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Vacuum Systems for Accelerators

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https://indico.cern.ch/event/1326947/

Outline

1. Vacuum Fundamentals

2. Vacuum Components

3. Getting Ready with Beams: from Construction to Operation

1. Vacuum Fundamentals

A typical pump down

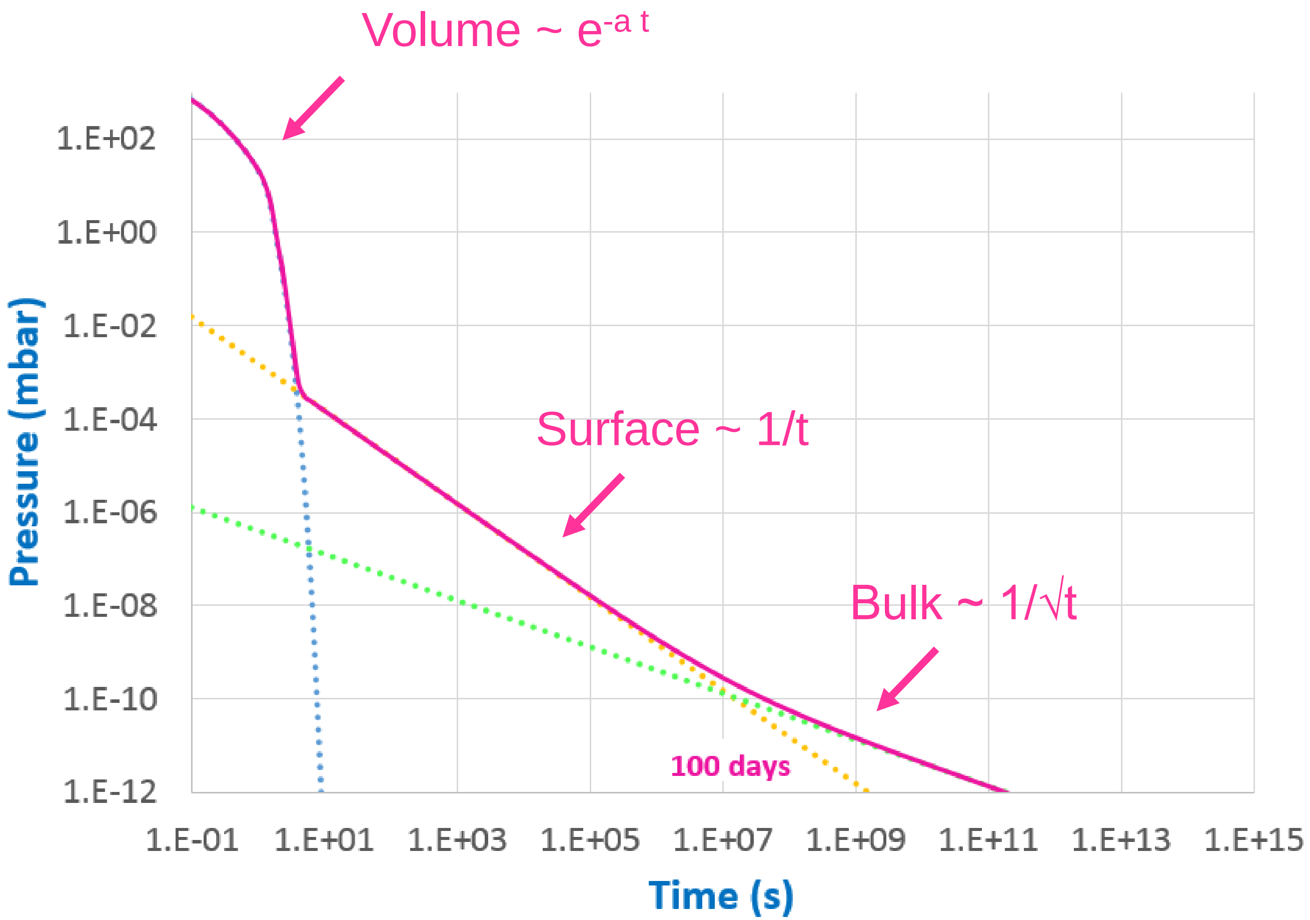
- Long term pump down of a vessel
- Consider 1 m long, Ø10 cm stainless steel tube pumped by 30 l/s
- 4 regimes

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

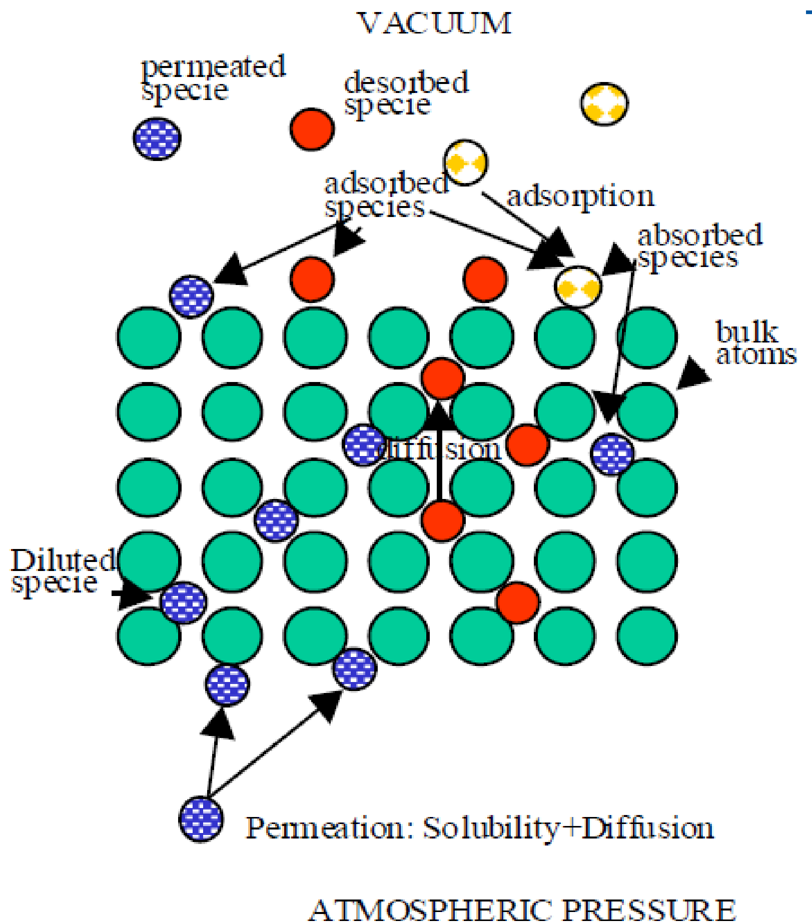


Fig. 1 Surface and bulk phenomena in vacuum.

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

The release of these molecules into the vacuum is named OUTGASSING

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

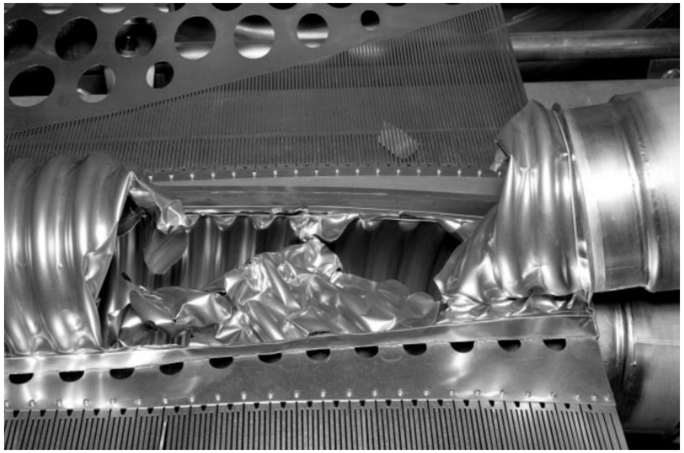

E. Torricelli, 1644


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)

$$P = n\,k\,T$$

Clapeyron 1834

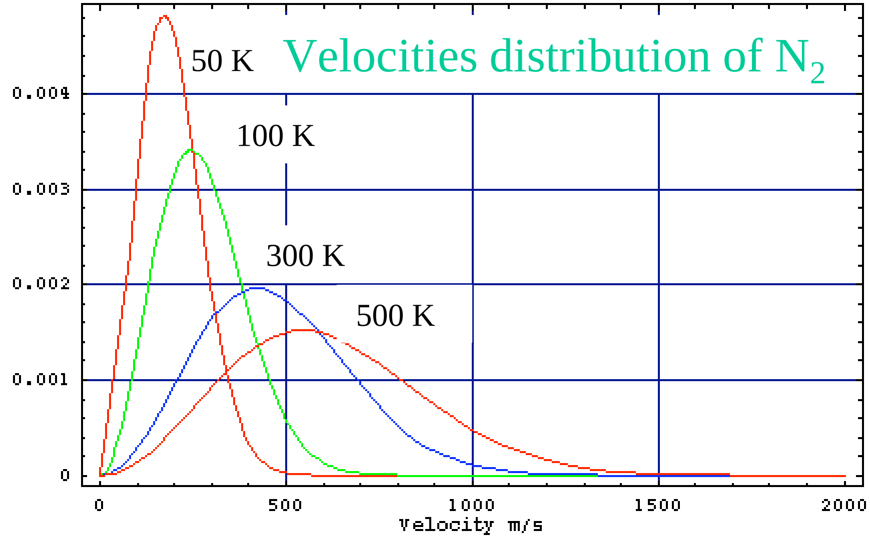
- The distribution of velocities, dn/dv, follows a Maxwell-Boltzmann function

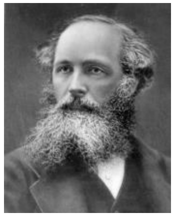
- The average velocity is :

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

- 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)

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

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	$5.2\ 10^{-4}$	$7\ 10^{-2}$

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.

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

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

R. Clausius

➔ Increasing mean free path when decreasing pressure

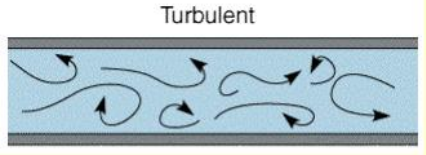
- Air at room temperature

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

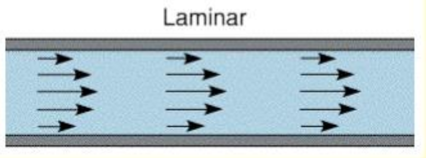
} accelerators (High Vacuum, Ultra High Vacuum, Extreme High Vacuum)

Type of flows

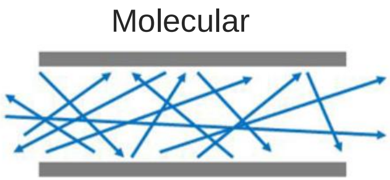
- The turbulent flow is established around the atmospheric pressure



- 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

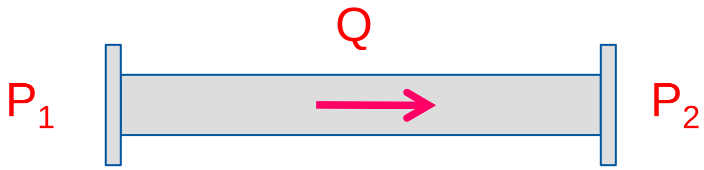
In this regime, the vacuum vessel has been evacuated from its volume.
The pressure inside the vessel is dominated by the nature of **the surface**.

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)

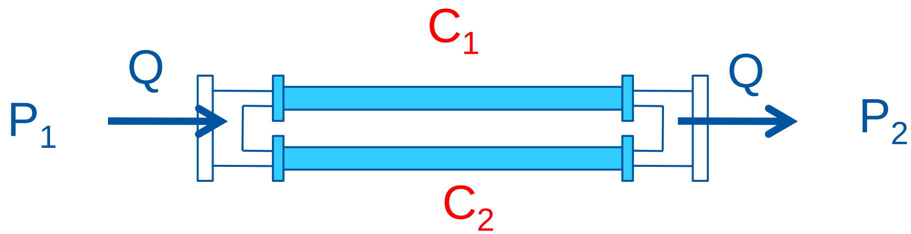
$$C = \frac{Q}{(P_1 - P_2)}$$



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

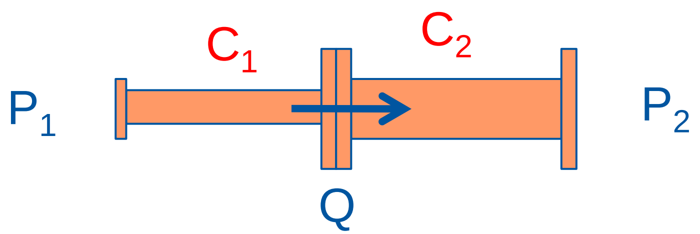
- Adding conductances in parallel

$$C = C_1 + C_2$$



- Adding conductances in series

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



Conductance in molecular regime

- **For an orifice :**

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

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

- **For a tube :**

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

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

Units of gas flow

- The flux of gas is the quantity of gas passing trough a tube section per of unit time : Pa m^3 s^{-1} (or Pa m s^{-1})

→	Pa m^3 s^{-1}	Torr l s^{-1}	mbar l s^{-1}	molecules s^{-1}
1 Pa m^3 s^{-1}	1	7.5	10	2.46×10^{20}
1 Torr l s^{-1}	0.133	1	1.33	3.27×10^{19}
1 mbar l s^{-1}	0.1	0.75	1	2.46×10^{19}

- Examples:
  - 1 10^{-13} Pa m^3 s^{-1} is converted to 10 x 1 10^{-13} = 1 10^{-12} mbar l s^{-1} cm^{-2}
  - 1 10^{-9} mbar l s^{-1} is converted to 10^{-9} x 2.46 10^{19} = 2.46 10^{-10} molecules / s

P. Redhead, Recommended practices for measuring and reporting outgassing data, J. Vac. Sci. Technol. A 20(5), Sep/Oct 2002, 1667-1675

Pumping speed

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

$$S = \frac{Q}{P}$$

S: ℓ/s; Q: mbar.ℓ/s; P: mbar

- S range from 10 to 20 000 ℓ/s

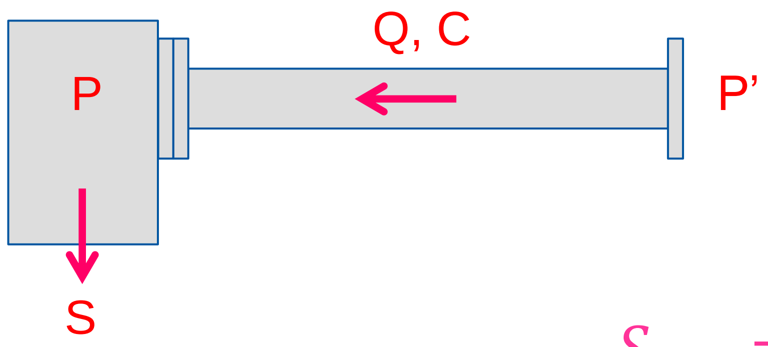
- Q = A q, with q specific outgassing rate (in eg mbar.ℓ/s/cm^2)
- q range from 10^{-14} mbar.ℓ/s/cm^2 for metalic tubes to 10^{-5} – 10^{-4} mbar.ℓ/s/cm^2 for polymers

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, S, seen from P' through 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

$$S_{eff} = \frac{SC}{S+C} = \frac{1}{{}^{1}/_{S} + {}^{1}/_{C}}$$

- 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"

Maximisation of the conductance improves the efficiency of the pumping system

Case of small tubes: LHC beam pipe

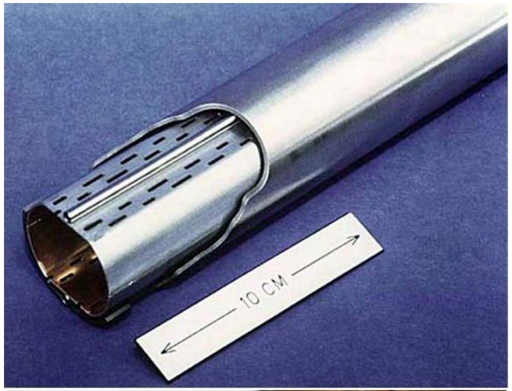
- Beam tube diameter 4.5 cm,
- Transparency 2.2 %,
- Slot size 8×1.5 mm^2

- 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 per meter

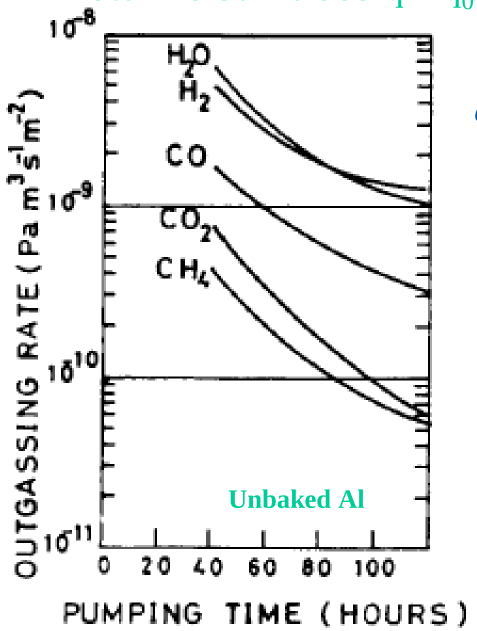


For small beam tube diameter, a distributed pumping system is required to compensate the reduced specific conductance

Outgassing

- The specific 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 $q \sim q_0/t$

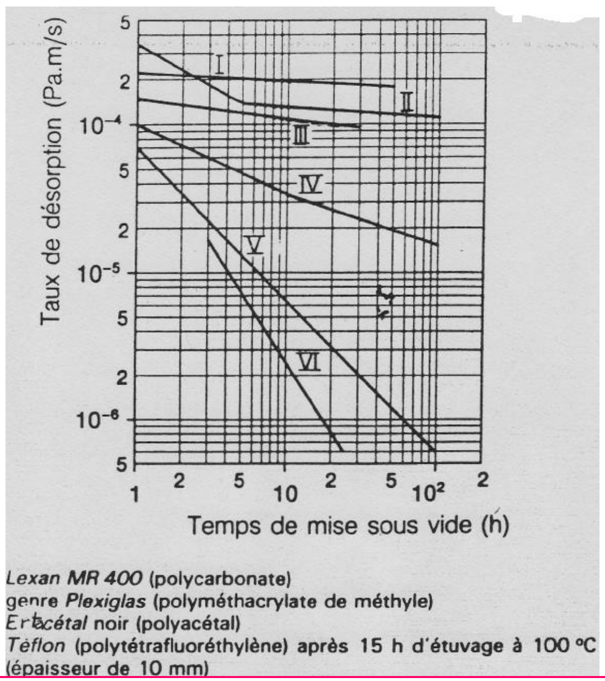


A.G. Mathewson *et al.*
J.Vac.Sci. 7(1), Jan/Fev 1989, 77-82

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

x 5 000 →

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



Good Vacuum Design :

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

Units of specific outgassing rate

- The (intrinsic) specific outgassing rate is the quantity of gas leaving the surface per unit time per unit of exposed geometric surface: Pa m^3 s^{-1} m^{-2} (or Pa m s^{-1} or W m^{-2})

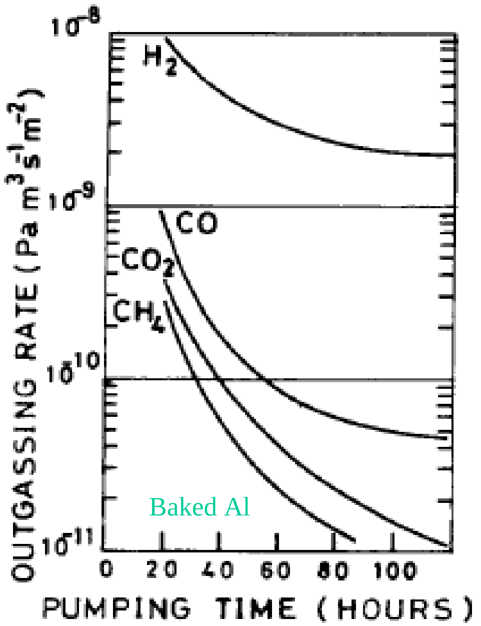
→	Pa m s^{-1}	Torr l s^{-1} cm^{-2}	mbar l s^{-1} cm^{-2}	molecules s^{-1} cm^{-2}
1 Pa m s^{-1}	1	7.5×10^{-4}	10^{-3}	2.46×10^{16}
1 Torr l s^{-1} cm^{-2}	1.33×10^{3}	1	1.33	3.27×10^{19}
1 mbar l s^{-1} cm^{-2}	10^{3}	0.75	1	2.46×10^{19}

- Examples:
  - 3 10^{-10} Torr l/(s cm^2) is converted to 1.33 10^3 x 3 10^{-10} = 4 10^{-7} Pa m s^{-1}
  - 5 10^{-13} Torr l s^{-1} cm^{-2} is converted to 1.33 x 5 10^{-13} = 6.7 10^{-13} mbar l s^{-1} cm^{-2}
  - 5 10^{-15} mbar l s^{-1} cm^{-2} is converted to 10^3 x 5 10^{-15} = 5 10^{-12} Pa m s^{-1}
  - 5 10^{-15} mbar l s^{-1} cm^{-2} is converted to 123 000 molecules / (s cm^2)

P. Redhead, Recommended practices for measuring and reporting outgassing data, J. Vac. Sci. Technol. A 20(5), Sep/Oct 2002, 1667-1675

In situ bake-out

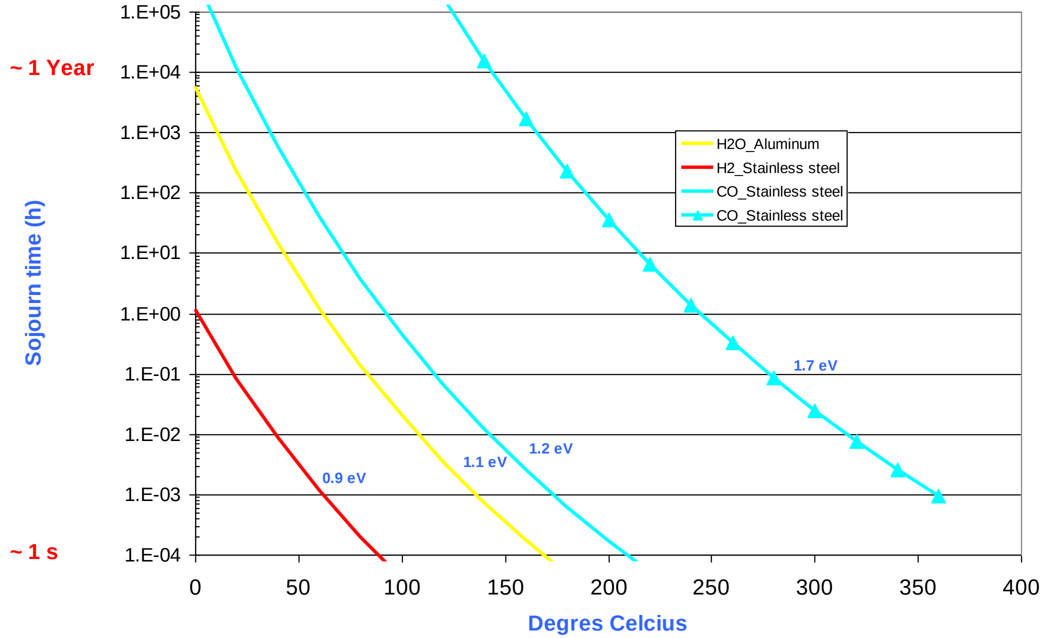
- The outgassing rate of unbaked surfaces is dominated by H_2O.
- A bake-out above 150°C increase the desorption rate of H_2O and reduce the H_2O sojourn time in such a way that H_2 become the dominant gas



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	$7\ 10^{-12}$	$5\ 10^{-13}$	**$3\ 10^{-10}$**	$5\ 10^{-12}$	$5\ 10^{-13}$
Baked	**$5\ 10^{-13}$**	$5\ 10^{-15}$	$1\ 10^{-14}$	$1\ 10^{-14}$	$1\ 10^{-14}$

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

Cleaning / outgassing methods

- Several methods 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 316LN stainless steel surface

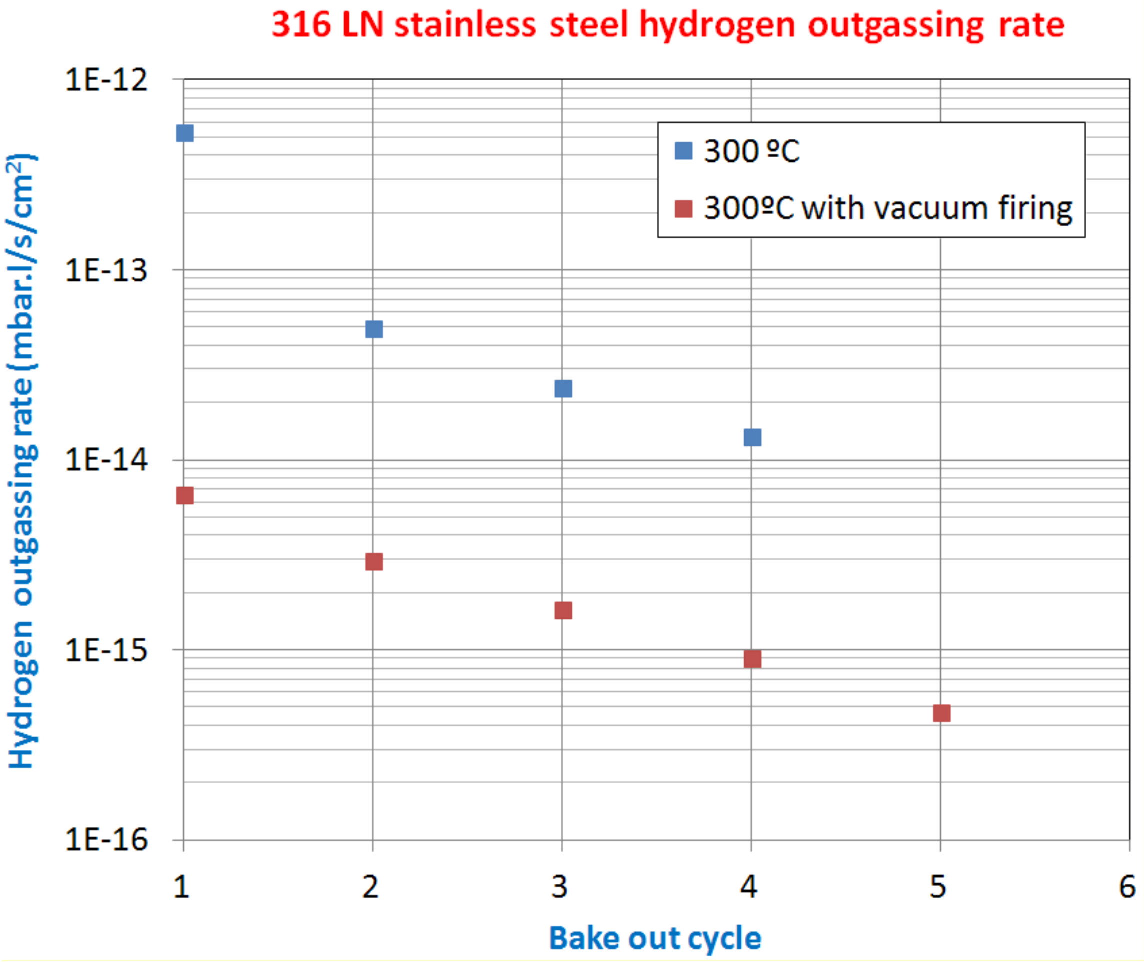
Length: 6 m
Diameter: 1 m
Maximum charge weight: 1000 Kg
Ultimate pressure: 8 10^{-8}Torr
Pressure at the end of the treatment: high 10^{-6} Torr

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

- Wear (clean & hydrocarbon free!) gloves to handle the material and use clean tools!

Vacuum fired stainless steel 316 LN

- 1.5 mm thick sheet held at 300°C for 24 h, rate measured 120 h after the end of bake-out
- As expected from diffusion theory:
  - H_2 outgassing rate of $6\ 10^{-15}$ mbar.ℓ/(s.cm^2) and a reduction of ~ 1.8 between each bakeout



B. Versolatto, N. Hilleret, CERN Vacuum Technical Note 2002

Outgassing of non-metallic surfaces

- Ceramics:
  - Function of porosity & composition
  - Al_2O_3, Macor and nitrides ceramics requires in-situ bakeout at 200˚C to reach ~ 10^{-11} mbar.ℓ/s/cm^2 at RT.

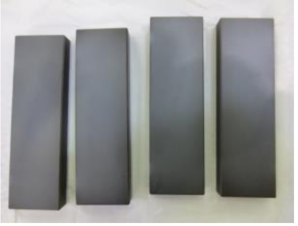

Alumina feedthrough

Alumina balls

Macor spacer

LHC TDI Boron Nitride block

- Ferrites:
  - TT2-111R, CMD5005 and CMD10
  - Treated at 400˚C – 1000˚C
  - low outgassing rate 10^{-11} mbar.ℓ/s/cm^2 (after bakeout), but can heat up during operation (by design), active cooling may be desirable.



CMD ferrite

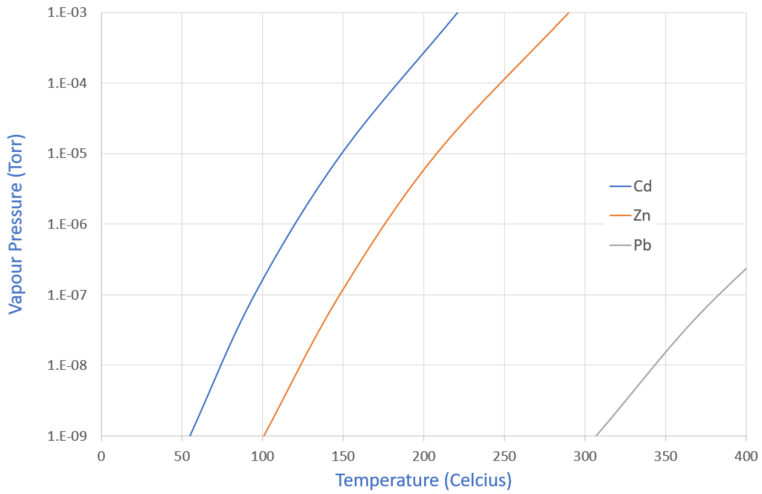
- Polymers:
  - Large permeability to helium: beware during leak detection
  - Large solubility of water: beware to humidity exposures, better dry air or N_2 venting
  - Bake-able to 150-200 ˚C
  - Thick materials requires long pumping time due to diffusion
  - Elastomers: Viton after 10h pump down unbaked ~ 2 10^{-7} mbar.ℓ/s/cm^2 , baked ~ 5 10^{-10} mbar.ℓ/s/cm^2
  - Hard plastics: unbaked 0.1 mm thick Kapton (polyimide) after 100h pump down ~ 5 10^{-10} mbar.ℓ/s/cm^2

Viton o'rings

Kapton wire

Warning: choice of material

- Always use material with low vapor pressure:
  - Zinc, cadmium, lead, sulphur, phosphorous are forbidden in vacuum systems



- Remember: brass is made of Cu+Zn !!!

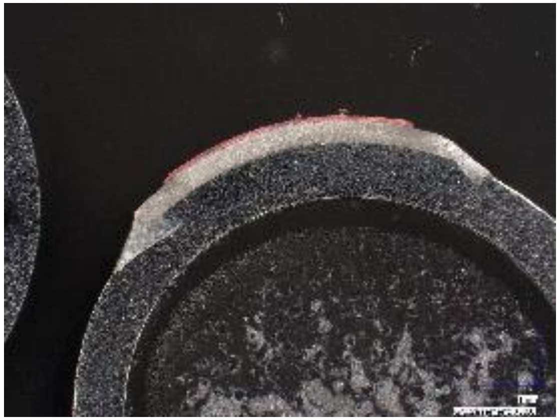
- White coating after bakeout following Zn evaporation

- P ≈ 10^{-5} mbar !

Welds

- Usual process for welding: TIG, Electron beam and Laser welding

- Some guidelines for UHV application
  - Use protective gas for TIG
  - The butt welds must be performed on the vacuum side (or fully penetrant).
  - The fillet welds shall not be fully penetrant
  - Welding on both inside and outside of the chamber means the welds cannot be leak detected
  - If required for mechanical strength reason, a continuous weld on the vacuum side can be made in combination with stitch welds on the opposite side



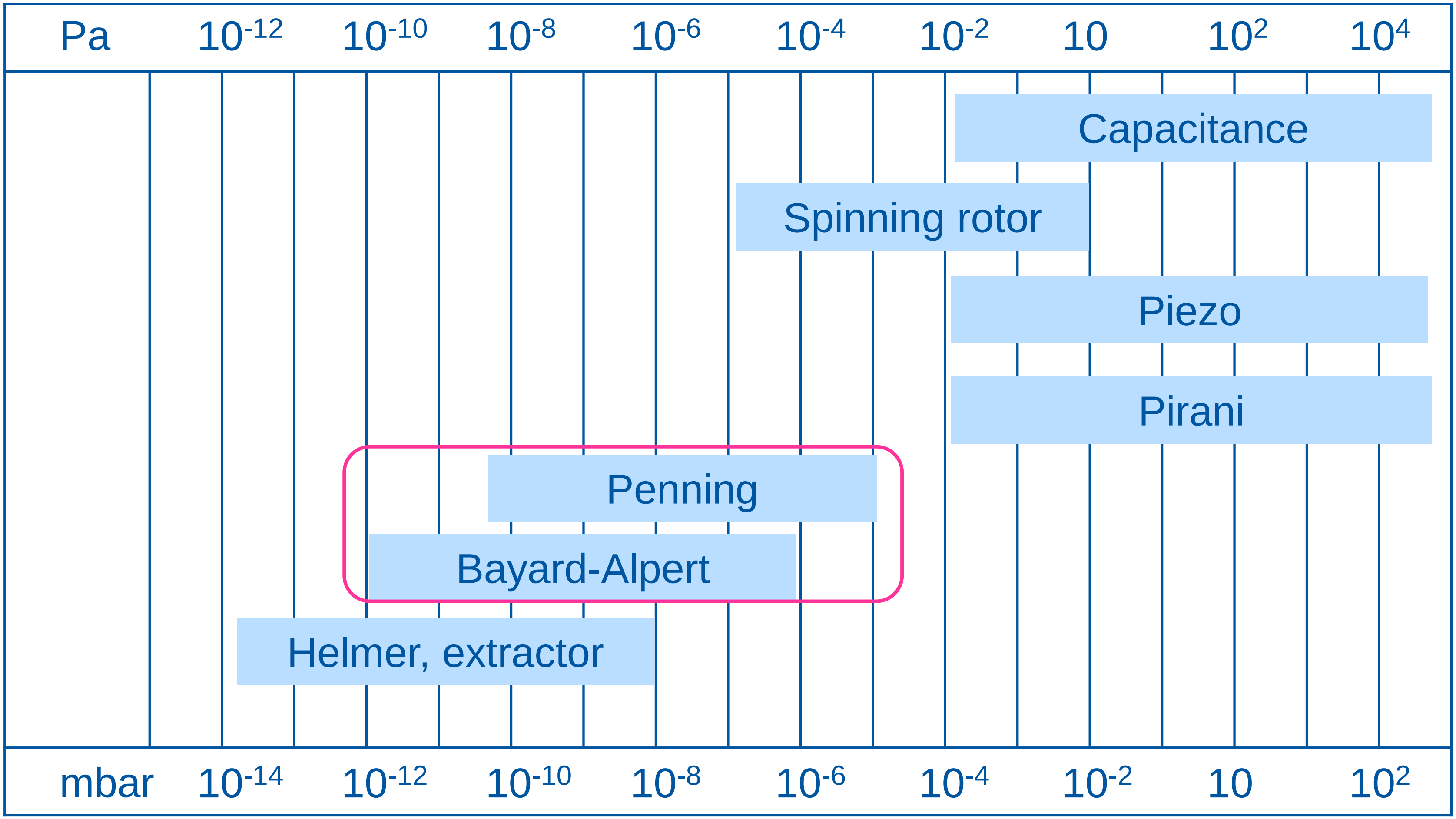
Metallography for butt and fillet weld qualification

Non compatible welds with leak detection

2. Vacuum Components

Vacuum gauges pressure range

16 orders of magnitude !



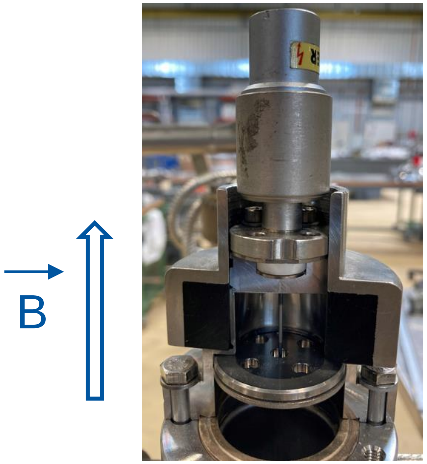
Penning gauge

- 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

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.

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

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

• Thin ion collector (10 µm)
➔X-ray limit of ~ 2 10^{-12} mbar

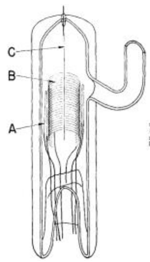
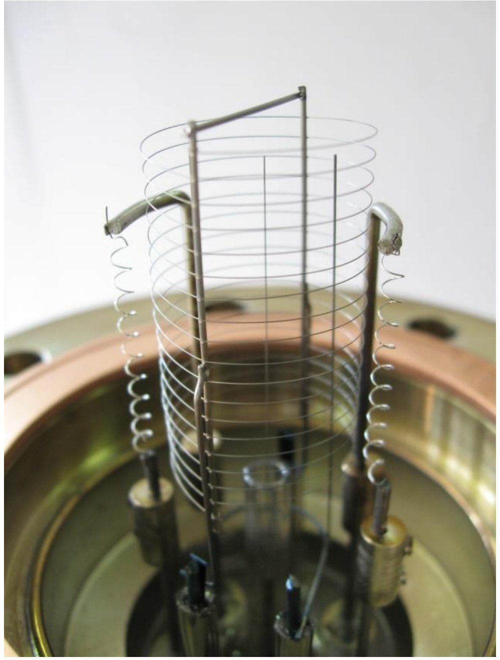
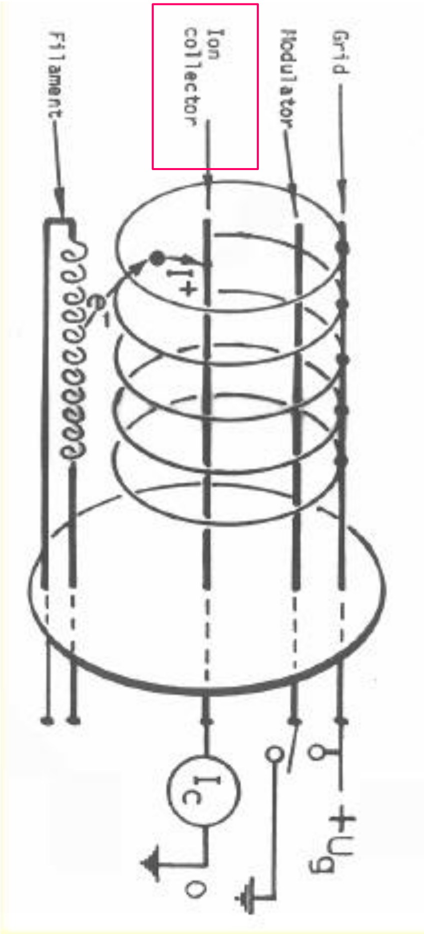


FIG. 2. Cutaway view of the new gauge showing filament A (an auxiliary filament is also shown), grid B, and ion collector C.

R. Bayard, D. Alpert, 1950





Residual Gas Analysers

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

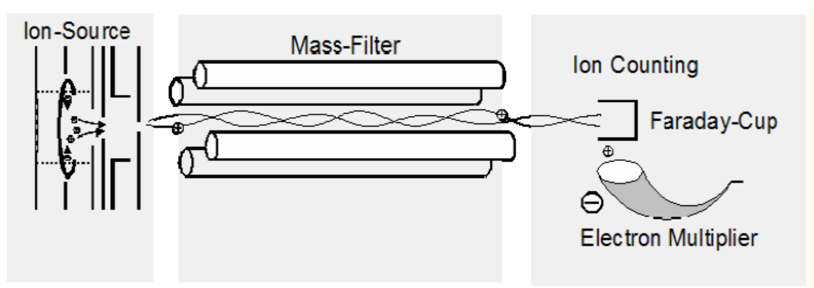
- A filament produces electrons which ionise the residual gas inside a grid. A mass filter is introduced between the grid and the ion collector. The ion current can be measured in Faraday mode or in secondary electron multiplier mode.

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

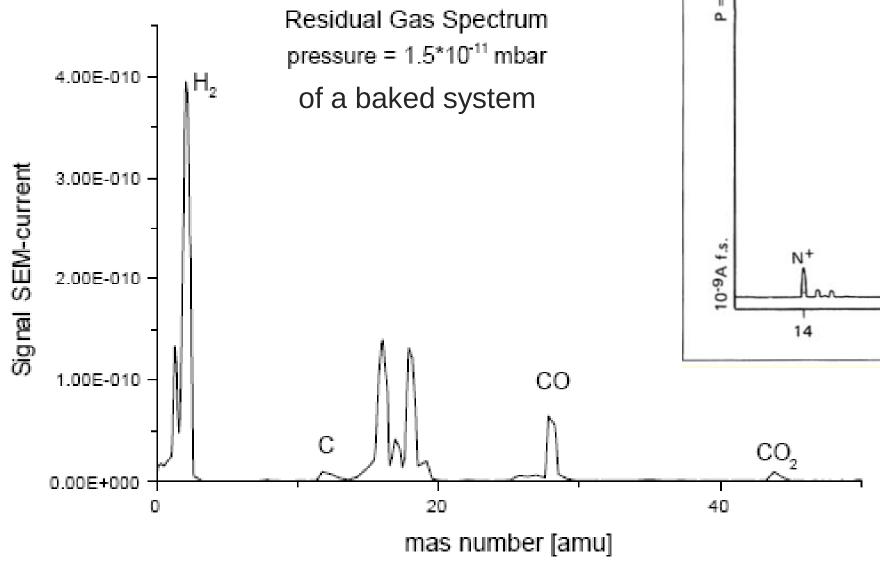
- It can be also used to identified/find leaks (Ar, N_2)

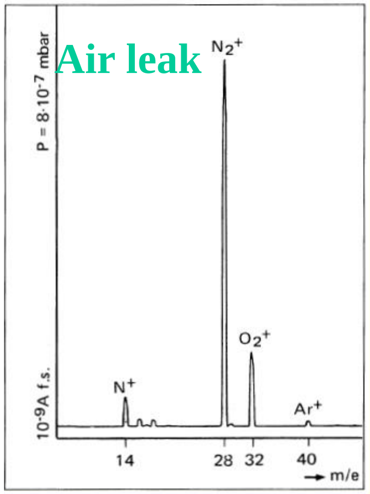
- The RGA needs to be calibrated

W. Paul 1953



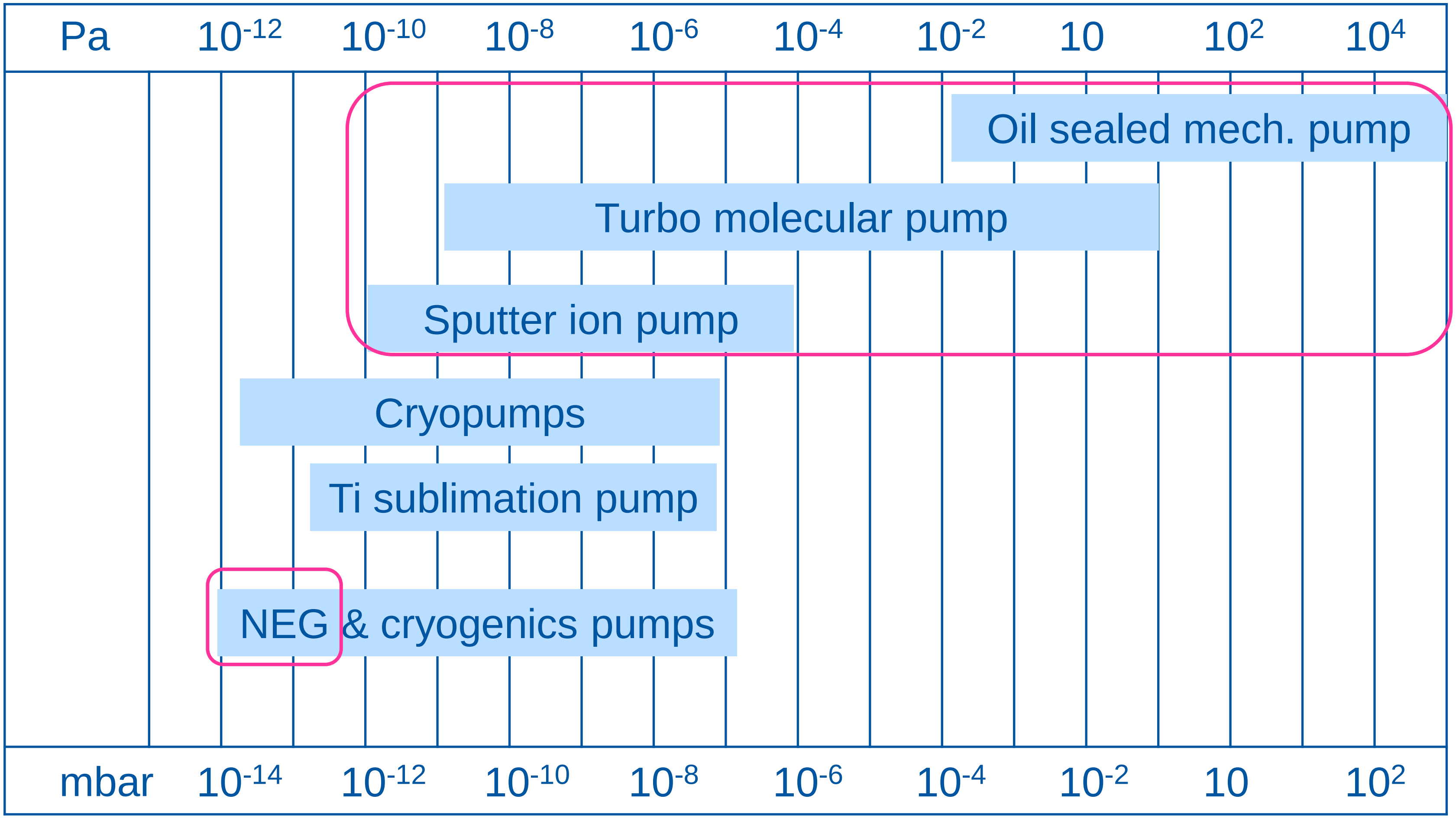
G.J. Peter, N. Müller. CAS Vacuum in accelerators CERN 2007-003





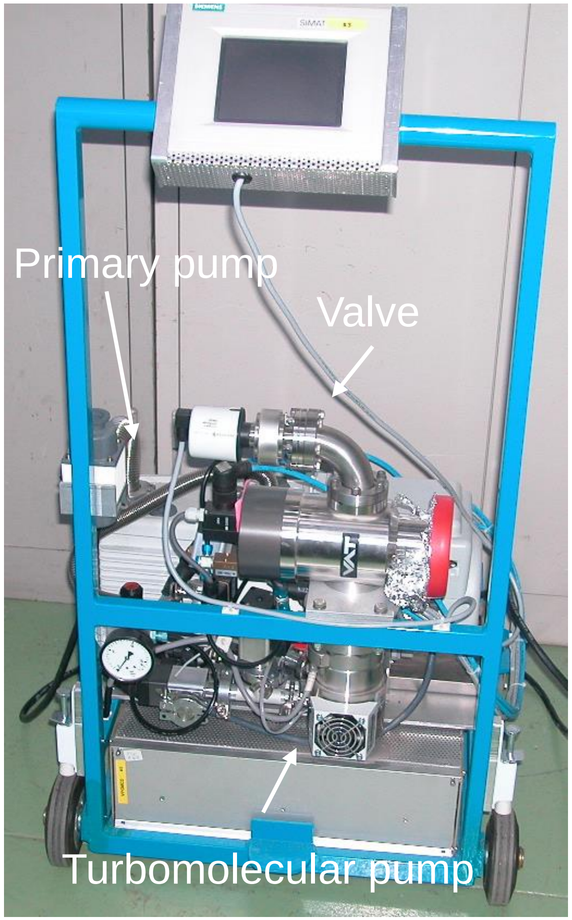
Vacuum pumps pressure range

16 orders of magnitude !



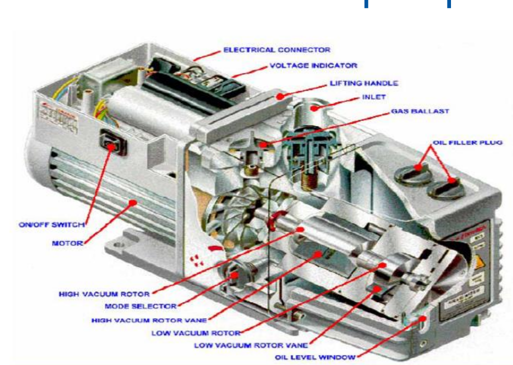
Turbomolecular pumping group

- 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

W. Becker, 1956
A. Pfeiffer GmbH



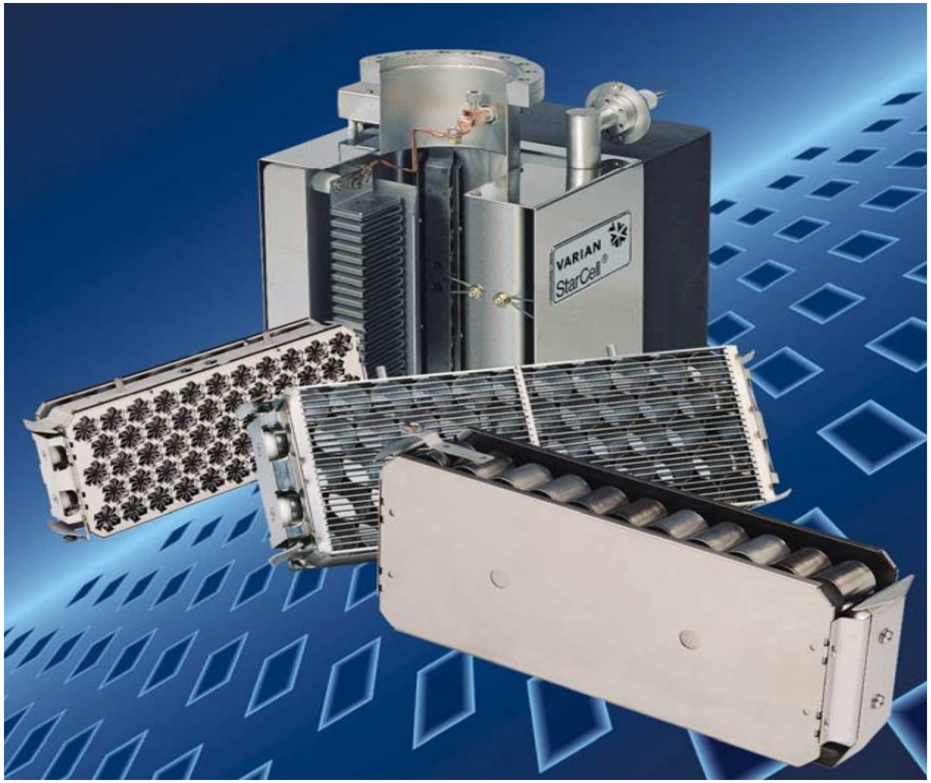
Primary pump

Sputter Ion Pump

- This pump operates 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

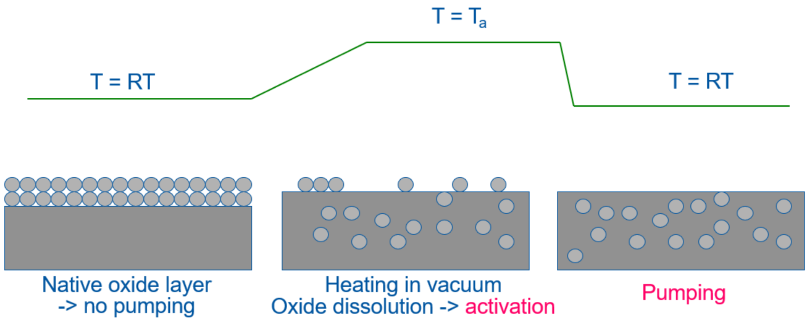
Varian, 1957
L.D. Hall, J.C. Helmer, R.L. Jepsen



Picture Agilent, Varian

Non-Evaporable Getter (NEG)

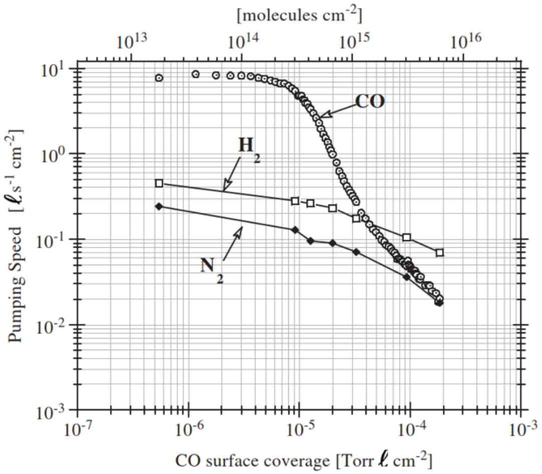
- Getters (eg Ti) are materials capable of chemically adsorbing gas molecules. To do so their surface must be clean.
- For Non-Evaporable Getters (eg TiZrV films) a clean surface is obtained by heating to a temperature high enough to dissolve the native oxide layer into the bulk.
- NEGs pump most of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



C. Benvenuti, 1996

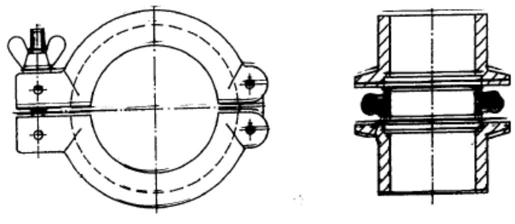
P. Chiggiato and P. Costa Pinto, Thin Solid Films, 515 (2006) 382-388

Flanges and gaskets

- For medium-high vacuum, elastomer seals and clamp flanges are used
- KF type components:

  Many fittings (elbows, bellows, T, cross, flanges with short pipe, reductions, blank flanges …)

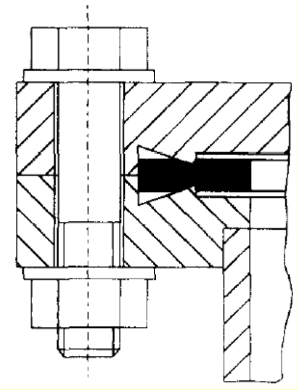
  ISO diameters

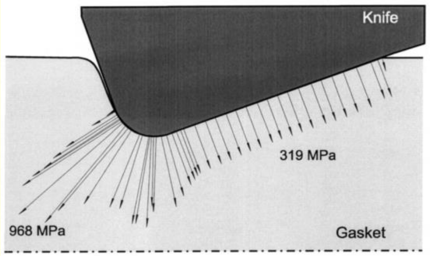


- For ultra high vacuum, metalic gaskets and bolds flanges are used
- Conflat® Type components :

  Copper gaskets, blank flanges, rotatable flanges, welding flanges, elbows, T, crosses, adaptors, zero length double side flanges, windows …

  ISO diameters





P. Lutkiewicz, C. Rathjen.
J.Vac.Sci. 26(3), May/Jun 2008, 537-544

Tubes, bellows, valves

- Metallic tubes are preferred (low outgassing rate)
- Stainless steel is appreciated for mechanical reason (machining, welding)

Copper tubes

- Bellows are equipped with RF fingers (impedance)

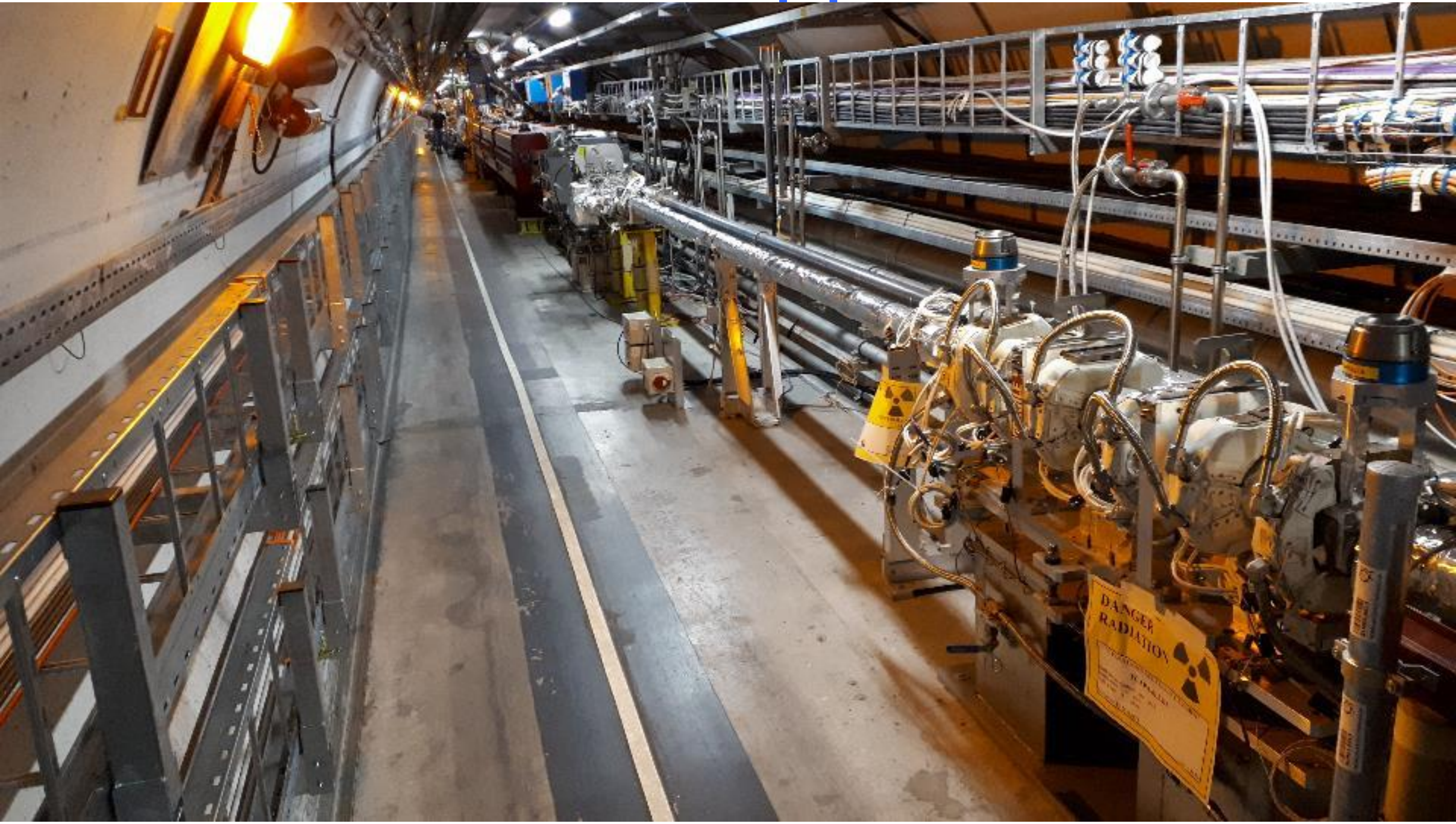
- Valves are used for roughing and sectorisation

Sector valves

Roughing valve

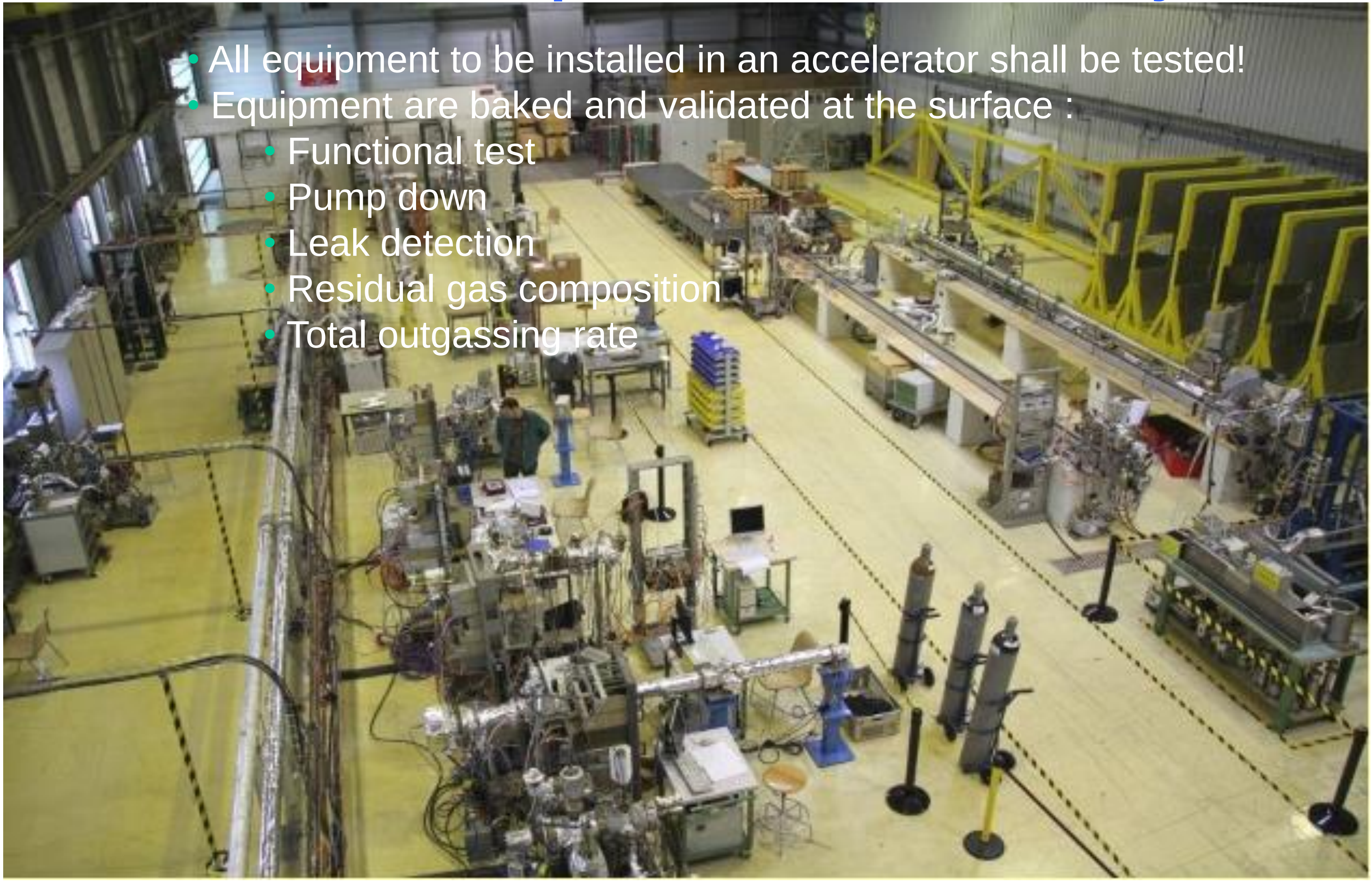
3. Getting ready with beams: from construction to operation

A vacuum system for accelerator is not only connected pipes…



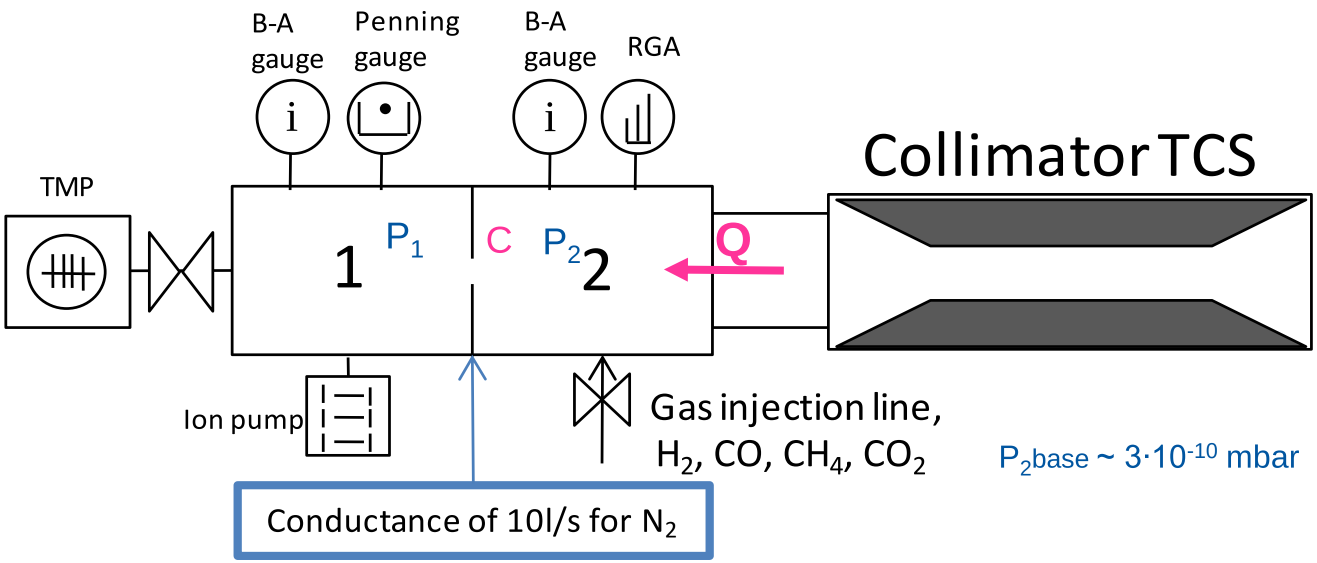
Vacuum Acceptance Test laboratory

- All equipment to be installed in an accelerator shall be tested!
- Equipment are baked and validated at the surface :
  - Functional test
  - Pump down
  - Leak detection
  - Residual gas composition
  - Total outgassing rate



LHC vacuum laboratory during LS1 (2013-2014)

Outgassing measurement: throughput method



J. Kamiya *et al.*, Vacuum 85 (2011) 1178-1181

- The component is connected to a pumping system via a conductance, C
- Background is determined by a dry run
- The outgassing rate is

$$Q_{N2eq} = C\,(P_2 - P_1)$$

In N_2 equivalent no RGA is needed!

$$Q_i = S_{eff} P_{2,i} = C_i\,(P_{2,i} - P_{1,i})$$

$$S_{eff} = \frac{C_i\,(P_{2,i} - P_{1,i})}{P_{2,i}} = C_i\left(1 - {P_1}/{P_2}\right)$$

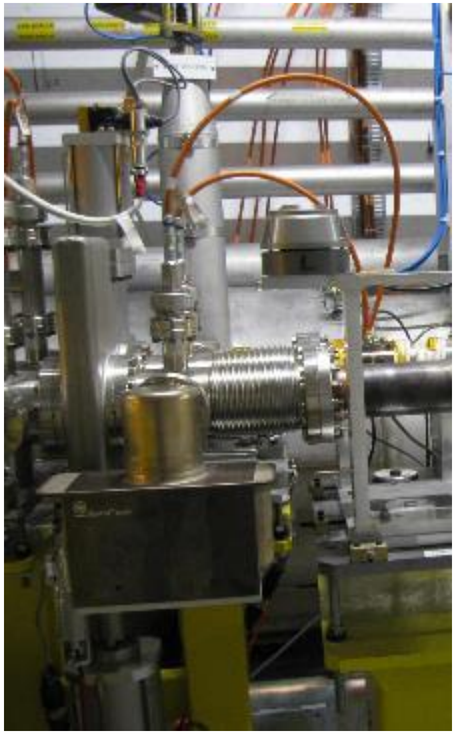
$$Q_i = C_i \alpha_i I_i\,\left(1 - {P_1}/{P_2}\right)$$

α the RGA calibration factor for gas, i
I_i the RGA current for gas I
c_i the conductance for gas i

Vacuum layout

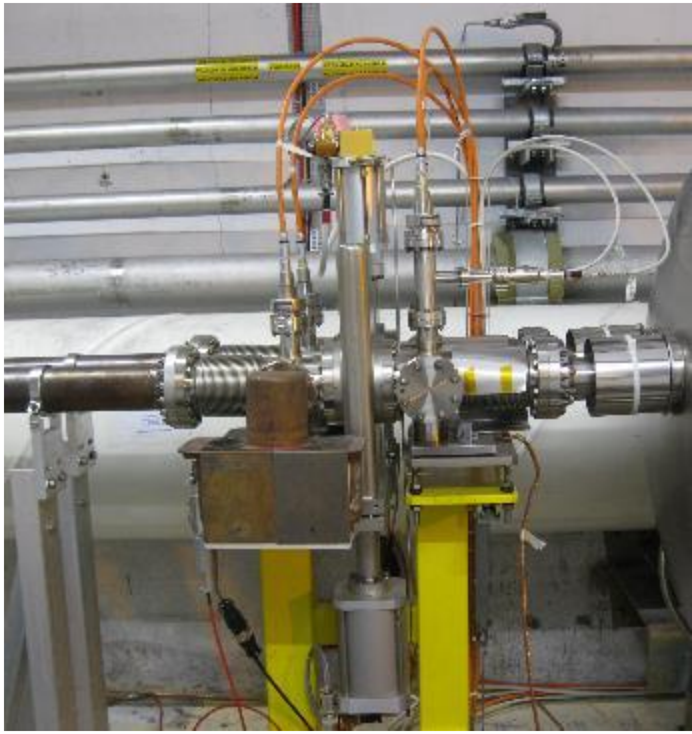
- The vacuum system is divided into vacuum sectors
  - There are ~ 300 sectors valves around the LHC

- A vacuum sector is made of:



A 1st interlocked sector valve

A measurement & pumping port



A 2nd interlocked sector valve

Fixed point

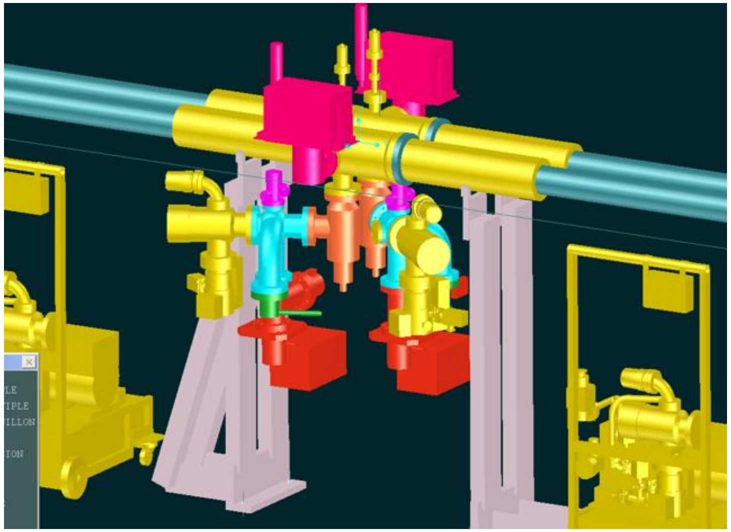
- Long vacuum chambers are hold by a single fixed support and mobile supports
- They are connected by compensator bellows
- LHC vacuum chambers are 7 m and expand by 35 mm during bakeout

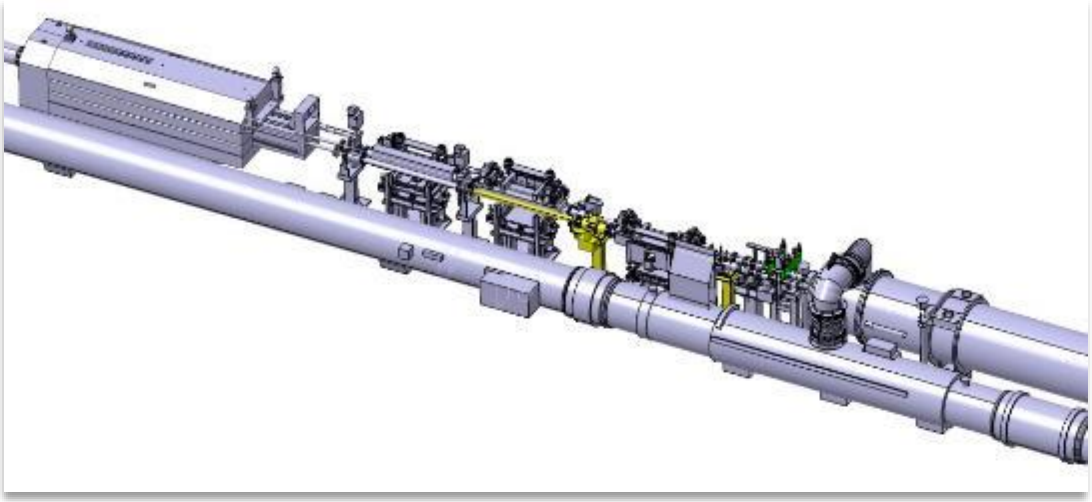
- NB: the fixed point shall be able to sustain the “vacuum force”!

Integration & vacuum Layout definition

- Integration studies allows to check :
  - volumes of equipment
  - feasibility of installation / de-installation
    - ➔ easy access by a technician to all screws shall be possible!

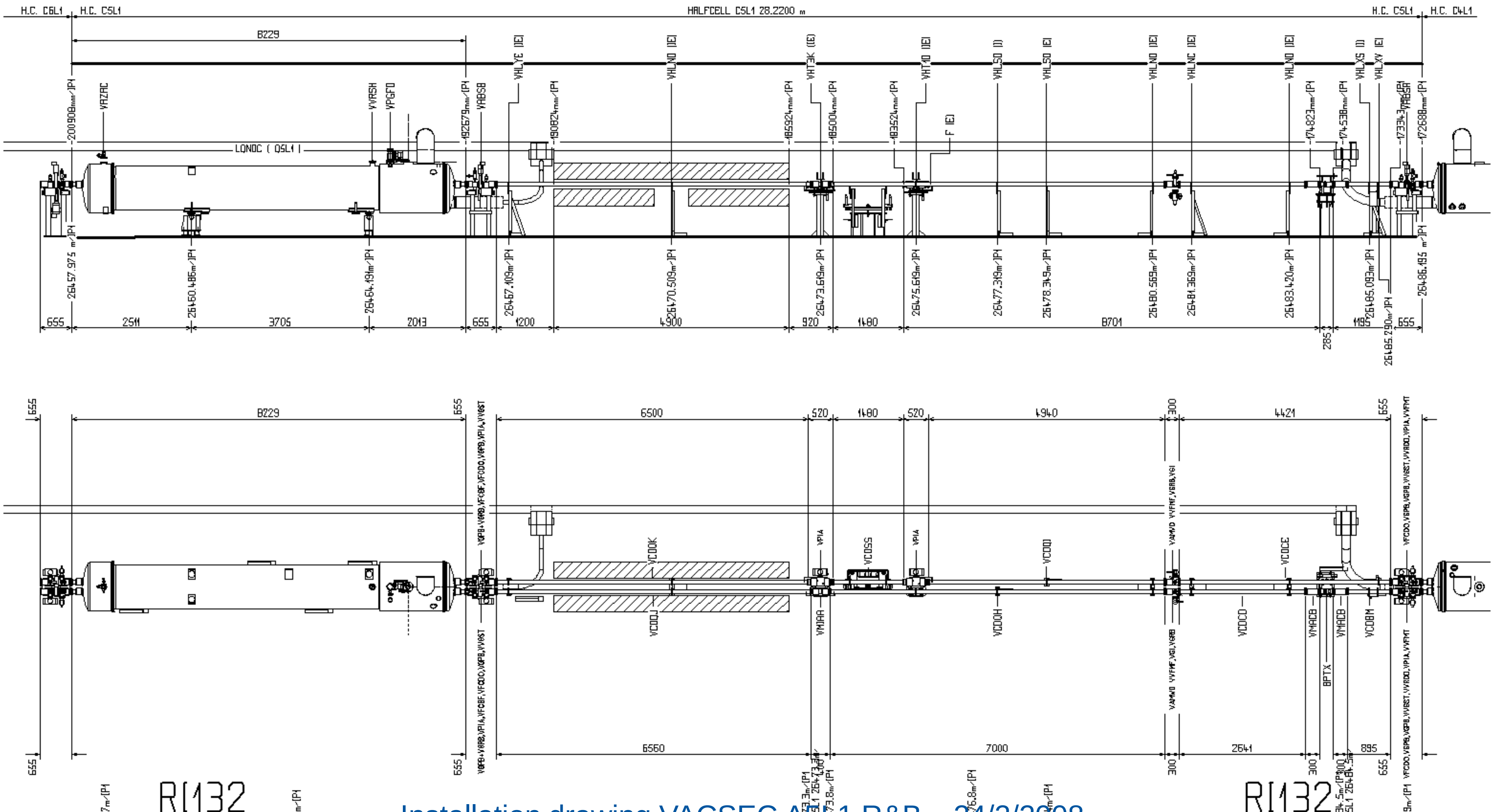
- ALL equipment shall be integrated: use of a database is mandatory





Installation drawings

- A must for the installation!
- Linked to the equipment database, follows the naming convention

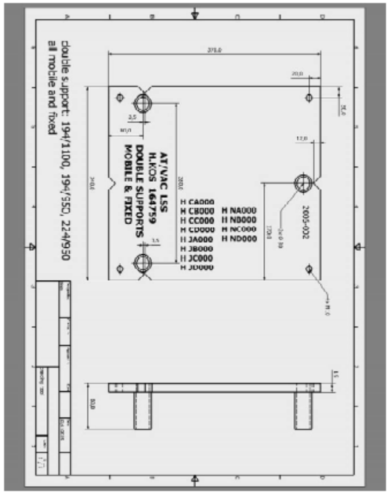


Installation drawing VACSEC A5L1 R&B – 24/2/2008

Installation preparation

- Understand the drawing !
    - Vacuum layout drawings are essential
- Drilling in the floor at marked positions defined by survey
    - Checking of the positions

Objet	Percage pour les chambres du système à vide
Nom du gabarit	**NB000**
Numero du percage	A
Positionnement du gabarit	**Croix interieure machine (passage)**
Declage	0.097
Diametre du foret	22 mm
Profondeur	125 mm
Type de cheville	HILTI HIS-N M12X1200258017
Trace au sol	**XM000 7L3**
Position	6456.5838
Elément	VCDA.A7L3.B
Image	



Sector valves assemblies

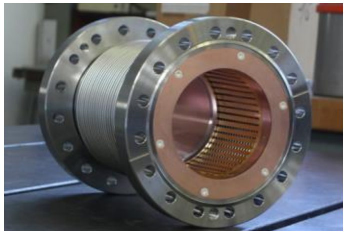
- Sector valves are fixed point!
- Sector valves are aligned!

The first sector valves assembly installation in LHC
VACHB in VACSEC A5L8 R&B 28/06/2006

Installing supports & vacuum chambers

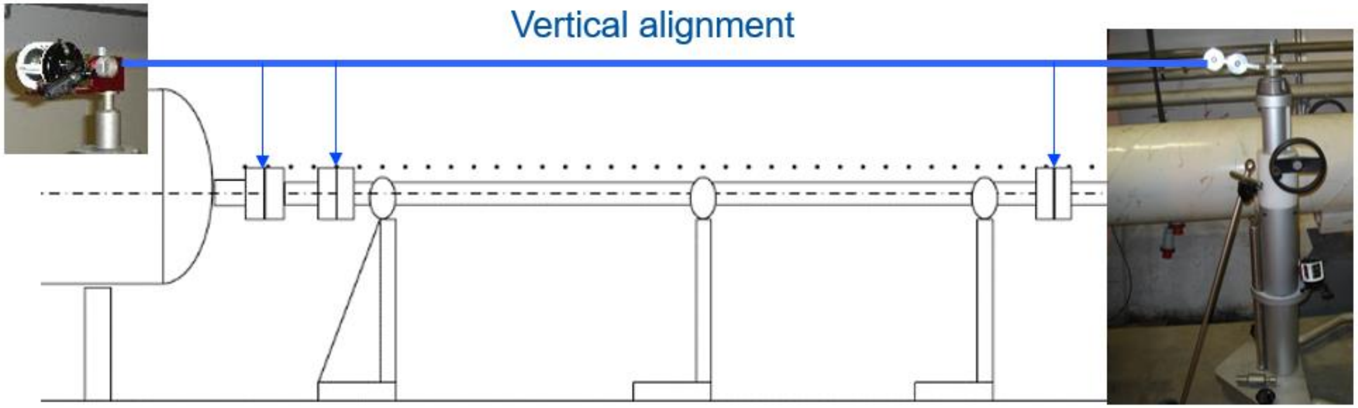
- Positioning and pre-alignment of supports
- Positioning and alignment of vacuum chambers
- Closure of vacuum sector with vacuum modules

The first LSS chambers installed in LHC (LSS8L 13/7/2006)



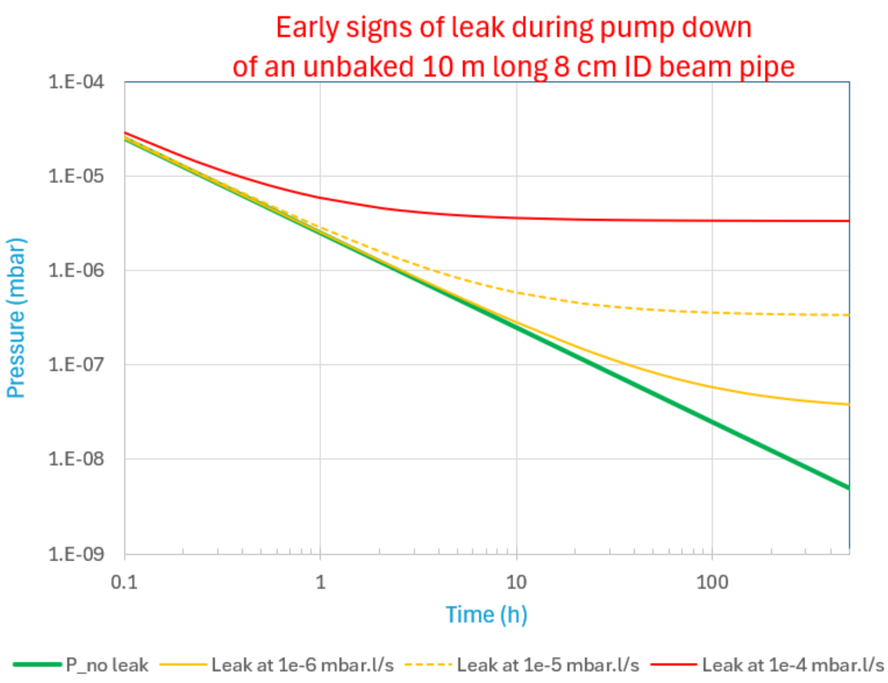
Vacuum module

Transverse alignment



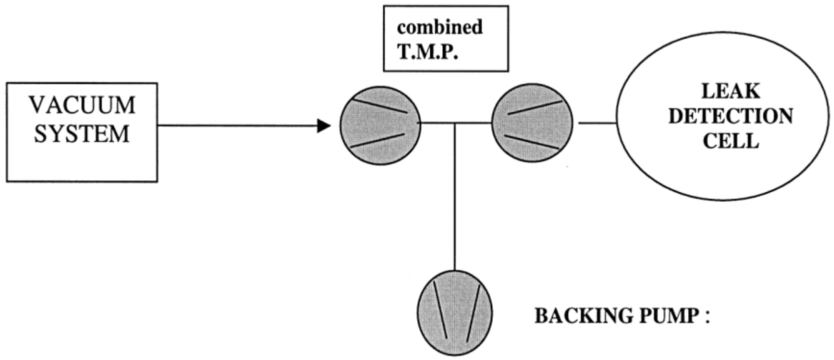
Leak detection

- Once assembled & pumped down, the leak detection of the vacuum sector starts
- All leaks greater than 10^{-11} mbar.l/s shall be eliminated
- Helium is sprayed around the test piece and a leak detector (*or a* RGA tuned to He signal) is connected to the device under test
- Usual candidates to leak:
  - gaskets (following bad installation or bad thermalization during bakeout),
  - welds
  - Beam induced heating at specific position, corrosion etc…

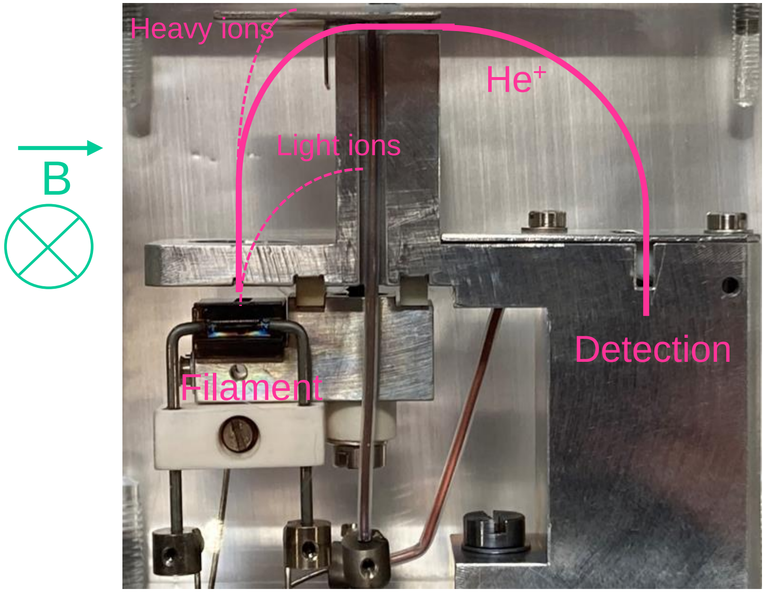


Leak detector

- Molecules are ionized, accelerated and deflected by a magnetic sector for detection
- The magnetic sector separate helium from other gases



Counter flow method



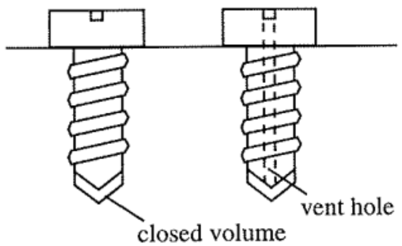
Leak detection cell

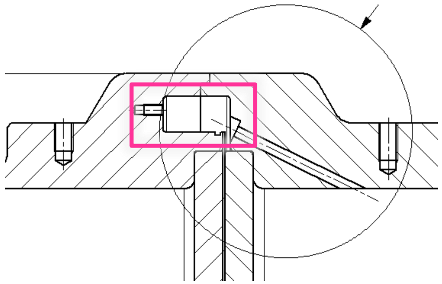
- In-situ calibration is possible

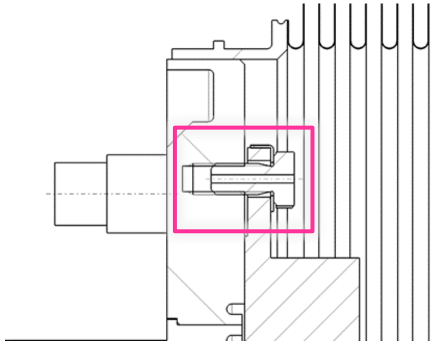
- Detection limit: 10^{-12} mbar.l/s (10^{-13} Pa.m^3/s)

Virtual leaks

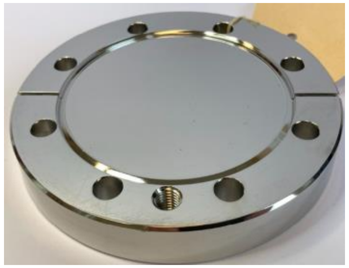
- Virtual leaks must be eliminated during the design phase.
- Air leakage from a trapped volume
  - Ventilation holes for screws

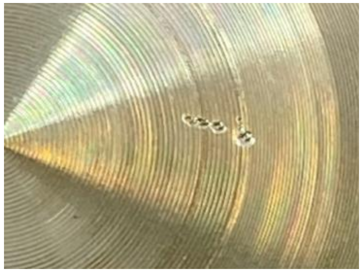






- Air diffusion out of a porous wall (or through the wall at the extreme)
  - X-ray control of materials
  - Use of 3 dimensionally forged flange material (do not use rolled material)

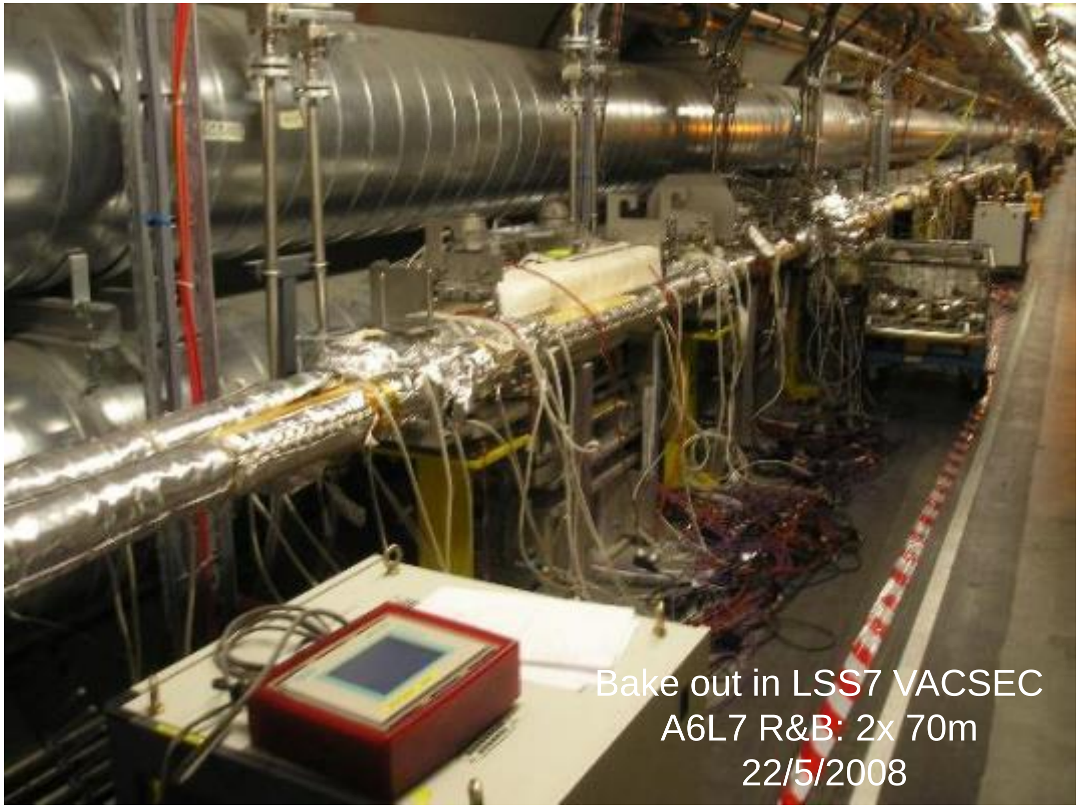




- Argon leakage out of porous welds

Bakeout installation

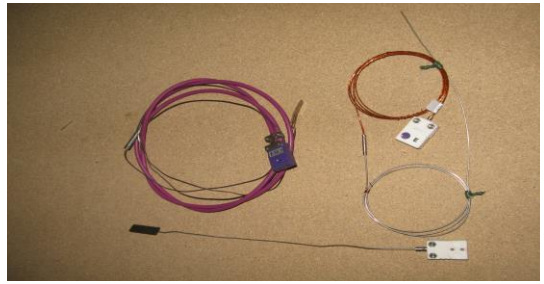
- All components are baked altogether, including beam pipes in warm magnets
- PLC controlled heating cycle
- Beware of possible long time constant and low temperature reach for components placed inside a vacuum system (due to poor thermal conductivity or heavy objects)
- Cold spot are forbidden
- Better higher temperature than long bakeout time duration (due to hydrogen diffusion)
- A bakeout above 130-150˚ C removes water



Bake out in LSS7 VACSEC
A6L7 R&B: 2x 70m
22/5/2008

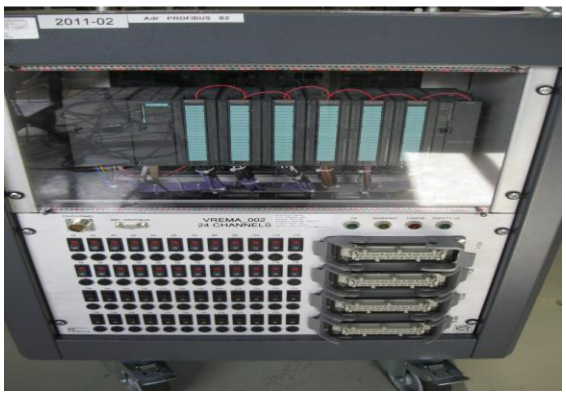
Material for bakeout

Collars



thermocouples

bakeout jackets



racks

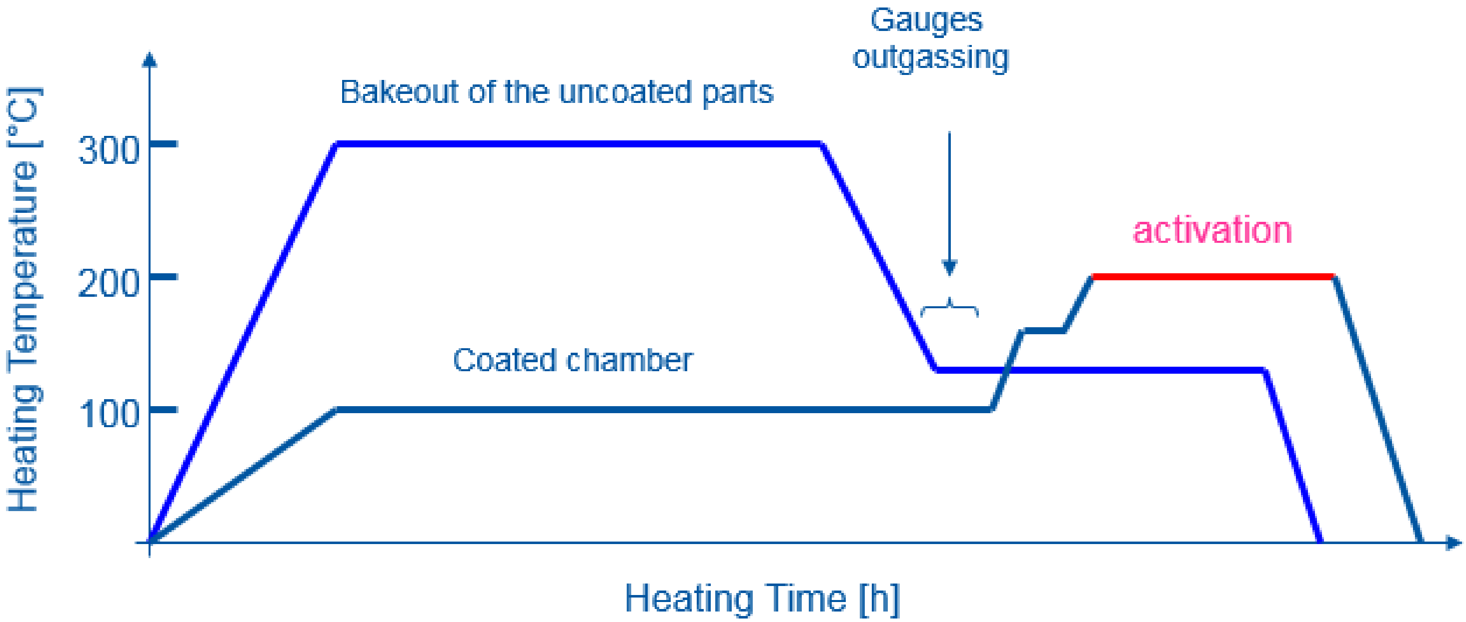
heating tape

Storage area

All parts shall be baked (including in vacuum assemblies) : cold spots are forbidden!

Commissioning of the NEG coated vacuum system

- Bake out of stainless-steel part first
- Followed by NEG activation at ~ 200 ºC

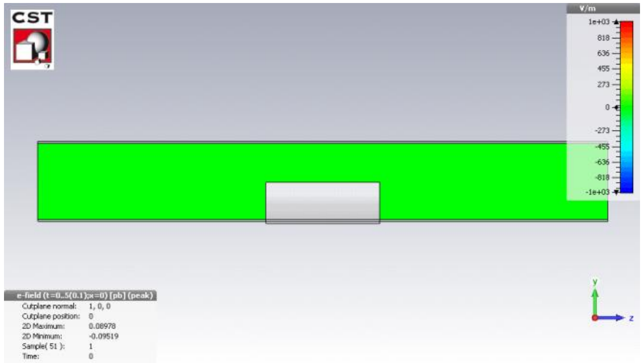


Courtesy G. Bregliozzi, P. Chiggiato

Let’s the beam circulates!

Beam impedance matters!

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

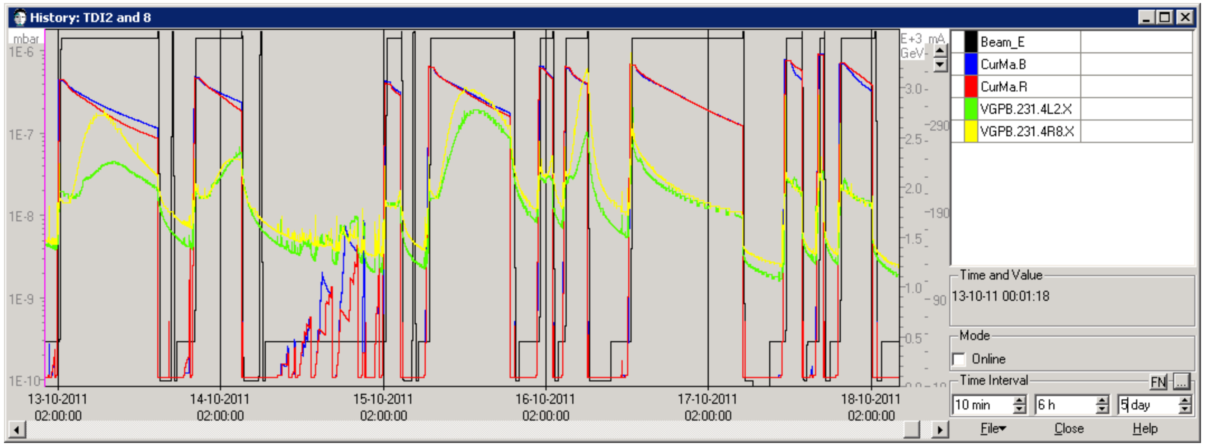


X. Buffat, CAS, 2024

➔ "Smooth" metallic beam pipe without aperture transitions

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

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

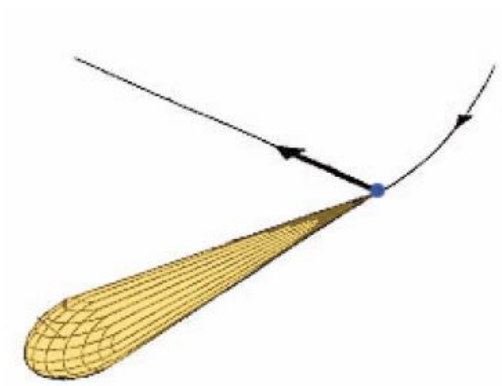


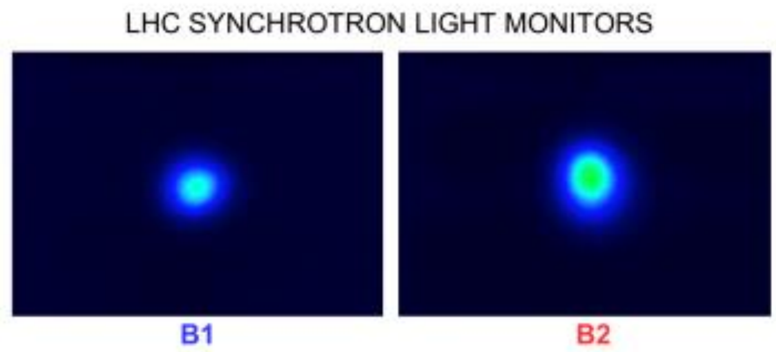
VMTSA – Nov 2011

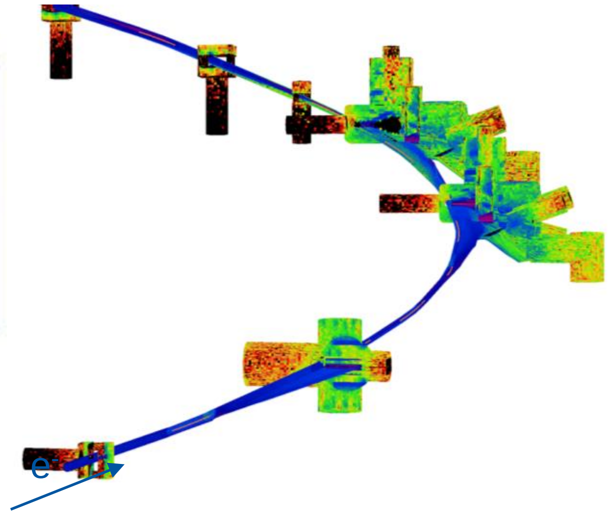
B. Salvant et al. Updated on beam induced RF heating in the LHC, Proc. IPAC 2013
E. Metral *et al.* Lessons learnt and mitigations measures for the CERN LHC equipment with RF fingers, Proc. IPAC 2013

Synchrotron radiation

- A charged particle which is accelerated produce radiation
- For a relativistic particle, the radiation is highly peaked (opening angle ~ $1/\gamma$)
- 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

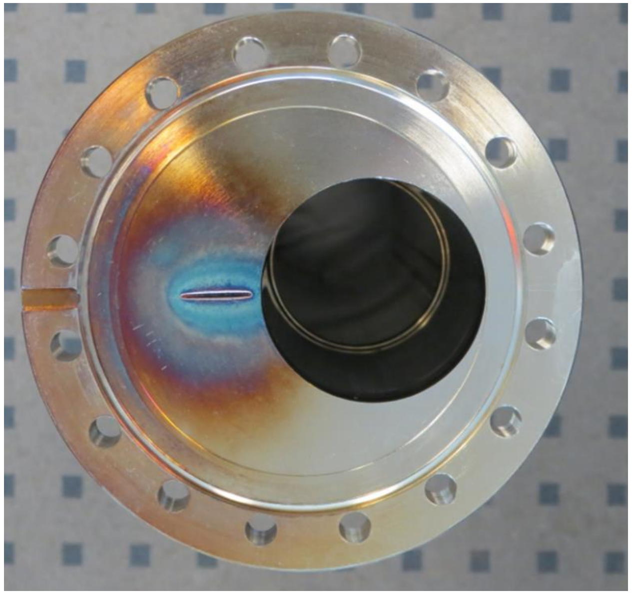
A. Hofmann, CAS 1996, CERN 98-04

L. Rivkin, CAS 2008

Ray tracing in a real machine
courtesy R. Kersevan

SR 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

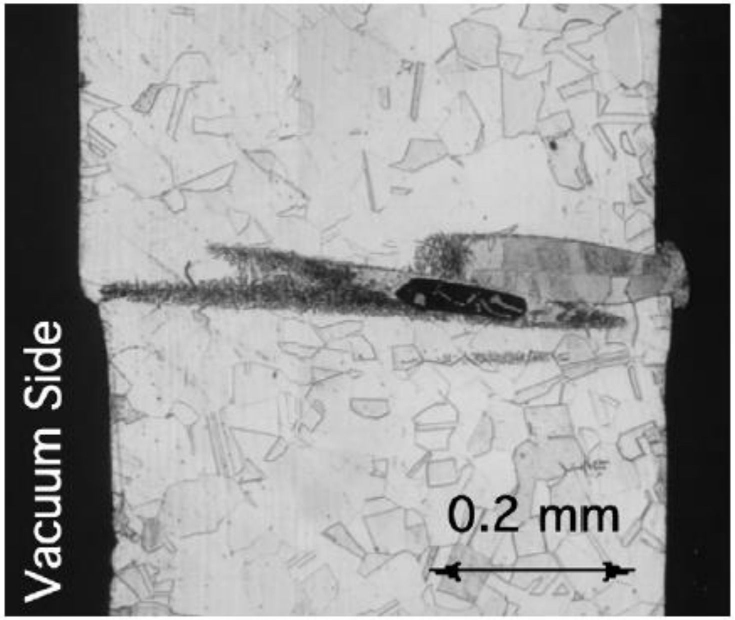


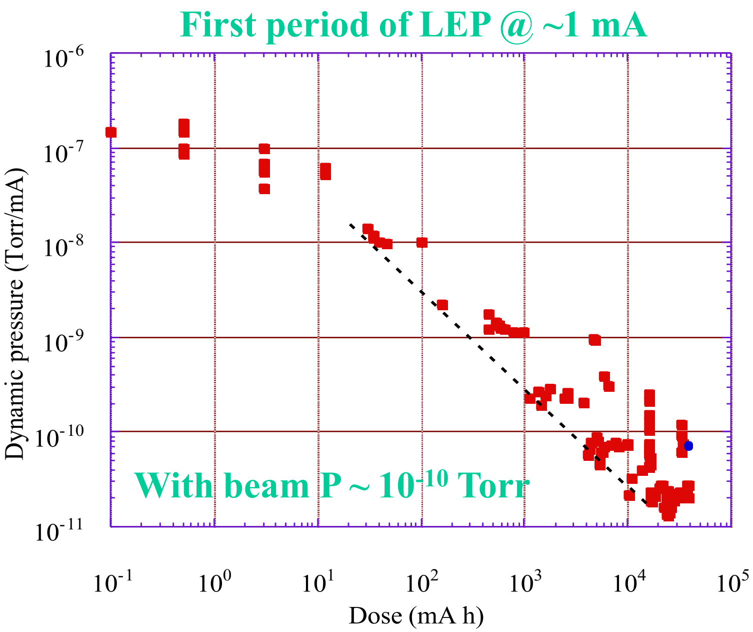
Fig. 6. Cross section of the injection chamber wall at the broken part. It seems that the electron beam hits the thin wall several times, since many traces of electron beam bombardment were found.

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

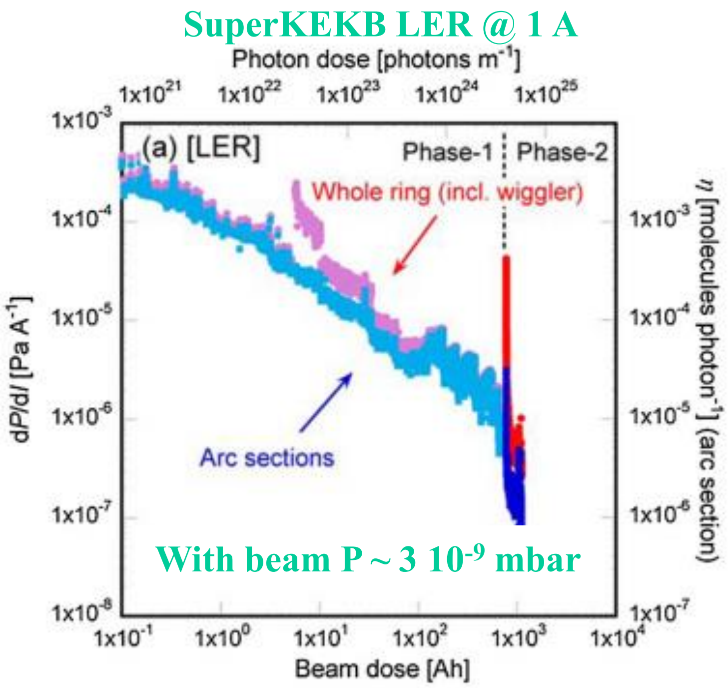
Photon stimulated molecular desorption

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

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



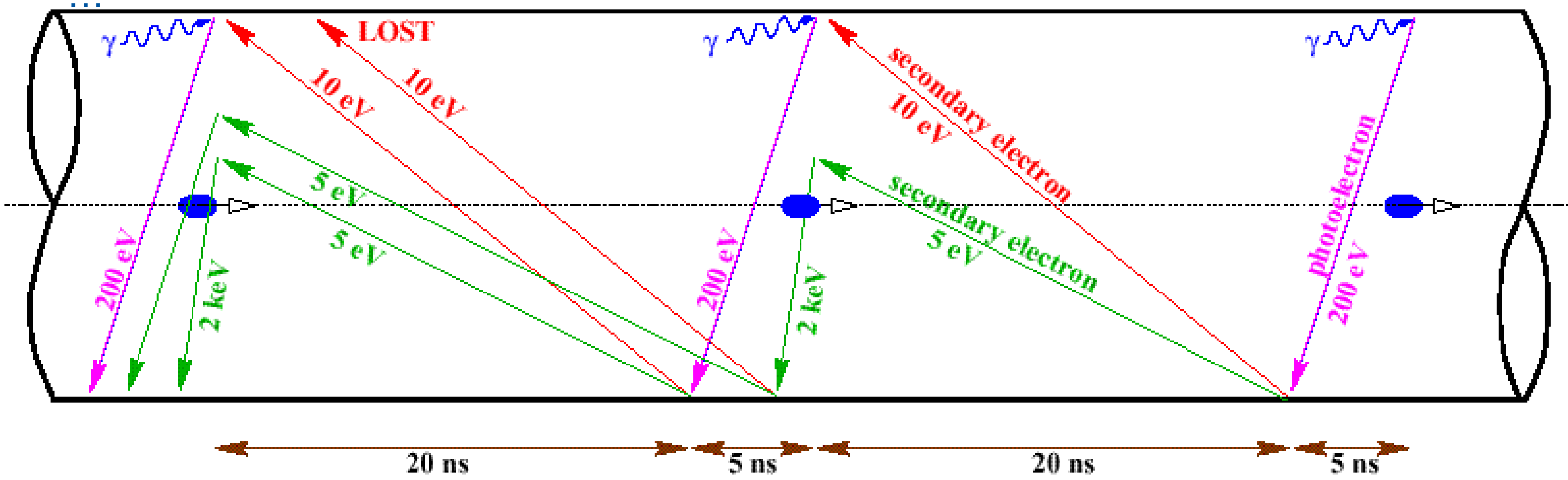
O. Gröbner. Vacuum 43 (1992) 27-30



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

Electron cloud: example of LHC

- Electron cloud is observed in most of modern machines …



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

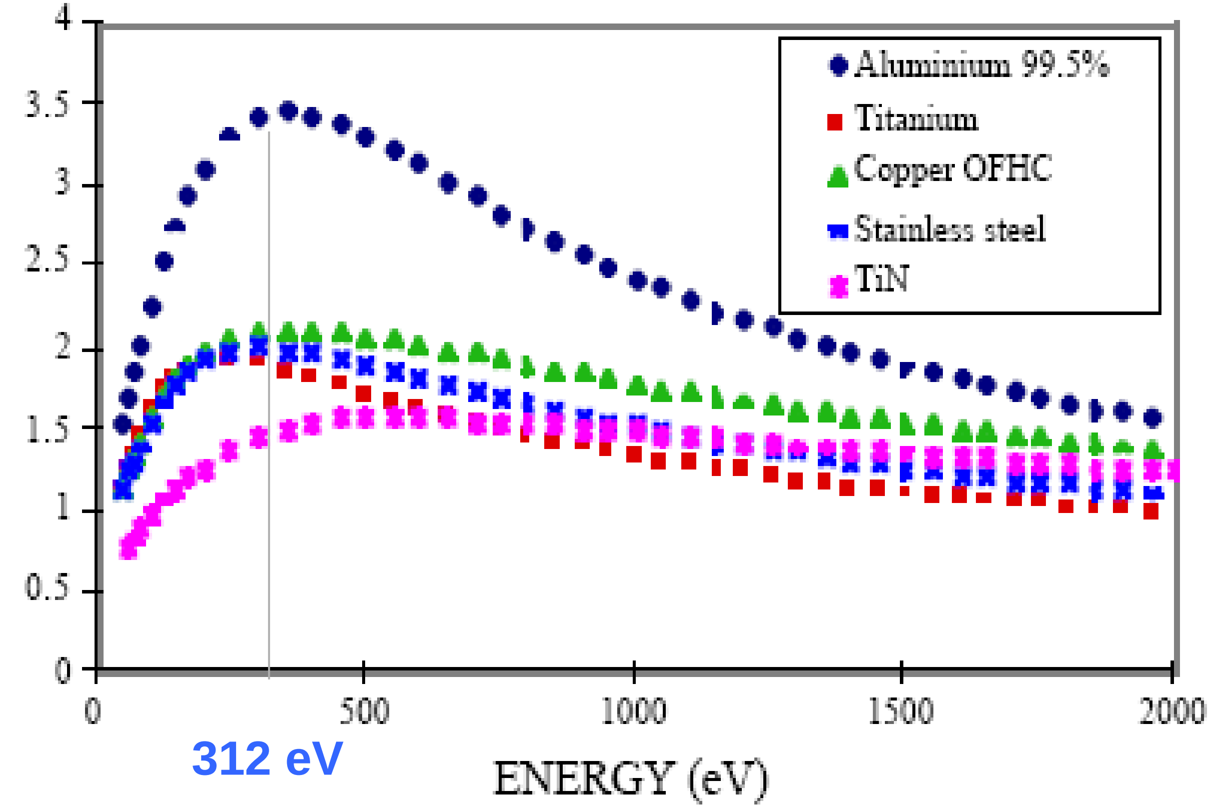
  …

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

SEY: surface nature and state matters!

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

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



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

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 of an accelerator.

Some selected references

- CAS of course !
  - Cern Accelerator School, Vacuum technology, CERN 99-05
  - Cern Accelerator School, Vacuum in accelerators, CERN 2007-03
  - Cern Accelerator School, Vacuum for particle accelerators, CERN-ACC-2020-0009

- Handbook of accelerator physics and engineering, world scientific, 2013

- Handbook of vacuum technology, K. Jousten, Wiley-VCH Verlag, 2016

- Bases en technique du vide, N. Rouviere, G. Rommel, SFV, 2017.

- Vacuum in particle accelerators, O.B. Malyshev, Wiley-VCH Verlag, 2019.

Thank you for your attention !!!

De tuin der lusten by Jheronimus Bosch, 1450-1516