Training on CERN's ultrahigh vacuum technology

Vacuum technology for accelerators

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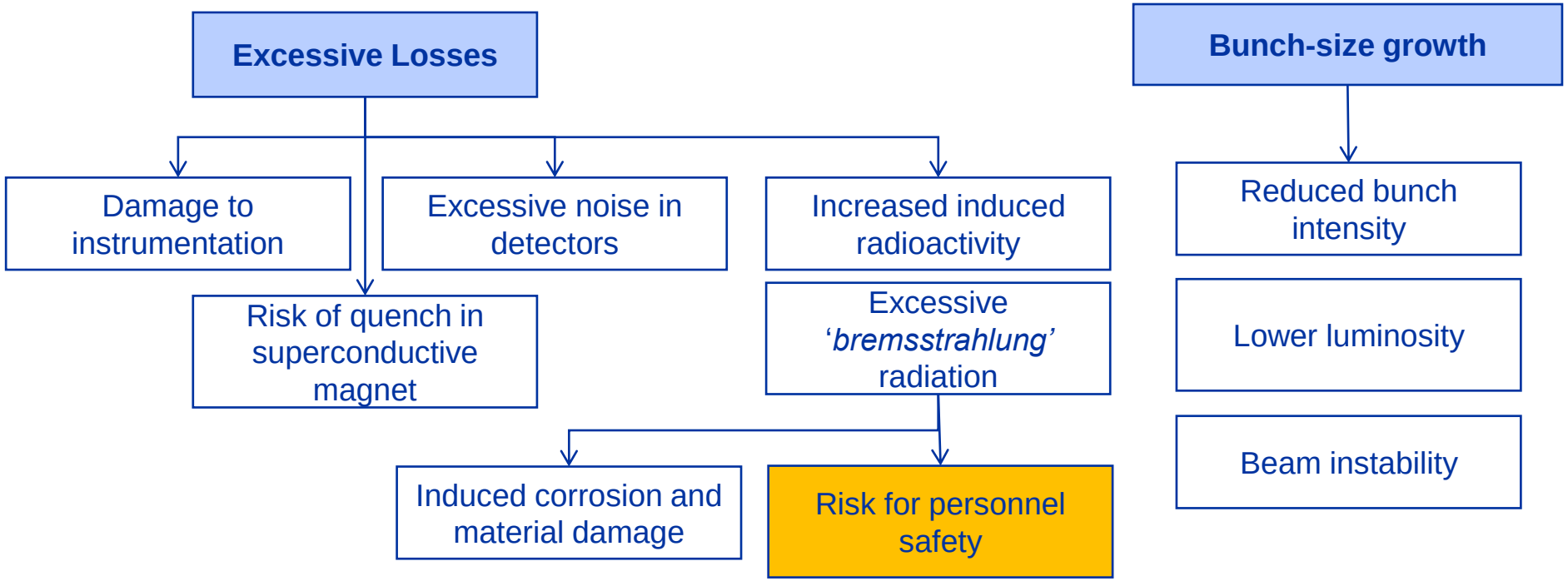
October 5th-6th, 2023

Why do we need vacuum in accelerators?

Collisions between gas molecules and particles have to be minimized, otherwise: particle energy is reduced, and trajectories are modified, so that:



Vacuum is also necessary:

- to avoid electrical discharge in high-voltage (tens di MV/m)…
- to thermically isolate cryogenic devices

Required pressures in CERN's accelerators

Machine	Type	Year	Energy	Bakeout	Pressure [mbar]	Length
Linacs, Booster, ISOLDE, PS, n-TOF and Antimater						**2.6 Km**
Linac 2	linac	1978	50 MeV	ion pumps	10^{-7}	40 m
ISOLDE	electrostatic	1992	60 keV	_	**10^{-6}**	150 m
REX-HIE ISOLDE	linac	2001-2016	5.5 MeV/u	partly	10^{-7}-10^{-12}	50 m
MEDICIS		2017	_	_	10^{-6}	10 m
Linac 3	linac	1994	4.2 MeV/u	ion pumps	10^{-8}	30 m
LEIR	accumulator	1982/2005	72 MeV/u	complete	**10^{-12}**	78 m
PSB	synchrotron	1972	1-1.4 MeV	ion pumps	10^{-9}	157 m
PS	synchrotron	1959	26 GeV	ion pumps	10^{-9} -10^{-10}	628 m
AD	decelerator	1999	100 MeV	complete	10^{-10}	182 m
ELENA	decelerator	2016		complete	**10^{-12}**	31 m
PS to SPS TL	transfer lines	1976	26 GeV	_	10^{-8}	1.3 km
SPS complex						**15.7 Km**
SPS	synchrotron	1976	450 GeV	extractions	10^{-9}	7 km
SPS North Area	transfer line	1976		_	10^{-3}-10^{-8}	1.2 km
SPS HiRadMat		2011		_	10^{-8}	1.4 km
SPS to LHC TL		2004/06		_	10^{-8}	2 x 2.7 km
AWAKE	wakefield acc	2017		_	10^{-8}	730 m
LHC						**109 Km**
LHC Arcs (Beam vacuum)	collider	2007	2 x 7 TeV	_	<10^{-8}	50 km
LHC Arcs (insulation vacuum)				_		50 Km
LSS RT separated beams				complete	<10^{-10}	2 x 3.2 km
LSS RT recombination						570 m
Rxperimental areas						180 m
Beam dump lines TD62/68	transfer lines	2006	7 TeV	_	10^{-8}	2 x 720 m

1 mbar = 100 Pa

High Vacuum	**≈ 12**
UHV-XHV	**≈ 65**
Insulation vacuum	**≈ 50**
	≈ 127 km

All pressures at room temperature.

To compare the degree of vacuum in environments **at different temperatures**, it is **better to report the density of molecules (number density) instead of pressure**.
Pressure P and number density n are correlated by the ideal gas equation of state:

$$P\,V = N k_B T \rightarrow P = n\,k_B T$$

$$k_B = 1.38\,10^{-23}\,\frac{J}{K}$$

The lowest density in CERN machines is required in the **LEIR** (heavy ion acceleration) and **ELENA** (a decelerator of antiprotons). For both we need pressures around **10^{-12} mbar at room temperature** with circulating beam, i.e. number density of 2.5x10^{10} molecules/m^3 or **2.5x10^4 molecules/cm^3**.

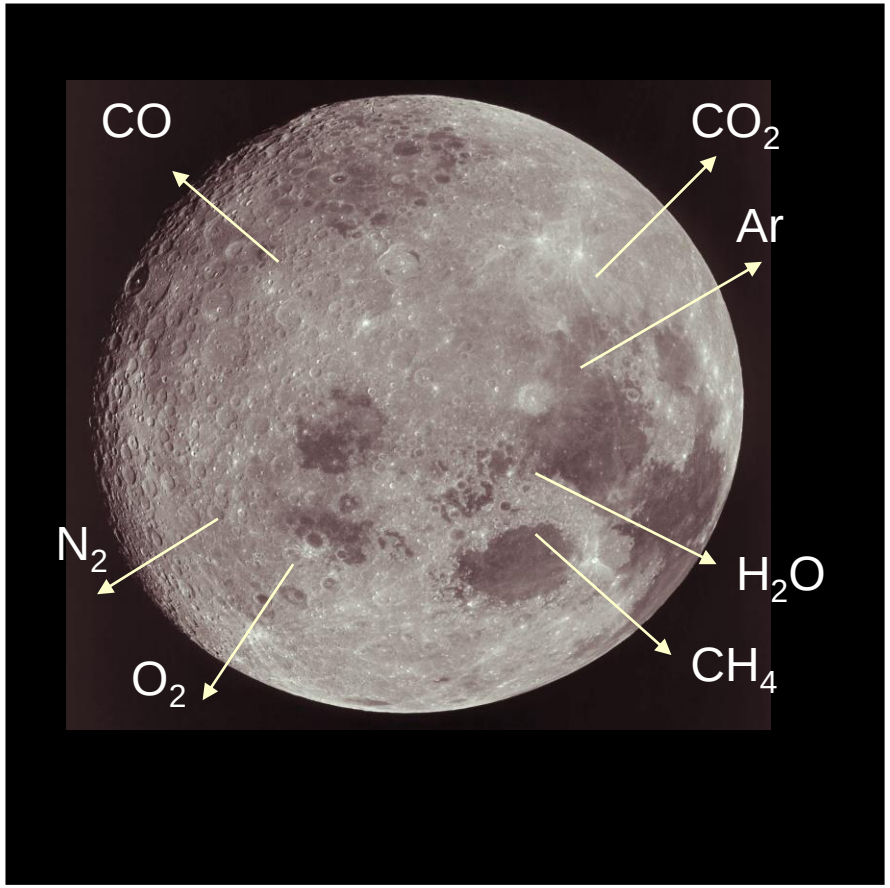
Best vacuum on Earth

The **best vacuum on Earth** (lowest number density) is obtained in closed cold traps operating at **4 K** for magneto-optic measurement of cold atoms or antimatter experiments in Penning traps. Number densities lower than 100 cm^{-3} are obtained [1]. The BASE experiment at CERN reported the achievement of number density of about **2 molecules cm^{-3}**, which corresponds to a pressure around 10^{-18} mbar at 4.3 K (**≈$7x10^{-17}$ mbar at room temperature**).

To my knowledge, this is the lowest vacuum ever measured on Earth. In these cases, the measurements of number density is performed indirectly recording the lifetime of antiprotons in the trap. The residual gas species in such traps are hydrogen and helium.

The lowest pressure measured at **room temperature in laboratory** is in the low 10^{-14} mbar range, which is equivalent to about **250 molecules cm^{-3}** [2-4].

[1] G. Gabrielse et al, Physical Review Letters 65, 1317 (1990)
[2] C. Benvenuti, P. Chiggiato, Vacuum 44, 511 (1993)
[3] C. Benvenuti, M. Hauer (1980) http://cds.cern.ch/record/314288/files/CM-P00064854.pdf
[4] P. Redhead, Vacuum 53, 137 (1999)



Vacuum on the Moon

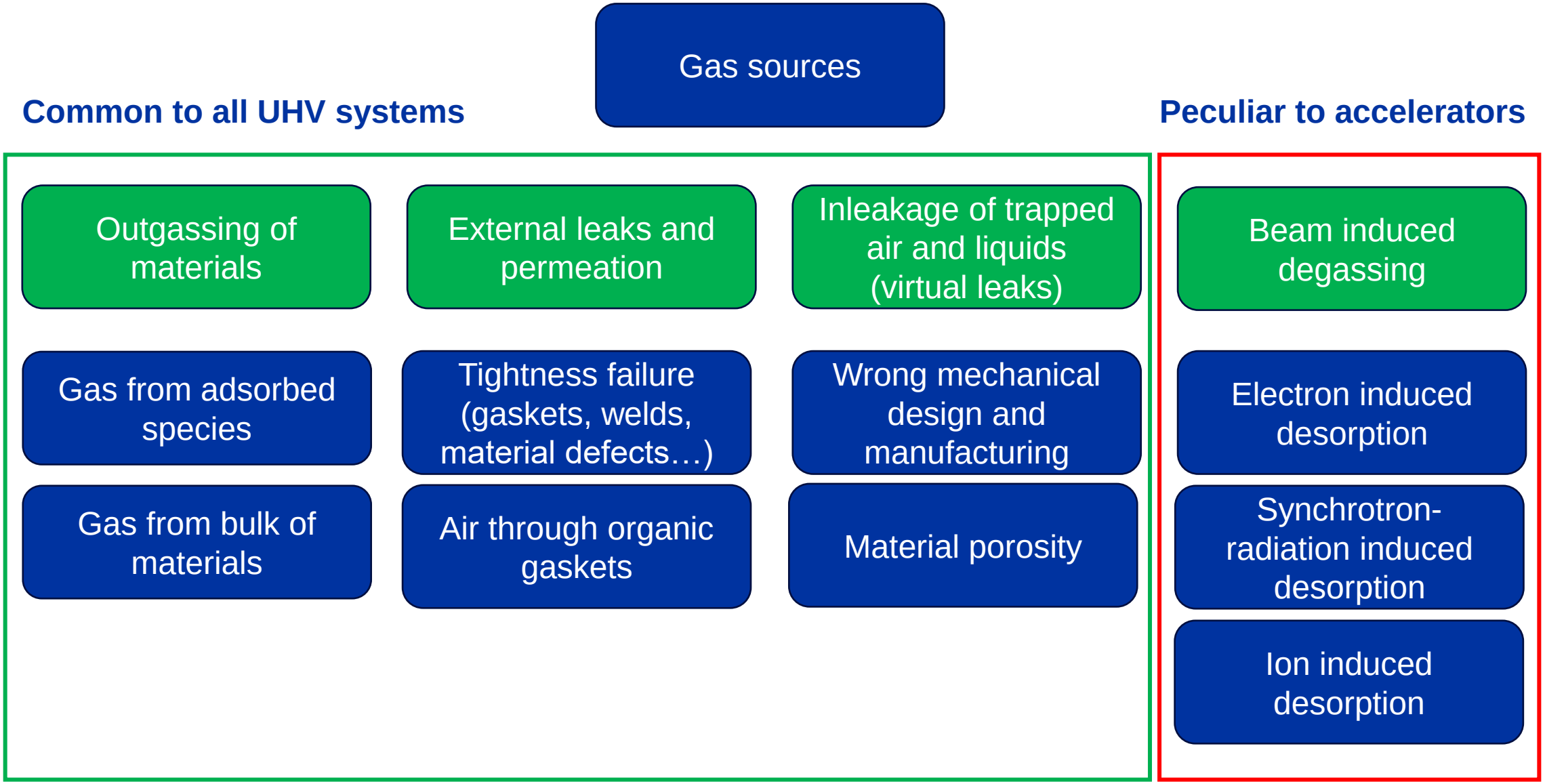
Gas density on the Moon: **10^5 cm^{-3}** (10^{-12} mbar) during night and 10^7 cm^{-3} (10^{-10} mbar) during lunar day → The vacuum on the Moon during a lunar night is **similar to the one required in LEIR and ELENA.**

Intergalactic medium

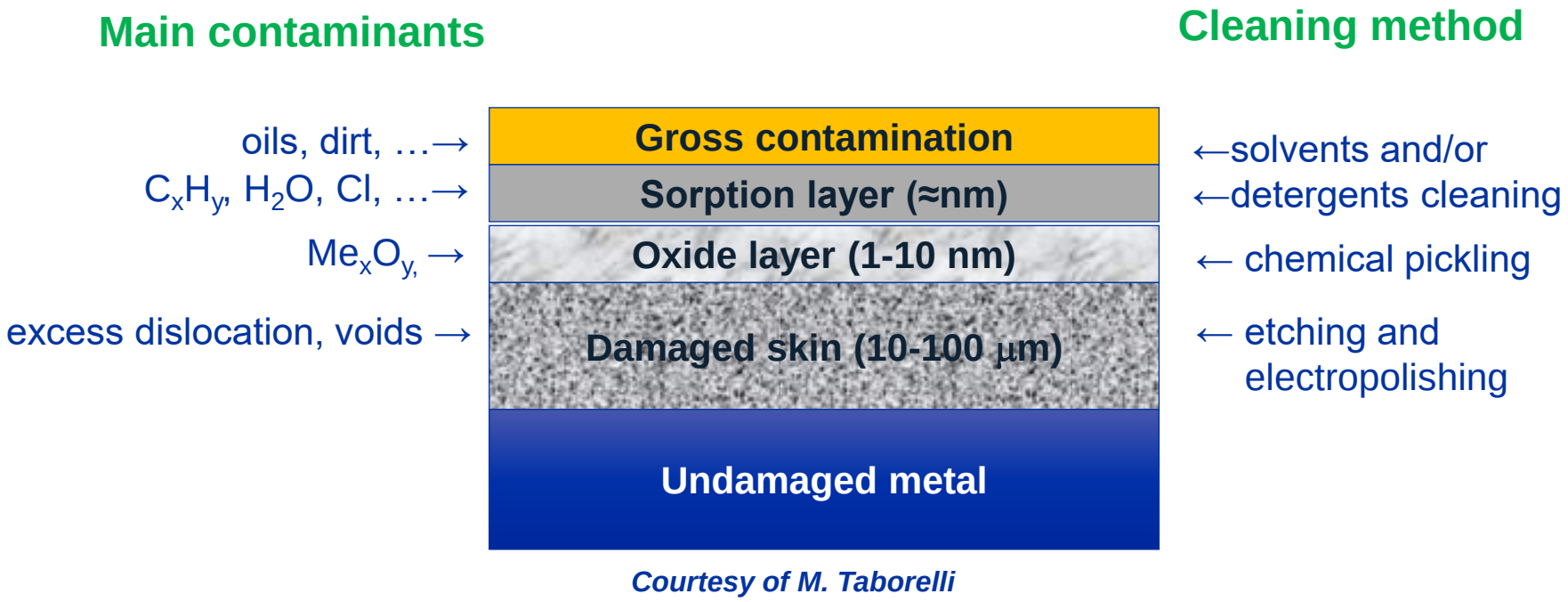
The gas density is about **10^{-6} particles/ cm^3**, i.e. **1 particles/ m^3** approaching the mean density of baryons in the Universe.

Intergallactical vacuum: 10^{-19} mbar
Vacuum in Via Lattea: 10^{-17} mbar

Gas sources in accelerators



Gas sources in accelerators: Outgassing of materials



Courtesy of M. Taborelli

Gas sources in accelerators: Outgassing of materials

Metals

After state-of-art surface cleaning:

- If not heated in situ: mainly **H_2O** for the first months in vacuum, then also H_2.

$$q_{H_2O} \approx \frac{3 \times 10^{-9}}{t[h]} \left[\frac{mbar\ l}{s\ cm^2}\right]$$

  The source of H_2O is recharged after each venting to air.

- If heated in situ (baked-out): mainly **H_2**. The outgassing rate can be assumed as constant; it depends on the accumulated effect of the previous thermal treatments.

Organics (Polymers)

- High solubility of gas in the bulk, in particular **H_2O.**
- In general, the outgassing process is dominated by H_2O release.
- In the initial phase of pumping:

$$q_{H_2O} \propto \frac{1}{\sqrt{t}}$$

- Heavier gas molecules can be outgassed (remnant of polymerization, fraction of polymeric chains).
- The **permeation** of light molecules is not negligible, in particular He.

Gas sources in accelerators: Outgassing of materials

Indicative values of specific outgassing rates

At room temperature

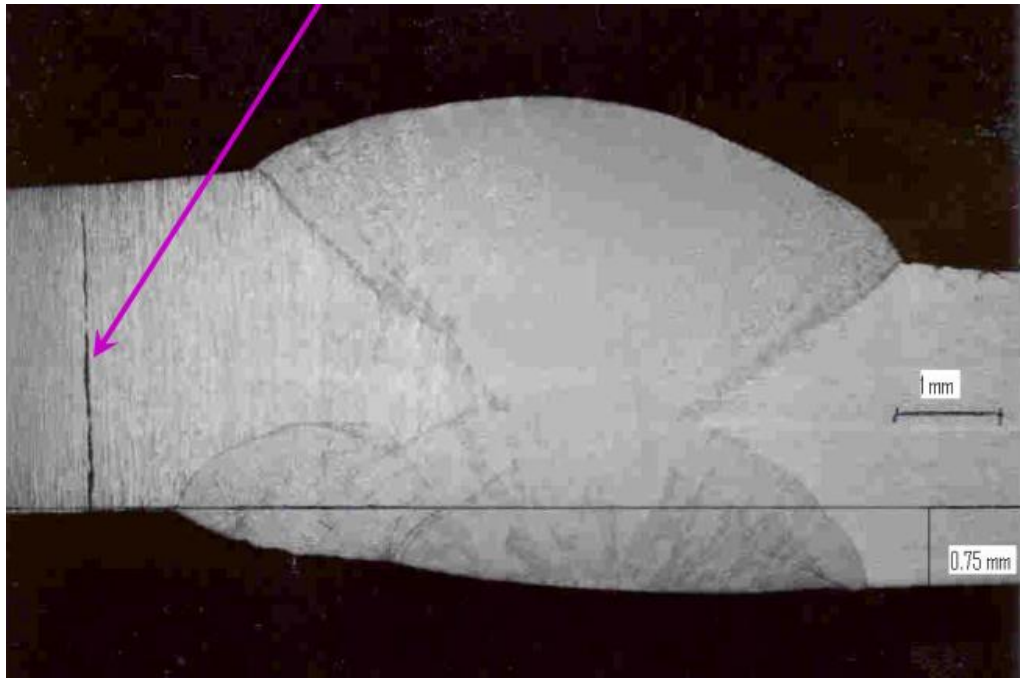
Material	q (mbar l s^{-1} cm^{-2})	Main gas species
Neoprene, not baked, after 10 h of pumping	order of 10^{-5}	H_2O
Viton, not baked, after 10 h of pumping	order of 10^{-7}	H_2O
Austenitic stainless steel, not baked, after 10 h of pumping	3×10^{-10}	H_2O
Austenitic stainless steel, baked at 150°C for 24 h	3×10^{-12}	H_2
Austenitic stainless steel, vacuum fired at 950°C for 2 h, then baked at 150°C for 24 h	From $3x10^{-13}$ to low 10^{-15} depending on thickness, and pressure in the furnace	H_2
OFS copper, baked at 200°C for 24 h	order of 10^{-14}	H_2

1 mbar l = 2.5×10^{19} molecules

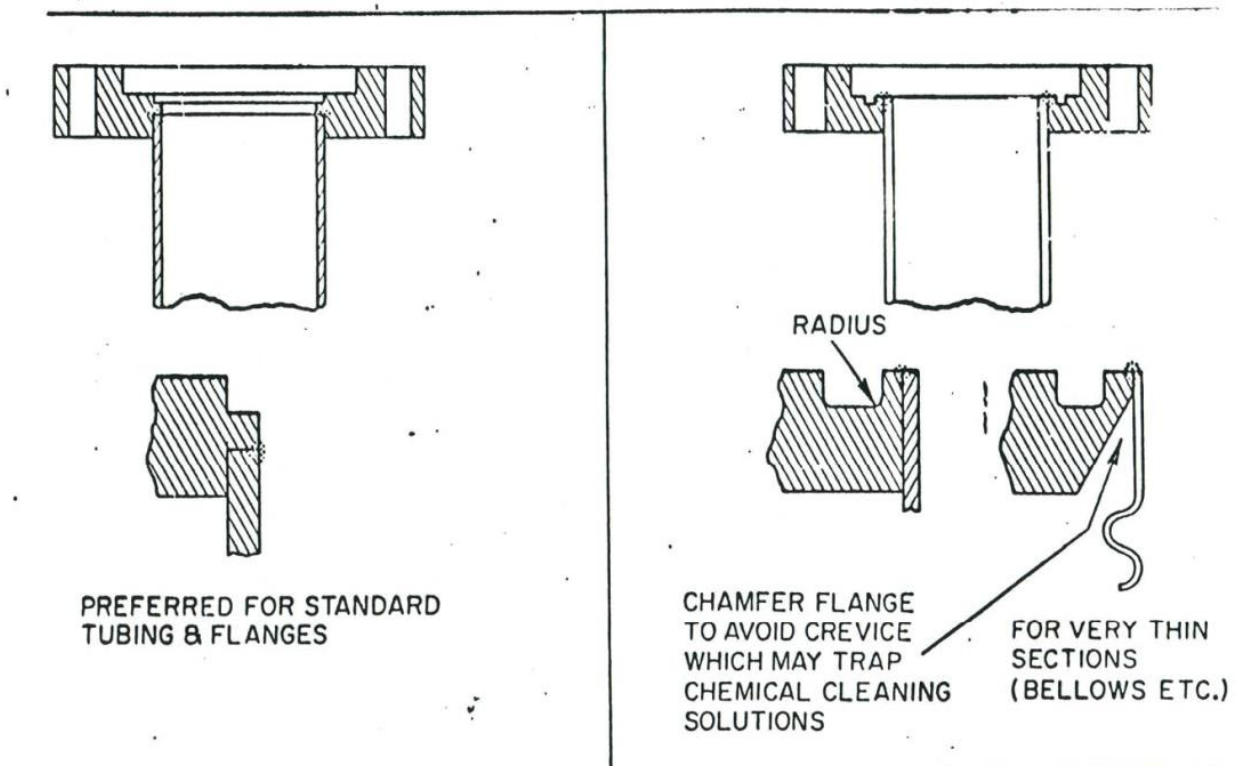
Gas sources in accelerators: External leaks

Maximum acceptable leak rate: from 10^{-9} to **10^{-10}** mbar l s^{-1}, depending on application.

Material (304L) cracks close to weld



Good practice for welding flanges to tubes



Claude Hauviller: https://cds.cern.ch/record/1046848/files/p31.pdf

Gas sources in accelerators: External leaks

Quality control of materials is essential: our specifications are used by several other Institutes

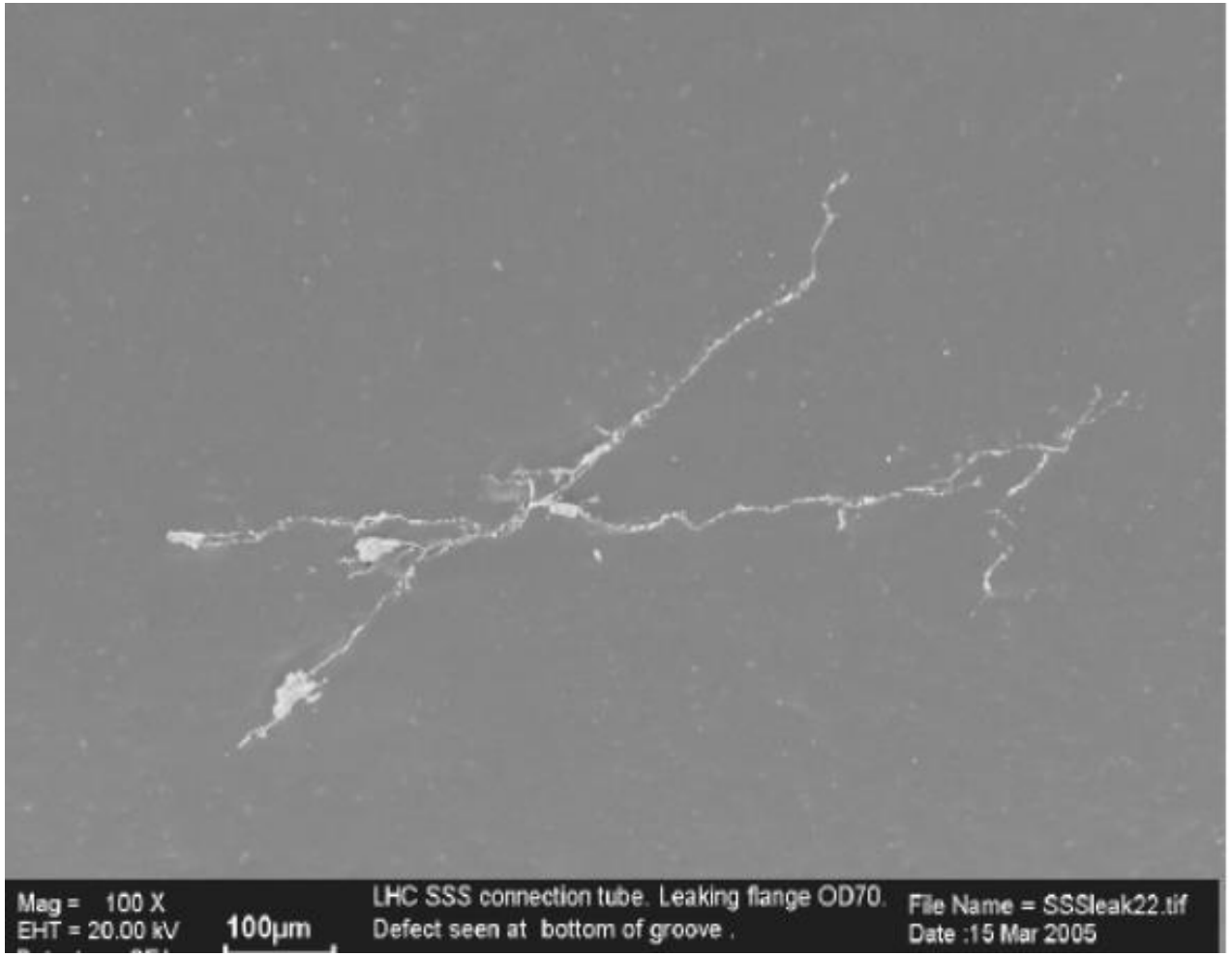
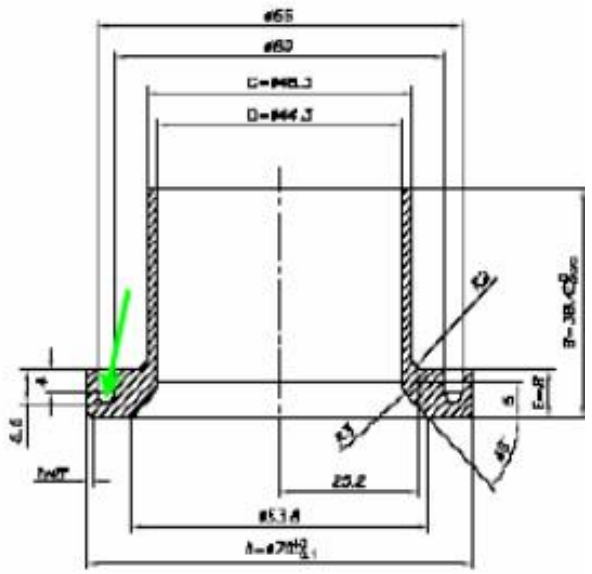


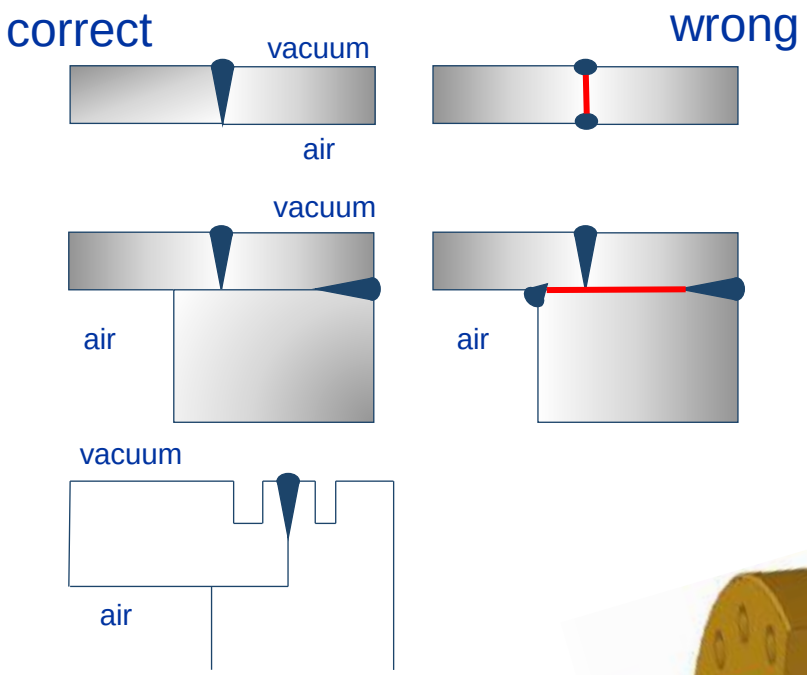
Fig. 6.1.
Mag.: × 100
Electro-polished sample.
Defect seen at the bottom of the groove at position pointed by He leak detection.



Claude Hauviller: https://cds.cern.ch/record/1046848/files/p31.pdf

Gas sources in accelerators: Inleakage

Other gas sources: virtual leaks → trapped air and impossible leak detection



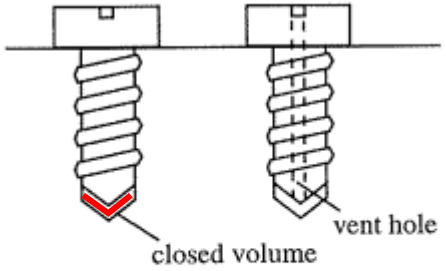
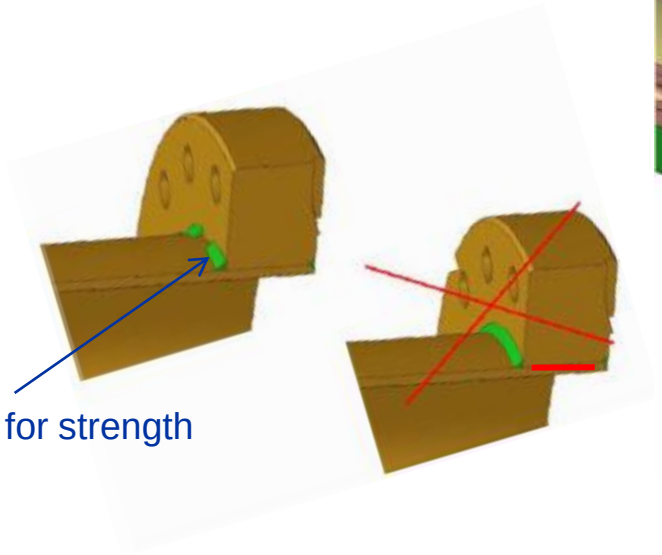
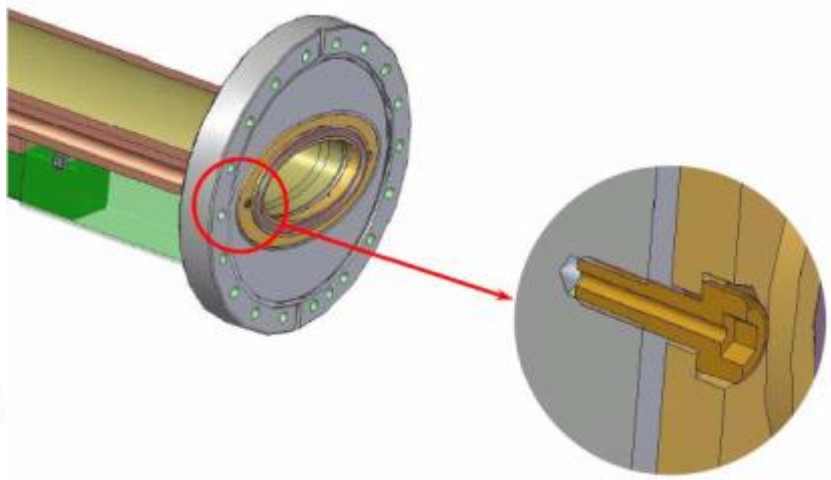


Fig 1 The screw to the right has a bored through ventilation hole to prevent virtual leaks and slow pump-down

Courtesy of L. Westerberg, CAS Vacuum 1999

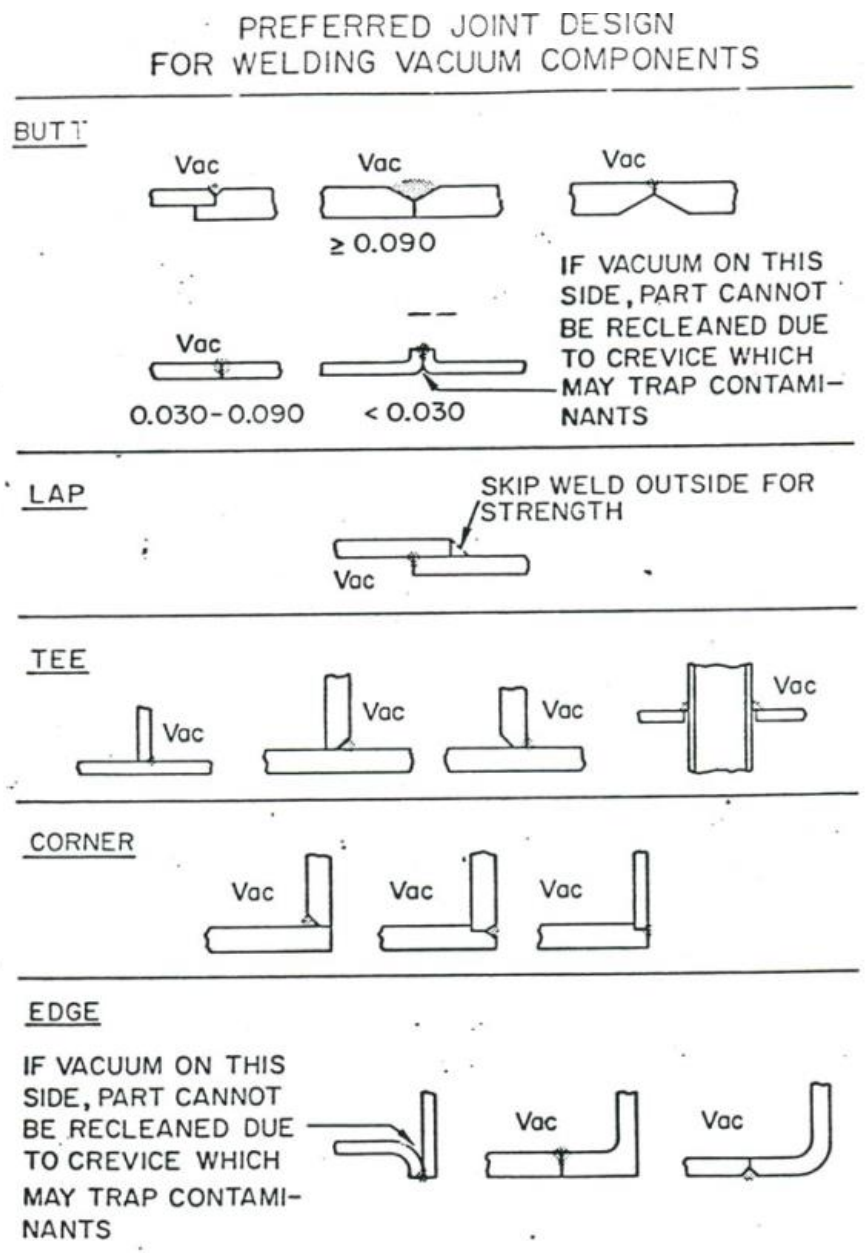


Skip weld outside for strength



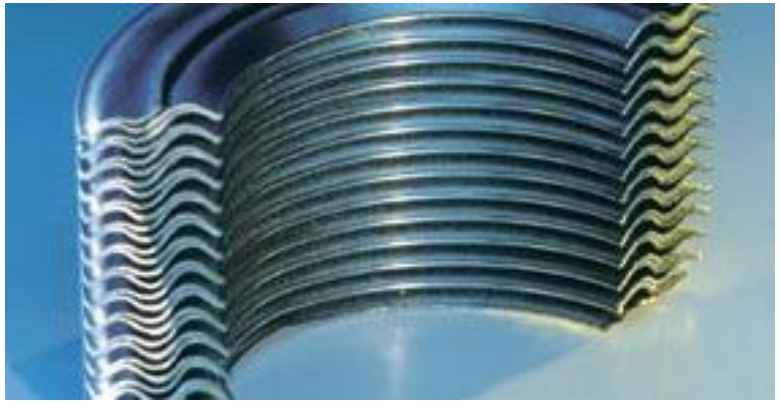
Courtesy of K. Zapfe, CAS Vacuum 2006

Gas sources in accelerators: Inleakage



Edge welded bellows should **not be recleaned** in aqueous environment due to potential liquid trapping.

Source: https://www.lesker.com/newweb/flanges/bellows_tubeend_edgewelded.cfm?pgid=0

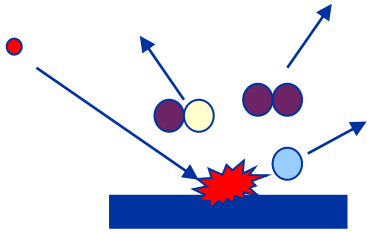


Source: https://ekksc.com/welded-metal-bellows/

Beam induced gas release

Gas sources in accelerators : Beam induced desorption

The impingement of electron/photon/ions on surfaces can result in ion and neutral gas desorption.



In **1918**, Dempster observed ion desorption from electron bombarded salts (Phys. Rev. 11, 323)

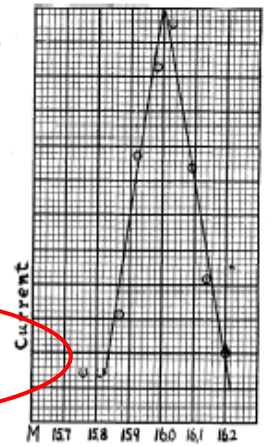
ESD: electron stimulated desorption

POSITIVE IONS FROM ELECTRON BOMBARDMENT.

It was thought that the bombardment of salts by electrons might break up the chemical compounds and give rise to many positive ions. At first a Wehnelt cathode was used; the ions formed passed beside the cathode (Fig. 1) and were then accelerated by a large potential difference. Aluminium phosphate on a piece of platinum foil was first bombarded. The intensity of the rays increased very rapidly with a slight increase in the amount or energy of the bombarding electrons, indicating that the salt needs to be heated to a certain degree before the ions are separated. Although the aluminium phosphate was chemically pure, the rays obtained under the bombardment of 128 volt electrons were very complex; the following ions were observed besides a couple of unresolved groups; H_1, H_2, Li (weak), O_1 (strong), Na (strong), O_3 (?) (weak), $M = 62$ (weak, possibly Na_2O), $M = 67$ (strong, possibly $H_3PO_2 = 66$), $M = 76$ (strong), $M = 86$ (weak, possibly Rb = 85.5), $M = 112$ (strong, possibly $P_2O_3 = 110$).

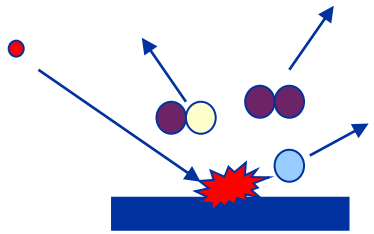
The experiments indicated the convenience of the method of obtaining positive rays and opened up an interesting field for investigation.

The experiments were however first directed



Gas sources in accelerators : Beam induced desorption

Millikan reported the first evidence of **photon induced desorption** in 1909 during the measurement of the photoelectric current of metals exposed to ultraviolet radiation.



The first interpretation is given by Winch in 1930 (Phys. Rev. **36**, 601).

He was the first to see the implication of **photoelectrons** on photon induced desorption.

PSD: photon stimulated desorption

Outgassing

specimen to ultraviolet fatigue curves, taken by leaving the specimen in a vacuum of 10^{-7} mm of Hg unexposed, showed during the first stages a rapid decrease in photo-current with time of standing, but, after 360 hours of exposure for the film and 160 hours for the solid gold, the photo-current from the former held constant for 3 hours, and from the latter 1½ hours. This seemed to indicate that a fairly stable equilibrium had been reached, and the subsequent fatigue was consistent with the idea that it was due to return of gas to the surface.

The experiment was repeated, using a silver filament approximately 0.025 mm thick, and an increase in emission comparable to that for the gold film was obtained.

The probable explanation is that photo-electrons, both when ejected and returned to the surface by a reverse field, remove adsorbed gas from the surface.

Millikan[1] noted an increase in photoelectric emission on exposure of certain metals to ultraviolet, but did not note the corresponding change in long wave-length limit or that the photoelectrons themselves apparently play an important part in the outgassing.

Work is being carried forward testing this explanation and obtaining more data on photoelectric properties of thin films.

RALPH P. WINCH
Laboratory of Physics,
University of Wisconsin,
Madison, Wisconsin,
July 15, 1930.

Millikan, Phys. Rev. **29**, 85 (1909).

The probable explanation is that photo-electrons, both when ejected and returned to the surface by a reverse field, remove adsorbed gas from the surface.

Gas sources in accelerators : Beam induced desorption

The **desorption yield** η, i.e. the number of molecules desorbed per impinging particle, is an essential input to design vacuum systems of particle accelerators:

$$\eta = \frac{\textbf{number of molecules desorbed}}{\textbf{number of particules impinging on the surface}}$$

η depends on many parameters, in particular:

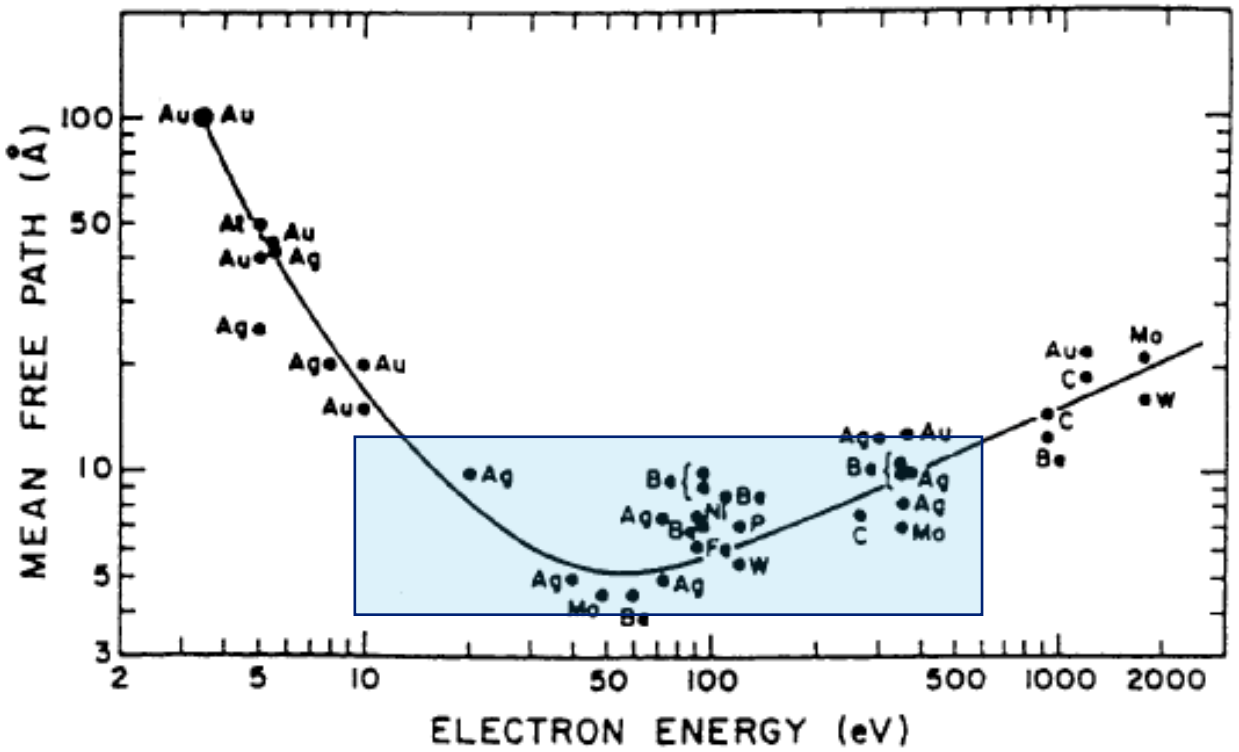
- on the nature and energy of the **impinging particle**;
- the **material** of the vacuum chamber;
- the nature of the **desorbed gas**;
- quantity of particles that have already impinged on the surface, namely **the dose D** $\left[\text{particles}/\text{cm}^2\right]$.

The **cleanliness of the surfaces** has also a crucial influence.

Gas sources in accelerators : Beam induced desorption

In general, ESD is correlated with **beam induced multipacting** (electron accelerated by positively-charged beams that impinge onto beampipe surfaces and extract additional electrons).

The **penetration depth** of electrons kicked by beams is **lower than 1 nm**. ESD strongly depends on the chemical composition of the **oxide layer** (typical thickness is 1-10 nm).



Universal curve for inelastic mean free path as a function of electron kinetic energy.
M. Seah and W. Dench, Surf, Interface Anal. 1(1979)2

Gas sources in accelerators : Beam induced desorption

Example: OFHC copper, cleaned following CERN recipe, stored in plastic bag for weeks, 24 h pumping, **not baked *in situ***.

$$\eta(E) = \eta(E_0)\left(\frac{E - E_0}{E_0 - E_c}\right)^{\gamma}$$

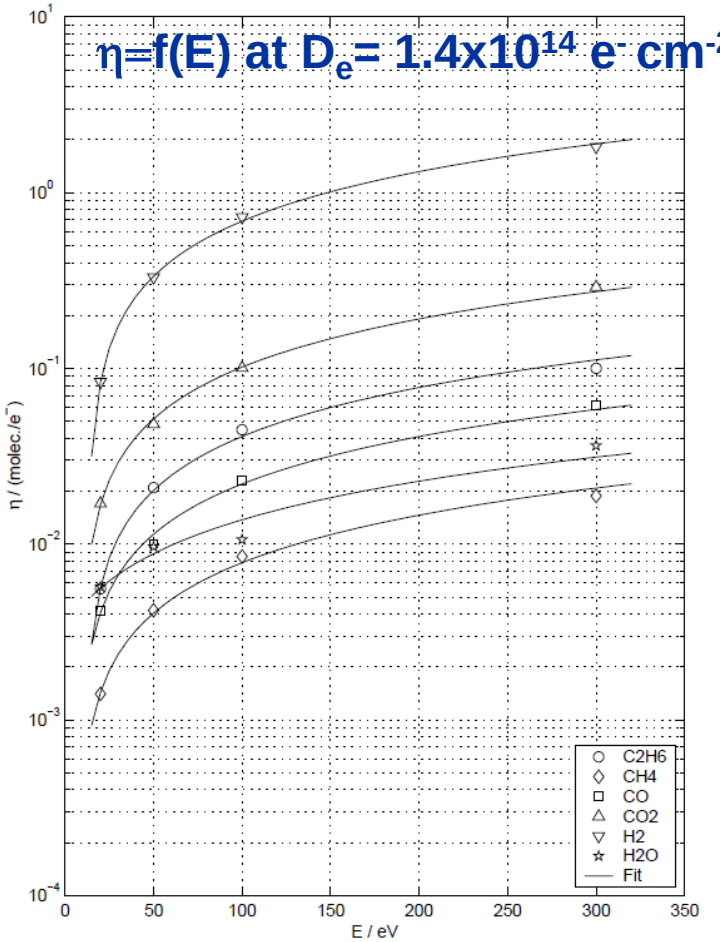
$E_0 = 300eV$

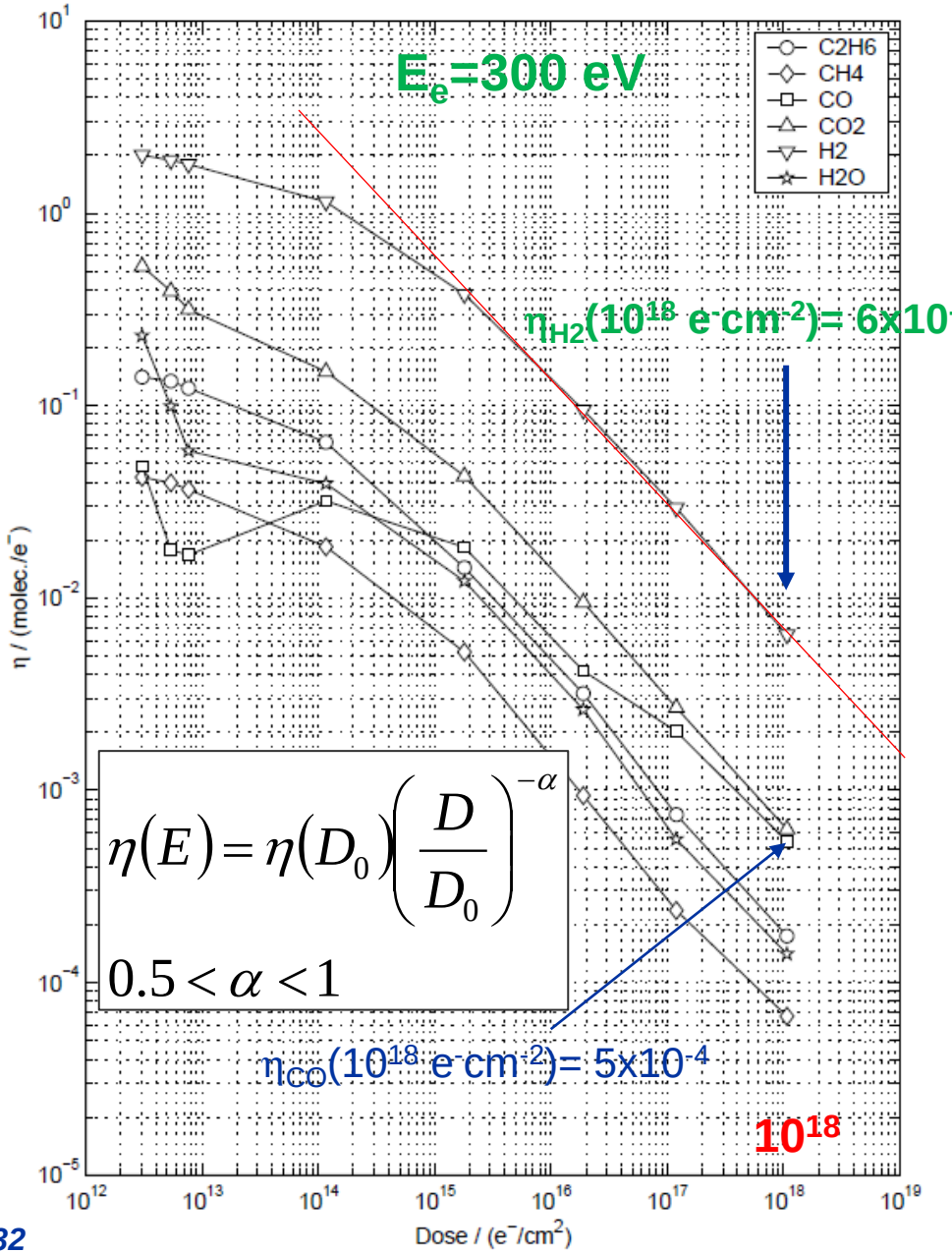
$\gamma = 0.85$

E_c cut off electron energy

$\rightarrow \eta(E_c) = 0$

$E_c \approx 10eV$





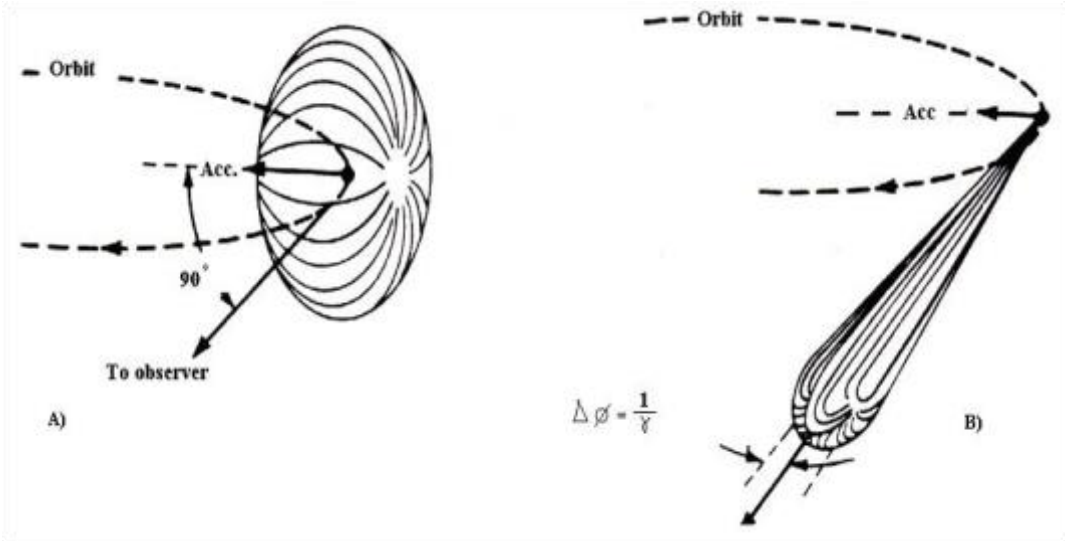
F. Billard, N. Hilleret, G. Vorlaufer, CERN, Vacuum Technical Note 00-32

Gas sources in accelerators : Beam induced desorption

In relativistic beams, **synchrotron radiation** emission is **strongly beamed** along the direction of motion, which is perpendicular to the acceleration vector.

The emission is concentrated into an angle of the order of **2/γ rad** along the direction of motion:

$$\gamma = 1/\sqrt{1-(v/c)^2} = E/mc^2$$



Non-relativistic beams Relativistic beams

Gas sources in accelerators : Beam induced desorption

A particle of charge ‘e’, energy E and rest mass m_0, moving on a circular orbit (radius ρ) radiates electromagnetic radiation with the following power P_{rad}:

$$P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0 \left(m_0 c^2\right)^4} \frac{E^4}{\rho^2}$$

where ε_0 and c are the vacuum permittivity and the speed of light, respectively.

The emitted power depends strongly on the **beam energy,** the **radius of the bent trajectory**, and **the mass of the charged particle.**

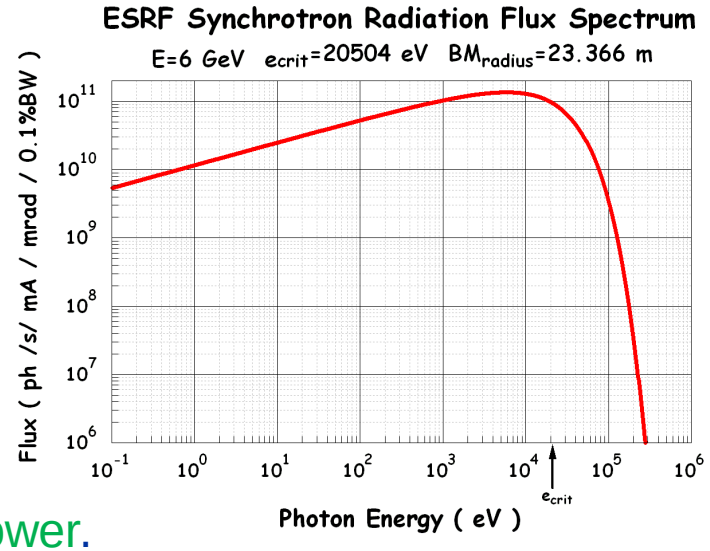
Consequently, **electrons emit much more synchrotron radiation power than protons** for the same bending radius and energy:

$$\frac{\left(P_{rad}\right)_{electrons}}{\left(P_{rad}\right)_{protons}} = \left(\frac{m_p c^2}{m_e c^2}\right)^4 = 1.13 \times 10^{13}$$

Gas sources in accelerators : Beam induced desorption

Synchrotron radiation from bending magnets has a **very broad energy spectrum**, which is characterised by the **critical energy ε_C**:

$$\varepsilon_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3 = \frac{3\hbar c}{2\left(mc^2\right)^3}\frac{E^3}{\rho}$$

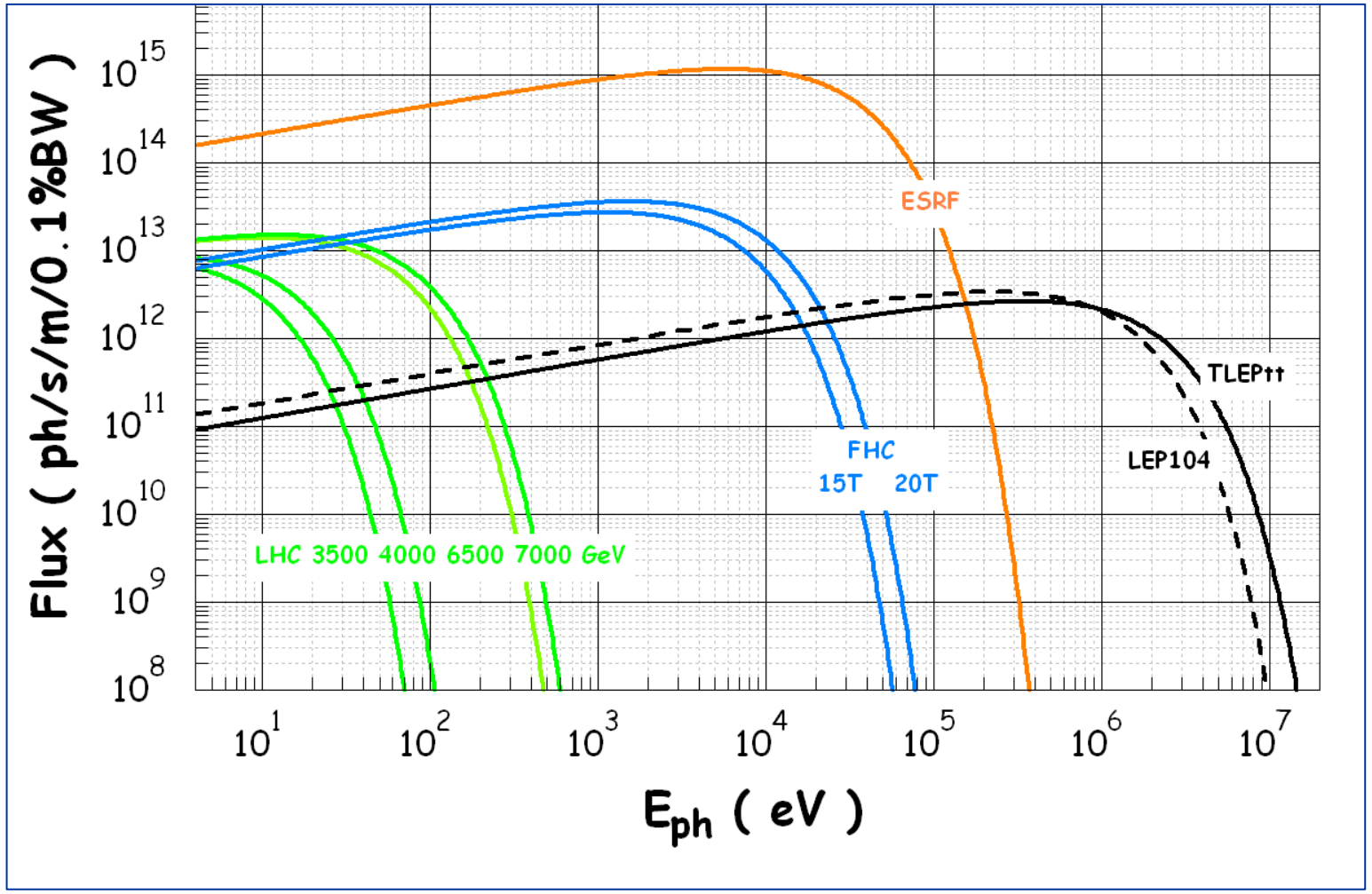


The critical energy subdivide the photon spectrum in two parts of equal emitted power.

For electrons $\varepsilon_c\left[KeV\right] = 0.665 \times E^2\left[GeV^2\right] \times B\left[T\right]$

For protons $\varepsilon_c\left[KeV\right] = 1.1 \times 10^{-10} \times E^2\left[GeV^2\right] \times B\left[T\right]$

Gas sources in accelerators : Beam induced desorption



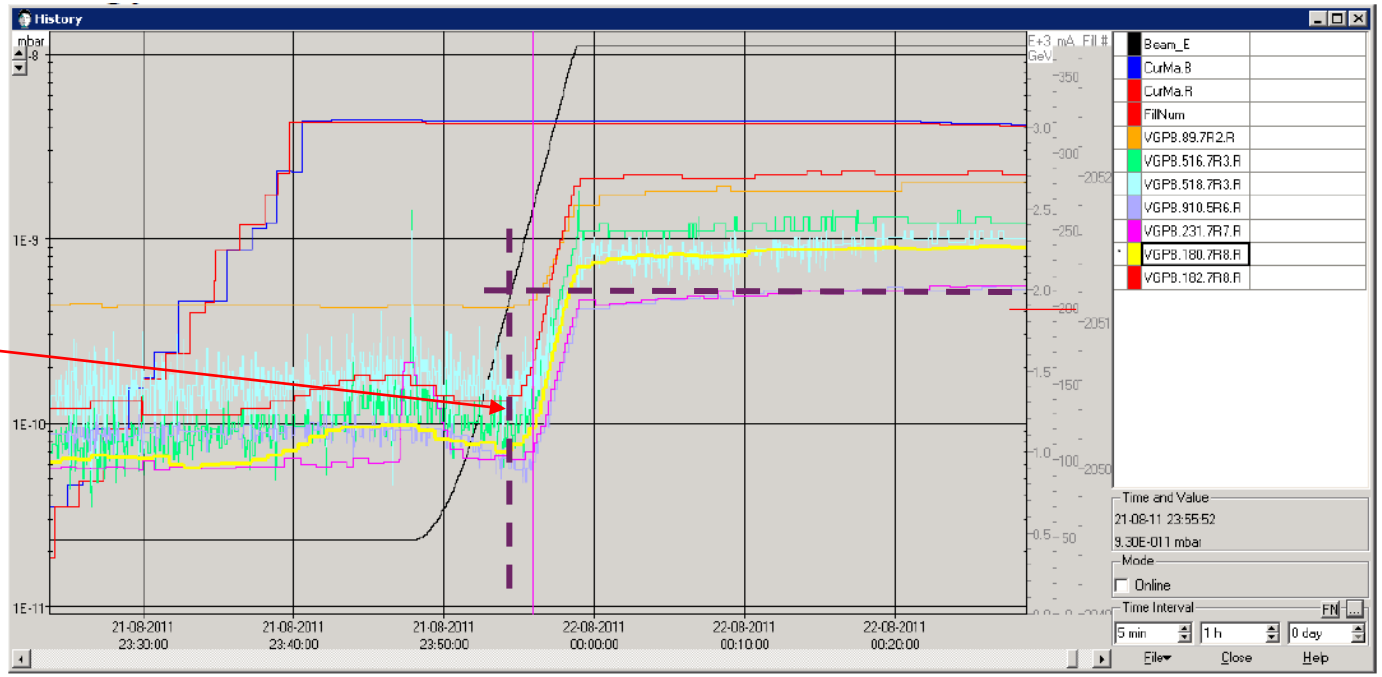
Courtesy of Roberto Kersevan

In the **LHC**, the proton energy is so high that **PSD is significant**. The **critical energy** of the emitted radiation is around **40 eV** at the maximum proton energy.

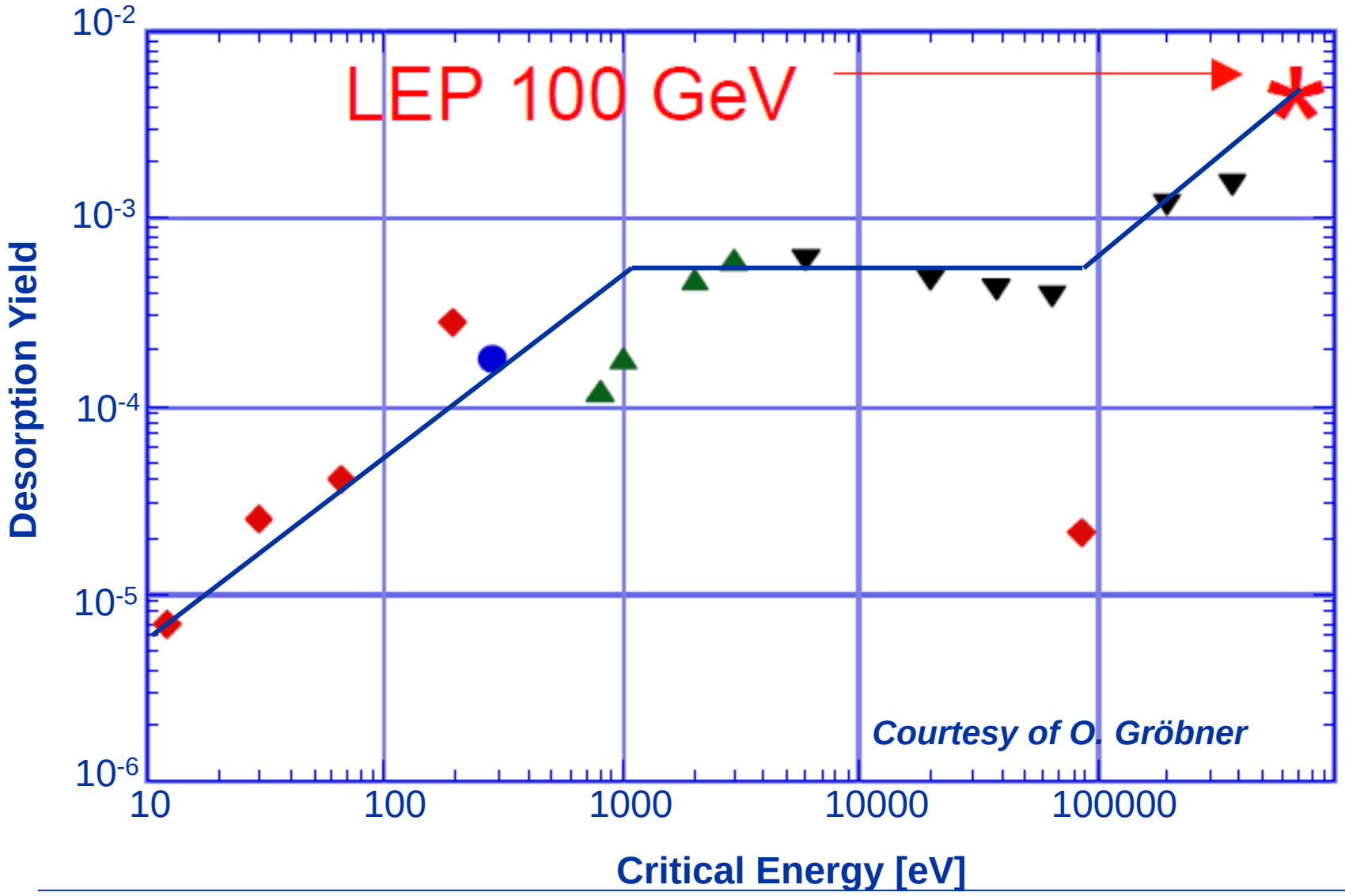
Gas sources in accelerators : Beam induced desorption

Photons below **4 eV** cannot generate photoelectron emission, and SR-induced desorption as well.

Note the onset of pressure rise at 2 TeV, as seen by the vacuum gauges in the LHC **during energy ramp.**



Gas sources in accelerators : Beam induced desorption



Above 60 keV, the **Compton scattering** plays a predominant effect in the interaction of photons with the material of the vacuum chamber.

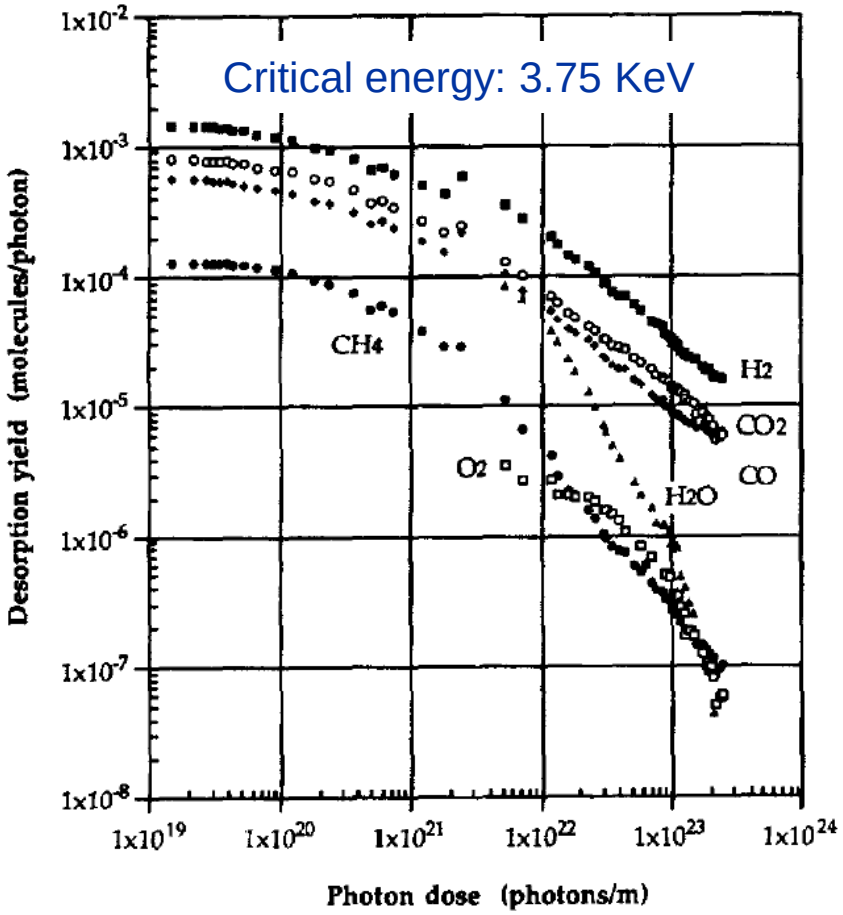
The high number of energetic recoil electrons and scattered photons increase the desorption yields.

Gas sources in accelerators : Beam induced desorption

Example: OFHC copper, baked in situ at 150°C for 24 h

For doses higher than 10^{20} photons/m doses, η_{ph} varies as a **power law function of the dose**:

$$\eta_{ph} \propto D^{-\alpha}$$



J. Gomez-Goñi et al, J. Vac. Sci. Technol. A 12, 1714 (1994)

Gas sources in accelerators : Beam induced desorption

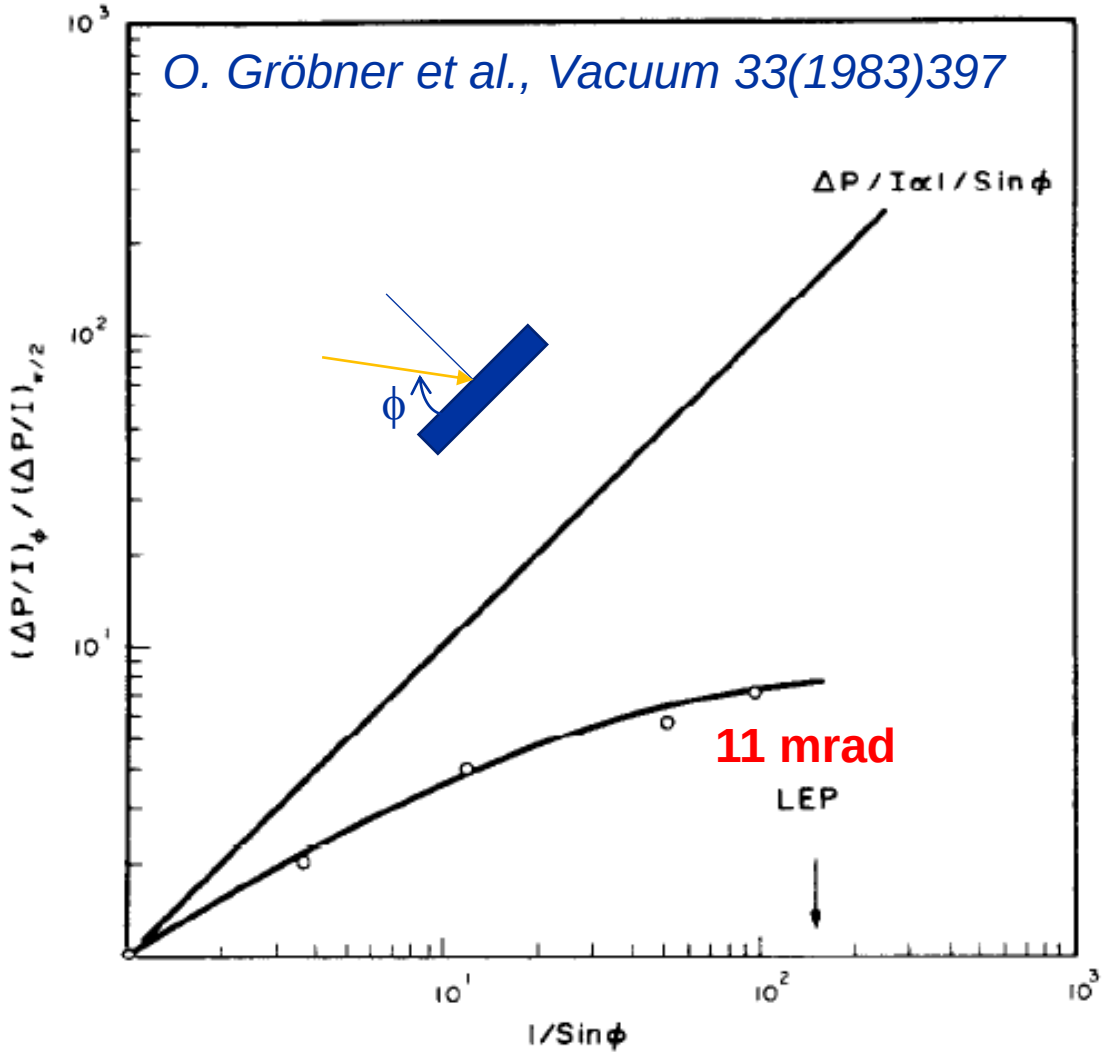


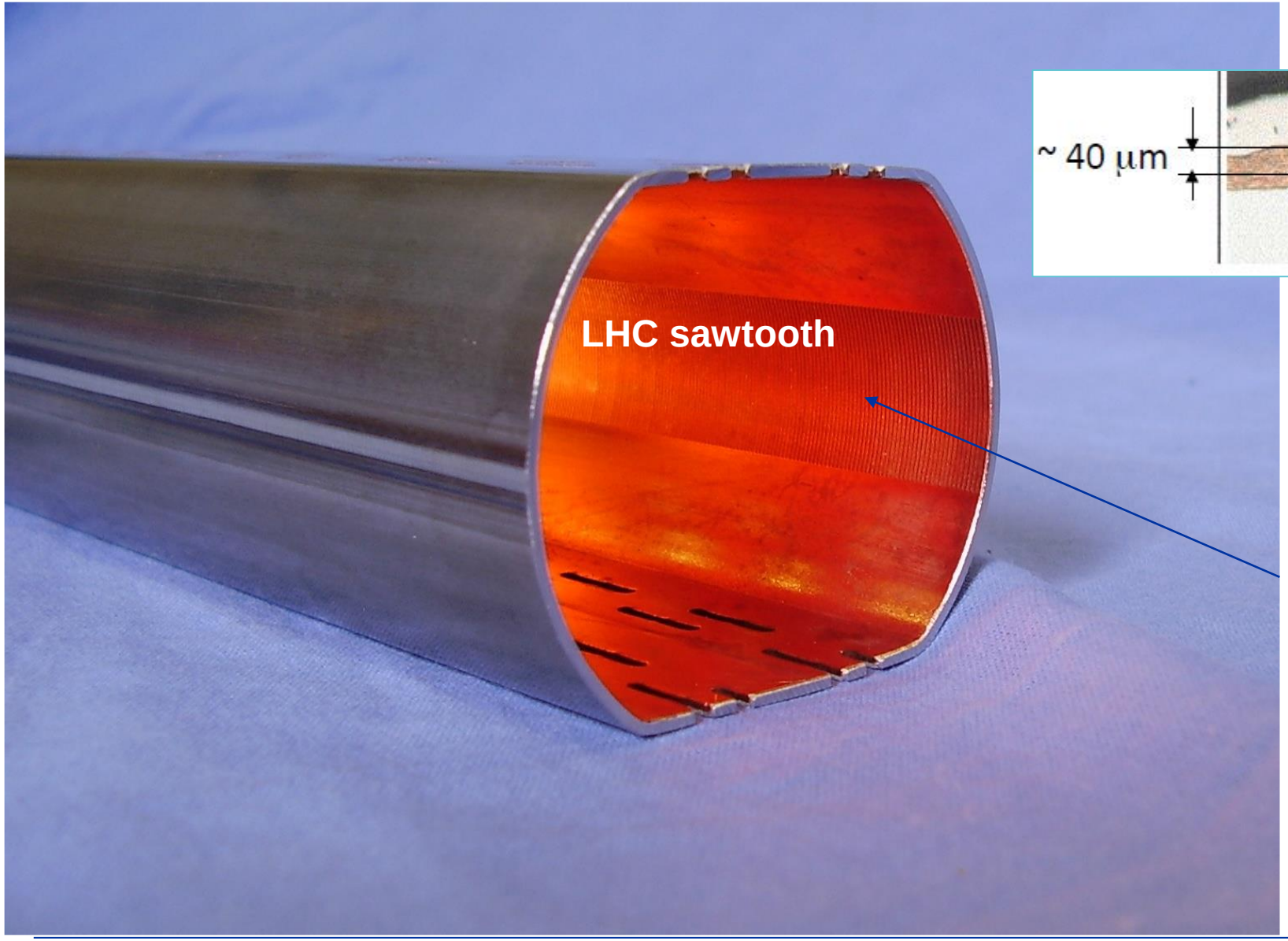
Figure 11. The dependence of the total specific pressure rise on the glancing angle of incidence at a beam energy of 1.72 GeV.

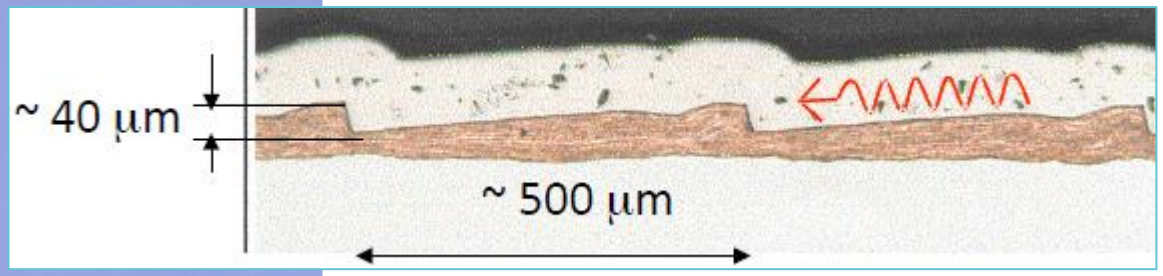
Photo-desorption yields depend on the **incidence angle**

The photodesorption yield is higher when the angle of incidence is lower.

In most of the accelerators the incidence is at grazing angle.

Gas sources in accelerators : Beam induced desorption





In the LHC beam screen, the inner wall was machined so that photons impinge nearly perpendicularly onto the copper layer.

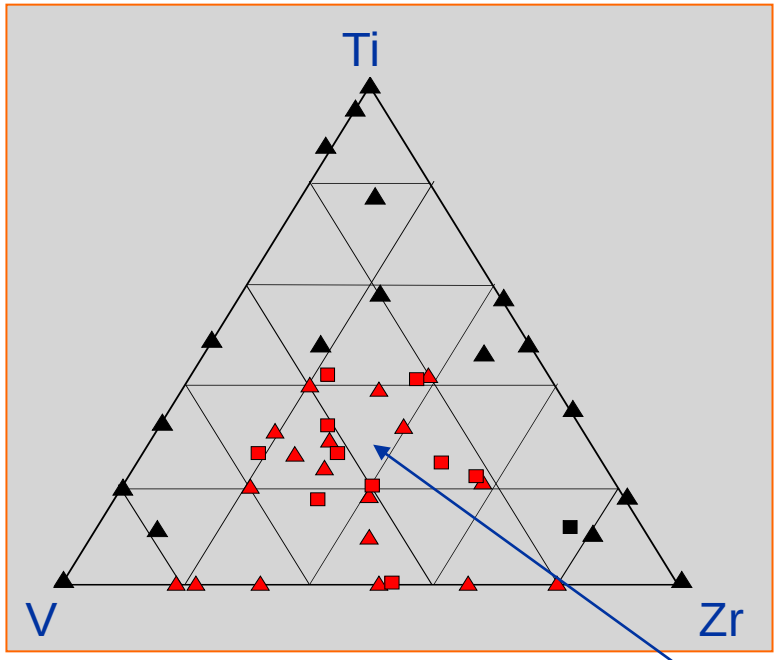
Desorption yield, photoelectron yield and photon reflectivity are reduced.

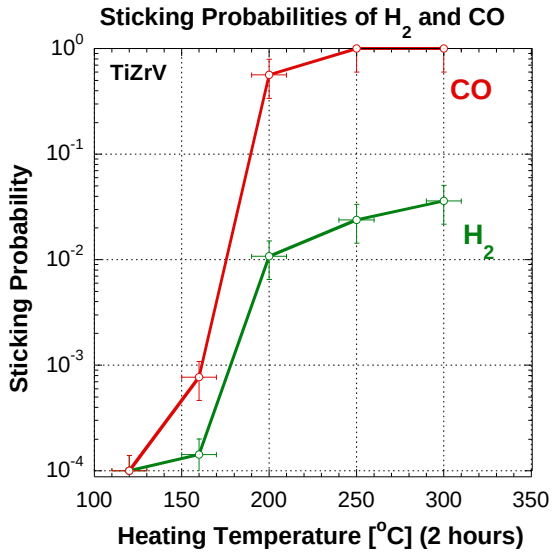
Gas sources in accelerators : Mitigation

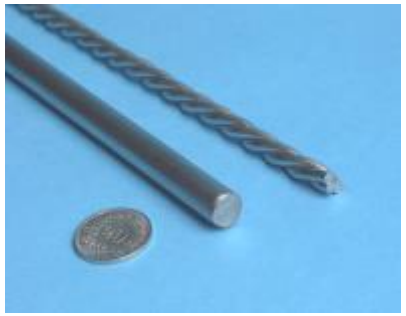
Beam induced desorption is reduced by beam conditioning (accumulation of dose). Non-evaporable getter coating are also available today to speed up the decrease of the desorption yields.

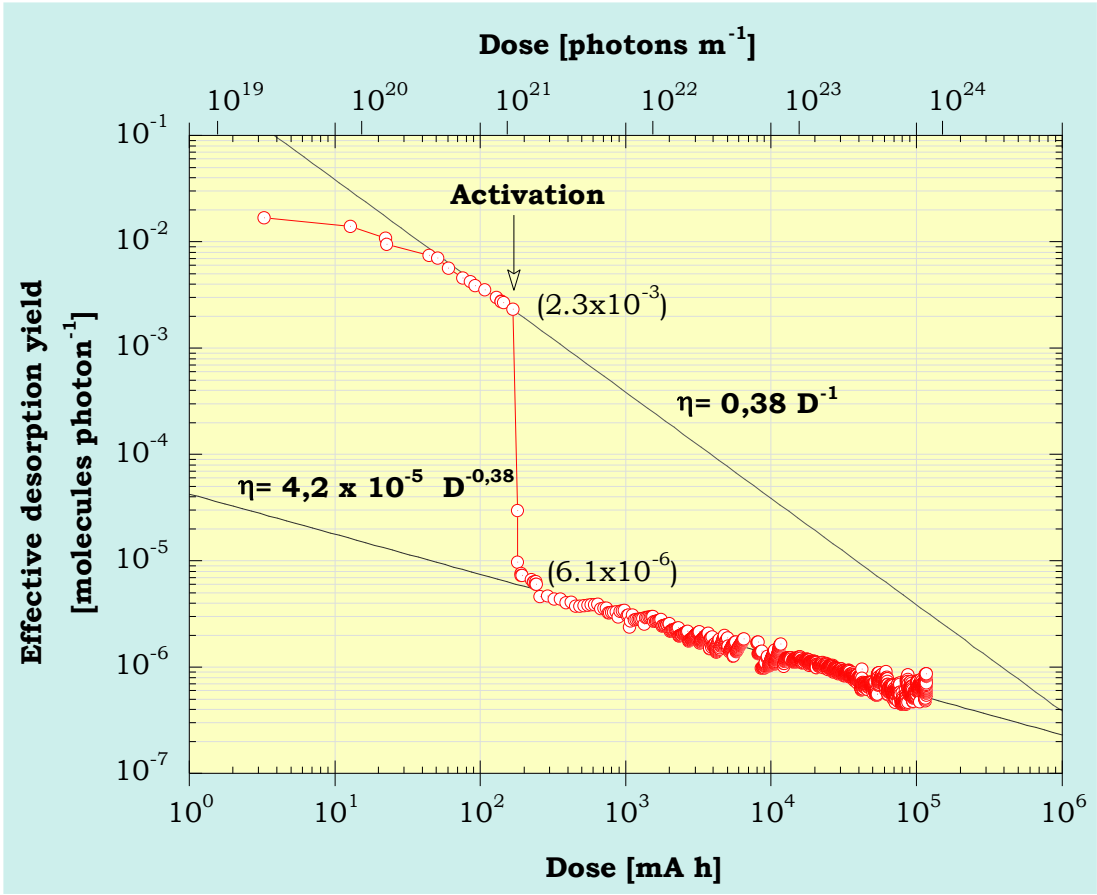
Mitigation: Ti-Zr-V coating

A. Prodromides et al., *Vacuum 60(2001)35*





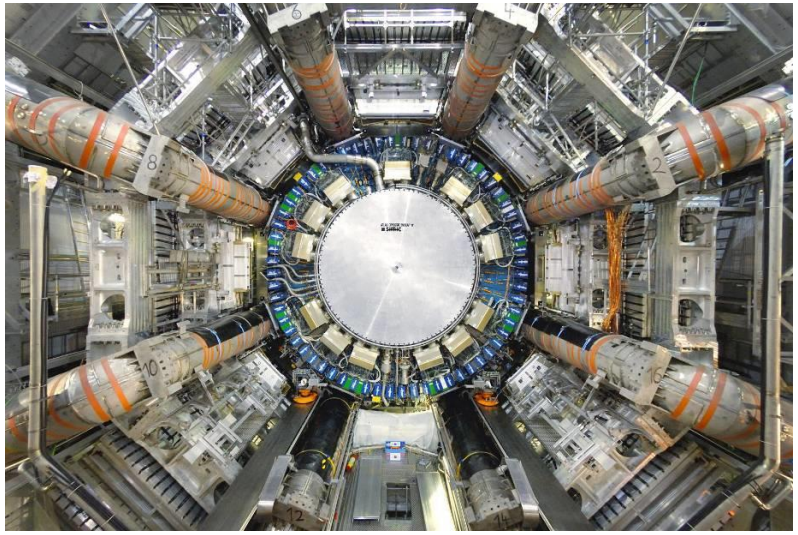


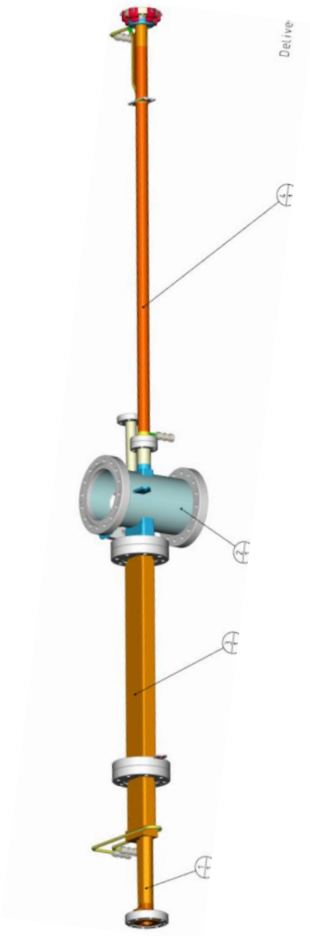


P. Chiggiato and R. Kersevan, *Vacuum 60(2001)67*

Mitigation: Ti-Zr-V coating

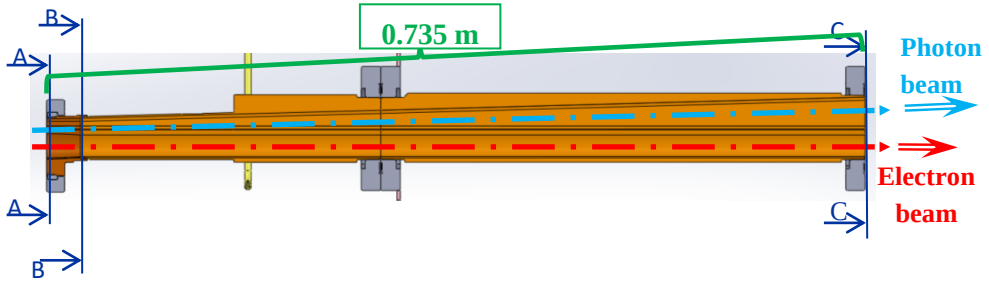
LHC Long Straight Sections

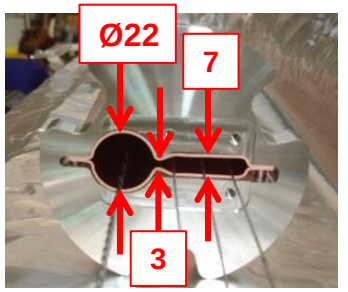


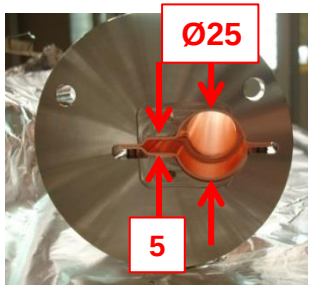


MAX IV at Lund (S)

Courtesy of Marek Grabki







Gas pumping in particle accelerators

In molecular regime:

- Gas molecules cannot be removed by suction: the molecules do not transfer energy and momentum among them; the pumps act on each molecule singularly.
- Pumps are classified in two families:

    1. **momentum transfer pumps**;
    2. **capture pumps**.

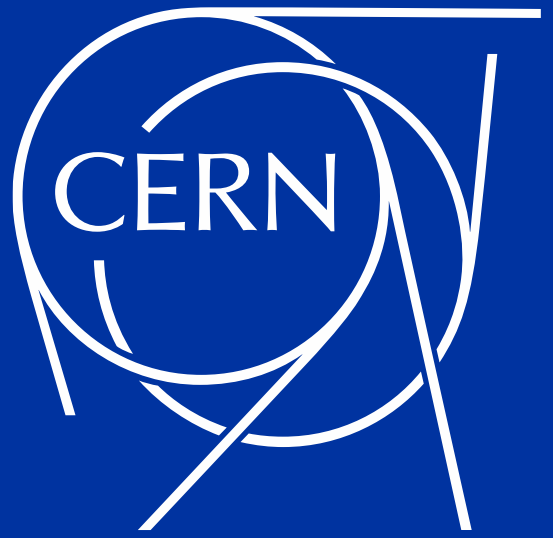
- Capture pumps remove molecules from the gas phase by fixing them onto an internal wall.
- To do so the sojourn time on the wall has to be much longer than the typical time of the accelerator run. An estimation of sojourn time is given by the Frenkel law *J. Frenkel, Z. Physik, 26, 117 (1924*):

$$\boldsymbol{t_s = t_0 e^{\frac{E_a}{k_B T}}}$$

where E_a is the adsorption energy and $t_0 \approx \frac{h}{k_B T} \approx 10^{-13}$s.

$E_a >> k_B T \rightarrow$ Chemical pumps (**getter pumps**)

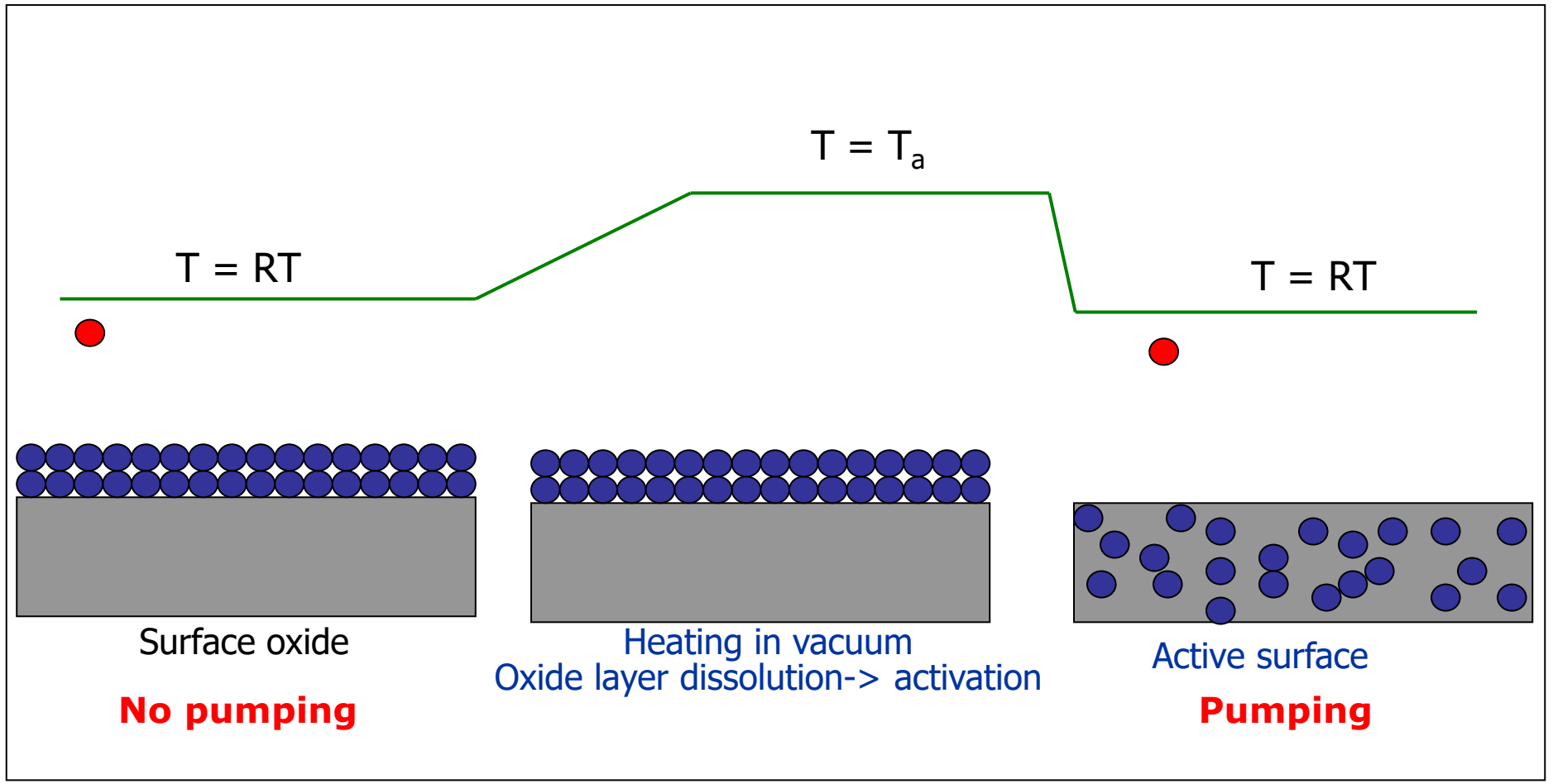
$T << \frac{E_a}{k_B} \rightarrow$ **Cryopumps**


CERN

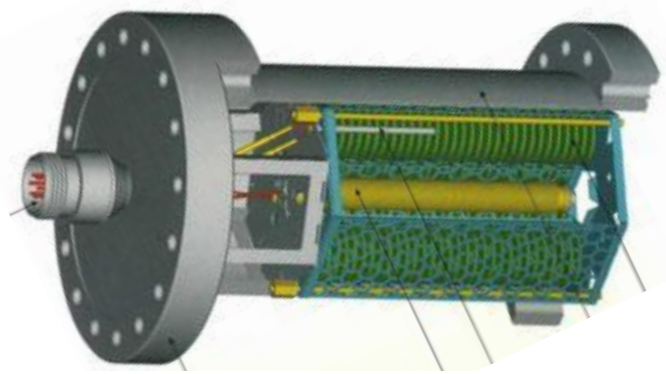
Spare slides

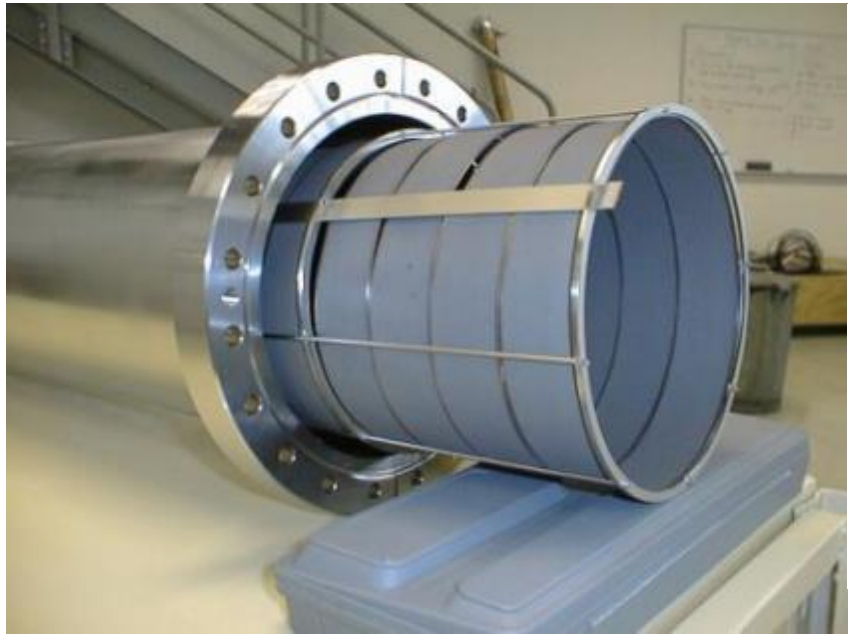
Gas Pumping: Non-Evaporable Getter Pumps

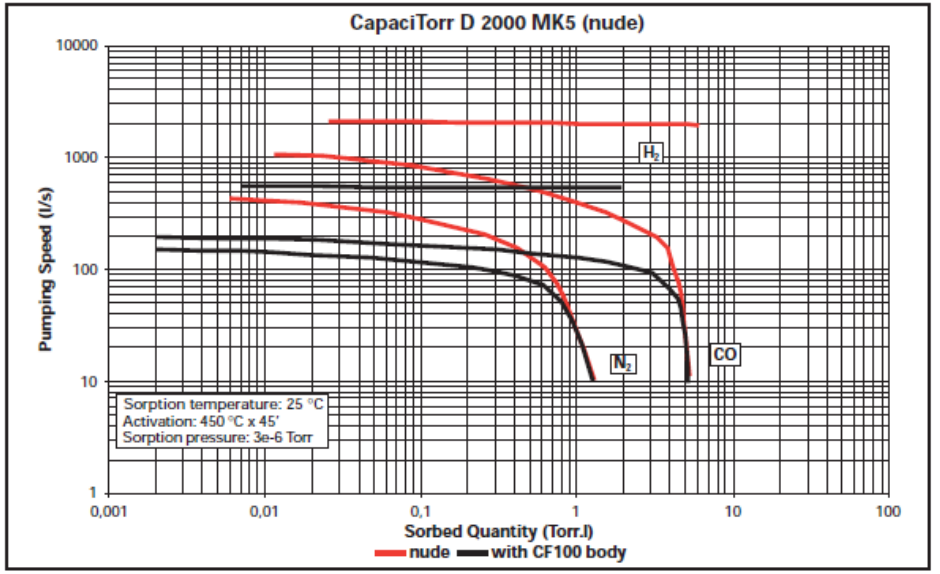
The dissolution of the oxide layer is possible only in metals having very high oxygen solubility limit, namely the elements of the 4th group: Ti, Zr and Hf.



Gas Pumping: Non-Evaporable Getter Pumps







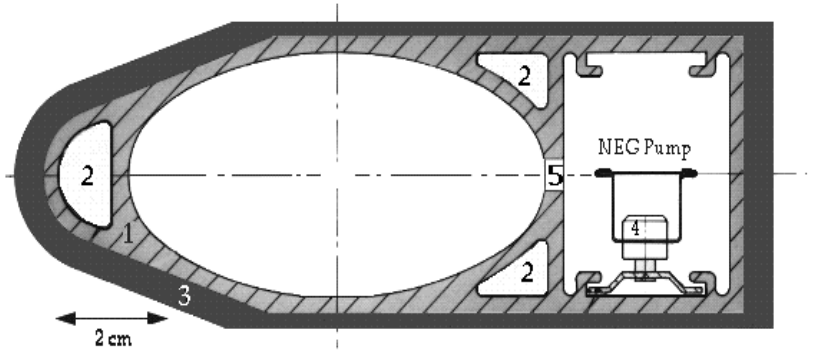
Courtesy of SAES Getters, www.saesgetters.com

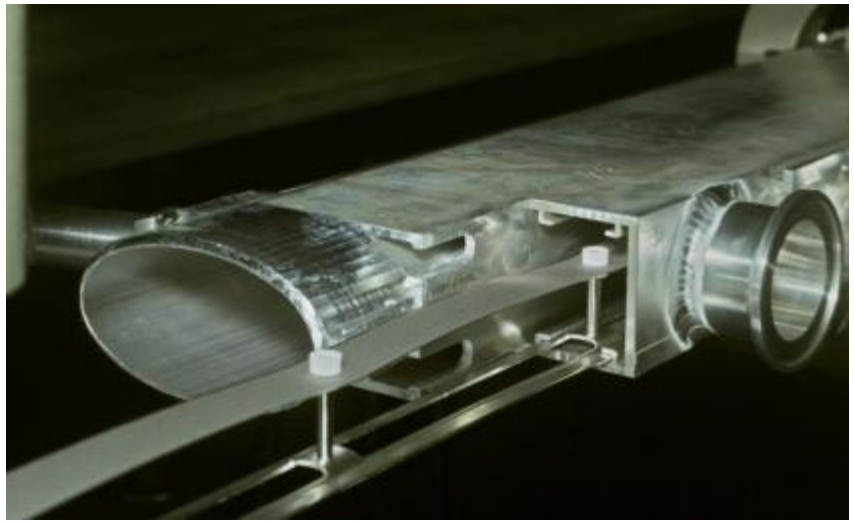
The **high porosity of NEG materials** allows pumping of relatively high quantities of gas without reactivation.

Gas Pumping: Non-Evaporable Getter Pumps

Linear pumping may be obtained by NEG ribbons.

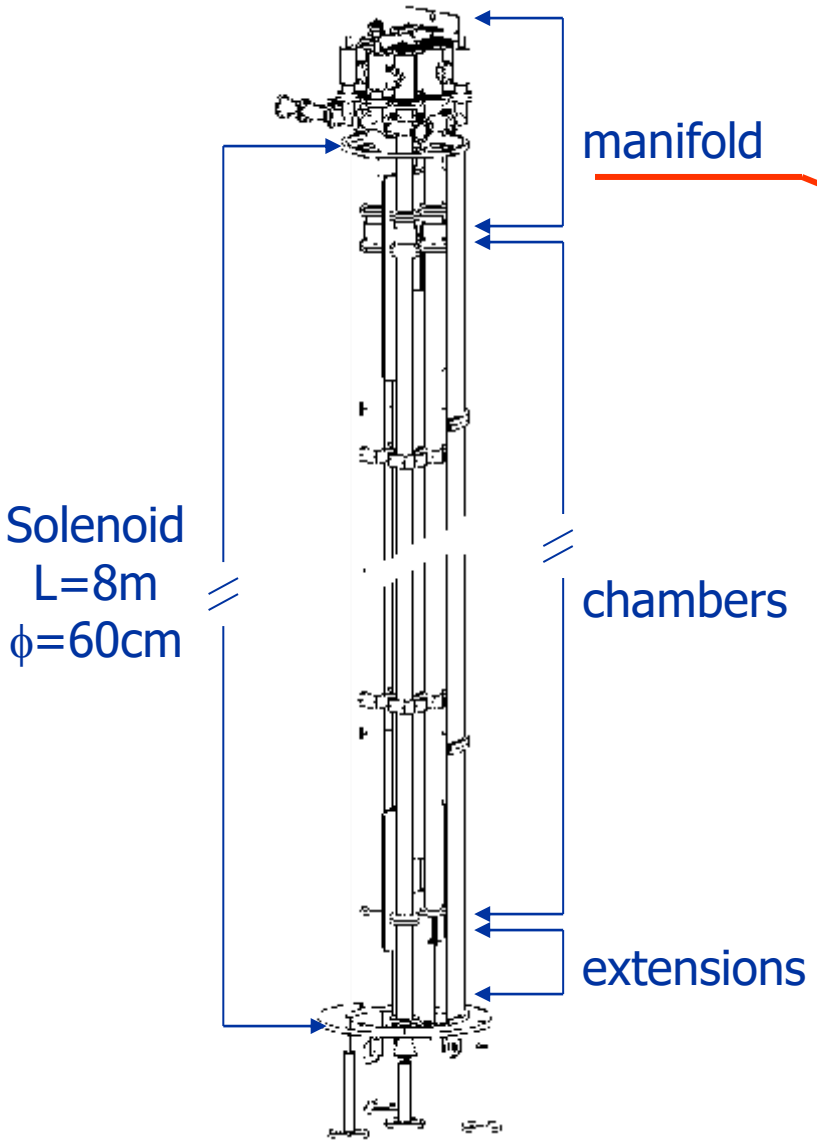
LEP dipole vacuum chamber



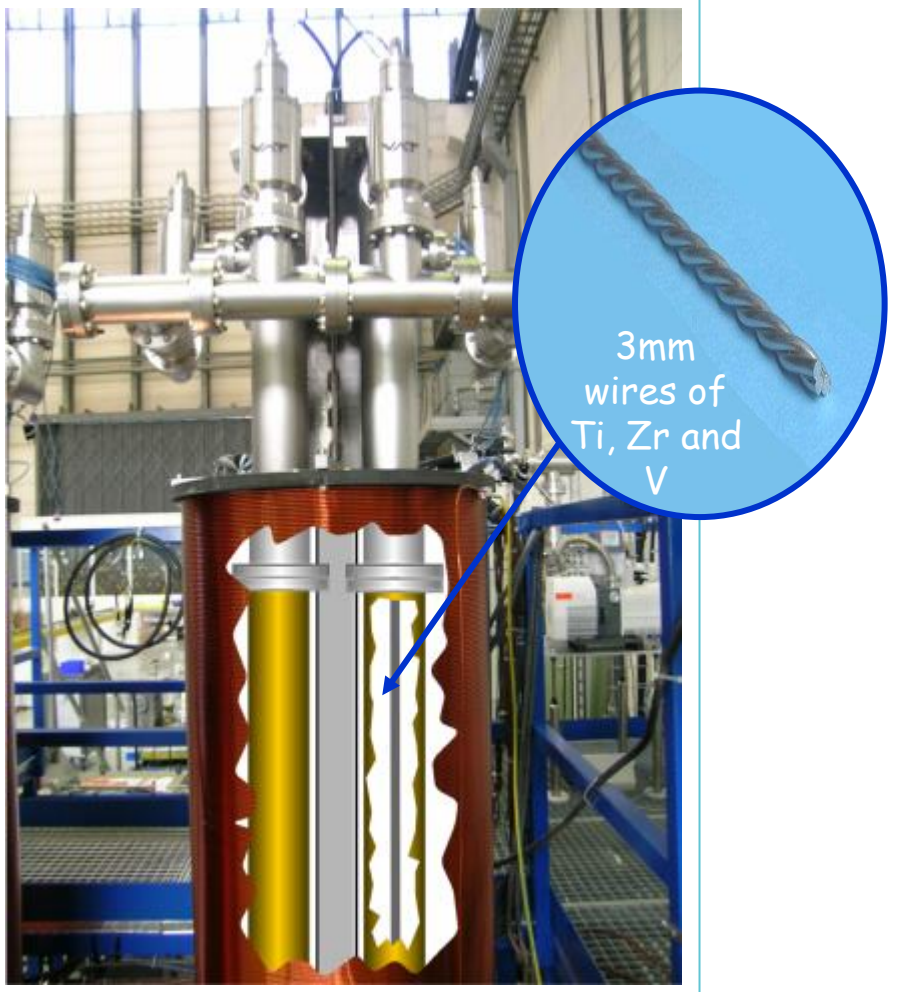


The first application was in the LEP**.**

Gas Pumping: Non-Evaporable Getter Coatings



NEG coating unit

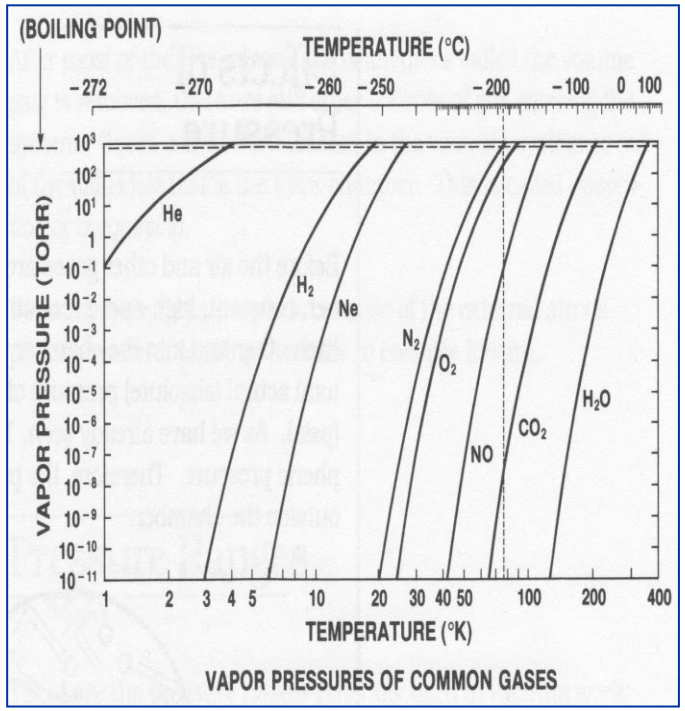


Gas Pumping: Non-Evaporable Getter Coatings

Gas Pumping: Cryopumping

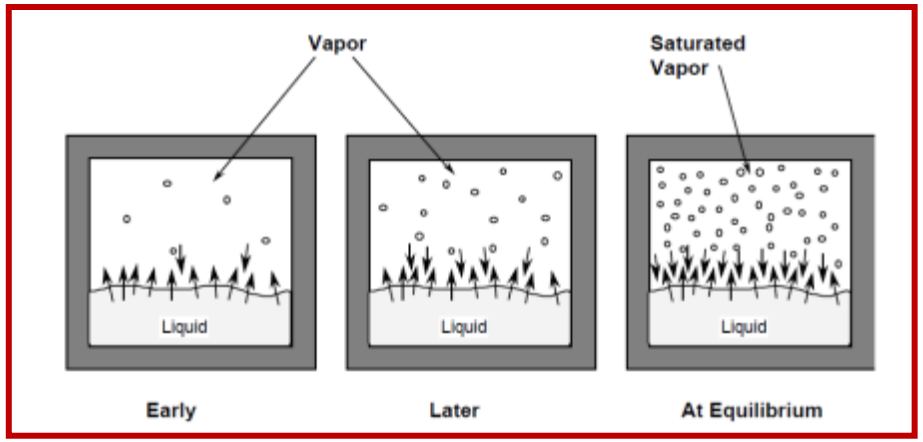
Cryopumping relies on three different pumping mechanisms:

1. **Cryocondensation**: is based on the mutual attraction of **similar** molecules at low temperature:
   a. the key property is the **saturated vapour pressure**, i.e. the pressure of the gas phase in equilibrium with the condensate at a given temperature. It limits the attainable pressure.
   b. Only Ne, H_2 and He have saturated vapour pressures higher than 10^{-11} mbar at 20 K.



   c. The vapour pressure of H_2 at 4.3 K is in the 10^{-7} mbar range, at 1.9 lower than 10^{-12} mbar.

   d. Large quantity of gas can be cryocondensed (limited only by the thermal conductivity of the condensate phase and the thermal flow)



Courtesy of F. Dylla, CAS vacuum 2006

Gas Pumping: Cryopumping

2. **Cryosorption**: is based on the **attraction between molecules and substrate**. The interaction is much stronger than that between similar molecules:

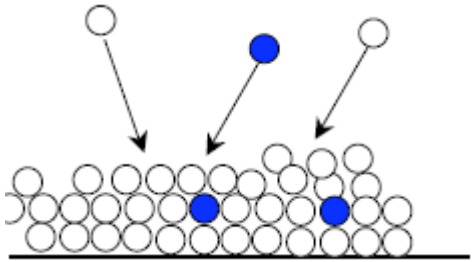
   a) Gas molecules are pumped at pressures much lower than the saturated vapour pressure providing the adsorbed quantity is lower than one monolayer.

   a) Porous materials are used to increase the specific surface area; for charcoal about 1000 m^2 per gram are normally achieved.

   b) The important consequence is that significant quantities of H_2 can be pumped at 20 K and He at 4.3 K.

   c) Submonolayer quantities of all gases may be effectively cryosorbed at their own boiling temperature; for example at 77 K all gases except He, H_2 and Ne.

3. **Cryotrapping** : low boiling point gas molecules are trapped in the layer of an easily condensable gas. The trapped gas has a saturation vapor pressure by several orders of magnitude lower than in the pure condensate. Examples: Ar trapped in CO_2 at 77 K; H_2 trapped in N_2 at 20 K.



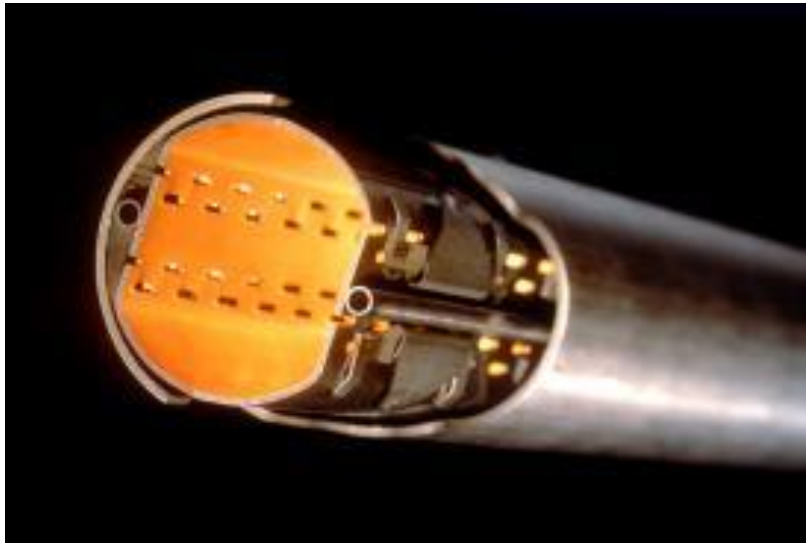
Gas Pumping: Cryopumping

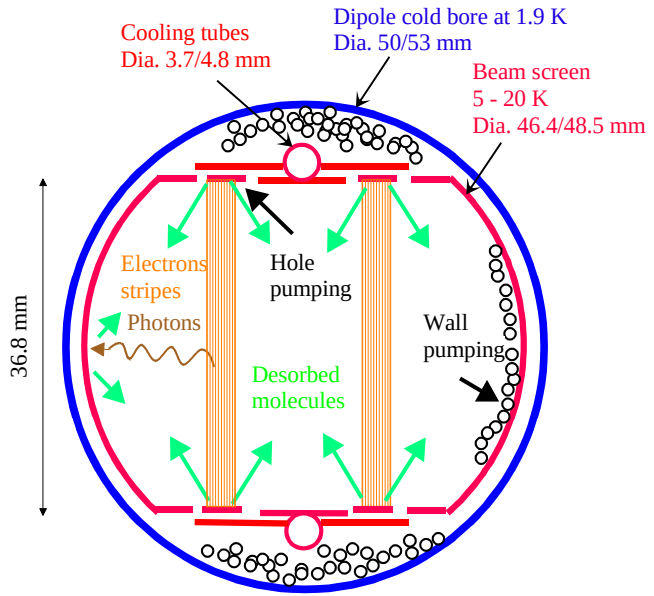
→ **Main gas source**: desorption stimulated by photon, electron and ion bombardment.

→ **Pumping:**

Molecules with a low vapour pressure are first cryopumped onto the beam screen (CH_4, H_2O, CO, CO_2) and then onto the cold bore.

Most of the H_2 is cryopumped onto the cold bore.





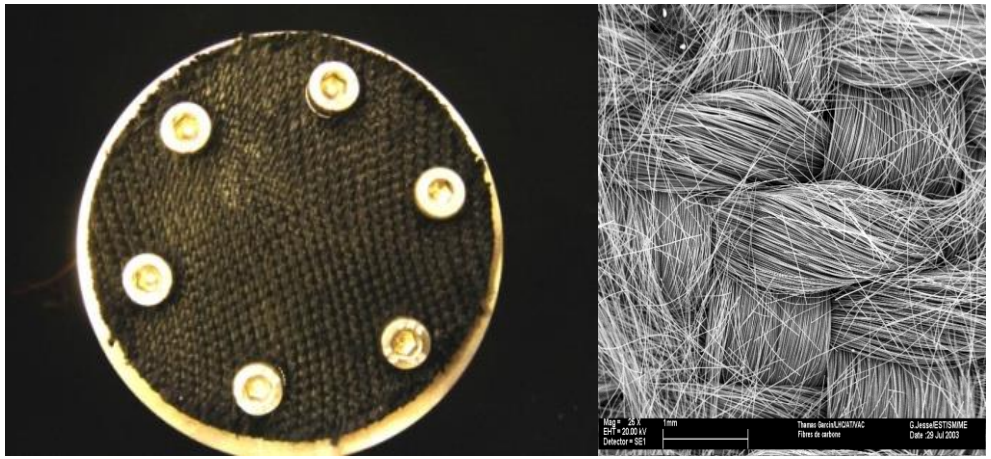
Courtesy of V. Baglin

Gas Pumping: Cryopumping

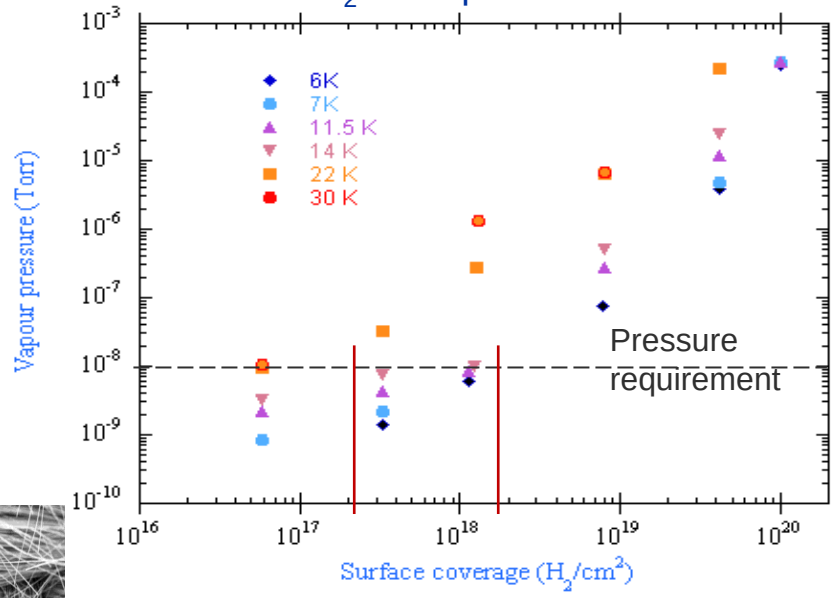
In a few cases, the cold bore temperature is higher than 1.9 K (stand alone magnets).

High specific surface materials are used to cryosorb H_2.

Woven carbon fibers, developped at BINP



H_2 adsorption isotherms



Courtesy of V. Baglin

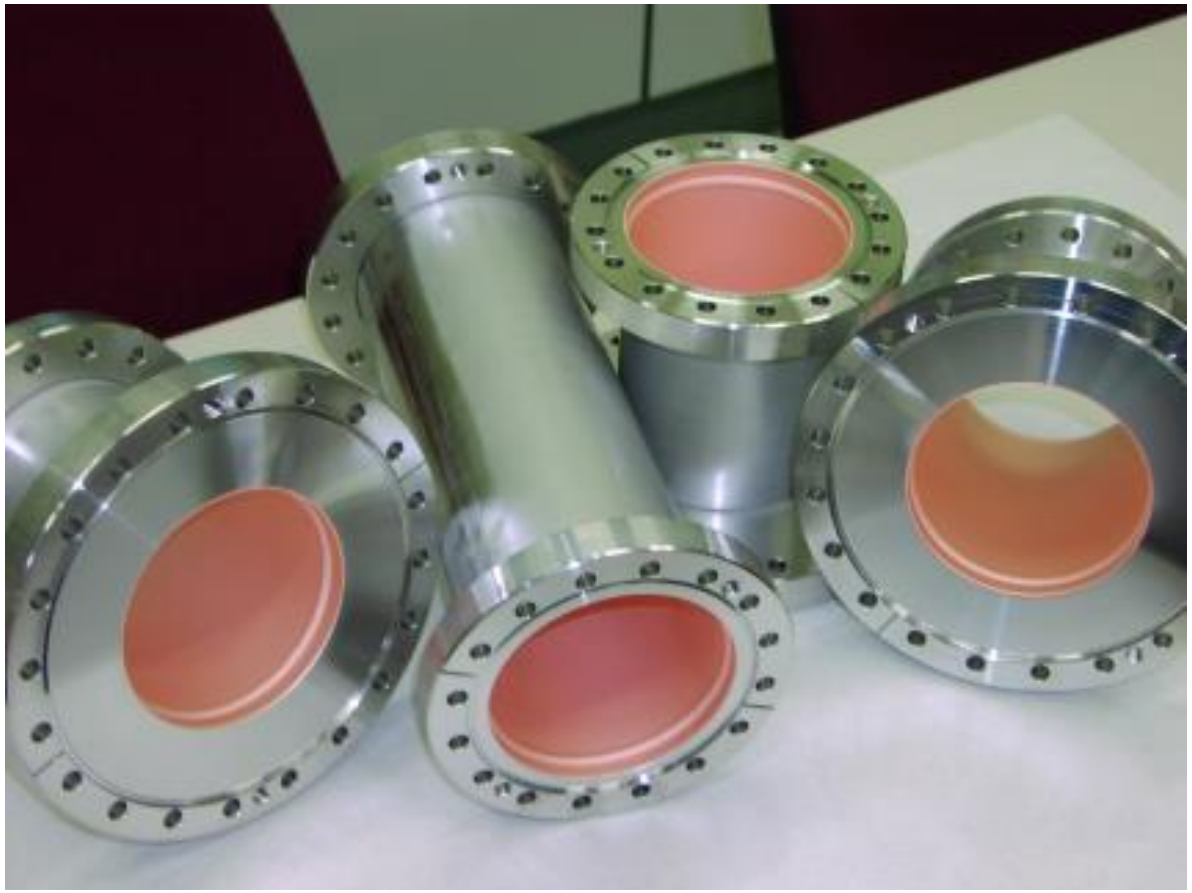
Coverage limits :

- **10^{18} H_2/cm^2 at 6 K**
- **10^{17} H_2/cm^2 at 30 K**

Other peculiarities of vacuum technology for particle accelerators

Other peculiarities of vacuum technology for particle accelerators

Heating issues: reduction of beam pipe electrical resistance



When the beam pipe has a small diameter and it is not made of copper, copper electroplating is applied.

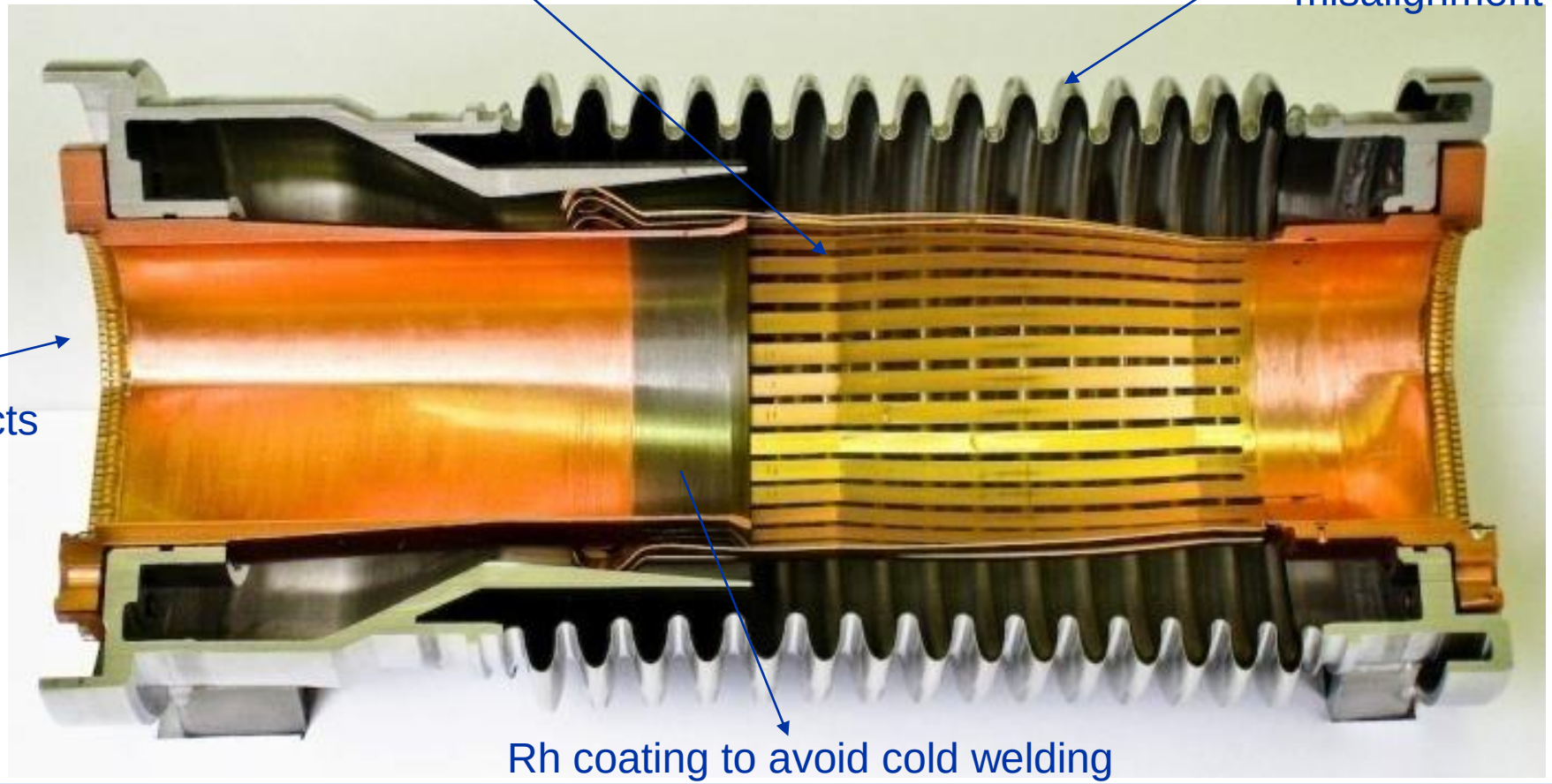
Other peculiarities of vacuum technology for particle accelerators

Heating issues: smoother beam pipe transitions

Cu-Be fingers ensure **short-path electrical contacts** and ‘geometrical uniformity’ between two chambers

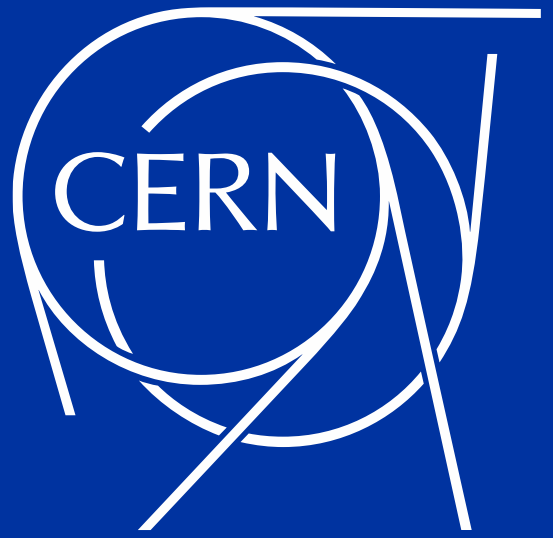
Au coated Cu-Be fingers for electrical and geometrical continuity

Bellow for compensation of thermal expansion and small misalignment



Electrical contacts

Rh coating to avoid cold welding


CERN