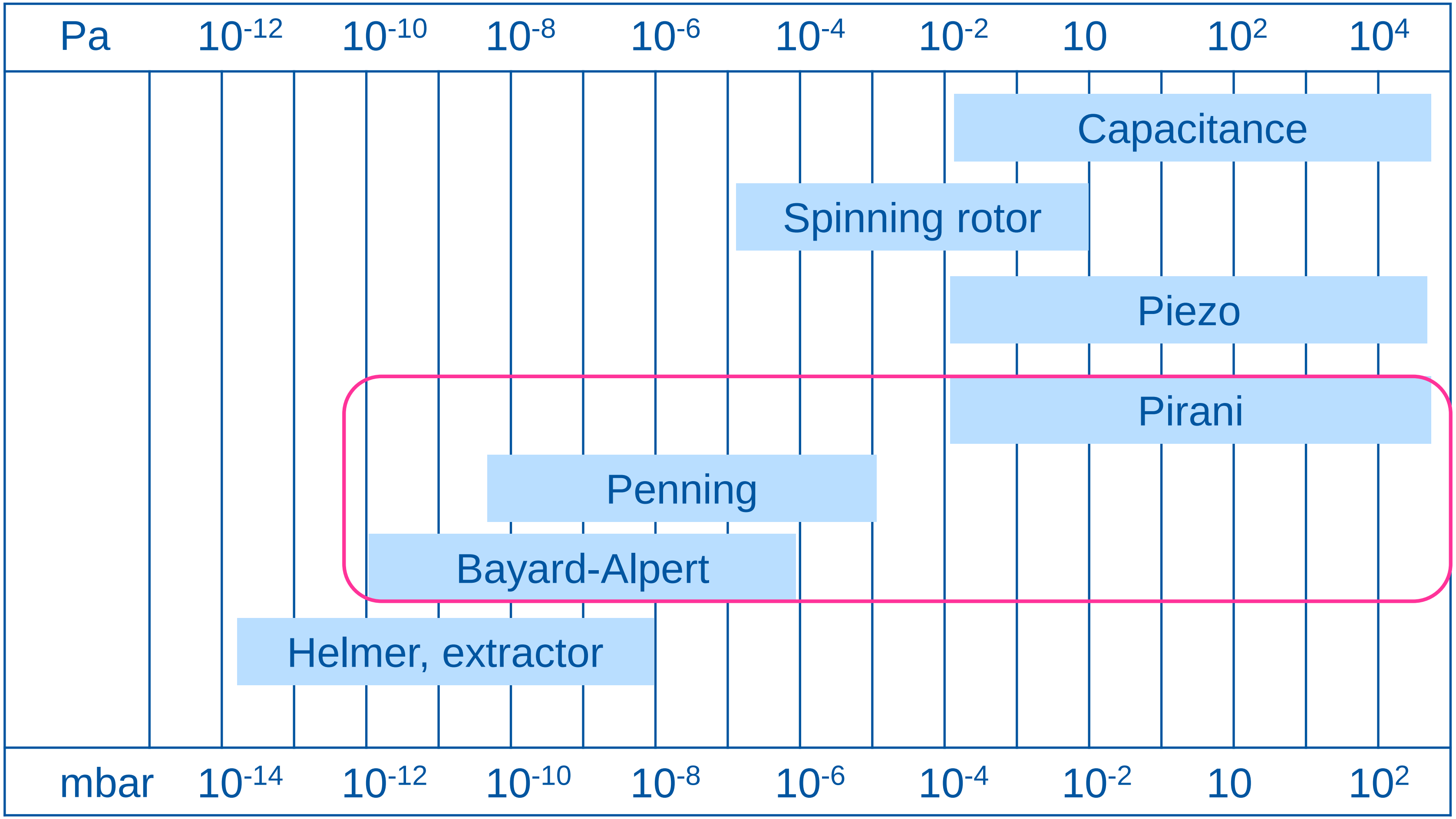
- Glow discharges cleaning is used to remove by sputtering the adsorb gases and the metal atoms

- Wear gloves to handle the material

2. Vacuum Components

Vacuum gauges pressure range

16 orders of magnitude !



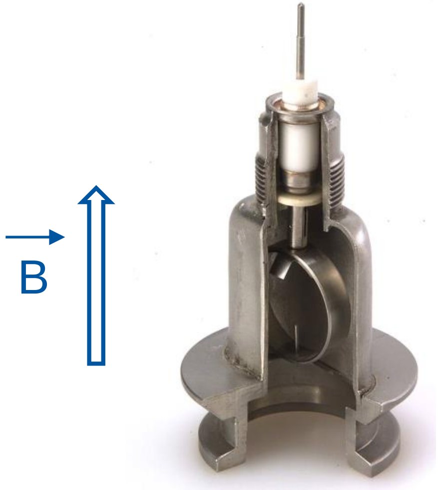
Penning Gauge

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

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

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

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




Pfeiffer Penning gauge

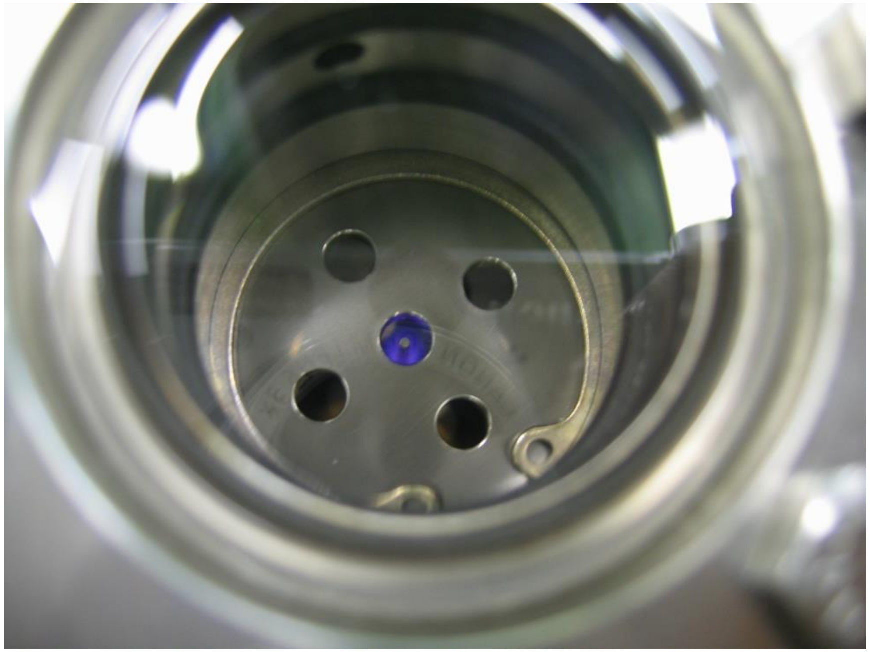

F. Penning 1937

A discharge in a Penning gauge

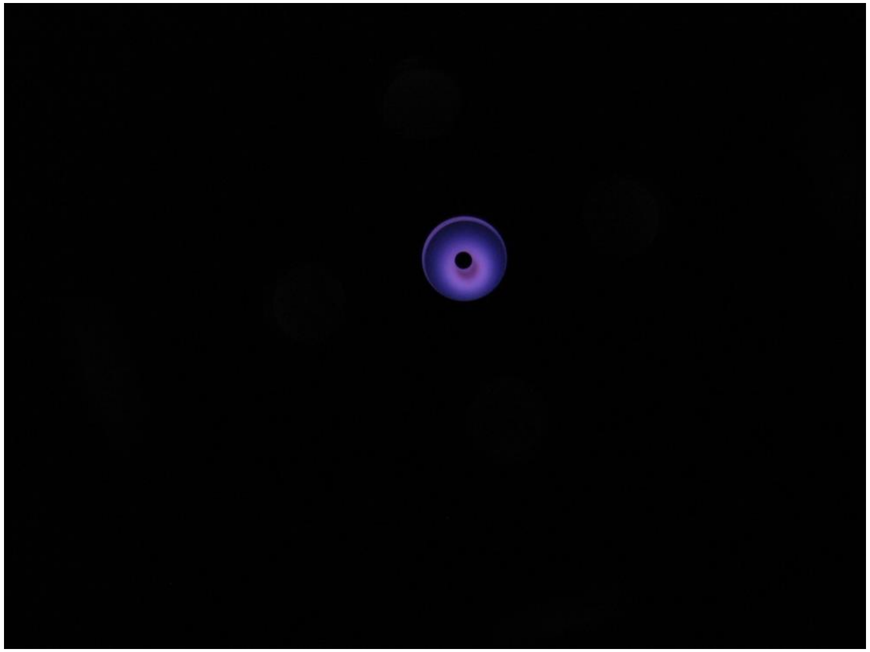
- a Penning gauge:

Courtesy Pfeiffer

Penning gauge ON behind a window



In the dark, the discharge is seen



Pictures courtesy B. Henrist, TE-VSC

Bayard-Alpert Gauge

- Bayard-Alpert gauges are used for vacuum measurement purposes in the range 10^{-5} -10^{-12} mbar.

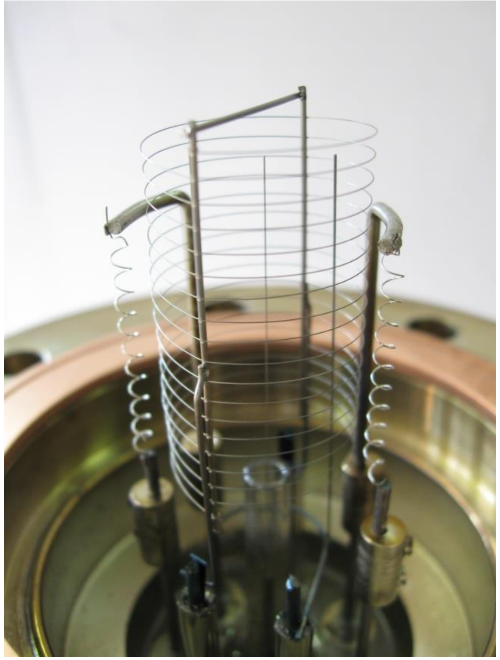
- It is a hot filament ionisation gauge. Electrons emitted by the filament perform oscillations inside the grid and ionise the molecules of the residual gas. Ions are then collected by an electrode.

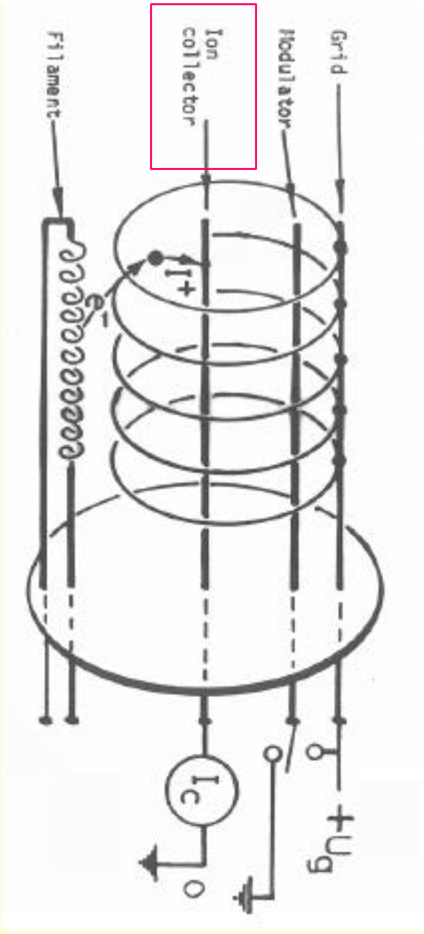
$$\boxed{I^{+} = I^{-} \sigma n L}$$

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

- The gauge needs to be calibrated

- X-ray limit of a ~ 2 10^{-12} mbar





Residual Gas Analysers

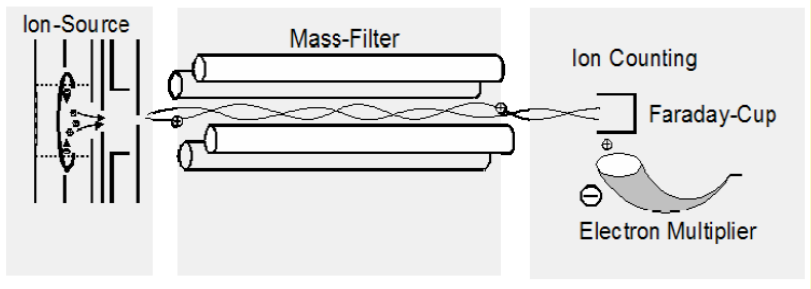
- Residual Gas Analysers are used in the range 10^{-4} -10^{-12} mbar. Their purpose is to do gas analysis

- A filament produces electrons which ionise the residual gas inside a grid. A mass filter is introduced between the grid and the ion collector. The ion current can be measured in Faraday mode or in secondary electron multiplier mode.

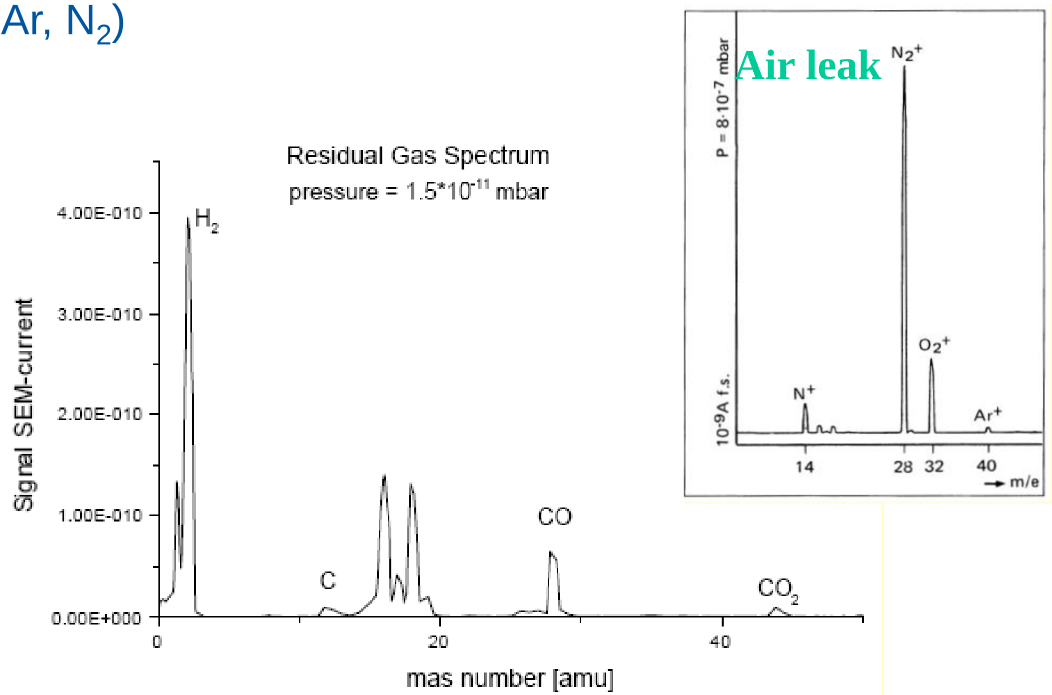
- It is a delicate instrument which produces spectrum sometimes difficult to analyse

- It can be also used to identified/find leaks (Ar, N_2)

- The RGA needs to be calibrated

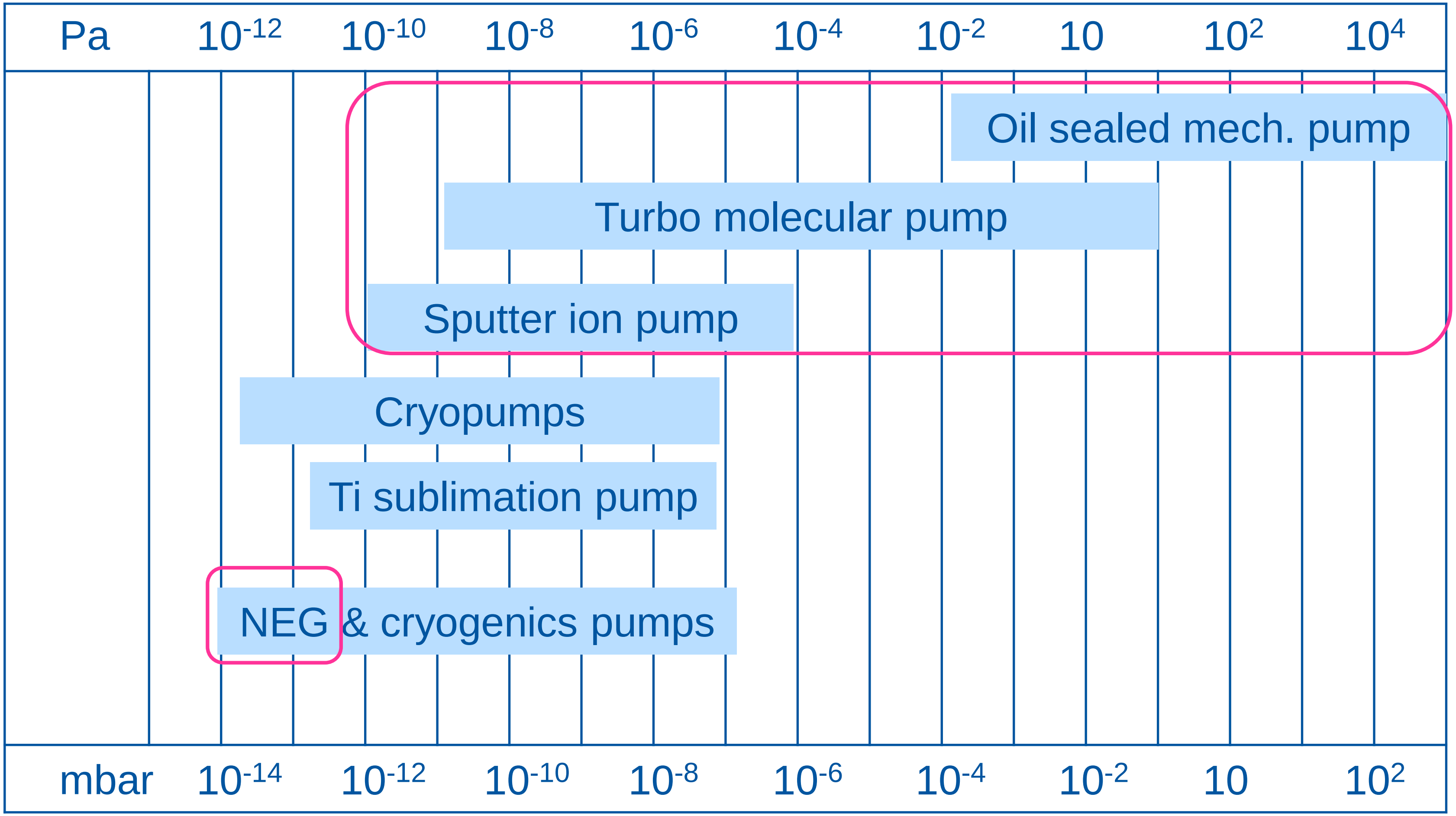


G.J. Peter, N. Müller. CAS Vacuum in accelerators CERN 2007-003



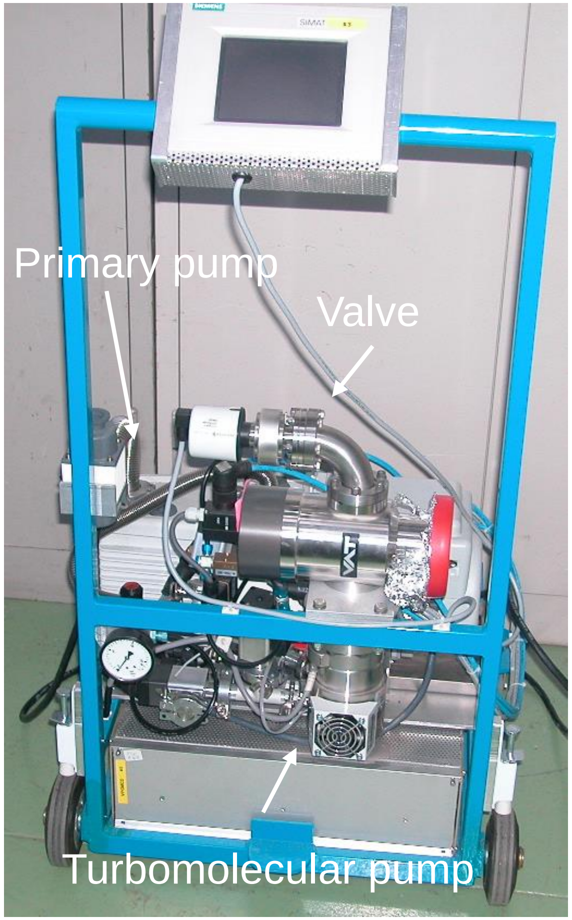
Vacuum pumps pressure range

16 orders of magnitude !

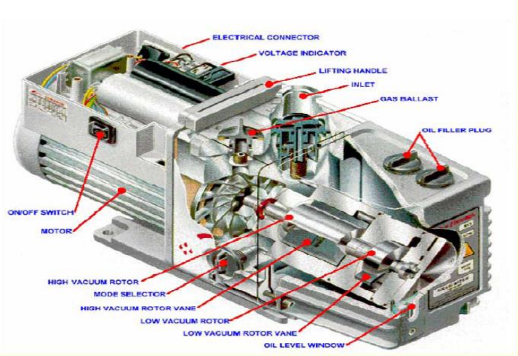


Turbomolecular pumping group

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



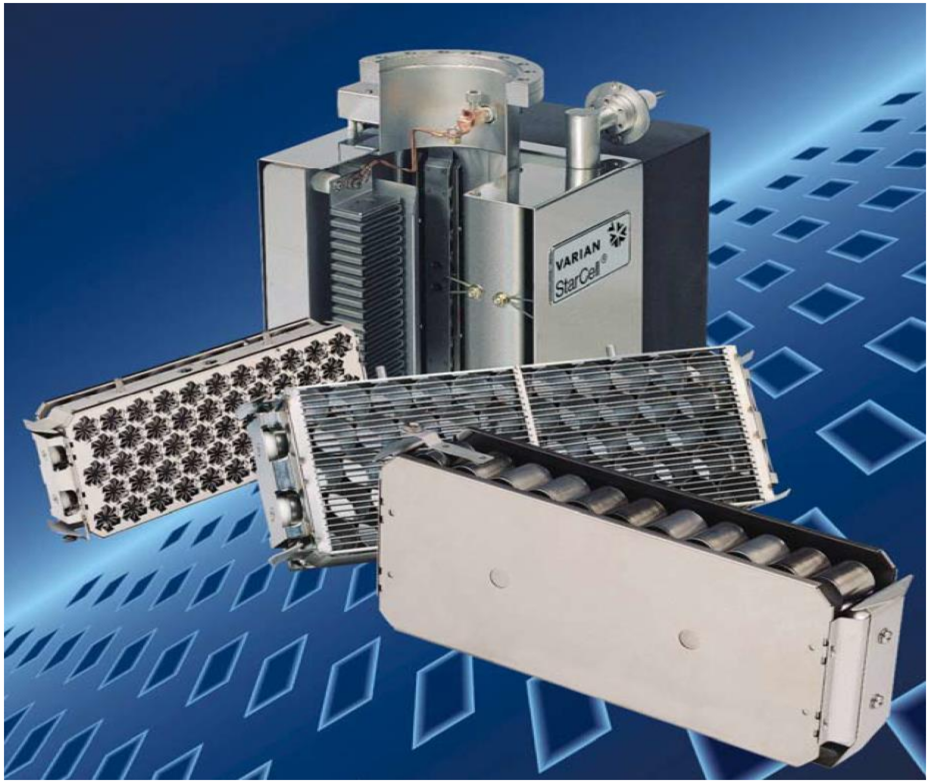
Turbomolecular pump



Primary pump

Sputter Ion Pump

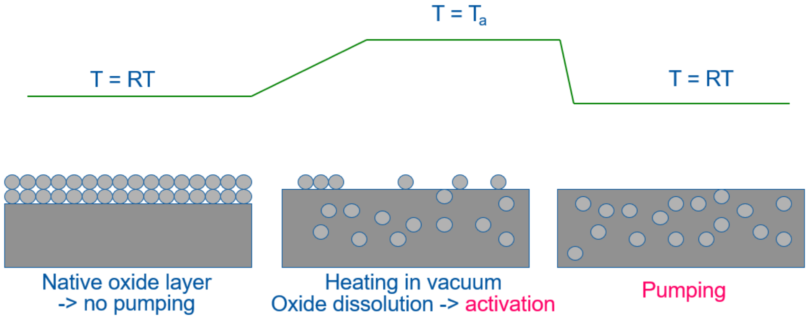
- This pump operate in the range 10^{-5} -10^{-11} mbar. It is used to maintain the pressure in the vacuum chamber of an accelerator.
- Pumping is provided by Penning cells, the speed range from 1 to 500 l/s.
- Titanium sputtered from the cathode bombarded by accelerated ions provides pumping.
- The ion current is proportional to pressure, hence these pumps are used for interlocks



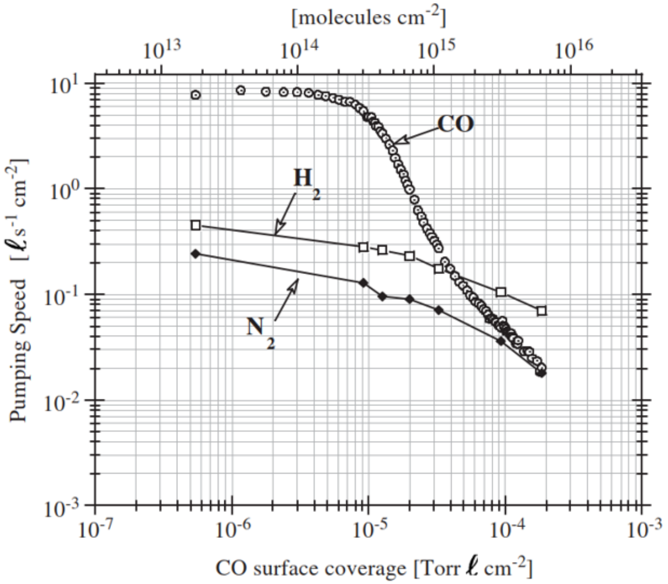
Picture Agilent, Varian

Non-Evaporable Getter (NEG)

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



- 1 µm thick film coated at 300˚C
- Very large pumping speed : ~ 250 l/s/m for H_2, 20 000 l/s/m for CO ➔ distributed pumping
- Very low outgassing rate (~200 CH_4/s/cm^2)
- But : limited capacity and fragile coating sensitive to pollutant (hydrocarbons, Fluor …)

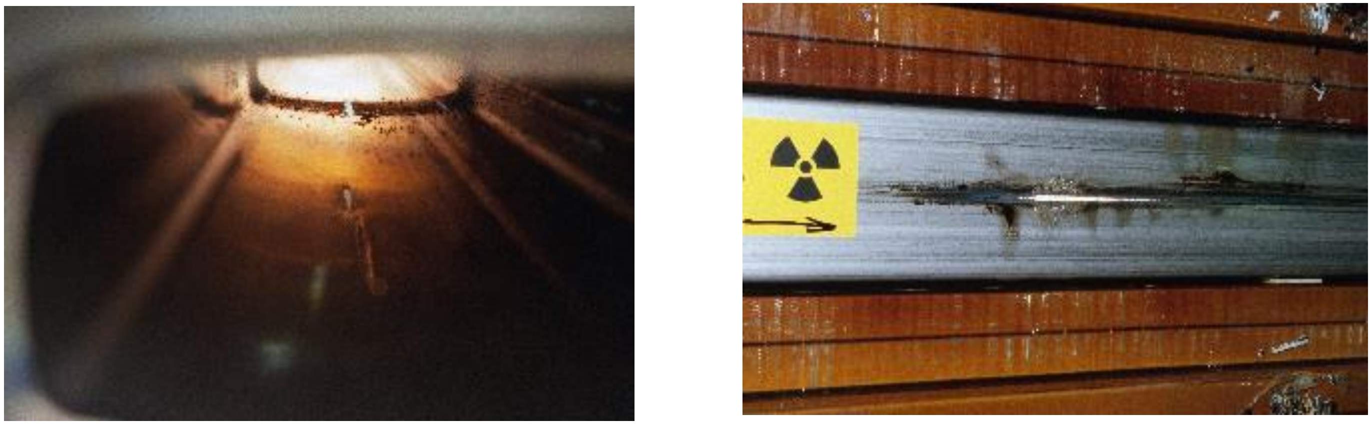


P. Chiggiato and P. Costa Pinto, Thin Solid Films, 515 (2006) 382-388

3. Vacuum with Circulating Beams

First … minimise beam losses

- Beam losses generate radioactive materials and ultimately vacuum loss !



Perforated LEP vacuum chamber

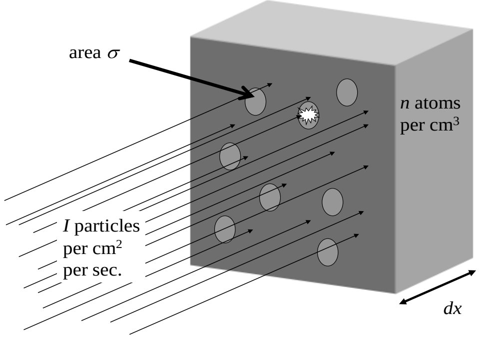
- To minimise beam gas-collision leading to the beam current decrease, the control of the gas density level is required.

- “Vacuum lifetime”:

$$\tau = \frac{1}{n\,\sigma\,v}$$

$$\frac{dI}{dt} = -I\,n\,v\,\sigma$$

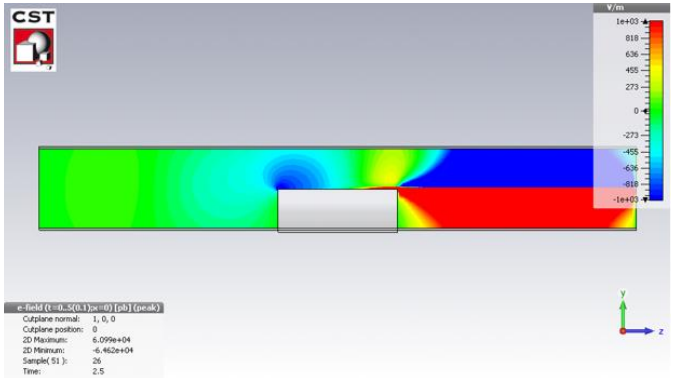
$$I = I_o\,e^{-\frac{t}{\tau}}$$



Beam residual gas interactions, SP Møller, CAS, CERN 99-05
Lifetime, cross-section and activation, P. Grasfström, CAS, CERN 2007-003

Second … consider the beam impedance

- Any beampipe component generates EM wakefields and may behave like a resonator or a damper



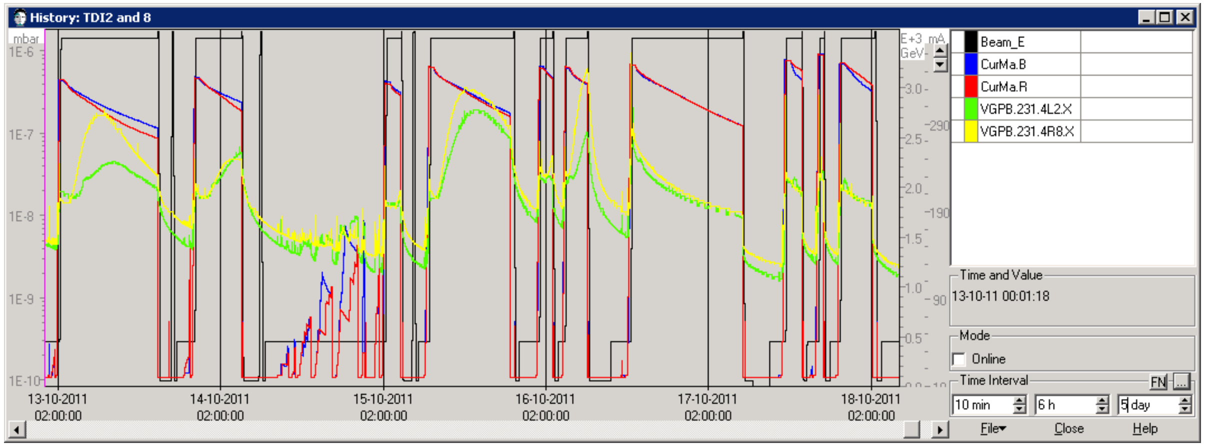
e-field (t=0..5(0.1);x=0) [pb] (peak)
Cutplane normal: 1, 0, 0
Cutplane position: 0
2D Maximum: 6.099e+04
2D Minimum: -6.462e+04
Sample(51): 26
Time: 2.5

X. Buffat, CAS Webminar, 2021

➔ "Smooth" beam pipe without aperture transitions

R. Veness *et al.* Proc. PAC 2001

Beam induced heating $Q = Q_o e^{-\frac{E}{k\,T}}$



■ Beam_E
🟦 CurMa.B
🟥 CurMa.R
🟩 VGPB.231.4L2.X
🟨 VGPB.231.4R8.X

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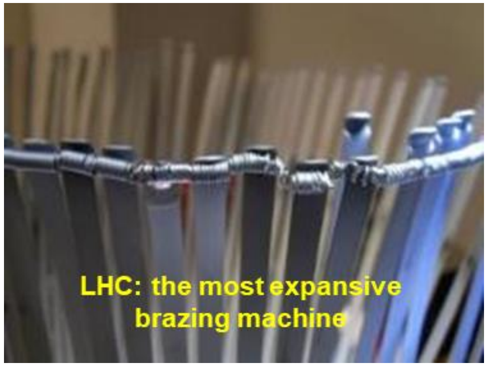
Mode: ☐ Online
Time Interval: 10 min, 6 h, 5 day



Third … beam induced molecular desorption

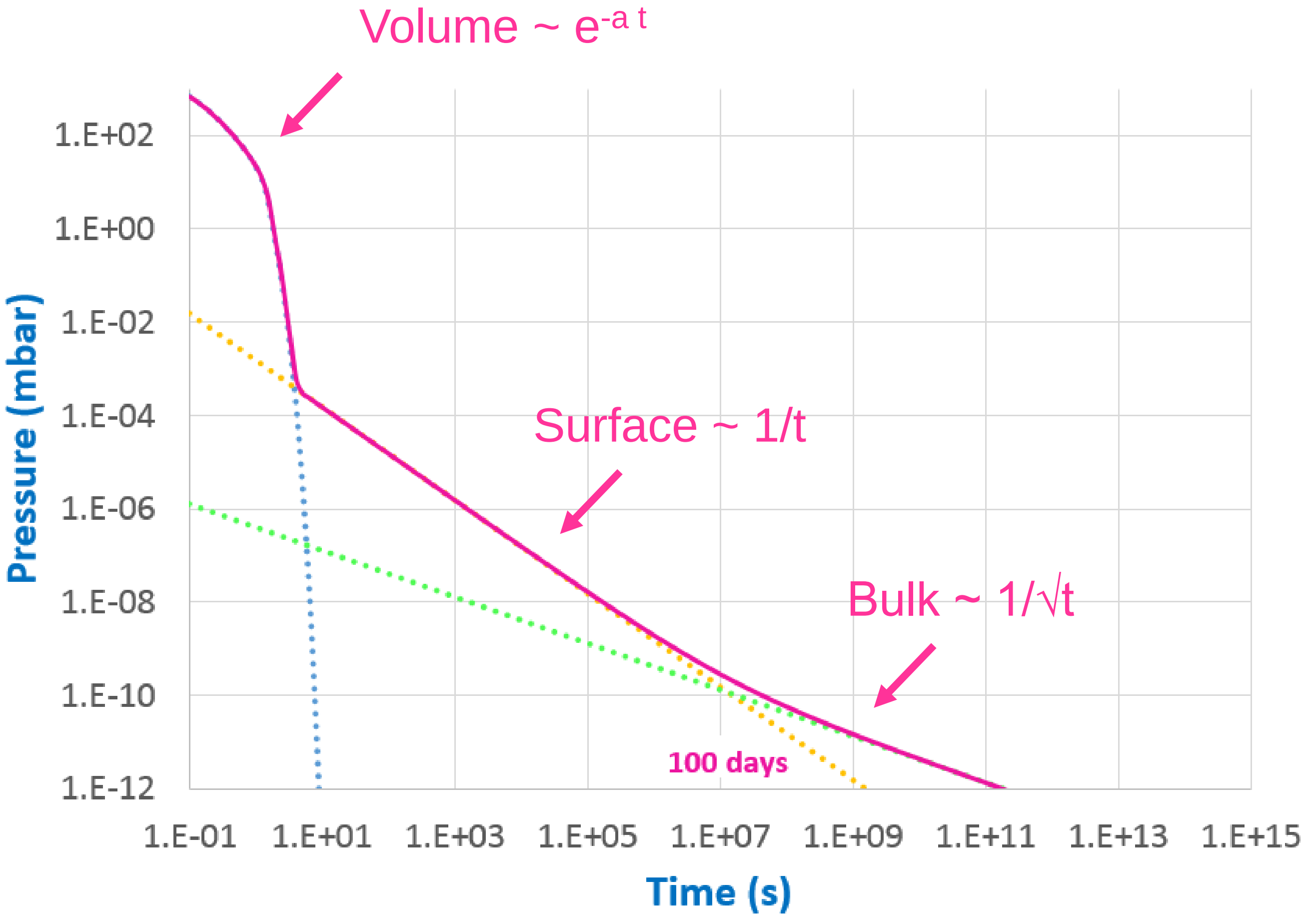
- Long term pump down of a vessel
- Consider 1 m long, Ø10 cm stainless steel tube pumped by 30 l/s
- 4 regimes

1) Volume pumping

2) Surface desorption

3) Diffusion from the bulk

4) Permeation trough the wall (solubility+diffusion)



A schematic description

- Desorbed molecules originates from:
    - Adsorption
    - Absorption
    - Diffusion
    - Permeation

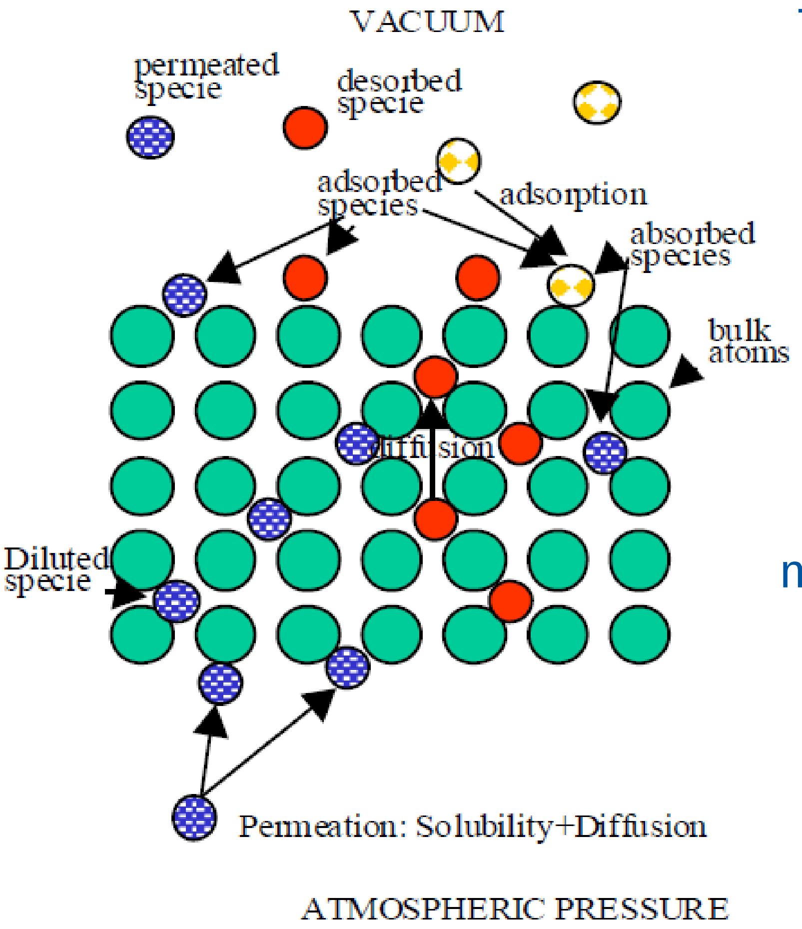


Fig. 1 Surface and bulk phenomena in vacuum.

J De Segovia, Physics of Outgassing, CAS, CERN-99-05

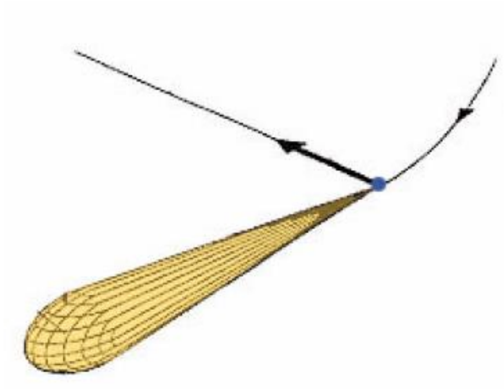
The release of these molecules into the vacuum is named OUTGASSING

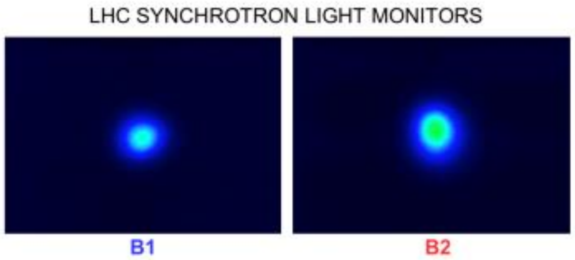
Beam induced molecular desorption

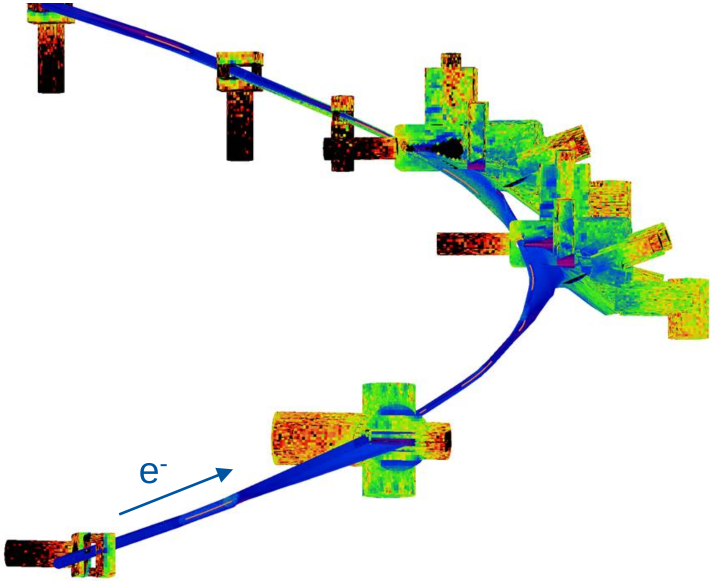
3.1 Synchrotron Radiation

Synchrotron radiation

- A charged particle which is accelerated produce radiation
- For a relativistic particle, the radiation is highly peaked (opening angle ~ 1/γ)
- The radiation energy range from infra-red to gamma rays: from meV to MeV







K. Hübner, CAS 1984, CERN 85-19

R.P. Walker, CAS 1992, CERN 94-01

A. Hofmann, CAS 1996, CERN 98-04

L. Rivkin, CAS 2008

Ray tracing in a real machine
courtesy R. Kersevan

SR impact on different type of machines …

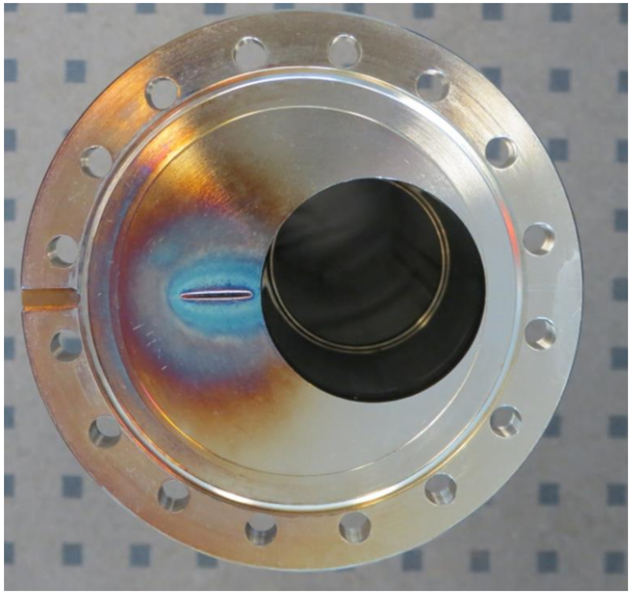
		Soleil	KEK-B		LEP			LHC	
			LER	HER	Inj.	1	2	Inj.	Col.
Particle		e^-	e^+	e^-	e^-	e^-	e^-	p	p
Beam current	mA	500	2600	1100	3	3	7	584	584
Energy	GeV	2.75	3.5	8	20	50	96	450	7000
Bending radius	m	5.36	16.31	104.46	2962.96			2784.302	
Power	W/m	14 030	20 675	5 820	0.8	30	955	0	0.2
Critical energy	eV	8 600	5 800	11 000	6 000	94 000	660 000	0	44
Photon flux	photons/m/s	$3\ 10^{19}$	$7\ 10^{19}$	$1\ 10^{19}$	$3\ 10^{15}$	$7\ 10^{15}$	$3\ 10^{16}$	$7\ 10^{15}$	$1\ 10^{17}$
Dose at 3000 h	photons/m	$4\ 10^{26}$	$8\ 10^{26}$	$1\ 10^{26}$	$3\ 10^{22}$	$7\ 10^{22}$	$3\ 10^{23}$	$7\ 10^{22}$	$1\ 10^{24}$

- In LEP, and all synchrotron light sources, the evacuation of the **power is an issue**
- The LHC operates at 7 TeV with ~ .6 A. **Power evacuation is an issue for the cryogenic system (1 kW/arc !!)**

- The critical energy varies from a few 10 eV to 660 keV. **Strongly bound molecules can be desorbed**
- The photon flux is large, so large gas load. **Adequate dimensioning of the effective pumping** speed is required
- The annual photon dose is large. **Implications on gas reduction and radiation**

SR power requires appropriate design & operation…

A melted stainless steel following a misalignment



Courtesy N. Bechu, SOLEIL

An air leak in SPRING 8: 8 GeV electron beam with 15 micron vertical beam size on a 0.7 mm thick stainless steel wall

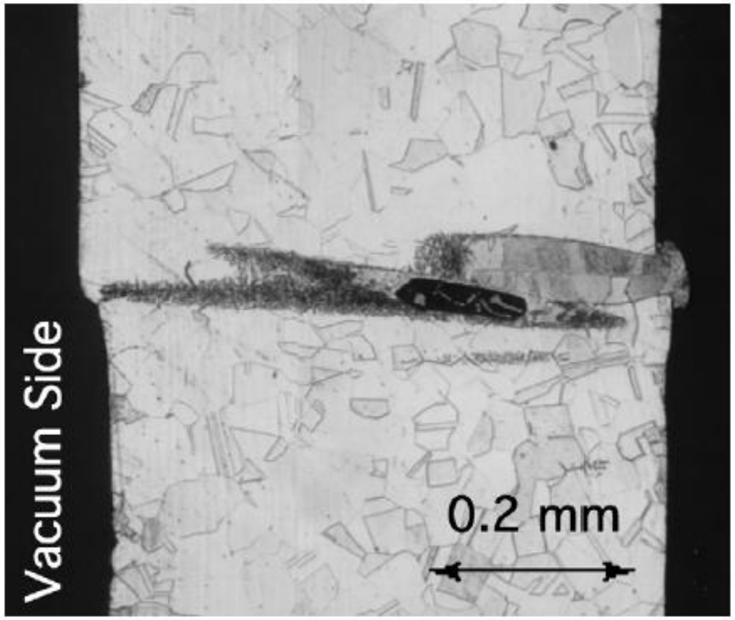


Fig. 6. Cross section of the injection chamber wall at the broken part. It seems that the electron beam hits the thin wall several times, since many traces of electron beam bombardment were found.

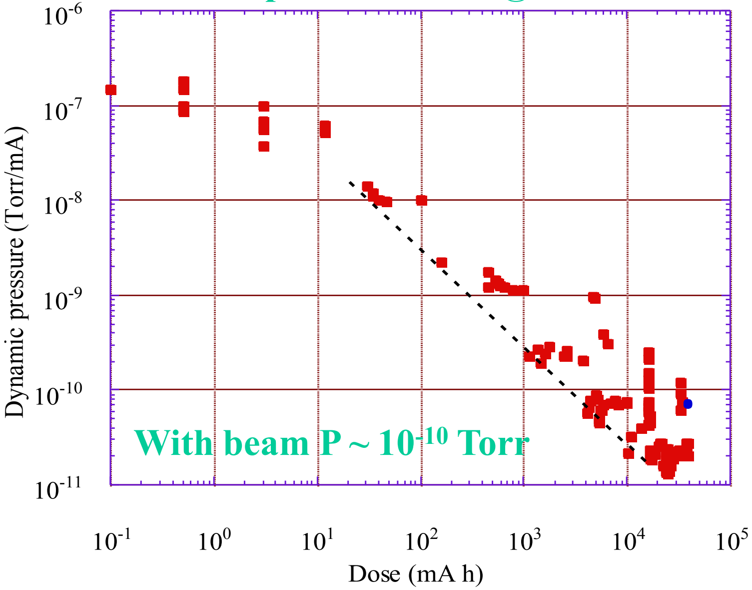
M. Shoji *et al.*
Vacuum 84 (2010) 738–742

Photon Stimulated Desorption

- The observed dynamic pressure decreases by several orders of magnitude with photon dose: “photon conditioning”
- The photon desorption yield is characterised by η_{photon}

$$\boxed{P = P_o + P_{Dyn} = \frac{Q + \eta_{Photons}\dot{\Gamma}_{Photons}}{S}}$$

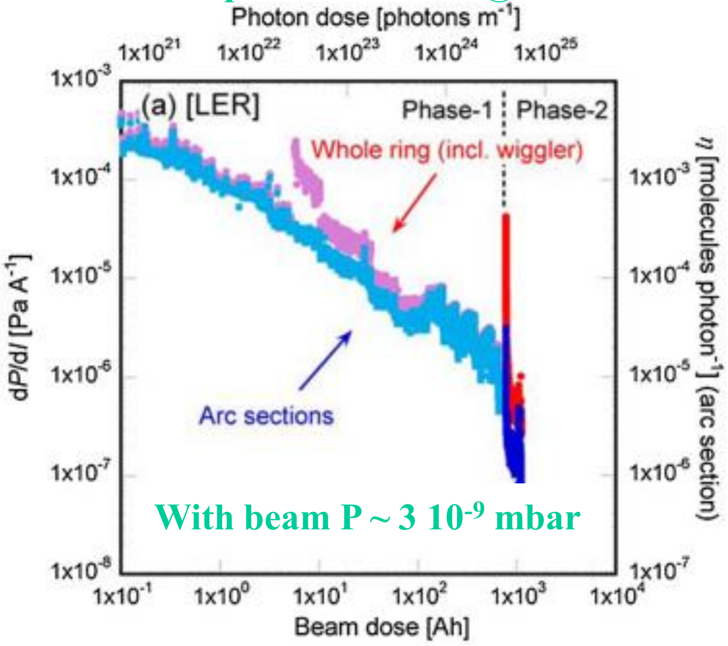
First period of LEP @ ~1 mA



With beam P ~ 10^{-10} Torr

O. Gröbner. Vacuum 43 (1992) 27-30

SuperKEKB LER @ 1 A



With beam P ~ 3 10^{-9} mbar

Y. Suetsugu et al., J. Vac.Sci.Technol. A37 021602 (2019)

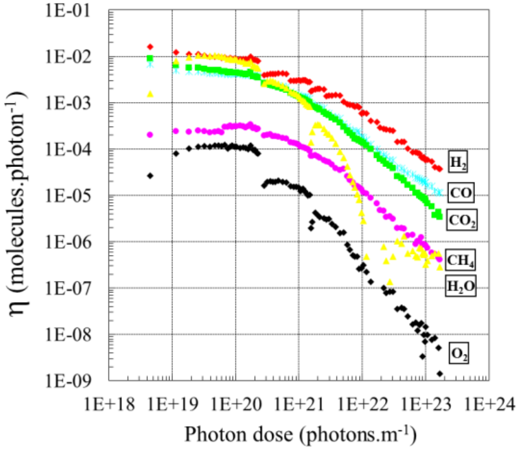
Photon Desorption Yield

- Initial yield ~ 10^{-3} – 10^{-2} molecules/photon
- Rapidly decrease with dose until ~ 10^{-7} - 10^{-6} molecules/photon at 10^{25}-10^{26} ph/m
- Scales like

$$\eta_{Photons} = \eta_{0}\left(\frac{D}{D_{0}}\right)^{-a}$$

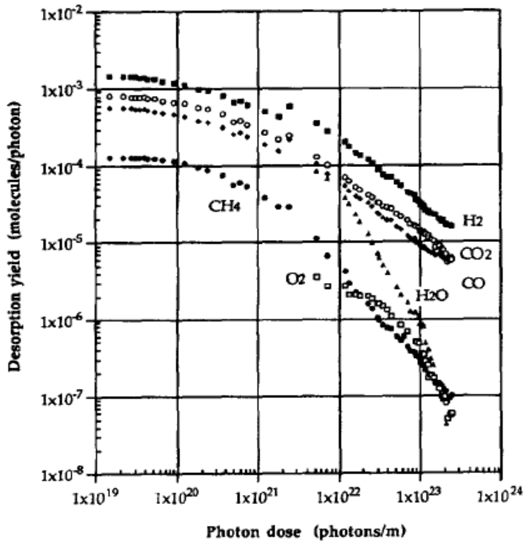
- Several monolayers of gas can be desorbed

Unbaked stainless-steel
3.75 keV

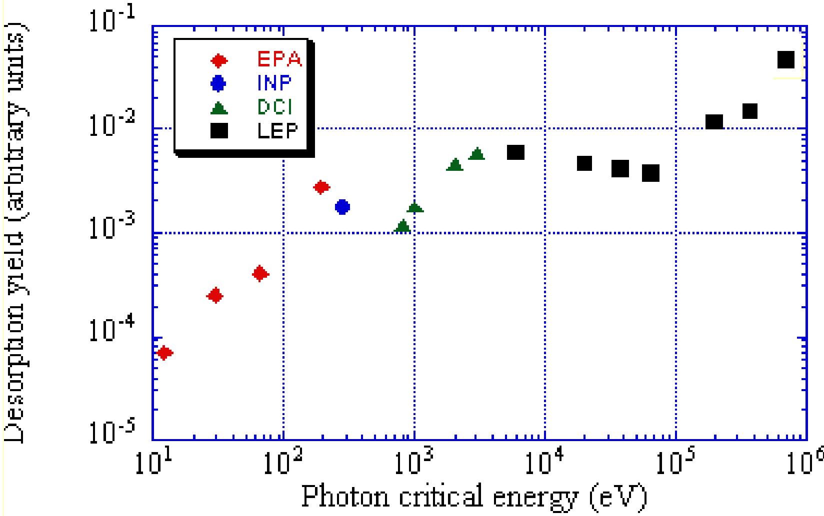


C. Herbeaux et al.
JVSTA 17(2) Mar/Apr 1999, 635

Cu baked at 150°C



O. Gröbner et al.
J.Vac.Sci. 12(3), May/Jun 1994, 846-853

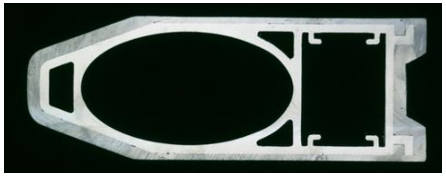


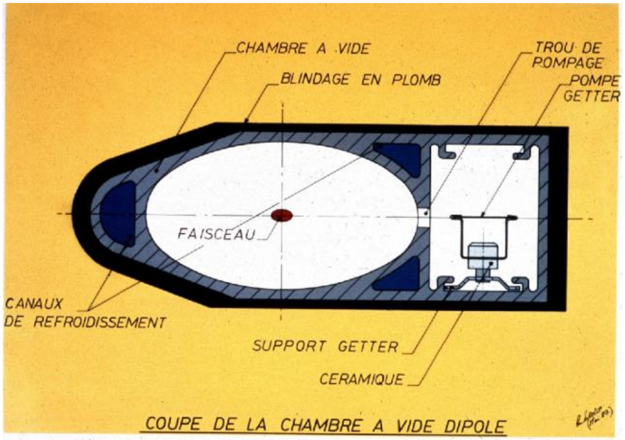
O. Gröbner. CAS 99-15

Vacuum chambers designs

- Follow the machine specificities/requirement & new technology availlability

LEP - 1989

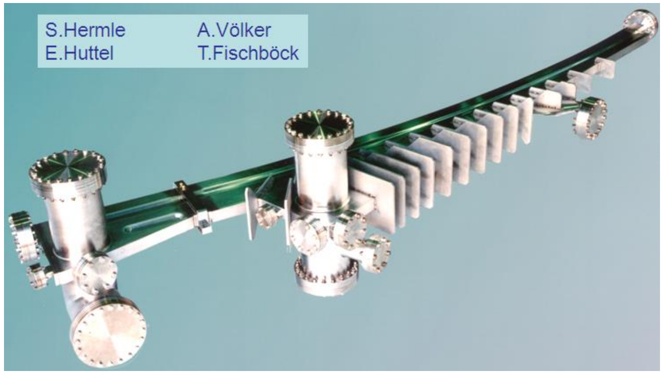




- ~ 100x50 mm Extruded Al
- Antechamber
- NEG strip
- Water cooled
- Lead shielding

ANKA - 2000

courtesy E. Huttel



- ~ 70x30 mm stainless steel with ribs stiffeners
- Antechamber
- Ion pumps
- Lumped absorbers

MAX IV - 2015

Courtesy M Grabsky

- 22 mm diameter Cu
- NEG coating

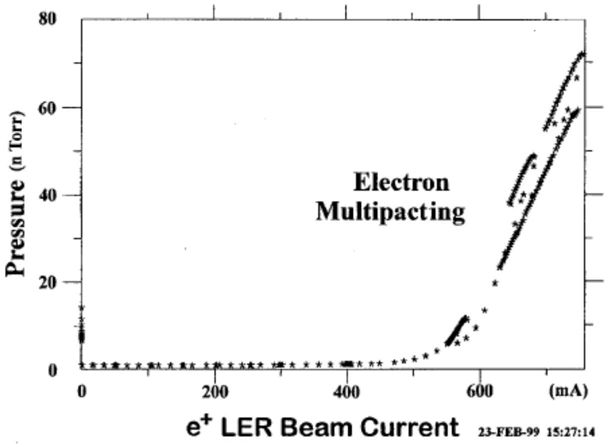
3.2 Electron Cloud

Some electron cloud sensitive machines

	PEPII	KEKB	DAFNE	LHC	HL-LHC	Super KEKB	ILC DR	FCC-hh
Particle	e+	e+	e+	p	p	e+	e+	p
Energy [GeV]	3.1	3.5	0.51	7 000	7 000	4	5	50 000
Luminosity [Hz/cm^2]	3×10^{33}	2×10^{34}	5×10^{32}	1×10^{34}	5×10^{34}	8×10^{35}	na	5×10^{34}
Circumference [km]	2.2	3	0.1	26.7	26.7	3	3.2	97.8
Nb of bunches	1 658	1 284	120	2 808	2 748	2 500	1 312	10 426
Bunch population	6×10^{10}	9×10^{10}	2×10^{10}	1.2×10^{11}	2.2×10^{11}	9×10^{10}	2×10^{10}	1×10^{11}
Bunch spacing [ns]	4.2	7	2.7	25	25	4	554	25
Bunch length [ns]	0.05	0.02	0.1	0.25	0.25	0.02	0.02	0.25
Instability threshold [e/m^3]	1×10^{12}	4×10^{11}	1×10^{13}	5×10^{11}	1×10^{12}	3×10^{11}	4×10^{10}	4×10^{10}
Material	Al	Cu	Al	Cu/SS	Cu/SS	Cu/Al	Cu	Cu

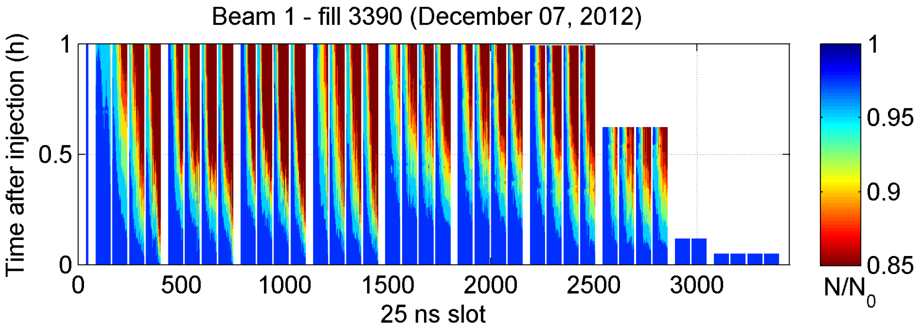
Effects of electron cloud

Pressure increase



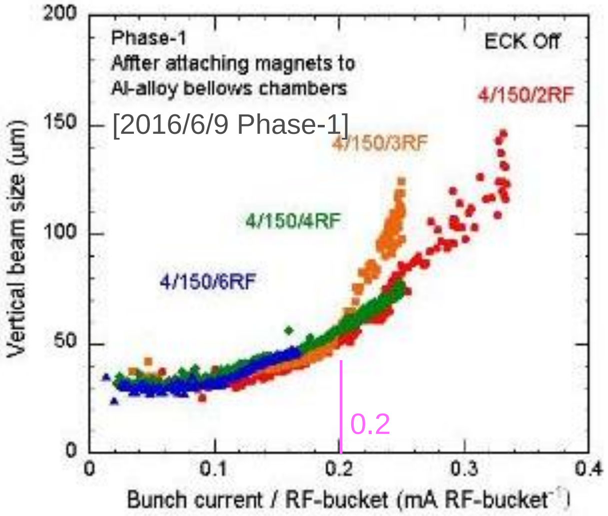
J. Seeman et al., EPAC 2000, Vienna, Austria

Bunch instability along the train



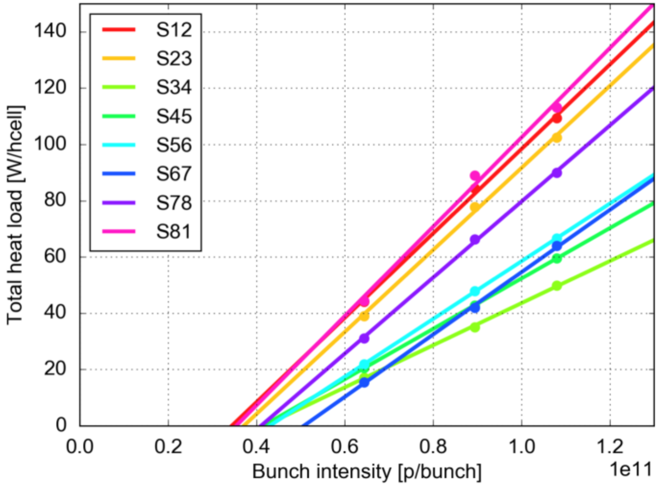
Courtesy G. Rumolo

Beam size increase



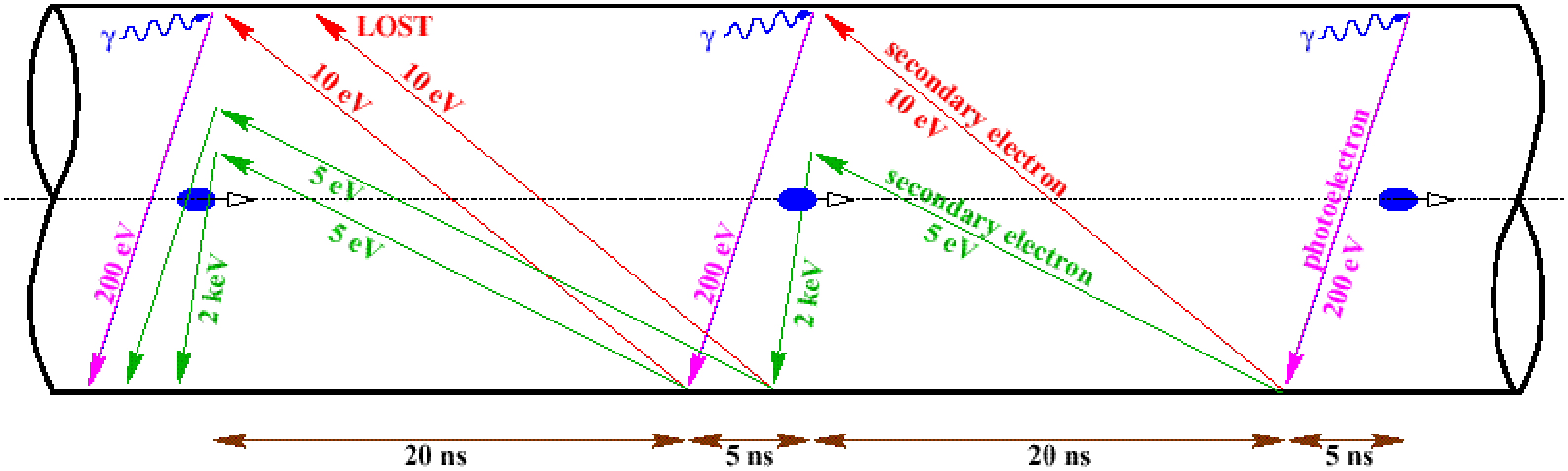
Y. Suetsugu et al., J. Vac.Sci.Technol. A37 021602 (2019)

Heat load: 15-50 kW at 5-20 K in LHC!



G. Iadarola, Proc. Ecloud Workshop 2018

LHC mechanism



Schematic of electron-cloud build up in the LHC beam pipe.

F. Ruggiero *et al.*, LHC Project Report 188 1998, EPAC 98

- Key parameters:
  - beam structure
  - bunch current
  - vacuum chamber dimension
  - secondary electron yield
  - photoelectron yield
  - electron and photon reflectivities
  - …

$$\boxed{P = \frac{Q + \eta_{Electrons}\dot{\Gamma}_{Electrons}}{S}}$$

Magnetic field

- Electrons moves along the magnetic field lines
- It modifies the threshold of multipacting:
  - $Th_{Quad} < Th_{Dip} < Th_{Drift}$

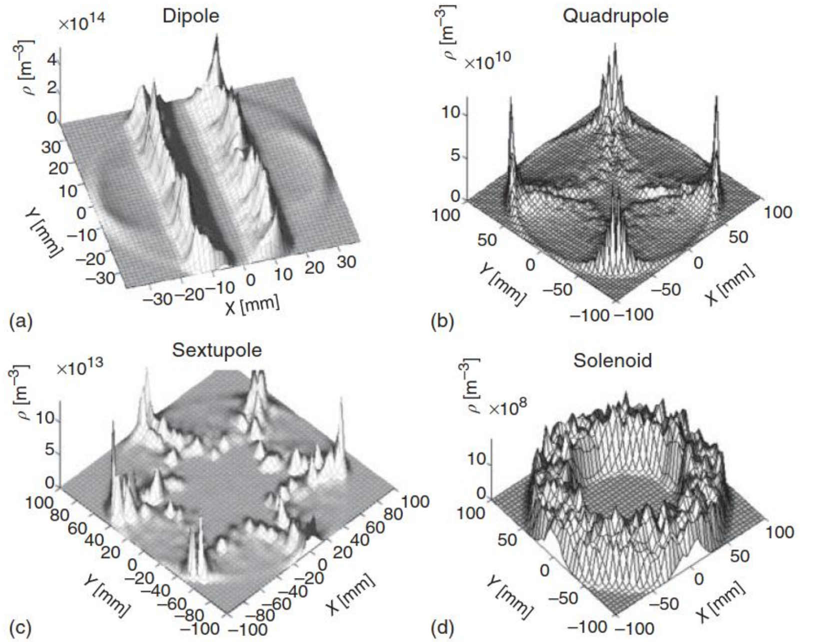


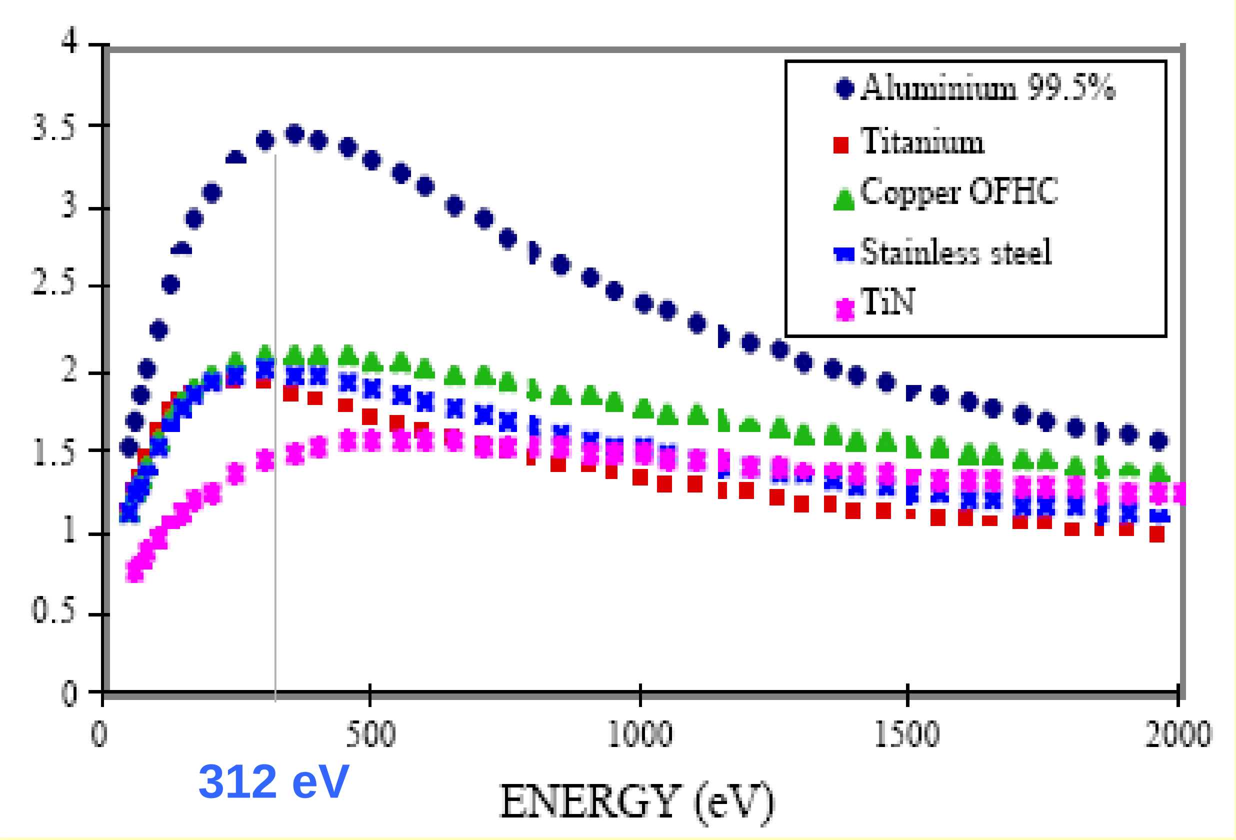
Figure 8.6 Effect of the magnetic field configuration on the electron cloud transverse distribution. (a) Dipole, (b) quadrupole, (c) sextupole, and (d) solenoid. Source: Wang et al. 2004 [43], Fig. 10 and Wang et al. 2004 [44], Figs. 25 and 26. Reprinted with permission of CERN.

Vacuum in particle accelerators, O. Malyshev, Wiley-VCH, 2020

Secondary Electrons Yield

$$\delta = \frac{\textit{number of produced electrons}}{\textit{incident electrons}}$$

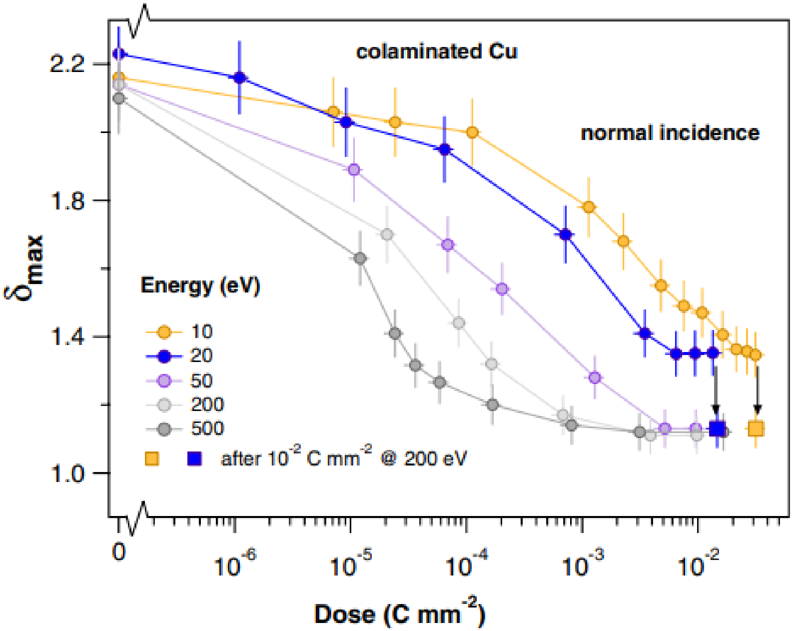
- Technical material
- Maximum around 200-300 eV
- δ_{max} ~ 2 to 3.5



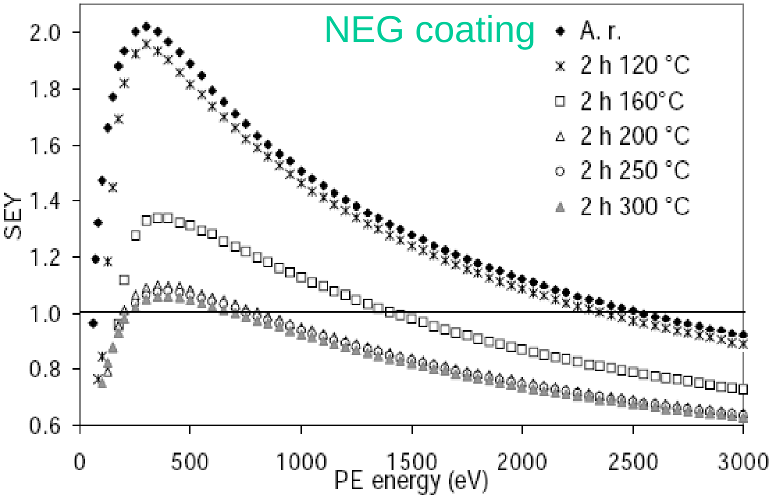
N. Hilleret *et al.*, LHC Project Report 433 2000, EPAC 00

Decreasing SEY

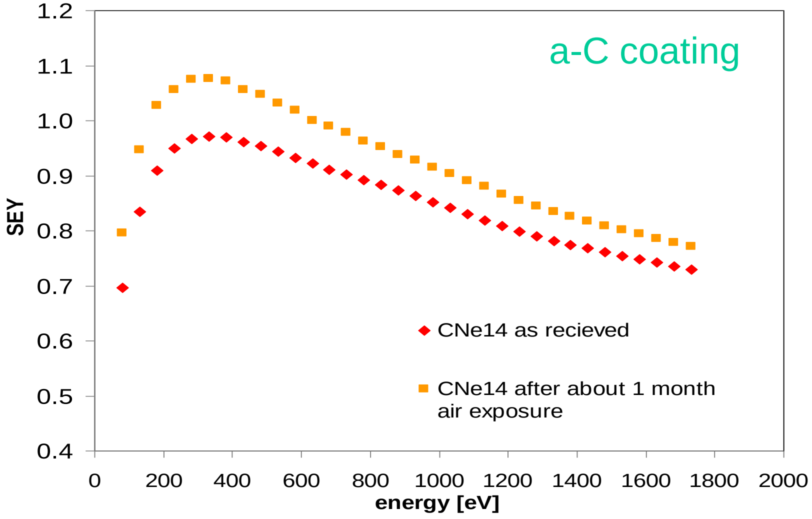
Beam conditioning i.e.
electron bombardment



R. Cimino et al. PRL 109 064801(2012)



C. Scheuerlein et al. Appl.Surf.Sci 172(2001)



M. Taborelli et al., Vacuum 98 (2013) 29-36

Electron desorption yield

- Unbaked copper
- Threshold around 10 eV

$$\eta(E) = \eta_0 \left(\frac{E - \mathrm{E_c}}{300 - \mathrm{E_c}} \right)^{0.85}$$

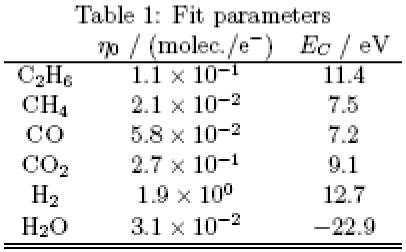


Table 1: Fit parameters

	η_0 / (molec./e^-)	E_C / eV
C_2H_6	1.1×10^{-1}	11.4
CH_4	2.1×10^{-2}	7.5
CO	5.8×10^{-2}	7.2
CO_2	2.7×10^{-1}	9.1
H_2	1.9×10^{0}	12.7
H_2O	3.1×10^{-2}	−22.9

$$\boxed{\eta = \frac{number\ of\ desorbed\ molecules}{incident\ electrons}}$$

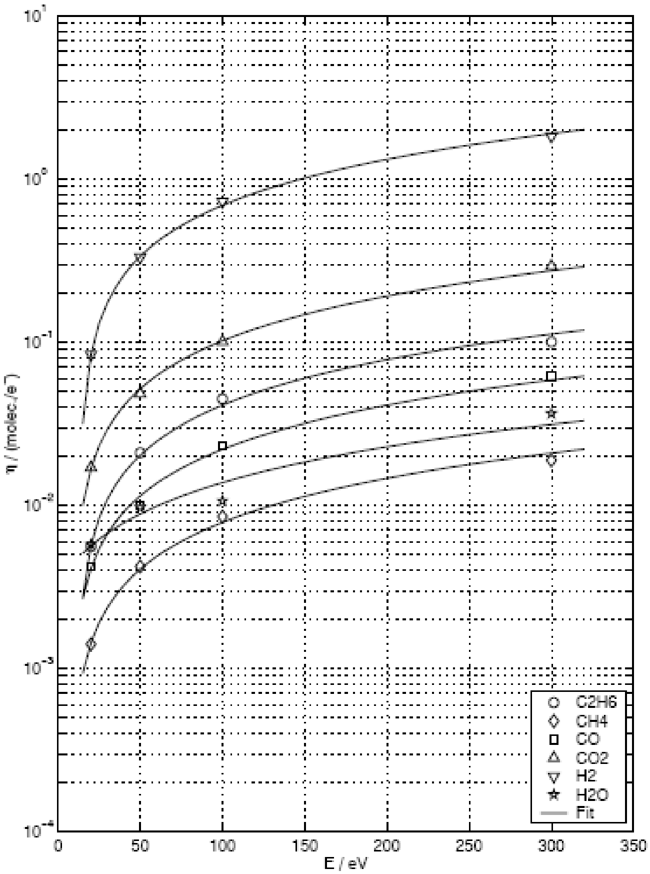


Figure 5: Electron induced desorption yield as a function of the electron energy. The values for 20, 50, and 100 eV have been obtained by interpolation between the two measurements shown in figure 4 at a constant dose of 1.4×10^{14} e⁻/cm².

G. Vorlaufer *et al.*, CERN VTN, 2000

Electron dose

- Reduction of the electron desorption yield with the electron dose: ~ 40 monolayers of gas desorbed from the surface during beam scrubbing

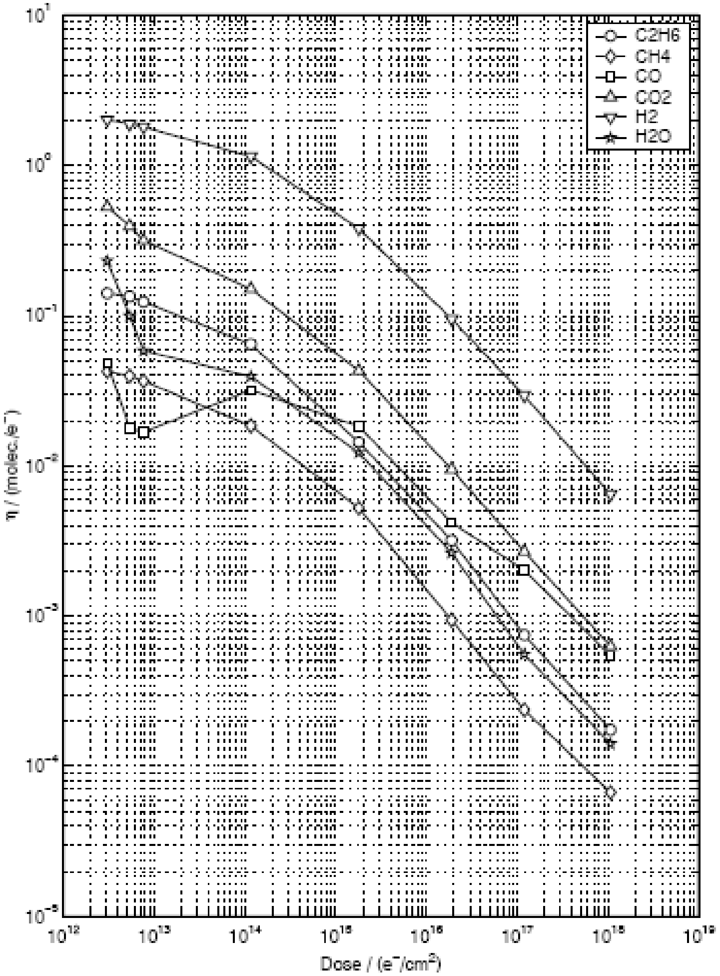


Figure 3: Effect of the electron dose on the electron induced desorption yield of an unbaked copper sample. The electron energy during bombardment and measurement was 300 eV.

G. Vorlaufer *et al.*, CERN VTN, 2000

$$\eta(\mathrm{D}) = \eta_0 \left(\frac{\mathrm{D}}{\mathrm{D}_0}\right)^{-a}$$

	H_2	CH_4	H_2O	CO	CO_2
η_0	$2\ 10^{-1}$	$2.5\ 10^{-2}$	$1\ 10^{-1}$	$3.5\ 10^{-2}$	$5\ 10^{-2}$
D_0 x 10^{14}	3	1	6	2	4
a	0.47	0.62	0.66	0.49	0.54

- Molecules/cm^2 desorbed after 10^{19} e/cm^2 i.e 16 mC/mm^2

	H_2	CH_4	H_2O	CO	CO_2
x 1e15	28	0.5	4.6	3.4	4.6

3.3 Vacuum instability

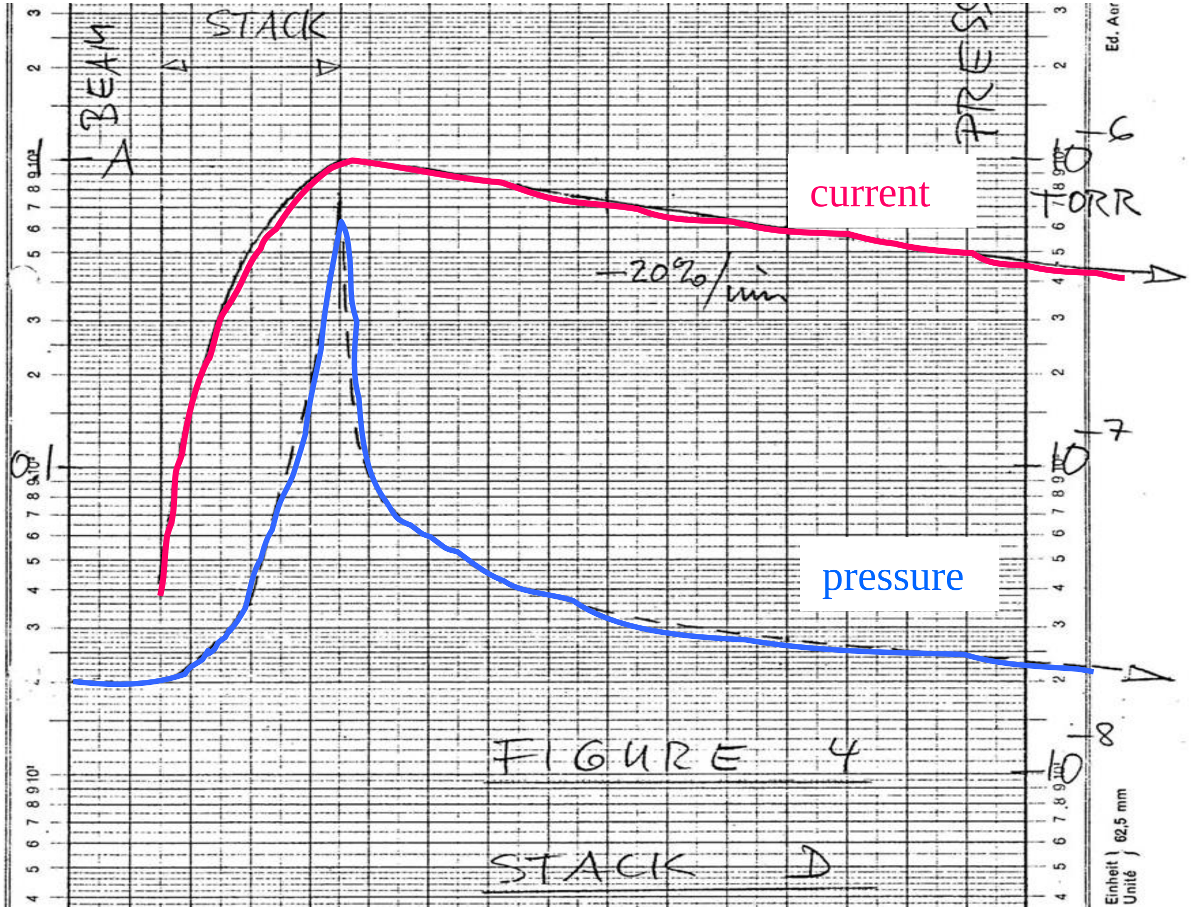
Vacuum Instability : the Effect

- In circular machine with large proton current :
  Intersecting Storage Rings (routine 40 A, record 57 A), LHC (0.6 A)

- Beam current stacking to 1 A

- Pressure increases to 10^{-6} Torr (x 50 in a minute)

- Beam losses



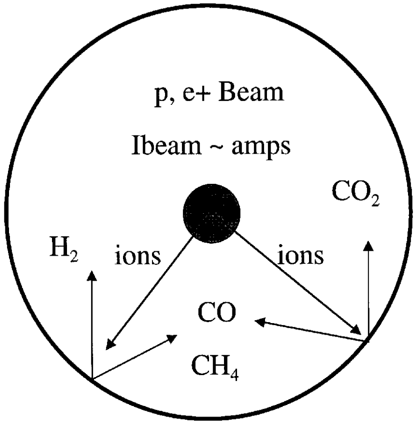
First documented pressure bump in the ISR

E. Fischer/O. Gröbner/E. Jones 18/11/1970

Vacuum Instability : Mechanism and Recipe

- Origin is ions produced by beam-gas ionisation
- Reduction of the effective pumping speed, S_{eff}

$$\boxed{P_{eq} = \frac{Q}{S_{eff}} = \frac{Q}{S\left(1 - \frac{\eta_{ion}}{S}\sigma\frac{I}{e}\right)}}$$

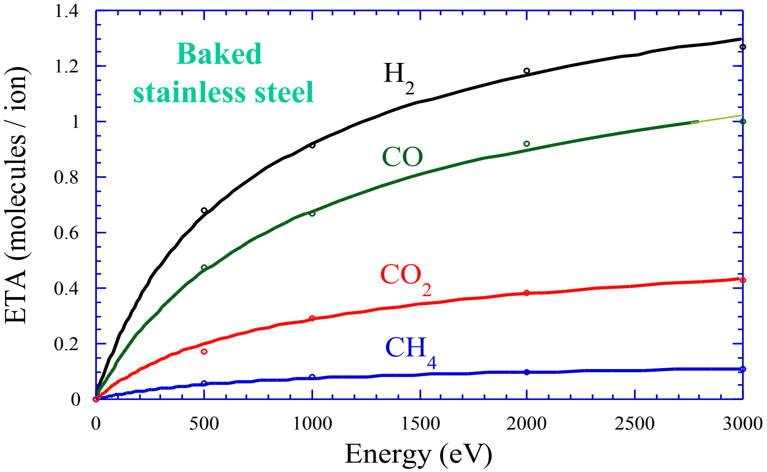


- When the beam current approach the **critical current**, the pressure increases to infinity

$$\boxed{(\eta_{ion} I)_{crit} = \frac{e\,S_{eff}}{\sigma}}$$

- Recipe:

Reduce η_{ion}
Increase pumping speed



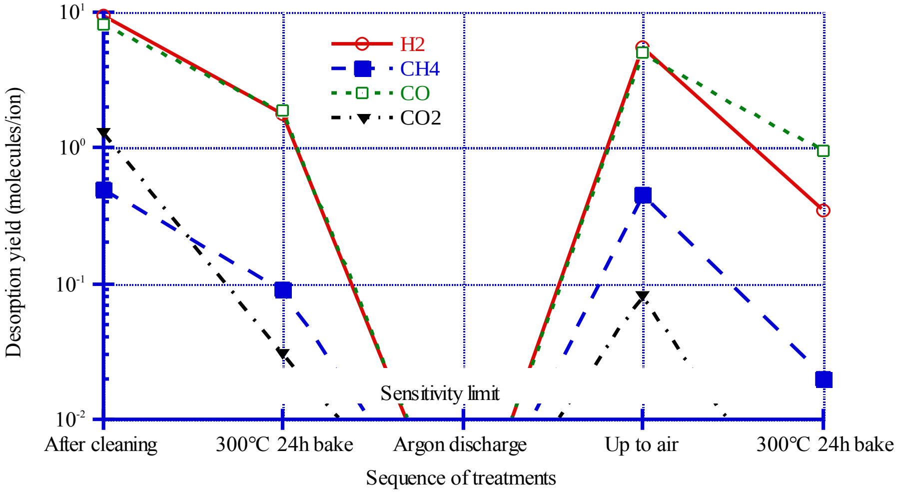
A.G. Mathewson, CERN ISR-VA/76-5

ISR Remedy

- Beam cleaning being negligible:
  - Increase number of pumps
  - Reduce outgassing using 300°C bakeout
  - Perform ex-situ Ar/O_2 glow discharge cleaning with in-situ bakeout

$$(\eta_{\text{ion}} I)_{\text{crit}} = \frac{e\,S_{\text{eff}}}{\sigma}$$

➔ ηI_{Crit} increased to ~ 60 A and the machine could reached 57 A and 2×10^{-12} Torr!



A.G. Mathewson, CERN ISR-VA/76-5

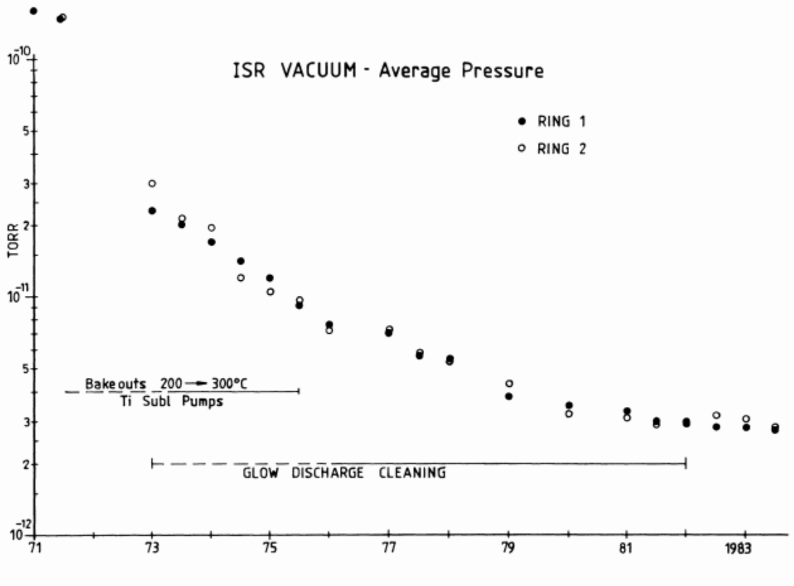


Fig 5 The average pressure of the ISR vacuum for the years 1971-83

M. Jacob and K. Johnsen, CERN 84-13, 1984

Vacuum Instability in J-Parc?

- J-Parc Rapid Cycling Synchrotron (RCS), Main Ring (MR) injector

- RF shielded (Cu stripes with capacitors) ceramic chambers in dipoles and quadrupoles and Ti chambers for straights

- Probable signature of Ion Stimulated Molecular Desorption

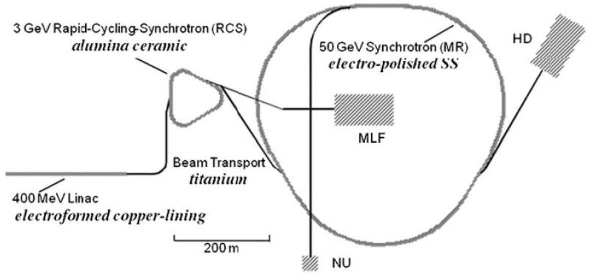


Fig. 1. Layout of the J-PARC and materials to be used for fabricating the cavity and the beam chambers. NU: neutrino to Super Kamiokande, HD: hadron experimental hall, and MLF: material and life science facility.

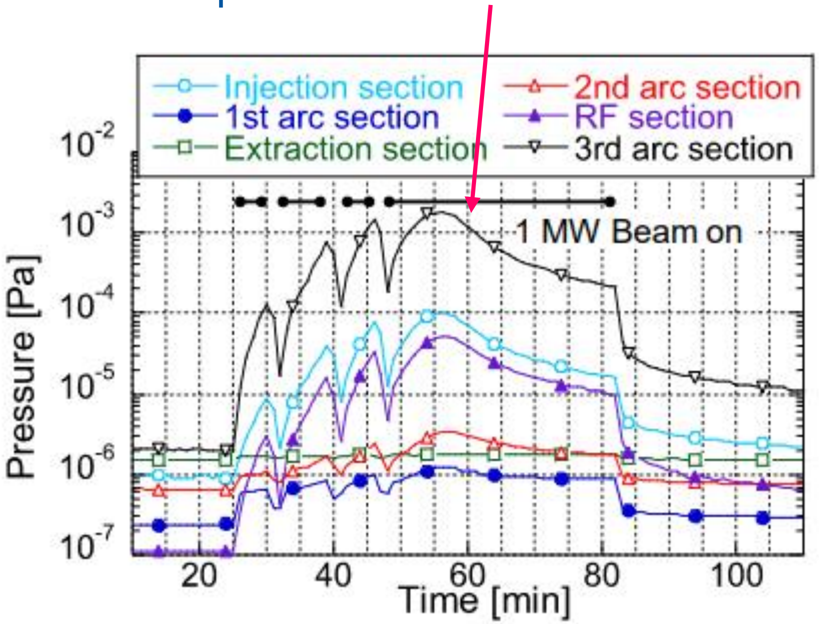


Fig. 3. Dynamic pressure in the beam line during the first beam operation trial with 1 MW beam power in July 2018.

J. Kamiya et al., JPS Conf. Proc. , 011023 (2021)

Summary

- The ideal gas law, Dalton law and Maxwell-Boltzmann distribution are used to describe the gas kinetic in a vacuum system.

- Given the large mean free path, most of vacuum systems operates in molecular flow regime

- A vacuum system can be computed using conductance, pumping speed and outgassing concepts.

- Many instruments, materials, techniques, technologies, methods and data are available to design, construct and operate a vacuum system

- In accelerators, the circulating beam can contribute to stimulate molecular desorption
  - Photon stimulated desorption originates from SR
  - Electron stimulated desorption originates from an electron cloud
  - Ion stimulated desorption originates from beam gas ionisation and can lead to vacuum instability

- Those phenomenon can lead to much larger gas load than the thermal outgassing rate and shall be considered during the design phase of an accelerator.

Some References

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Thank you for your attention !!!

CERN