

Vacuum Systems

by José Miguel JIMENEZ



Dr. José Miguel JIMENEZ
CERN, Technology Department
Head of the Vacuum, Surfaces and Coatings group



Vacuum Systems

Outline

- Vacuum in Particle Accelerators
- Vacuum Basics
- Instrumentation & Pumping
- The LHC Case



Vacuum in Particle Accelerators

Why is Vacuum needed in particle accelerators?

Vacuum aims to reduce beam-gas interaction which is responsible for:

- Machine performance limitations:
 - Reduction of beam lifetime (nuclear scattering)
 - Reduction of machine luminosity (multiple coulomb scattering)
 - Intensity limitation by pressure instabilities (ionization)
 - Electron (ionization) induced instabilities (beam blow up)
- Background to the experiments
 - Non-captured particles which interact with the detectors
 - Nuclear cascade generated by the lost particles upstream the detectors



Vacuum in Particle Accelerators

What are the Vacuum Engineering constraints? (1/2)

- Beam vacuum pipes are designed to:
 - Minimise beam impedance and HOM generation
 - Optimise beam aperture
 - Intercept heat loads (values are given for LHC)
 - Synchrotron radiation (0.2 W.m^{-1} per beam)
 - Energy loss by nuclear scattering (30 mW.m^{-1} per beam)
 - Image currents (0.2 W.m^{-1} per beam)
 - Energy dissipated during the development of electron clouds
- Vacuum systems shall be optimised for integration and radiation issues
 - Operation & Maintenance costs



Vacuum in Particle Accelerators

What are the Vacuum Engineering constraints? (2/2)

- Basic vacuum requirements
 - Depend more on beam performance than on beampipe sizes
 - Nature of particles, Energy, Intensity, Bunch densities, etc.
 - Dynamic effects dominate when increasing beam energy and intensity,
 - Low energy ion accelerators are an exception
- Higher beam energy means larger size
 - Requires a trade-off between performance and cost
 - Higher demand on integration and logistics



Vacuum in Particle Accelerators

LHC Injectors – Large diversity in age & Technologies

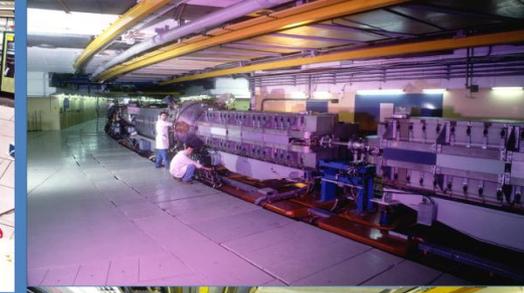
LINAC2 (Protons)
LHC Injector's chain



LINAC3 (Ions)
LHC Injector's chain



Proton Synchrotron (PS)
LHC Injector's chain



PS-BOOSTER
LHC Injector's chain



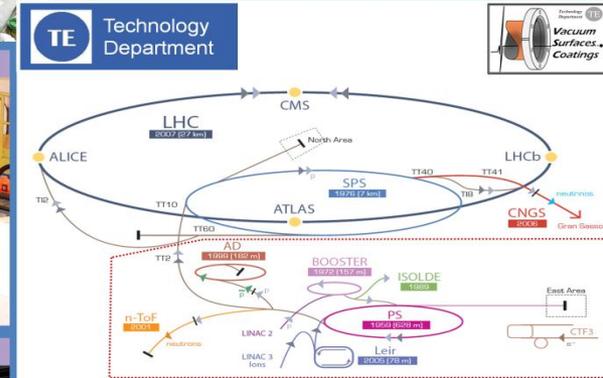
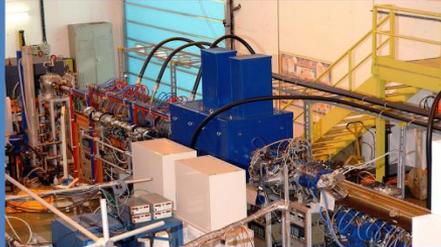
Low Energy Ion Ring (LEIR)



ISOLDE Experimental Hall
TE-VSC contribution to ISOLDE Operation

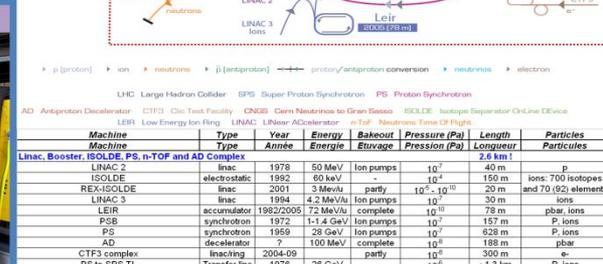
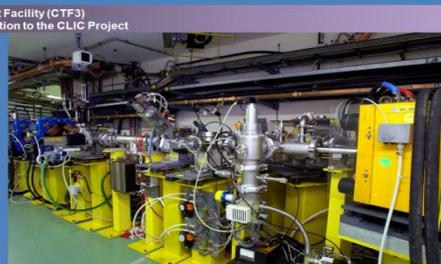
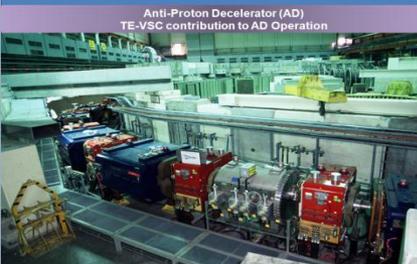


REX-ISOLDE Experimental Hall
TE-VSC contribution to REX-ISOLDE Operation



LHC: Large Hadron Collider, CMS: Compact Muon Solenoid, SPS: Super Proton Synchrotron, PS: Proton Synchrotron, AD: Antiproton Decelerator, CTF3: CLIC Test Facility, CNGS: CERN Neutrinos to Gran Sasso, ISOLDE: Isotopes Separator, CLIC: CLIC, LEIR: Low Energy Ion Ring, LINAC: Linear Accelerator, n-ToF: Neutrons Time Of Flight.

Machine	Type	Year	Energy	Boreout	Pressure (Pa)	Length	Particles
LINAC 2	linac	1978	50 MeV	Ion pumps	10^{-7}	40 m	p
ISOLDE	electrostatic	1992	60 keV	-	10^{-2}	150 m	ions, 700 isotopes
REX-ISOLDE	linac	2001	3 MeV/u	purify	$10^{-5} - 10^{-10}$	20 m and 70 (50) elements	p, ions
LINAC 3	linac	1994	4.2 MeV/u	Ion pumps	10^{-7}	30 m	ions
LEIR	accumulator	1982/2005	72 MeV/u	complete	10^{-10}	78 m	pbar, ions
PSB	synchrotron	1972	1-14 GeV	Ion pumps	10^{-7}	157 m	p, ions
PS	synchrotron	1959	28 GeV	Ion pumps	10^{-7}	628 m	p, ions
AD	decelerator	7	100 MeV	complete	10^{-10}	188 m	pbar
CTF3 complex	linac/ing	2004-09	-	purify	10^{-8}	300 m	e-
PS to SPS TL	transfer line	1976	26 GeV	-	10^{-6}	~1.3 km	p, ions



Vacuum in Particle Accelerators

LHC Arcs & Long Straight Sections – Cold & RT systems

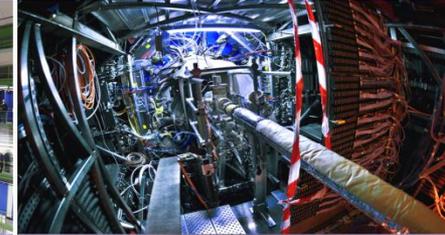
The Large Hadron Collider (LHC)



LHC bending sections (arcs)



LHC CMS Detector



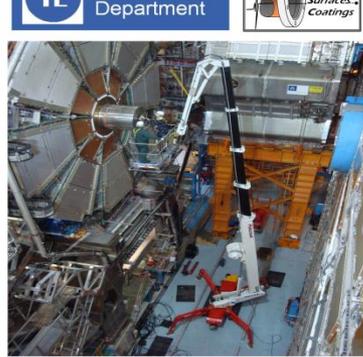
LHC Alice Detector



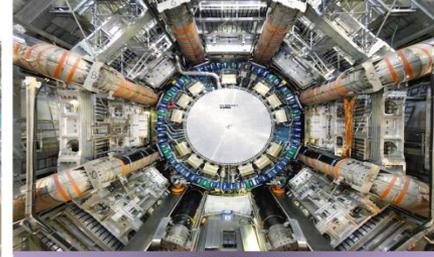
Cryogenic magnets interconnection



Beams get recombined: Twin to Single aperture



LHC ATLAS Detector



LHC-B Detector



Beampipes in the long straight sections



Beam dump line on top of circulating beams



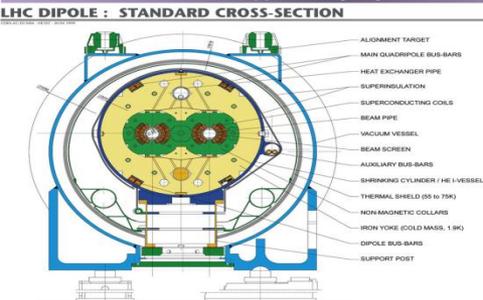
Beampipes in the long straight sections



Beampipes in the long straight sections



Beampipes in the long straight sections



Machine	Type	Year	Energy	Beamout	Pressure (Pa)	Length	Particles
LHC Accelerator							
LHC Acc (Beam G2 Magnets & QRL, insul.)	collider	2007	2.7 TeV	complete	< 10 ⁻¹⁰	2.4 x (2.25 km)	p, ions
LSS RF separated beams						2 x 3.2 km	
LSS RF recombinator						~ 270 m	
Experimental areas						~ 180 m	
Beam Dump Lines TDR268	Transfer line	2006	7 TeV	-	10 ⁻⁹	12 x 720 m	



Beampipe are entirely welded LHC Beam Dump transfer lines

Vacuum Basics

Physical Quantities

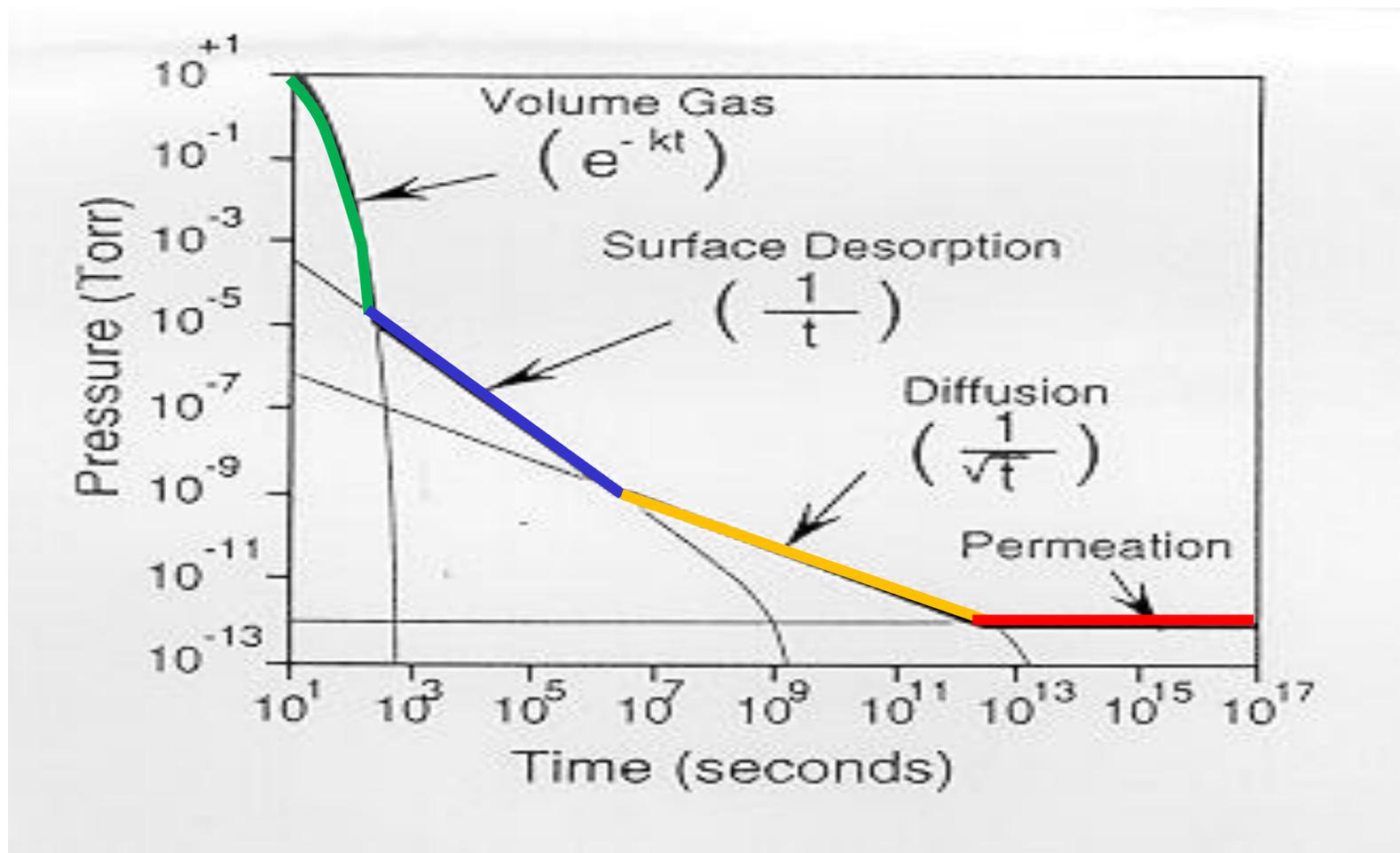
A gas in an enclosed space can be physically described by:

- Volume
 - Space occupied by the gas ; taken to be the volume of the vacuum enclosure since a gas will expand to fill the space in which it is confined; often measured in liters [S.I. in m³].
- Temperature
 - A measure of the kinetic energy possessed by the gas molecules; generally determined by the temperature of the surface in contact with the gas molecules; measured in Celcius [°C] or K Kelvin [K]
- Amount
 - Number of gas molecules; measured in gram-mole [6.022 x 10²³ atoms/mole]



Vacuum Basics

Limiting mechanisms during pump down



Vacuum Basics

Units of Pressure

The pressure is the force exerted by a molecule per unit of surface : $1 \text{ Pa} = 1 \text{ N/m}^2$

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

Never forget: Pressure = Force → 1 kg/cm² !

Vacuum Basics

Gas Laws (1/2)

- Avogadro's Law

- Under the same conditions of pressure and temperature, equal volumes of all gases have the same number of molecules: called a *mole*.

$$\frac{6.023 \times 10^{23} \text{ particles}}{22.4 \text{ l}} \Big|_{760 \text{ torr}, 273^\circ \text{ K}} = 2.69 \times 10^{22} \text{ particles / l} \Big|_{760 \text{ torr}, 273^\circ \text{ K}}$$

$$3.3 \times 10^{19} \text{ particles / l} \Big|_{1 \text{ torr}, 293^\circ \text{ K}} = 2.5 \times 10^{19} \text{ particles / l} \Big|_{1 \text{ mbar}, 293^\circ \text{ K}}$$

- Boyle's Law

- Original pressure times original volume equals new pressure times new volume

$$P_1 V_1 = P_2 V_2$$

- Charles' Law

- As we cool a gas, its volume gets smaller.
If we heat the gas, its volume increase.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Vacuum Basics

Gas Laws (2/2)

- Law of Gay-Lussac

- If the temperature of a volume of gas at 0°C is changed by 1°C, the volume will change (+/-) by 1/273 of its original value.

Lord Kelvin used this relationship to develop the absolute temperature scale (1 K = -273 °C)

$$V = V_0 + \left(\frac{^{\circ}\text{C}}{273}\right) \times V_0 \quad \text{or} \quad V = V_0 \left(1 + \frac{^{\circ}\text{C}}{273}\right)$$

- General Gas Law

- Resulted from the combination of Boyle's and Charles' Laws:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Vacuum Basics

Units of gas density

- The quantity of gas can be presented in number of molecules (N) or in pressure-volume (PV) units.

- The two values are related by the **ideal gas equation** of state:

$$P \cdot V = N \cdot K_B \cdot T \rightarrow N = \frac{P \cdot V}{K_B \cdot T}$$

- The pressure-volume units are transformed to number of molecules when divided by $K_B T$. A given number of molecules is expressed by different pressure-volume values at different temperatures. In general the pressure-volume quantities are quoted at room temperature

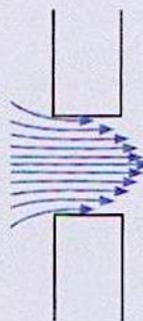
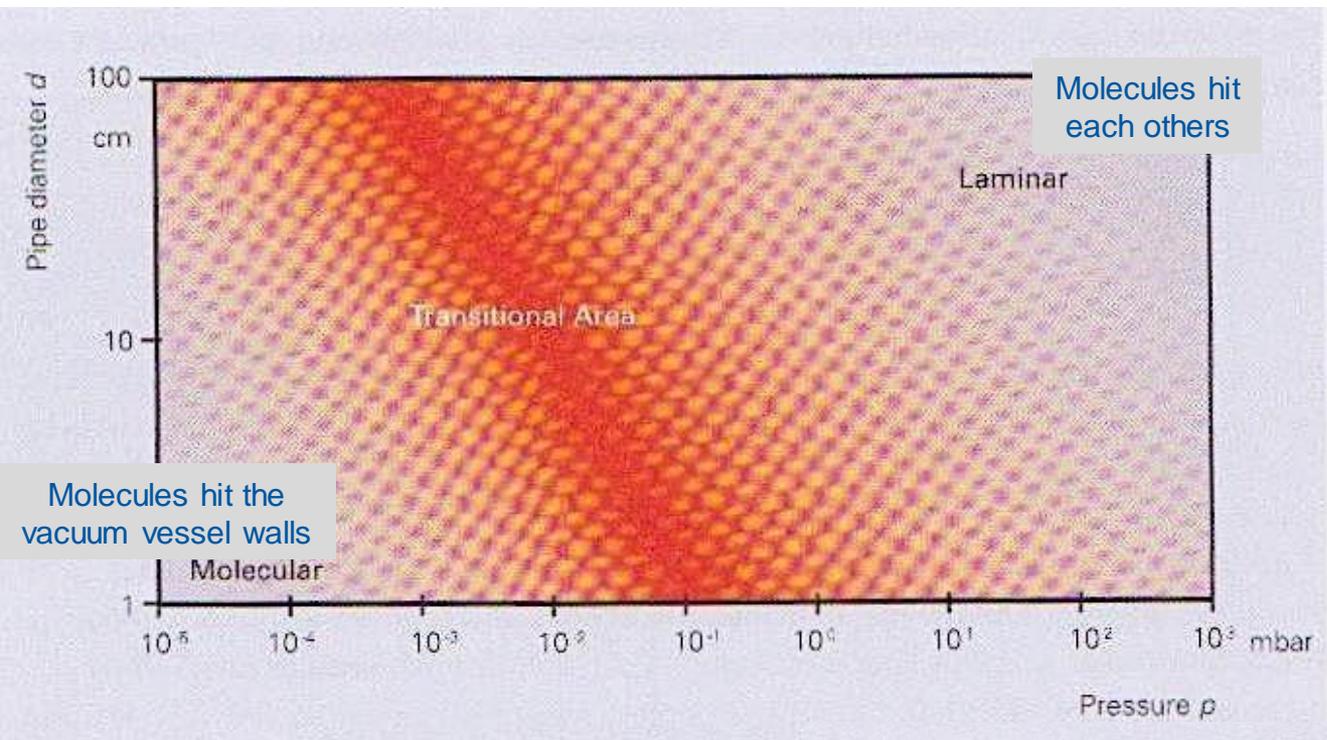
$$k_B = 1.38 \cdot 10^{-23} \left[\frac{N \cdot m}{K} = \frac{Pa \cdot m^3}{K} \right]$$
$$k_B = 1.38 \cdot 10^{-23} \left[\frac{Pa \cdot m^3}{K} \right] = 1.04 \cdot 10^{-22} \left[\frac{Torr \cdot \ell}{K} \right] = 1.38 \cdot 10^{-22} \left[\frac{mbar \cdot \ell}{K} \right]$$

for $T = T_{RT} = 296K$

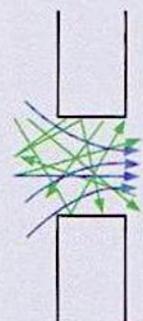
$$\frac{1}{k_B T_{RT}} = 2.45 \cdot 10^{20} [Pa \cdot m^3]^{-1} = 3.3 \cdot 10^{19} [Torr \cdot \ell]^{-1} = 2.5 \cdot 10^{19} [mbar \cdot \ell]^{-1}$$

Vacuum Basics

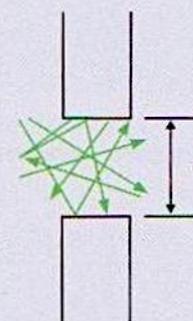
Gas Flow regimes



Continuous flow
 $Kn < 0.01$
Low vacuum



Knudsen flow
 $0.01 < Kn < 0.5$
Medium vacuum



Molecular flow
 $Kn > 0.5$
High / Ultra high vacuum

- ▶ **Continuous flow**
 - Laminar, $Re < 2,300$, for circular pipes
 - Turbulent, $Re > 4,000$, for circular pipes

- ▶ **Knudsen flow**
- ▶ **Molecular flow**

- ▶ Knudsen number $Kn = \frac{\bar{l}}{d}$

\bar{l} = Mean free path
 l_{char} = Characteristic clearance of a component through which gas flows



Vacuum Basics

Mean Free Path

- It is the path length that a molecules traverse between two successive impacts with other molecules. It depends on the pressure, the temperature and on the molecular diameter.

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

[with σ : molecule diameter]

- For air at room temperature : $\lambda_{air} [cm] = \frac{5 \times 10^{-3}}{P [Torr]}$

At atmospheric pressure, $\lambda = 70$ nm

At 1 Torr, $\lambda = 50$ μ m

At 10^{-2} Torr, $\lambda = 0.5$ cm

At 10^{-6} Torr, $\lambda = 50$ m

Vacuum Basics

Gas Throughput

- The gas throughput defines a gas flow or a pumping speed times the pressure.

$$Q = \frac{PV}{t} = P \times \frac{V}{t} = PS$$

- S being defined as the pumping speed (often in l/s)
- In steady-state or equilibrium conditions, **the throughput is conservative**, the same at one end of a vacuum system as it is at the other
- Gas Load
 - The major sources of gas loads in a vacuum system are: leaks, outgassing, contamination and permeation.
- Q and Power
 - The throughput is define as a “work” per unit of time so can be converted in Watts

$$7.50 \text{ torr } \frac{l}{s} = 1 \text{ Watt} = 1000 \text{ Pa } \frac{l}{s}$$

Vacuum Basics

Conductance (T,m) dependance

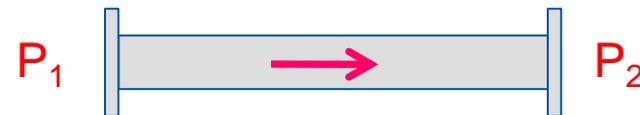
- The conductance is defined as: $C = Q/(P_1 - P_2)$
- Since the conductance is determined by the mean velocity of the gas molecule and the kinetic energy is given by: $(1/2)mv^2 = kT$
- The conductance varies as: $(T/m)^{1/2}$
- Conventionally conductance are given for: $N_2, m = 28$
- Conductance
 - Of a tube $C_{air,20^\circ} [l / s] = 12.1 \frac{D^3 [cm^3]}{l [cm]}$
 - Of an orifice $C_{air,20^\circ} [l / s] = 11.6 A [cm^2]$

Vacuum Basics

Conductance - Basic Formulas (1/2)

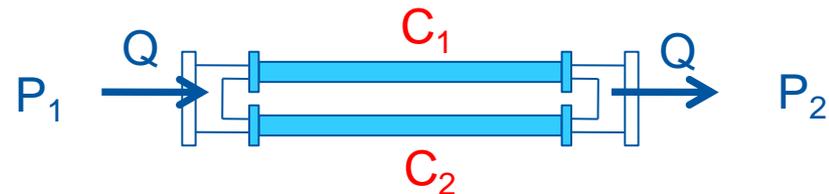
- The conductance is defined by the ratio of the molecular flow (Q) to the pressure drop along a vacuum vessel.
- Is a function of the shape of the vessel, the nature of the gas and temperature.

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



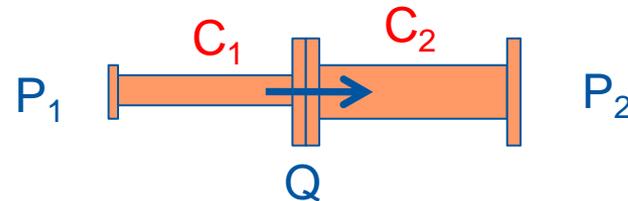
- Adding conductance in parallel

$$C = C_1 + C_2$$



- Adding conductance in series

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



Vacuum Basics

Conductance - Basic Formulas (2/2)

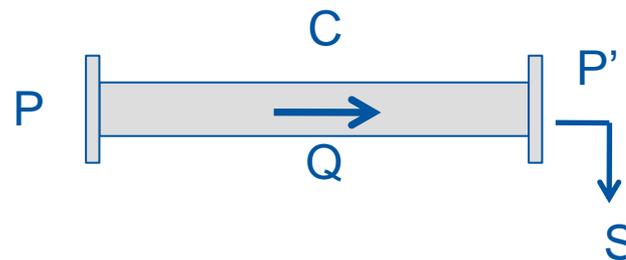
- The pumping speed (S) is the ratio of the flux of molecules pumped (Q) to the pressure (P)

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

Annotations: Q is labeled "mbar.l/s" and P is labeled "mbar". An arrow labeled "l/s" points to the S term.

- Coupling of a pump and of a vacuum chamber :

$$\begin{cases} Q = C(P - P') \\ Q = P'S \end{cases}$$
$$\Leftrightarrow S_{\text{eff}} = \frac{Q}{P} = \frac{CS}{C + S}$$



- if $C \gg S$, $S_{\text{eff}} \sim S$
- if $C \ll S$, $S_{\text{eff}} \sim C$

- Example :

- Consider a turbomolecular pump of 400 l/s (CHF 15'000) to evacuate a 10 cm diameter tube of 2 m long.
 - $S = 400$ l/s ; $C = 60$ l/s so $S_{\text{eff}} \sim 50$ l/s ... the assembly is conductance limited !
 - Alternative: $S = 60$ l/s (CHF 5'000) ; $C = 60$ l/s so $S_{\text{eff}} \sim 30$ l/s

Vacuum Basics

Total and Partial Pressure

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

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

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

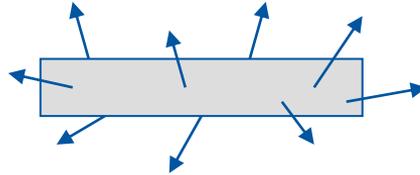
Partial pressures for atmospheric air

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

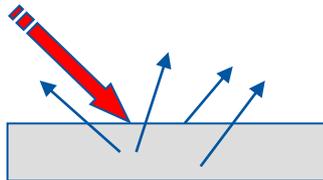
Vacuum Basics

Outgassing of Materials (1/4)

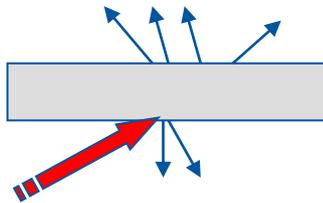
- Outgassing is the **spontaneous** evolution of gas from solid or liquid.



- Degassing is the **deliberate** removal of gas from a solid or a liquid.



- Desorption is the **release** of adsorbed chemical species from the surface of a solid or liquid.



Vacuum Basics

Outgassing of Materials (2/4)

- The various sources of gas in vacuum systems
 - Bulk thermal outgassing: Permeation and Diffusion
 - Surface thermal outgassing: Water, Hydrogen
 - Stimulated desorption: Ions, Electrons and Photons
- Reduction of gas loads by
 - Surface finishing, Chemical polishing, Bake-out and Firing
- Outgassing rates are measured by
 - Accumulation method
 - Throughput method
 - For both methods gas repumping has to be taken into account.
 - Pressure gauges interfere with the outgassing measurements by pumping and releasing gas molecules.



Vacuum Basics

Outgassing of Materials (3/4)

- Outgassing of Unbaked Metals
 - Water is the main gas desorbed
 - Outgassing rate of water decreases following a $1/t$ law
 - Water outgassing does not depend significantly on the nature of metals, on surface treatments and on temperature (for temperatures lower than 110°C)
 - No methods, except heating, exist to quickly remove water from unbaked metals
- Outgassing of baked metals
 - Hydrogen is the main gas desorbed by baked metals
 - Diffusion model predicts values for the hydrogen outgassing
 - Firing decrease the hydrogen outgassing rate by more than 2 orders of magnitude
- Outgassing of Polymers
 - Much higher gas content and gas mobility than metals – 3 to 5 orders of magnitude
 - Permeation of atmospheric gases is not anymore negligible
 - Elastomers – if could not be avoided - should be heat treated in air or in vacuum before any application in high vacuum



Vacuum Basics

Outgassing of Materials (4/4)

Unbaked stainless steel (10 h pumping):

$$q_{\text{H}_2\text{O}} = 2 \times 10^{-10} \text{ Torr } \ell \text{ s}^{-1} \text{ cm}^{-2}$$

$$q_{\text{H}_2\text{O}} = 6.6 \times 10^9 \text{ molecules cm}^{-2}$$

Baked stainless steel (150° C x 24 h):

$$q_{\text{H}_2} = 2 \times 10^{-12} \text{ Torr } \ell \text{ s}^{-1} \text{ cm}^{-2}$$

$$q_{\text{H}_2} = 6.6 \times 10^7 \text{ molecules s}^{-1} \text{ cm}^{-2}$$

Baked OFS Copper (200° C x 24 h):

$$q_{\text{H}_2} = 2 \times 10^{-14} \text{ Torr } \ell \text{ s}^{-1} \text{ cm}^{-2}$$

$$q_{\text{H}_2} = 6.6 \times 10^5 \text{ molecules s}^{-1} \text{ cm}^{-2}$$

Bayard-Alpert gauges (W filaments)

$$Q \approx 10^{-9} \text{ Torr } \ell \text{ s}^{-1}$$

$$Q \approx 3 \times 10^{10} \text{ molecules cm}^{-2}$$

Bayard-Alpert gauges (Thoria coated W filaments)

$$Q \approx 10^{-10} \text{ Torr } \ell \text{ s}^{-1}$$

$$Q \approx 3 \times 10^8 \text{ molecules cm}^{-2}$$

Residual gas analyzer (W filaments)

$$Q \approx 10^{-8} \text{ Torr } \ell \text{ s}^{-1}$$

$$Q \approx 3 \times 10^{11} \text{ molecules cm}^{-2}$$

Vacuum Basics

Electrical Analogy (1/2)

- The ground potential is equivalent to zero pressure.
- Long tubes are subdivided in smaller units and considered as single vacuum chambers (conductance + volume) in series.
- Non-linear electric characteristics can be used to simulate pressure and time dependent conductance and pumping speed.
- In this way pressure excursions into viscous regime can be evaluated

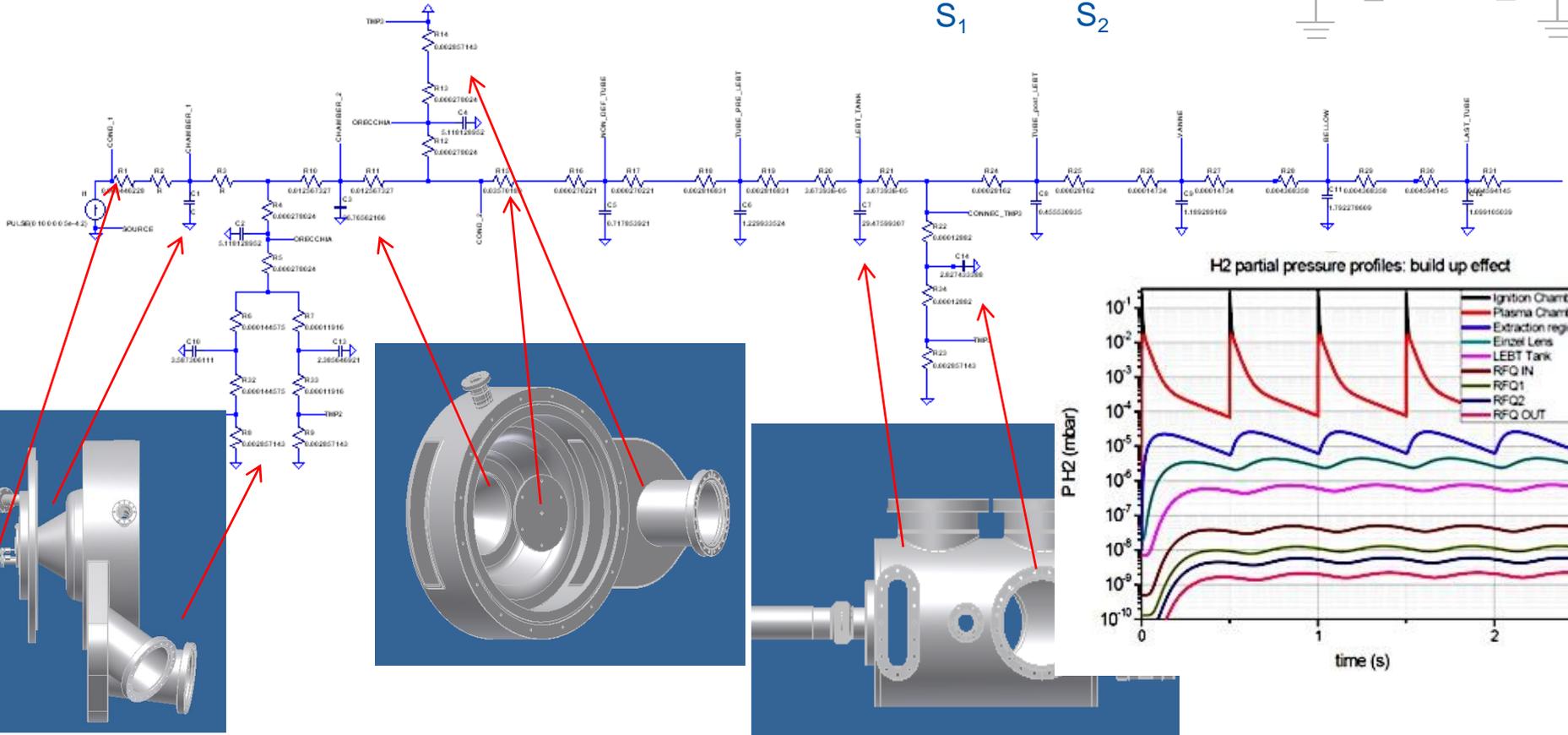
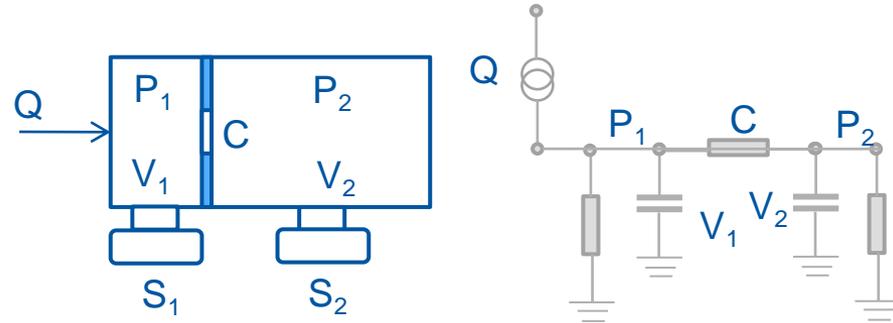
Vacuum element	Electrical elements
Conductance C	Conductance $1/R$ 
Gas Flow Q	Current I
Pressure P	Voltage V
Volume V	Capacitance C 
Pump	Conductance to ground 
Gas source	Current generator 
Constant pressure source	Voltage supply 
Vacuum chamber with conductance and volume	

Vacuum Basics

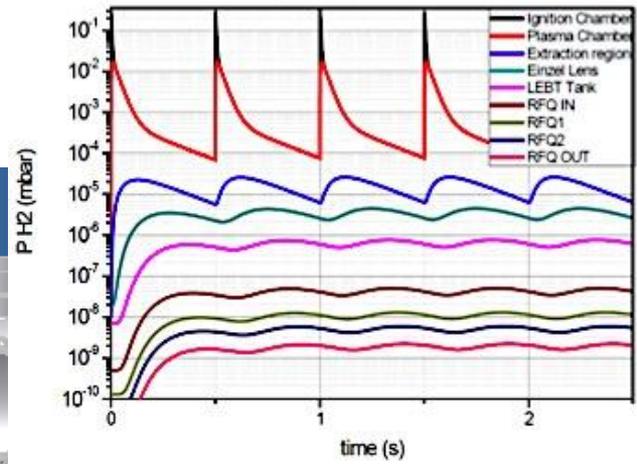
Electrical Analogy (2/2)

A more complex example: part of the Linac4 H-source (C. Pasquino et al., CERN, AT/Note/2012/043 TECH)

Simple example: differential pumping



H2 partial pressure profiles: build up effect



Vacuum Basics

Leak Detection

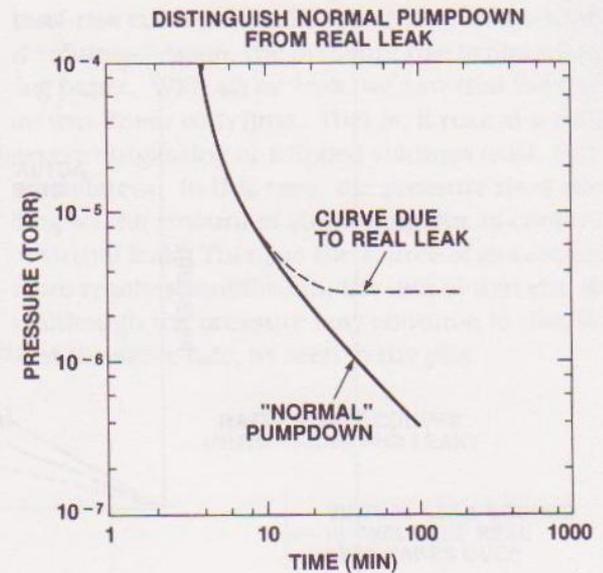
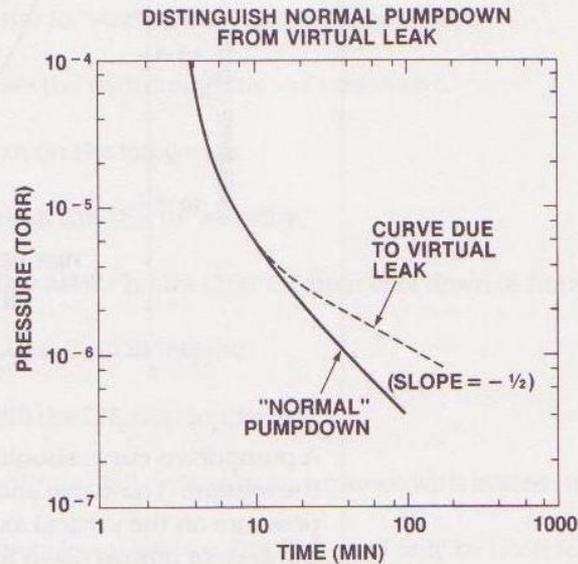
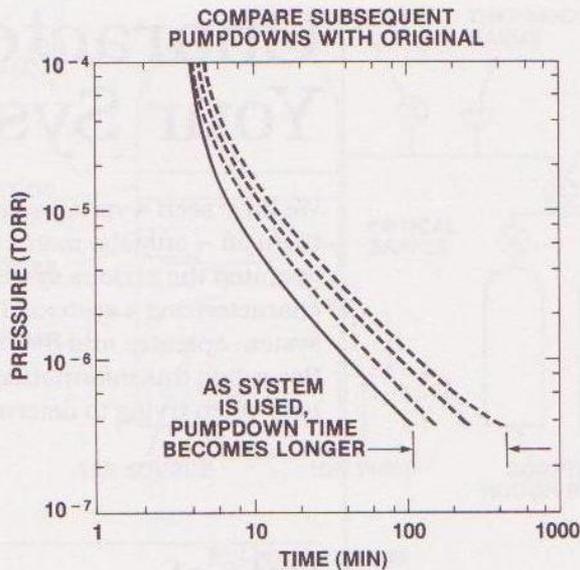
- Remind to estimate the leak rates before starting the leak detection
 - $Q = P \times S_{\text{eff}}$
- Check the leak tightness of the entire system
 - Leak detector + pumping station
- Start the leak detection by moving against the air flow towards the leak detector
- Identify all leaks and THE leak
 - Bigger leaks are more difficult to find
 - Install plastic bags to confine the helium spraying
 - Never saturate the leak detector unless you are SURE to be on THE leak
 - Recovering the helium leak detector background could require several hours (ex: trapping on super-insulation layers)
 - Use very small helium flows to find the leaks
- In case of doubt, go ahead with a confirmation by another team



Vacuum Basics

Leak Detection - Pump down curves

Careful Pressure follow-up during pump down provides indications on the leak tightness

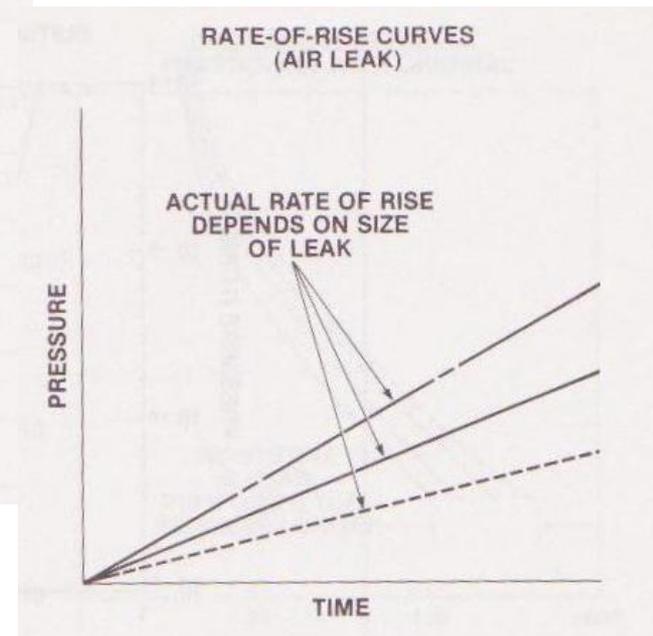
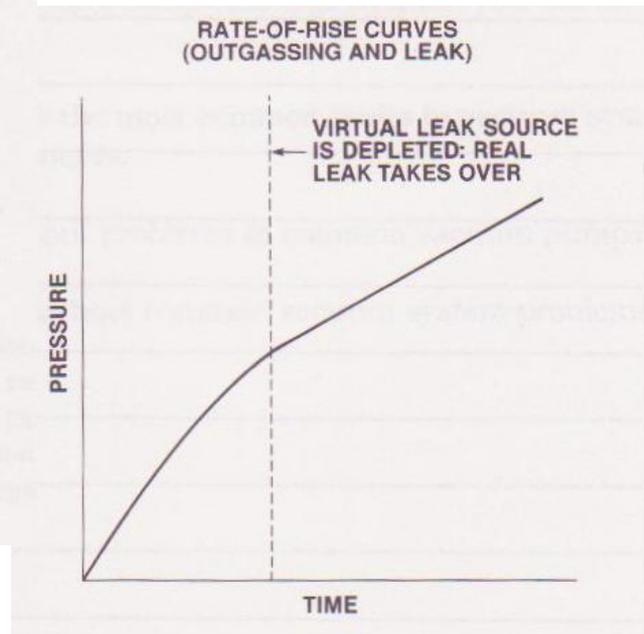
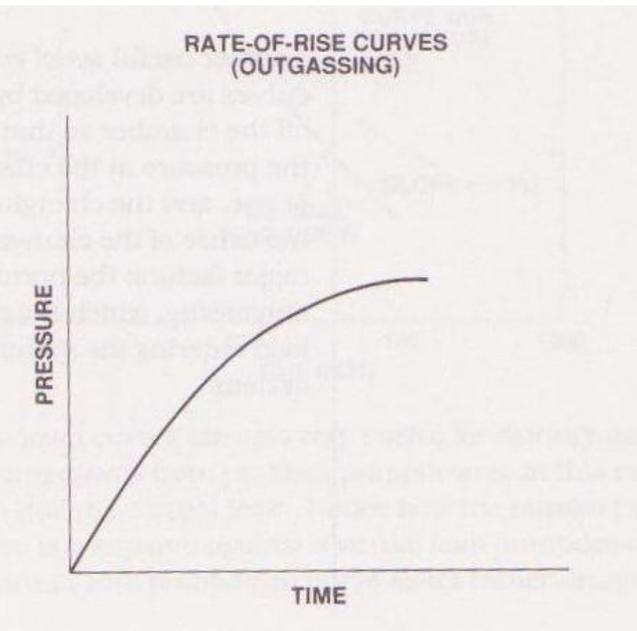


Remember, use log-log plots !

Vacuum Basics

Leak Detection - Pressure rise curves

Careful Pressure follow-up when valving off the pumping provides indications on the leak tightness



**Remember, No pumping
Use log-log plots !**

Instrumentation & Pumping

Pressure Gauges - Range of standard sensors (1/2)

Vacuum measurement is required to establish the **integrity** of an enclosed vacuum system, to determine the **total gas pressure** within the system, and to know the **residual gas** species present.

The total gas pressure is the quantity most often measured and it may vary over many orders of magnitude. Different methods need to be used to cover the entire range.

The instruments which measure the pressure induced forces by an elastic deformation of a membrane

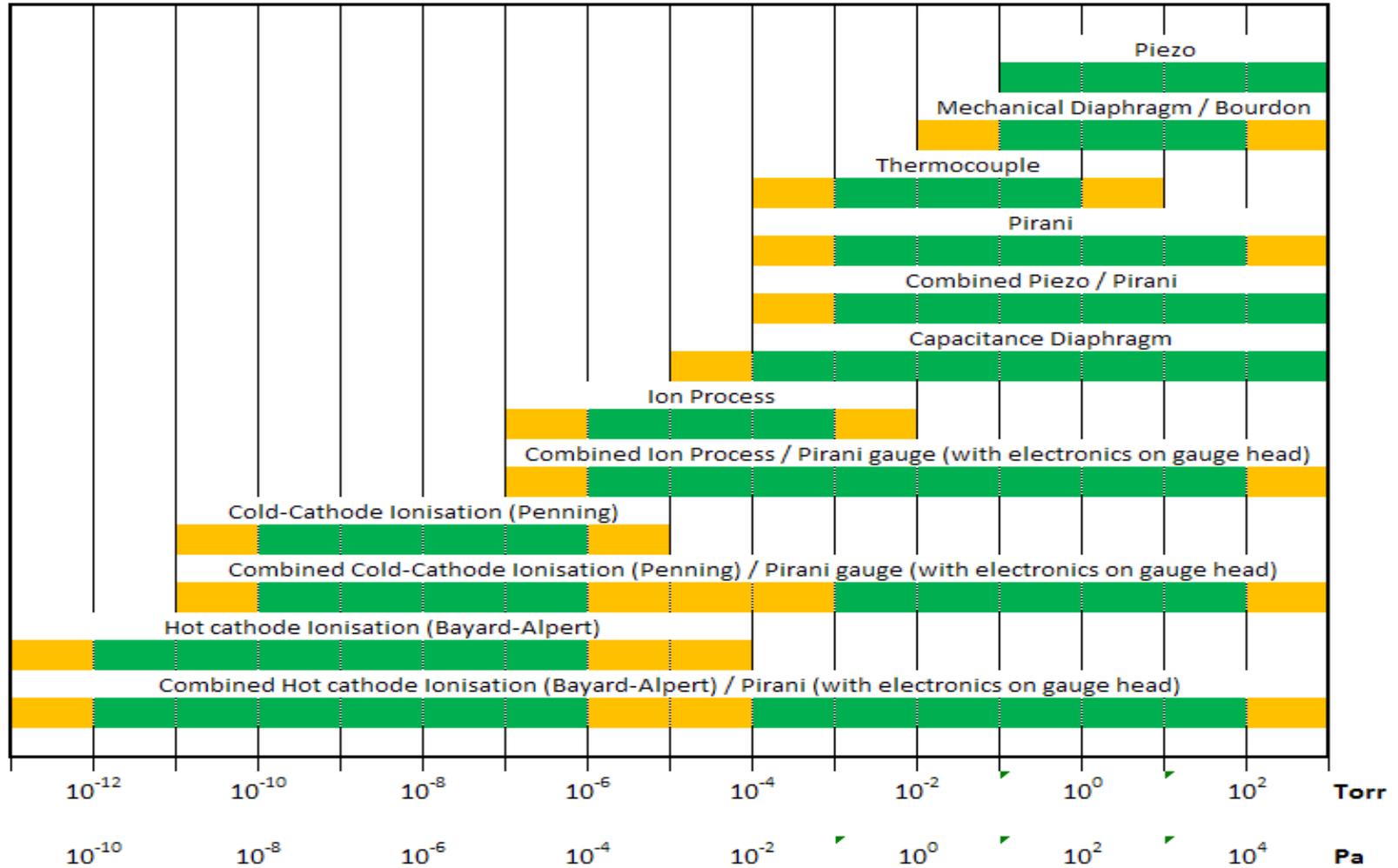
- **Independent of the gas composition**
- **Applicable only to low vacuum**
 - **Forces are too small at very low vacuum**

The instruments which measure well defined physical properties which are function of the gas density, e.g. Thermal conductivity or ionisation potential

- **Critically dependent on the physical properties of the gas species**
- **Applicable to ultra-high vacuum regime**

Instrumentation & Pumping

Pressure Gauges - Range of standard sensors (2/2)

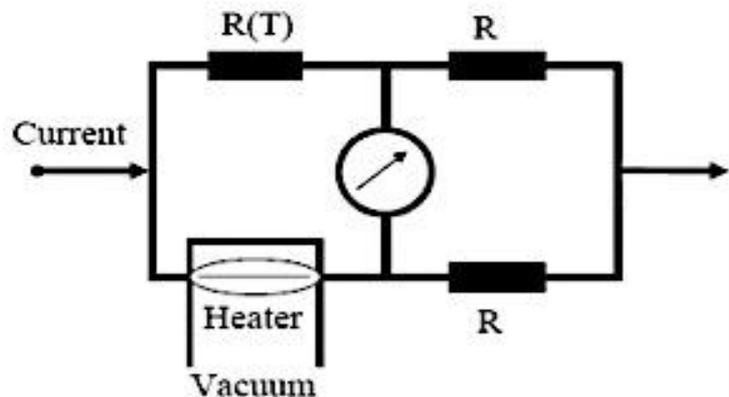


Instrumentation & Pumping

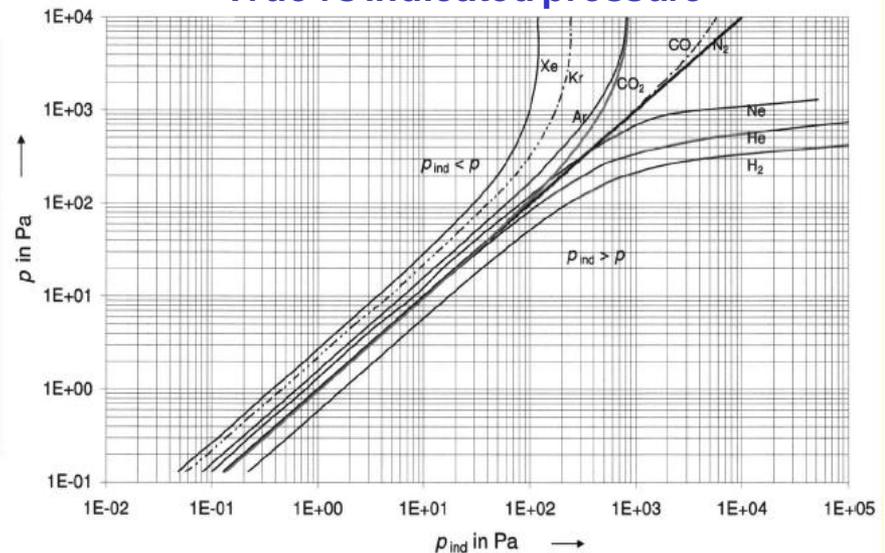
Pressure Gauges: PIRANI

Pirani gauges are commonly used in the range 1 atm - 10^{-4} mbar.

- The operating principle is based on the variation of the thermal conductivity of the gases as a function of pressure. A resistor under vacuum is heated at a constant temperature ($\sim 120^{\circ}\text{C}$). The heating current required to keep the temperature constant is a measure of the pressure.
- In the viscous regime, the thermal conductivity is independent of the pressure. Therefore pressure readings given above 1 mbar are wrong.



True vs indicated pressure



K. Jousten. J.Vac.Sci. 26(3), May/Jun 2008, 352-359

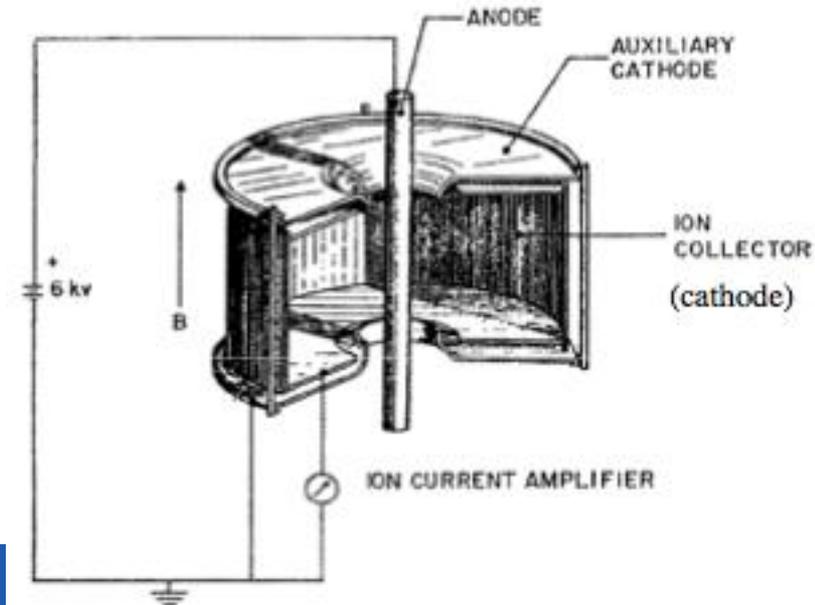
Instrumentation & Pumping

Pressure Gauges: PENNING

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

It's a cold cathode ionisation gauge i.e. there are no hot filament

- 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.
 - At high pressure the discharge is unstable due to arcing.
 - At low pressure, the discharge extinguishes which means zero pressure reading.
- Electrons are produced by field emission and perform oscillations due to the magnetic field
- Along the path length, molecules are ionised and ions are collected onto the cathode
- Leakage current on the HV cables simulates a higher pressure



Instrumentation & Pumping

Pressure Gauges: Bayard-Alpert

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

- It's 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

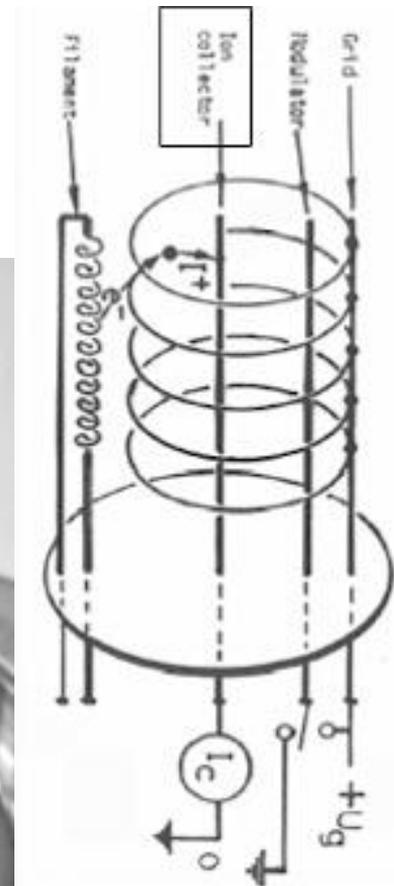
I^- is the filament current

σ is the ionisation cross section

n the gas density

L the electron path length

- The gauge needs to be calibrated
- X-ray limit of a few 10^{-12} mbar

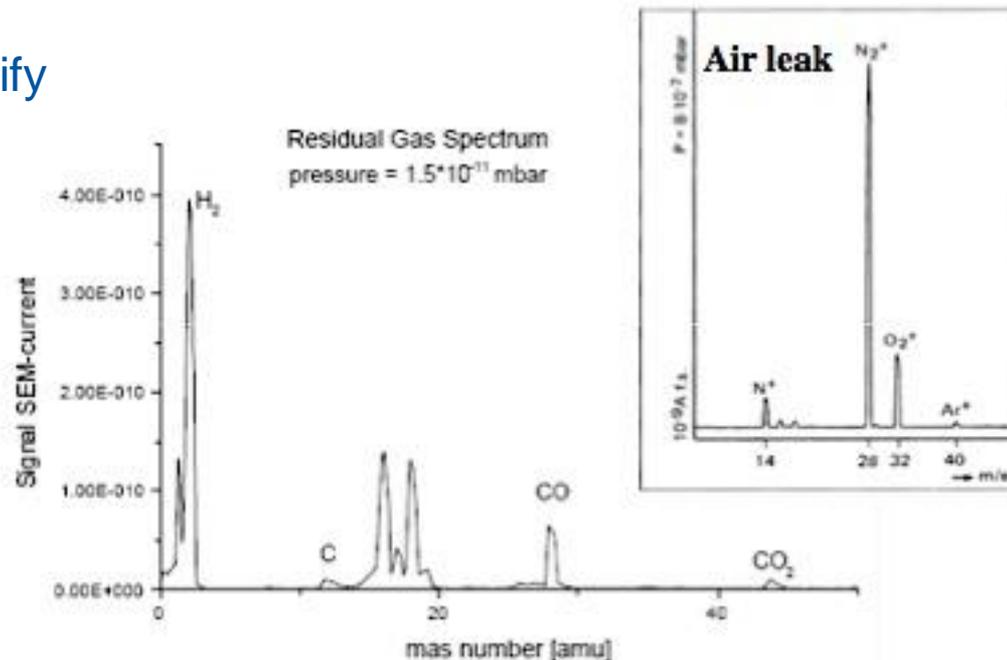
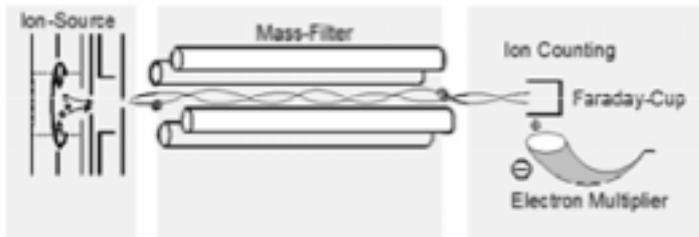


Instrumentation & Pumping

Residual Gas Analyser (RGA)

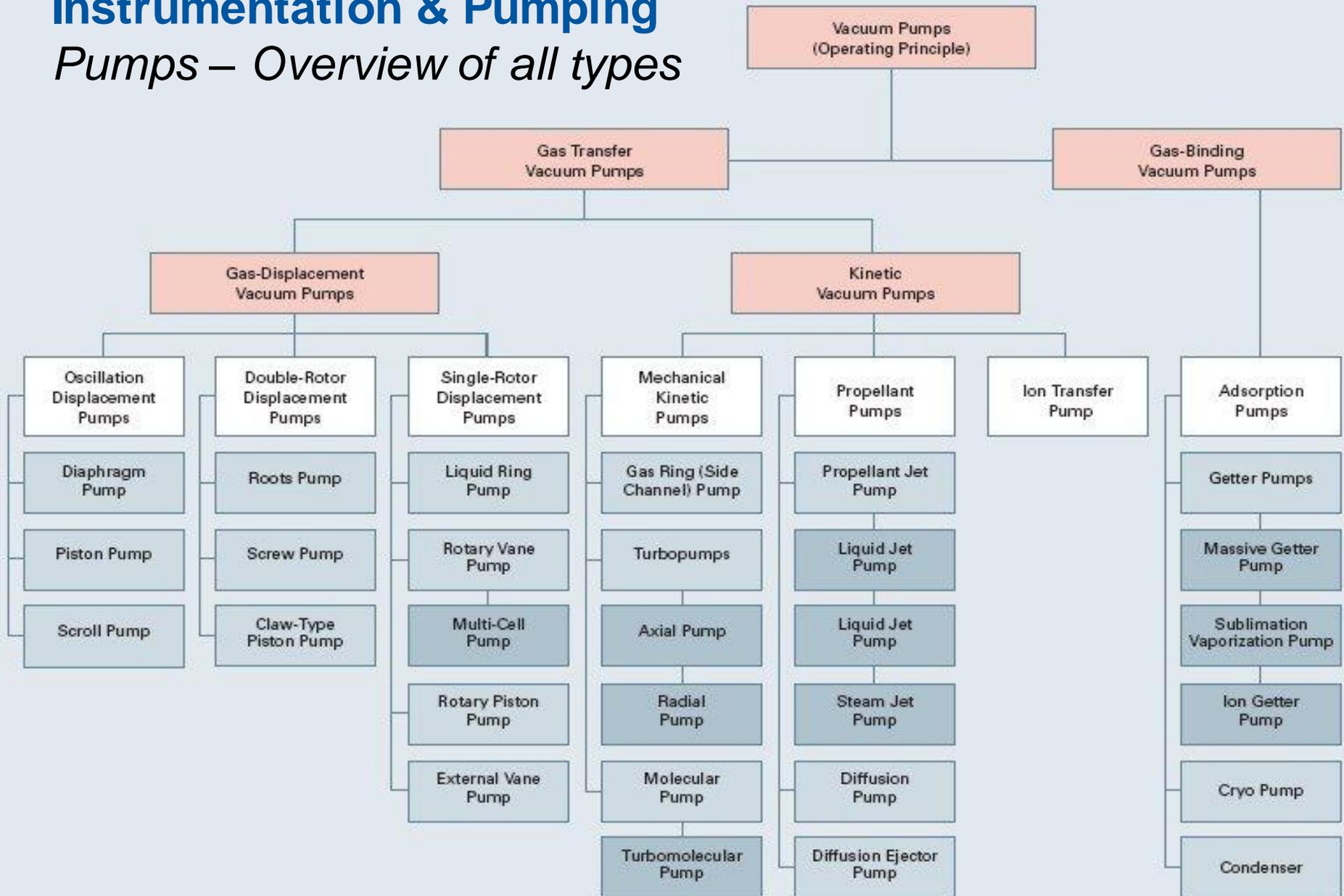
Residual Gas Analysers are used in the range 10^{-4} - 10^{-12} mbar. Their purpose is to do gas analysis

- 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 identify and find leaks (Ar, N₂)
- The RGA needs to be calibrated...



Instrumentation & Pumping

Pumps – Overview of all types

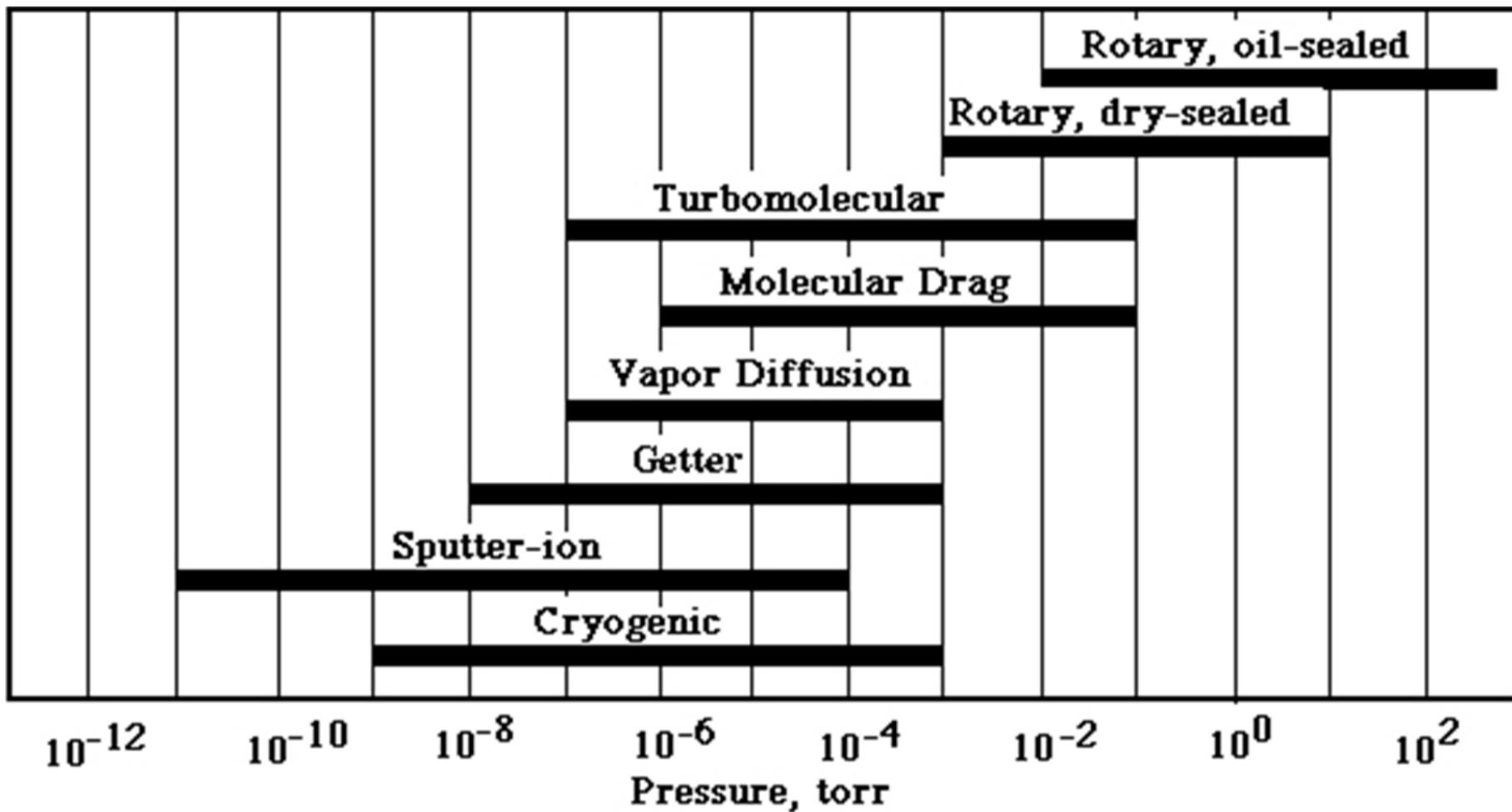


Courtesy of Pfeiffer Vacuum

www.pfeiffer-vacuum.com/know-how/

Instrumentation & Pumping

Useful range of standard pumps

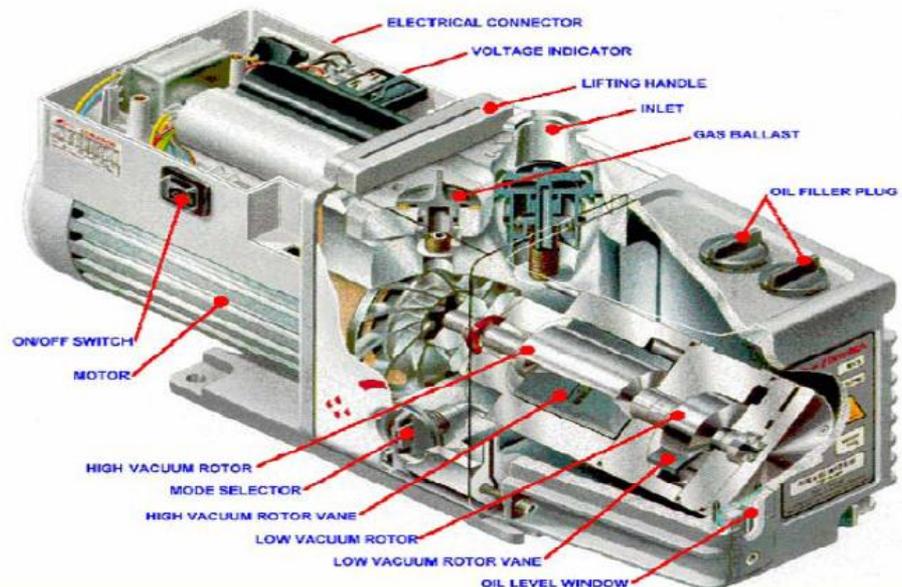
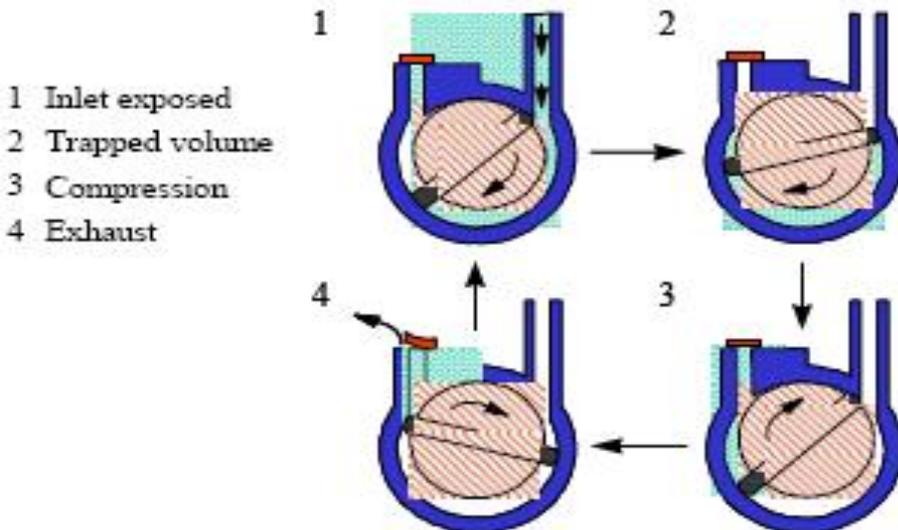


Instrumentation & Pumping

Pumps: Primary (or Roughing) Pumps (1/2)

- Are used to pump down from atmosphere down to 10^{-2} mbar with a speed of a few m^3/h
- Are often used as a baking pump for turbomolecular pumps
- Two categories : dry and wet pumps.
 - Dry pumps are expensive and have a higher ultimate pressure
 - Wet pumps are operating with oil which acts as a sealing, a lubricant, a heat exchanger and protects parts from rust and corrosion

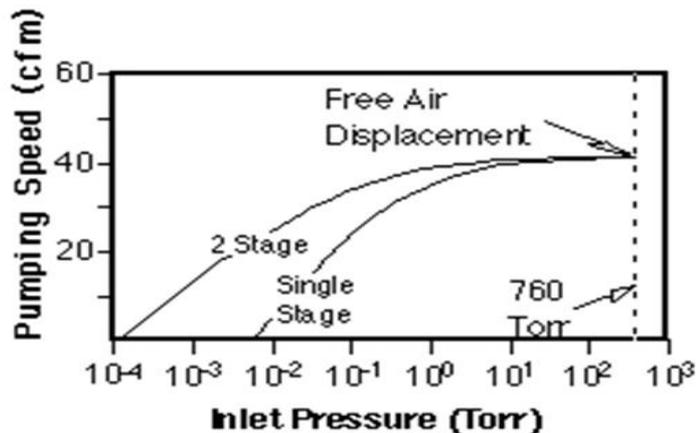
Oil Sealed Rotary Vane Pump



Instrumentation & Pumping

Pumps: Primary (or Roughing) Pumps (2/2)

Pumping speed versus pressure for a typical rotary-vane oil-sealed pump:



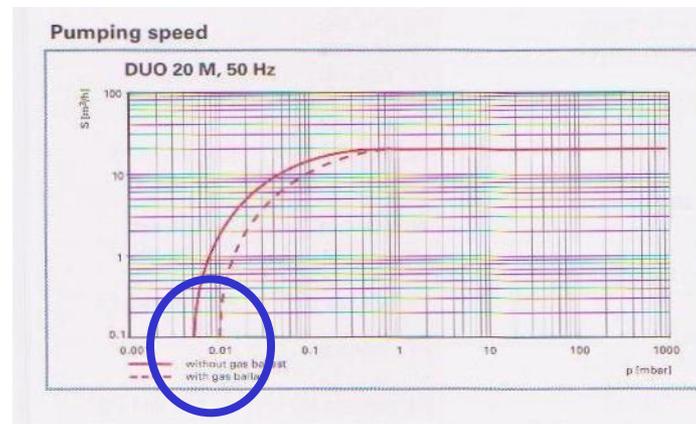
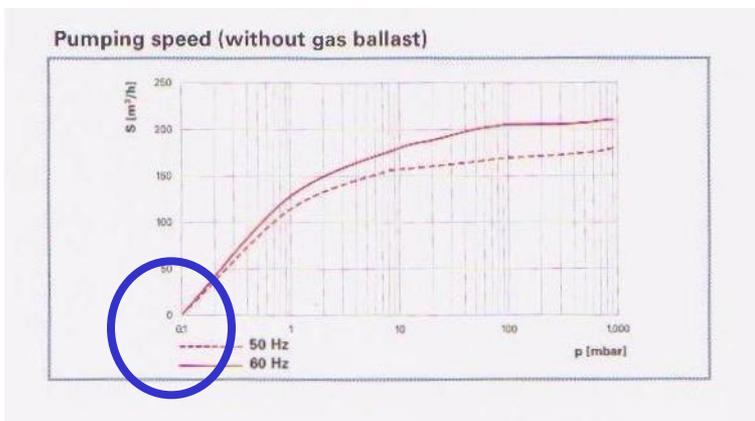
Performance Factors:

- pumping speed
- maximum throughput
- ultimate pressure

In general, to estimate the pump-down time for a system in the high pressure regime with volume V (liters) from P_0 to P (S_0 and S are respective pumping speeds) use the formula:

$$t = \frac{4.6V}{S_0 + S} \log \frac{P_0}{P}$$

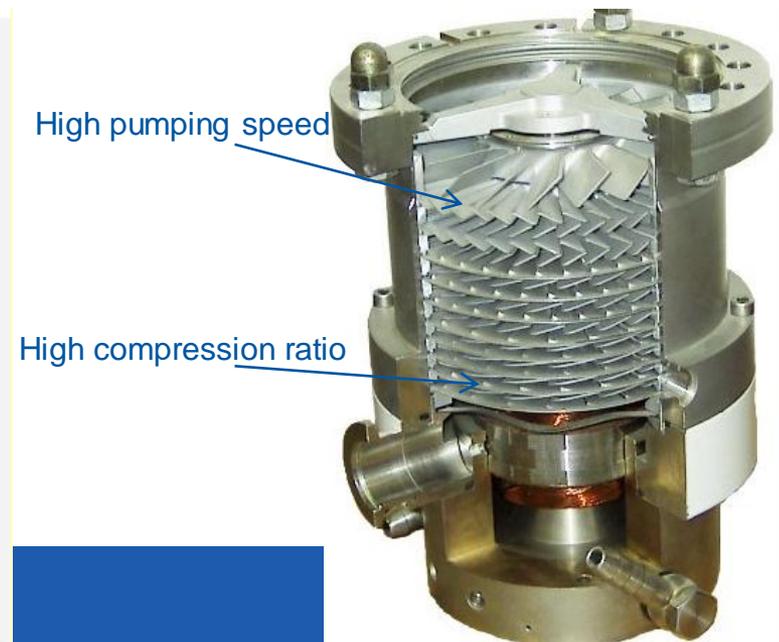
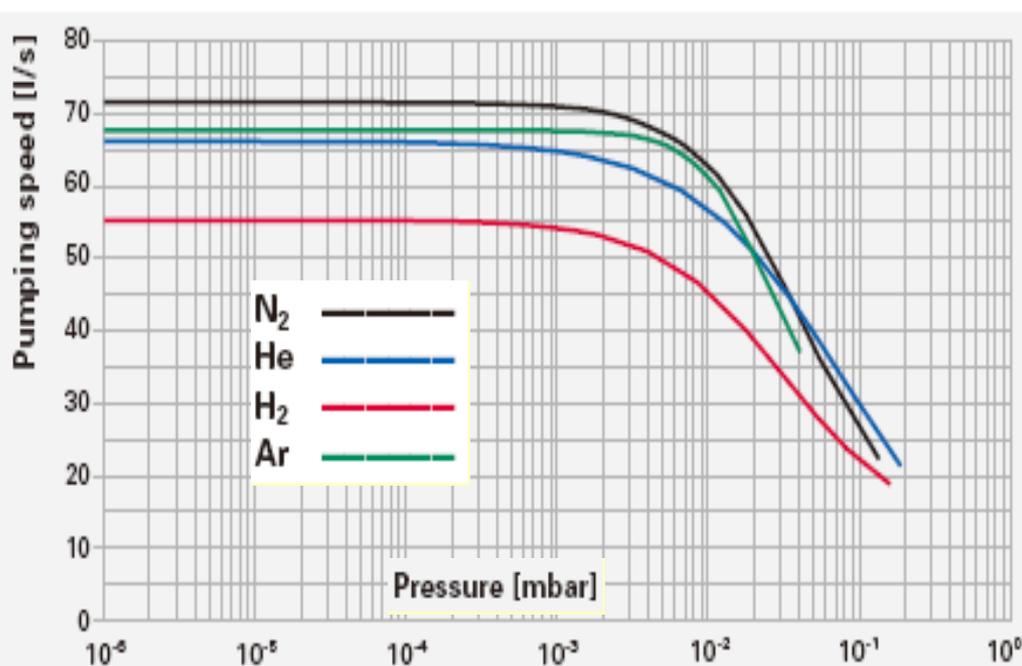
← Single
two-stage rotary oil
pumps →



Instrumentation & Pumping

Pumps: Turbo Molecular Pumps

- Operates in the molecular regime and is used to pump down small and large volumes in accelerator vacuum system.
- Often installed with its primary pump on a mobile trolley : it can be removed after valving-off
 - Ultimate pressure can be very low : 10^{-11} mbar
 - Pumping speed range from 10 to 3'000 l/s



Instrumentation & Pumping

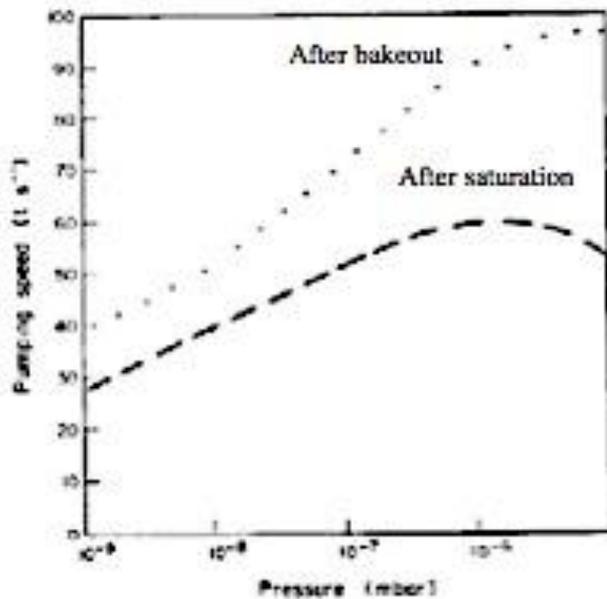
Pumps: Sputter Ion Pumps (1/2)

Operates in the range 10^{-5} - 10^{-11} mbar and is widely used to maintain the pressure in the vacuum chamber of particle accelerators.

- Pumping speed range from 1 to 500 l/s
 - When electrons spiral in the Penning cell, they ionise molecules. Ions are accelerated towards the cathode (few kV) and sputter Ti. Ti, which is deposited onto the surfaces, forms a chemical bounding with molecules from the residual gas.
 - Noble gases and hydrocarbons ,which does not react with Ti, are buried or implanted onto the cathode.
- Like for a Penning gauge, the collected current is proportional to the pressure. It is also use for interlock.

Instrumentation & Pumping

Pumps: Sputter Ion Pumps (2/2)

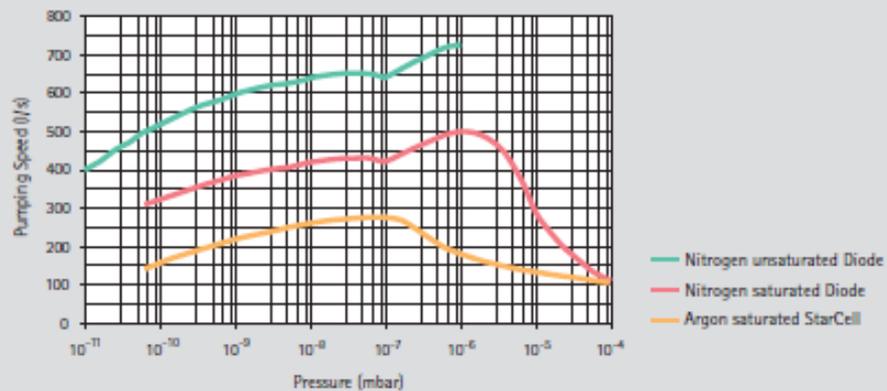


M. Audi. Vacuum 38 (1988) 669-671

Ion pump cutaway



Vaclon Plus 500 - Pumping Speed vs Pressure



<http://www.chem.agilent.com/en-US/Products/Instruments/Vacuum>

Courtesy of Agilent Vacuum



Dr. José Miguel JIMENEZ
CERN, Technology Department
Head of the Vacuum, Surfaces and Coatings group

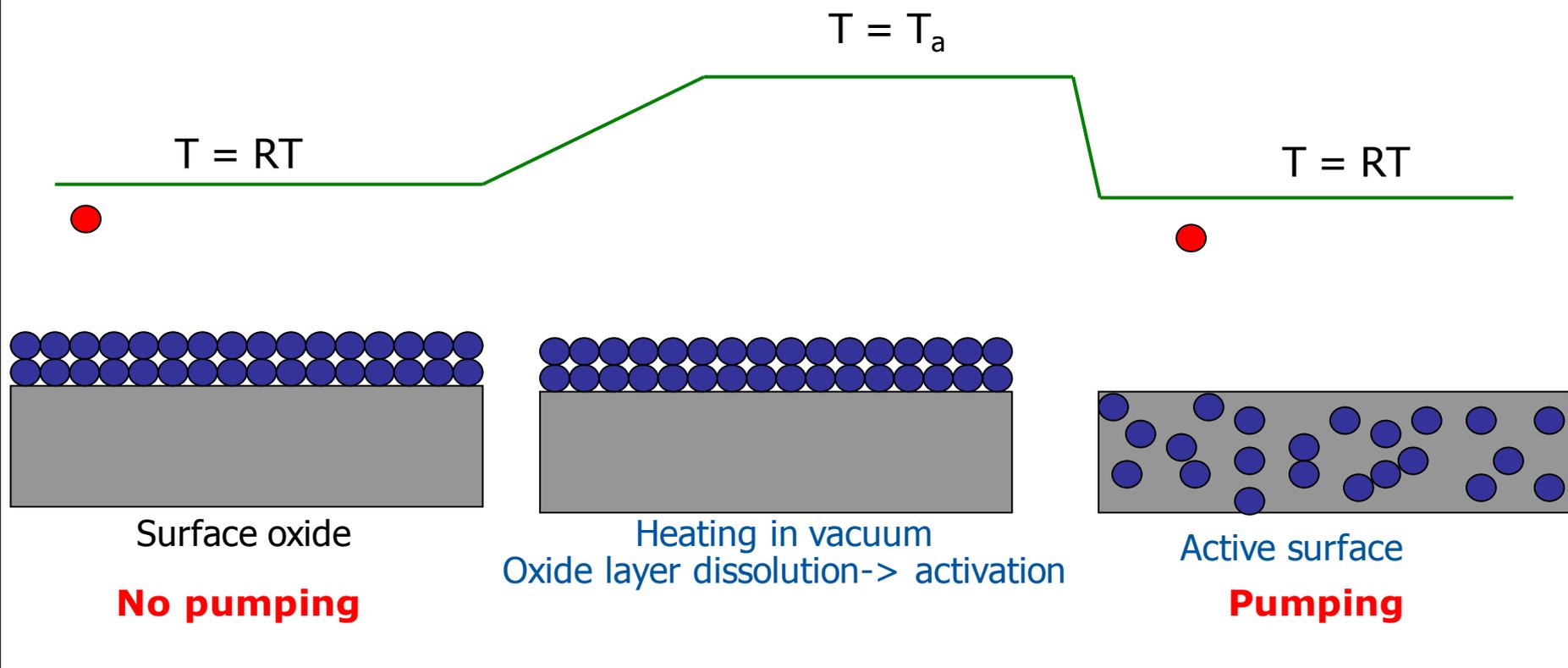


The CERN Accelerator School

Instrumentation & Pumping

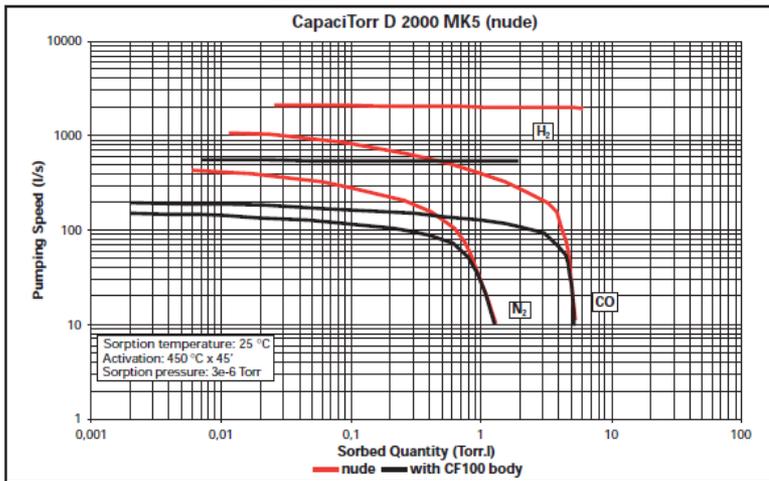
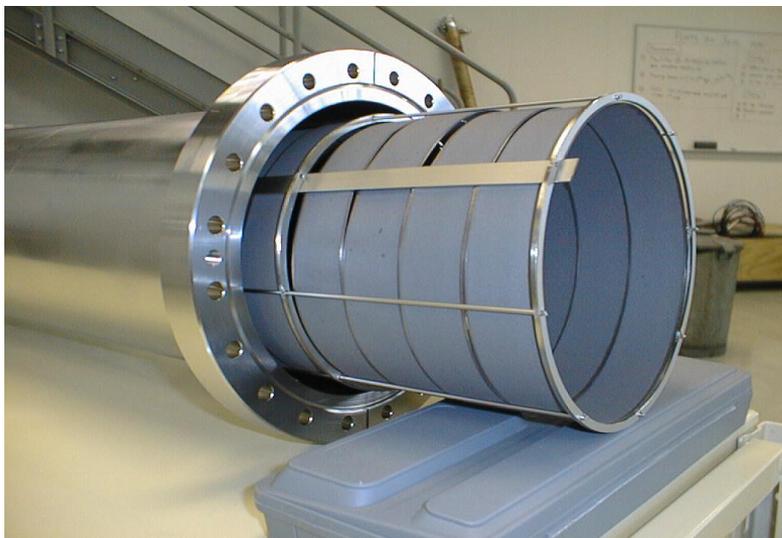
Pumps: NEG Pumps (Capture Pumps) (1/2)

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.

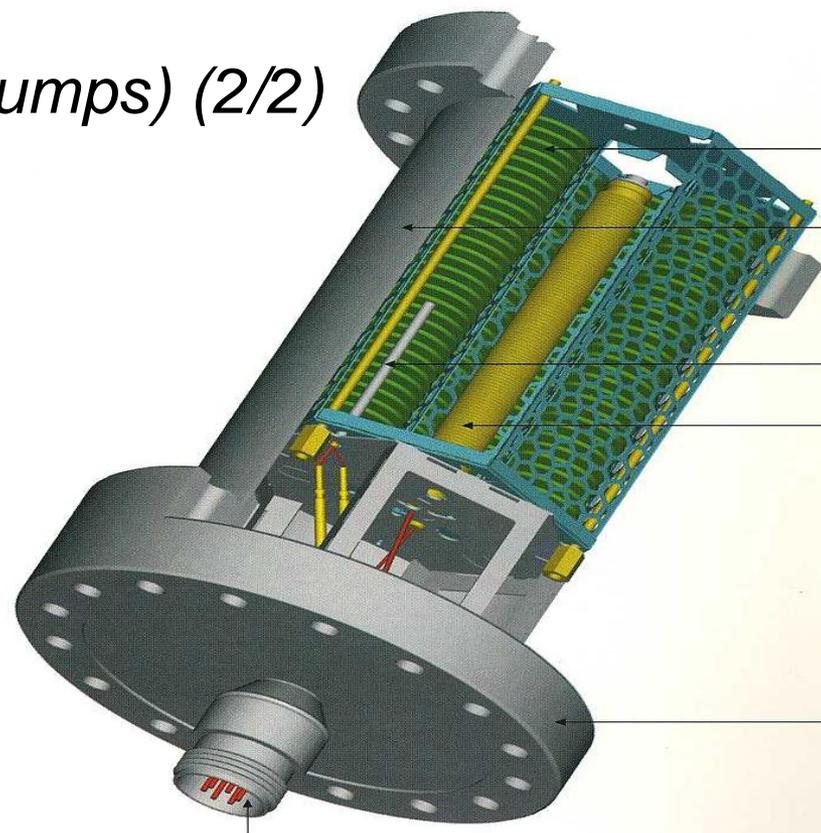


Instrumentation & Pumping

Pumps: NEG Pumps (Capture Pumps) (2/2)



Courtesy of SAES Getters, www.saesgetters.com



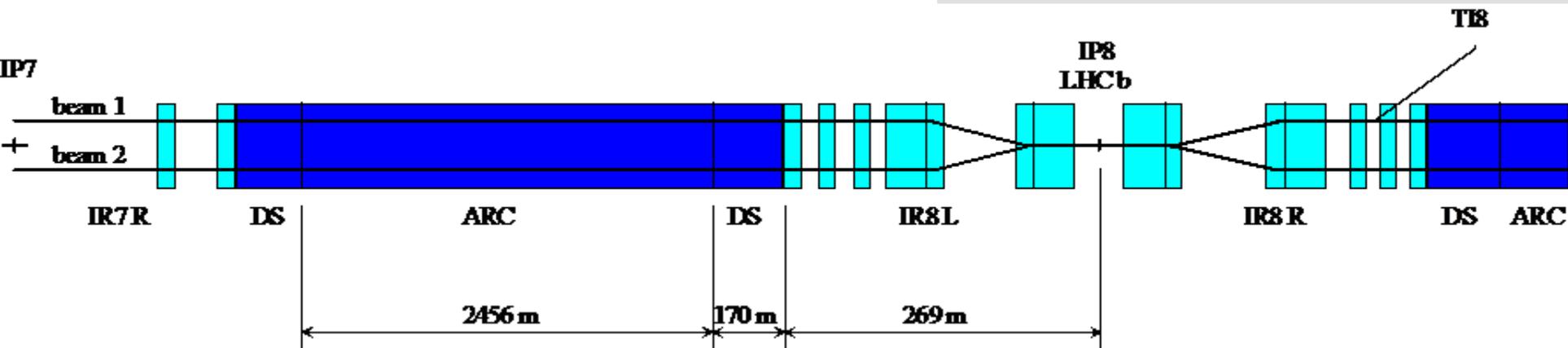
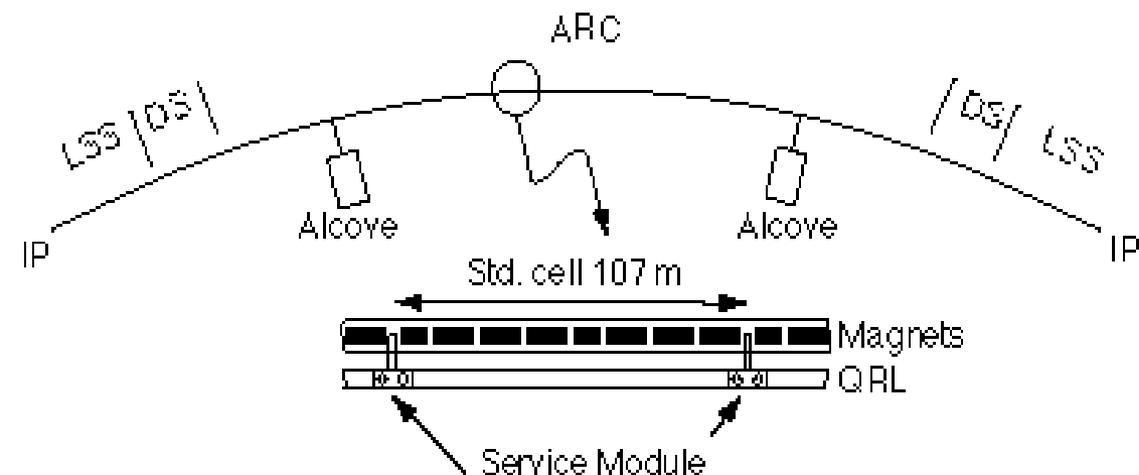
The maximum H₂ sorption capacity is limited by H₂ embrittlement of the NEG elements. In general a safe limit is 20 Torr l/g is given by the supplier.

The stored H₂ can be desorbed by heating and pumping with an auxiliary pump (for example a TMP).

The LHC Case

LHC Layout

- 8 arcs and 8 straight sections
 - Separation of cold and RT vacuum systems
 - Create vacuum sectors in long and fragile RT zones
 - Equipment which need and ex-situ conditioning
 - At the experimental areas
- 46 km at cryogenic temperature
 - 6.5 km at ambient temperature

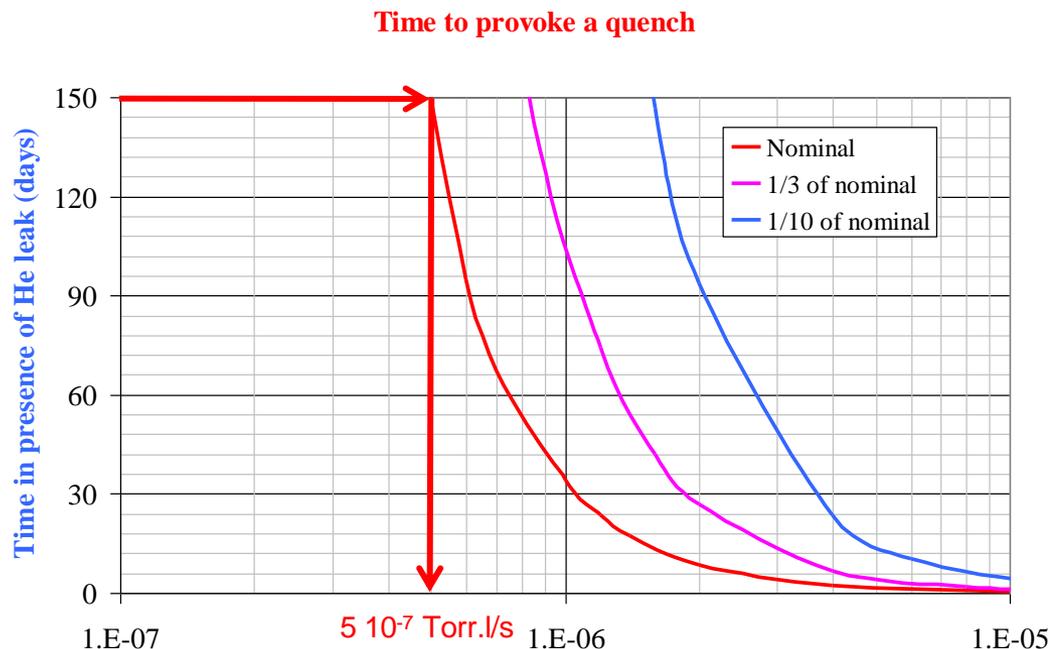


The LHC Case

Leak tightness is critical for the Beam Vacuum

1 year of operation ~ 150 days

Helium leak rate
above $5 \cdot 10^{-7}$ Torr.l/s
shall be detected to
avoid the risk of a
quench !



Lower leak rate :

Require a pumping of the beam tube on the yearly basis (cold bore $> \sim 4K$)

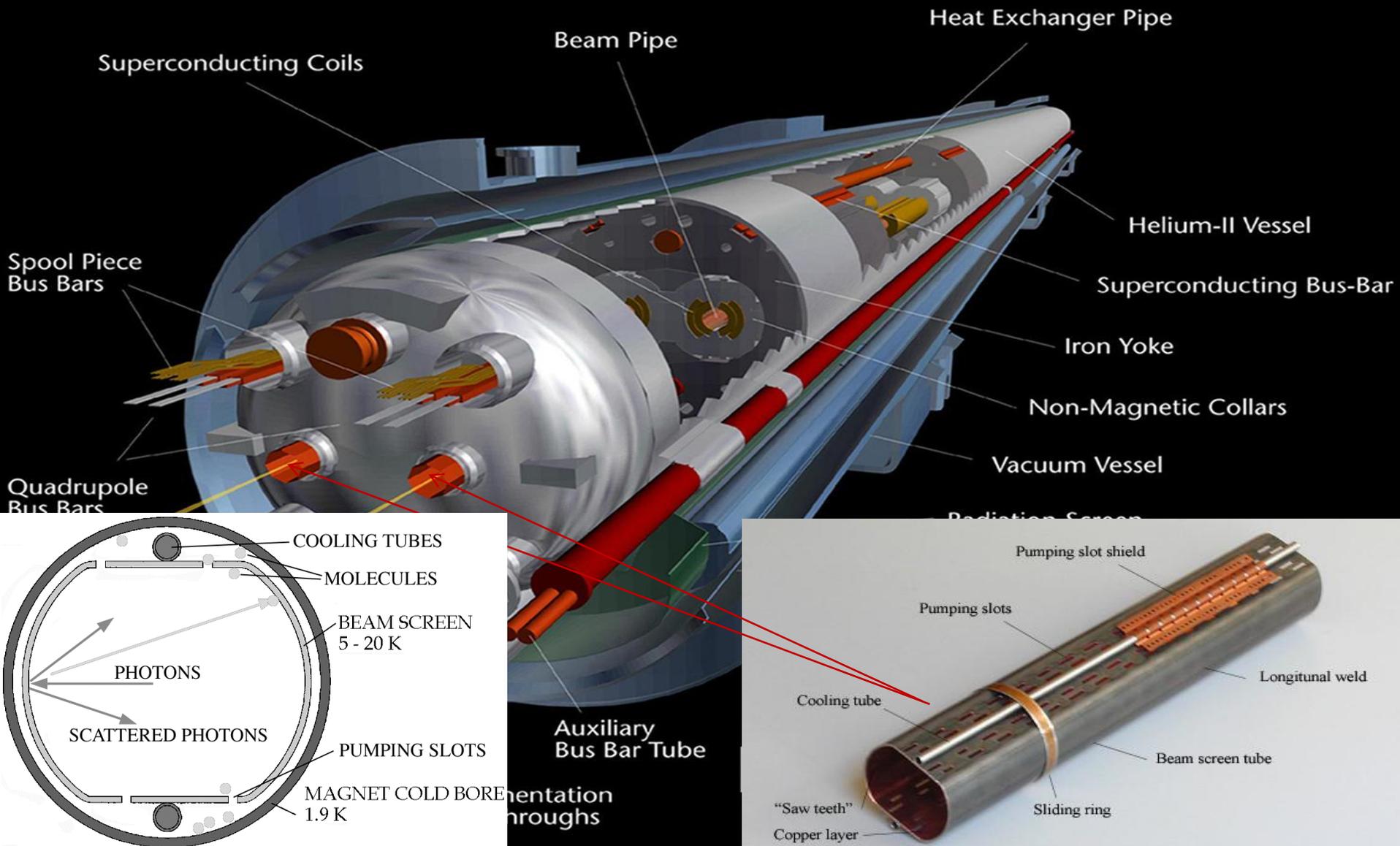
Larger leak rate will provoke a magnet quench within :

30 to 100 days beam operation for He leak rate of 10^{-6} Torr.l/s

A day of beam operation for He leak rate of 10^{-5} Torr.l/s

The LHC Case

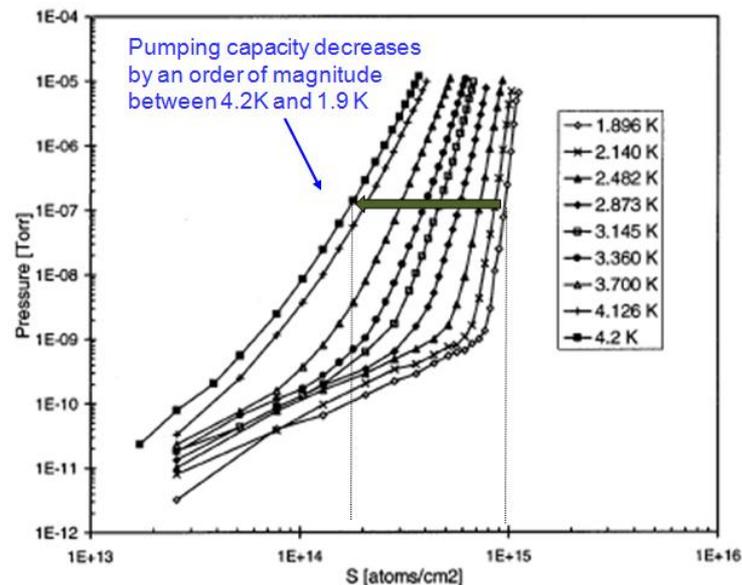
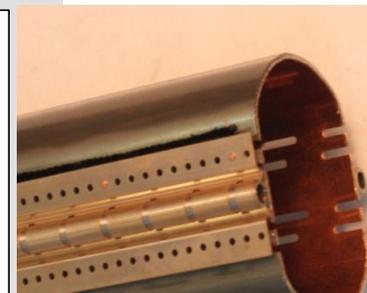
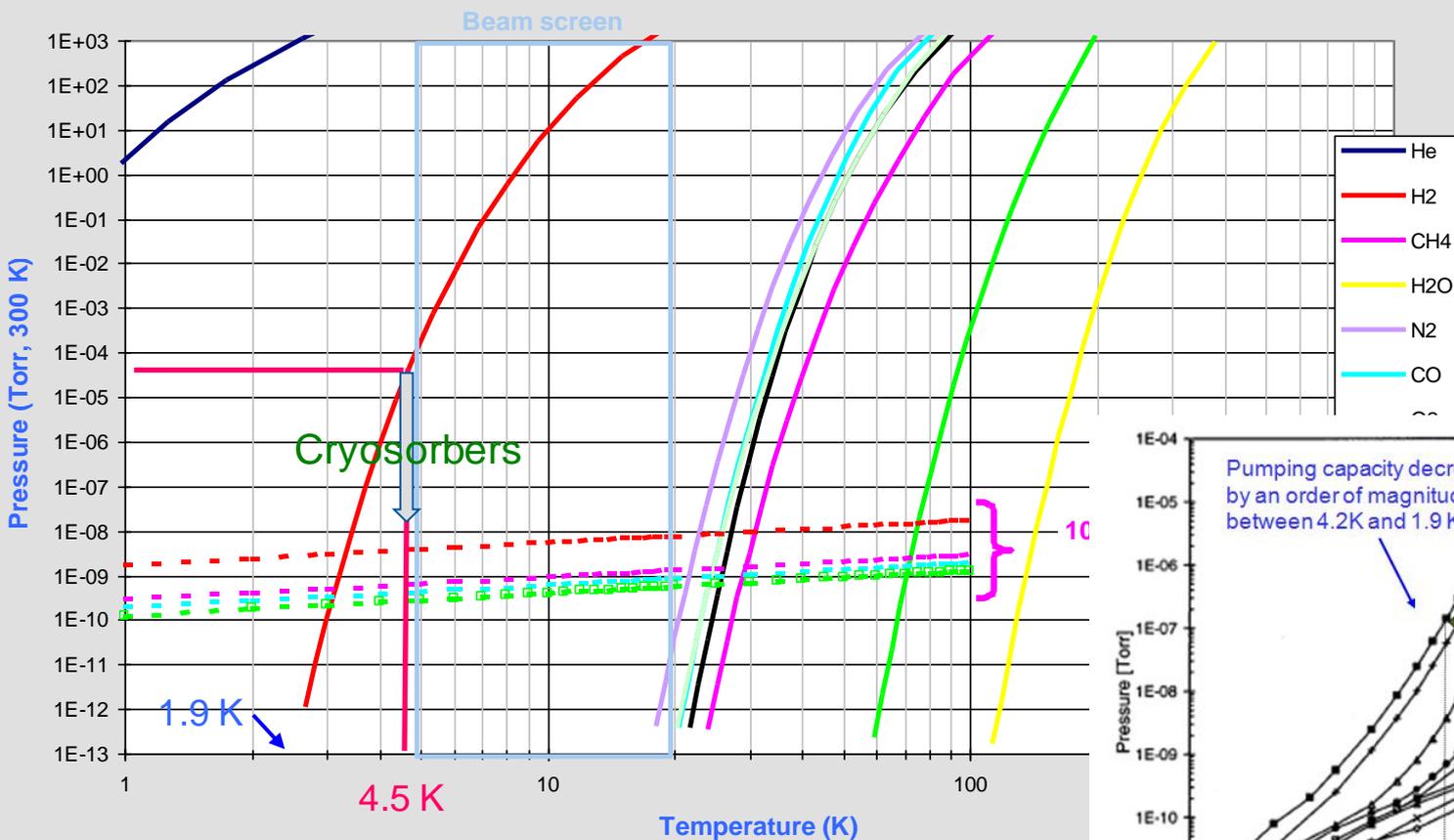
Hydrogen is the limiting gas... LHC needs a Beam Screen!(1/3)



The LHC Case

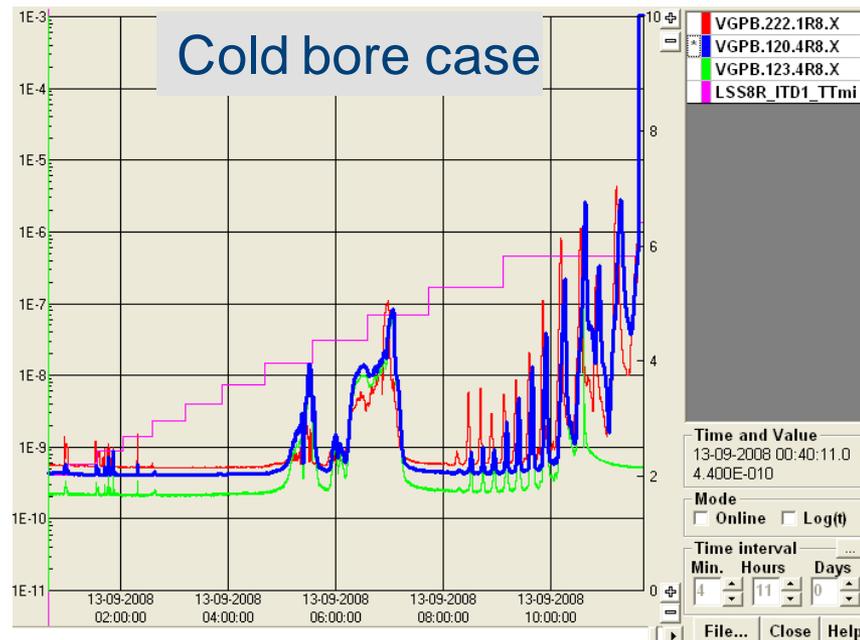
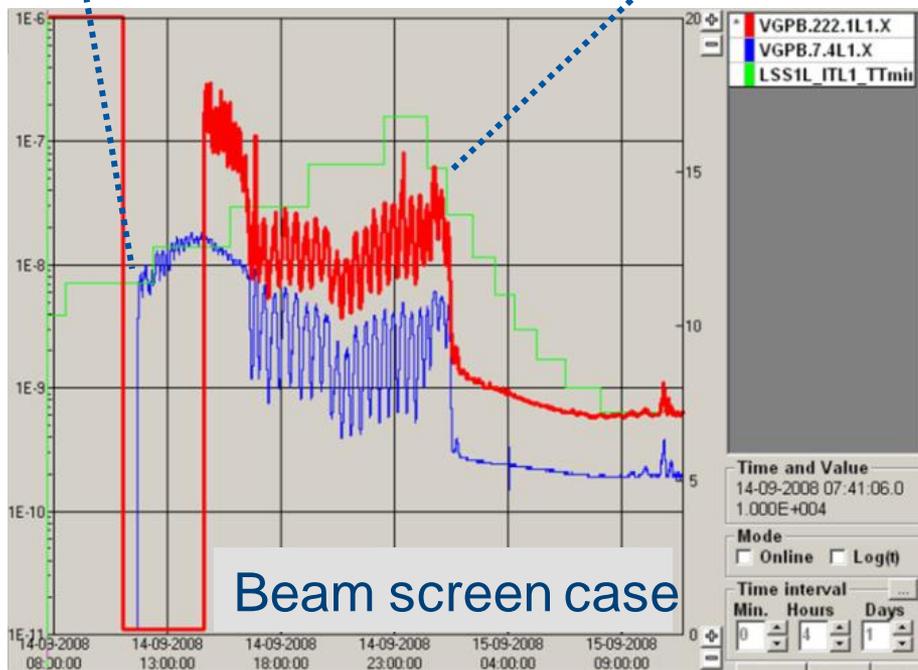
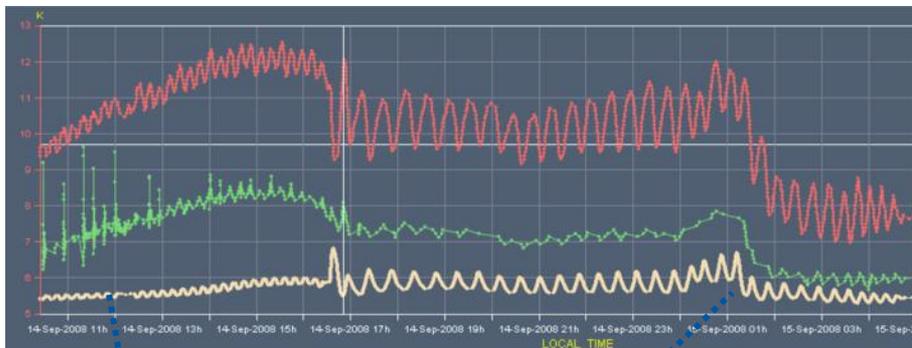
Hydrogen is the limiting gas... LHC needs a Beam Screen!(2/3)

Saturated vapour pressure from Honig and Hook (1960)



The LHC Case

Hydrogen is the limiting gas... LHC needs a Beam Screen!(3/3)



Temperature instabilities around 3 K lead to hydrogen oscillations in both beam screen and cold bore

The LHC Case

Beam-induced dynamic effects are dominant effects...

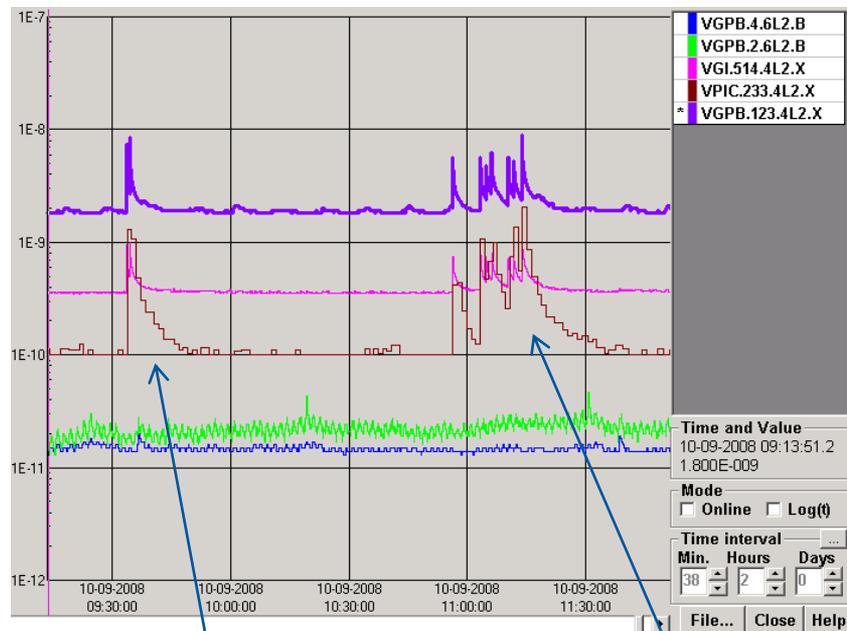
- Beam losses
 - Proton-induced desorption
 - LHC is “self-protected” by magnet quench levels
 - Proton-induced heating leading to thermal desorption
 - Case of the collimators
 - Adiabatic heating → several orders of magnitude in few seconds
- Beam-induced effects
 - Synchrotron Radiation
 - Photon stimulated desorption → observable above 2 TeV
 - HOM-induced heating leading to thermal desorption
 - Electron cloud

LHC relies both on Vacuum cleaning & Beam Scrubbing to operate at high Energy and Intensities!



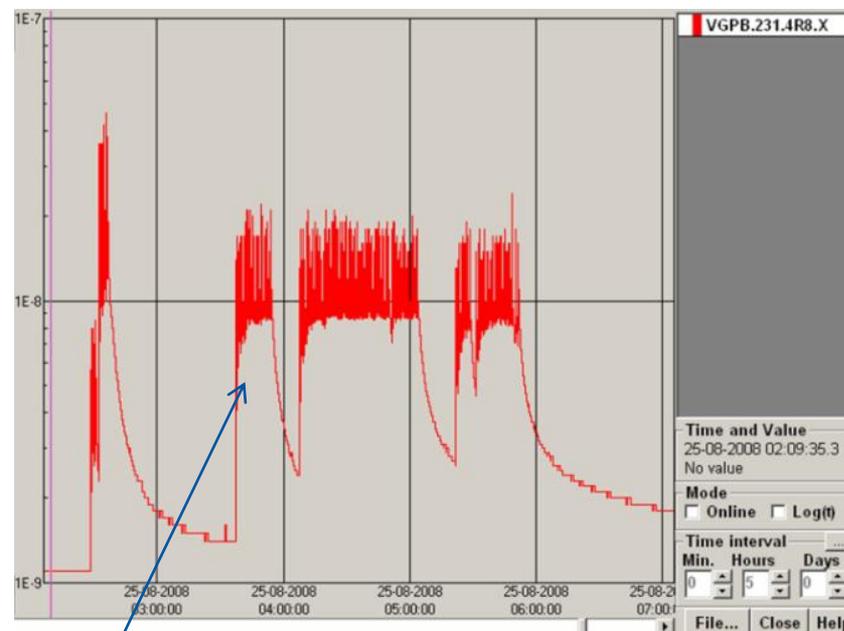
The LHC Case

Beam losses on Injection Collimators...



Single shot

Multiple shots



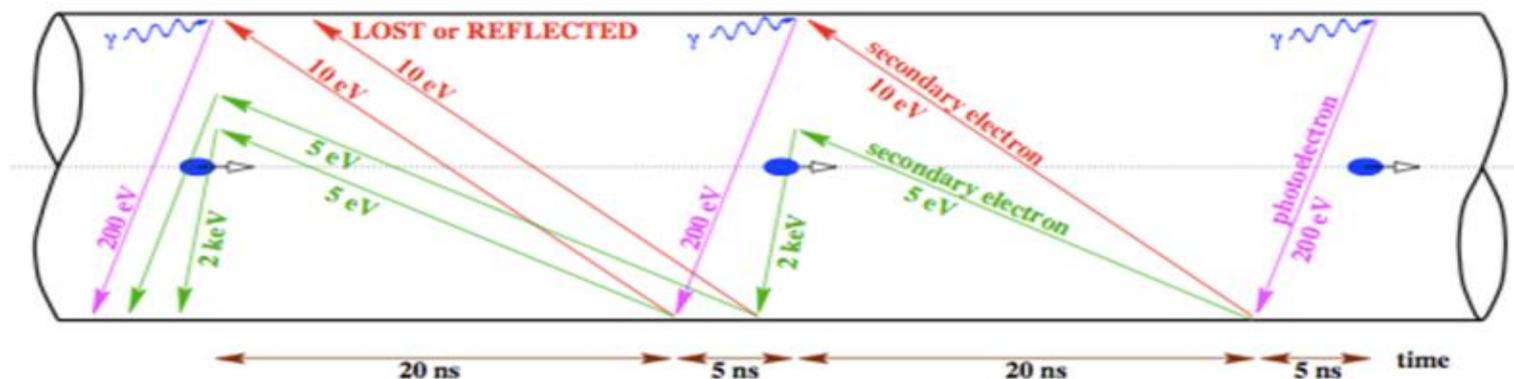
Pressure rise induced by the beam impact on the injection collimator
1 bunch (pilot) @ 450 GeV, $2 \cdot 10^9$ protons!

The LHC Case

When Beams generate Clouds of electrons... (1/3)

As foreseen, the LHC beams have reached a stage where beam-induced vacuum dynamic effects start to dominate...

- Smaller bunch spacing with trains can provoke electron clouds
 - Vacuum pressure rise in warm sections
 - Additional heat load on the cryogenic system in cold sections
 - Electrons in the beam pipe can feed back to affect the beam stability
- ➔ Can be eliminated by conditioning the surface - scrubbing

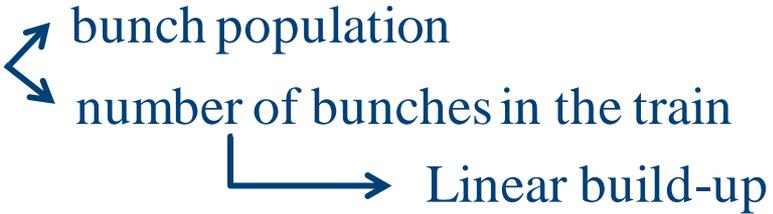


Schematic of e- cloud build up in LHC arc beam pipe, due to photoemission and secondary emission

The LHC Case

When Beams generate Clouds of electrons... (2/3)

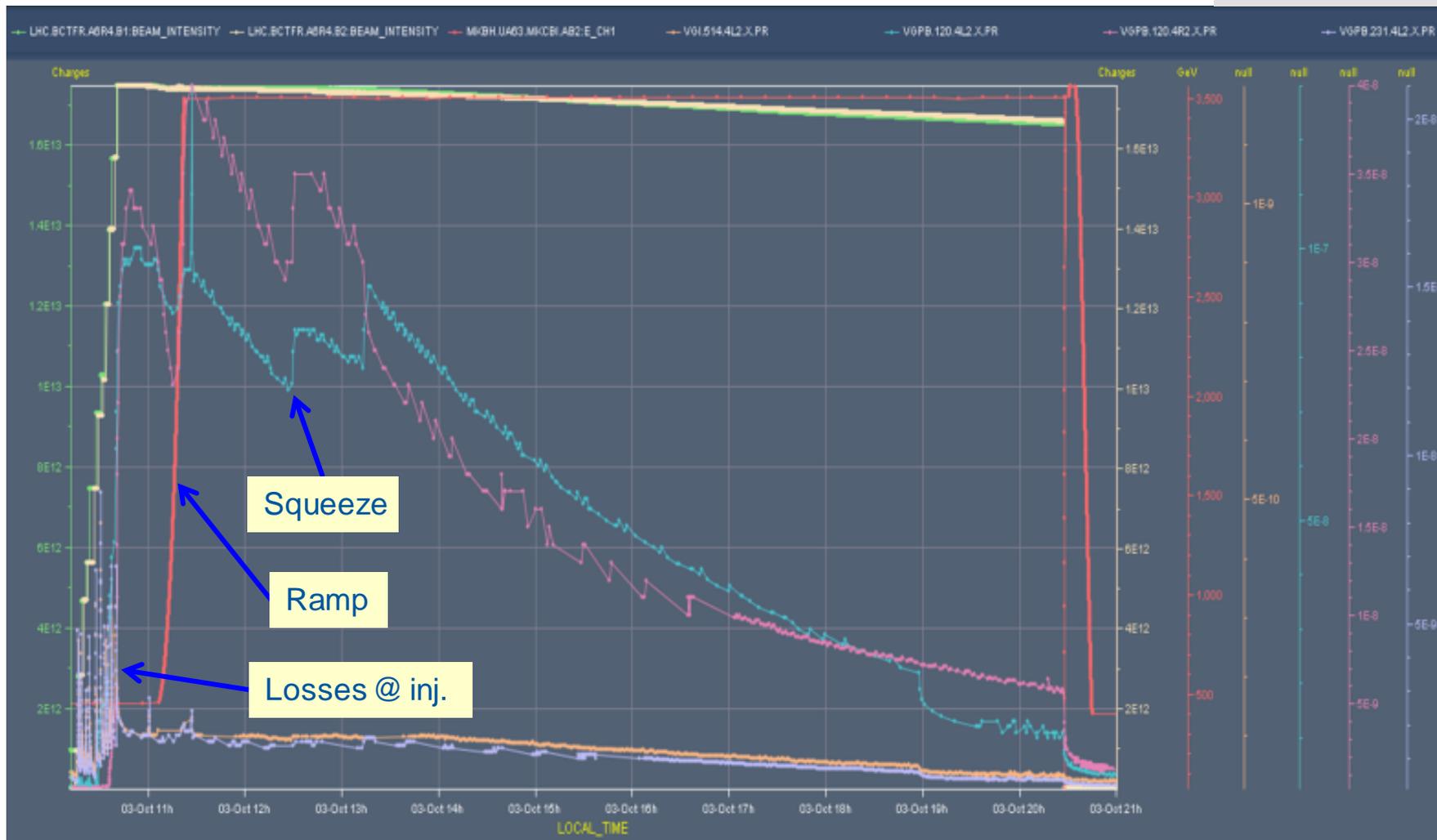
The electron cloud build-up:

- Is a threshold phenomenon 
 - bunch population
 - number of bunches in the train
 - Linear build-up
- Depends highly on the Secondary Electron Yield (SEY) δ
 - Is enhanced by the low energy electrons surviving the gaps between bunch trains (reflectivity of low-energy electrons)
- Is attenuated by the spacing between bunches and bunch trains
- Is affected by many other parameters like:
 - Size of the beam vacuum pipe
 - Magnetic field
 - Temperature of the beam pipe walls

The LHC Case

When Beams generate Clouds of electrons... (3/3)

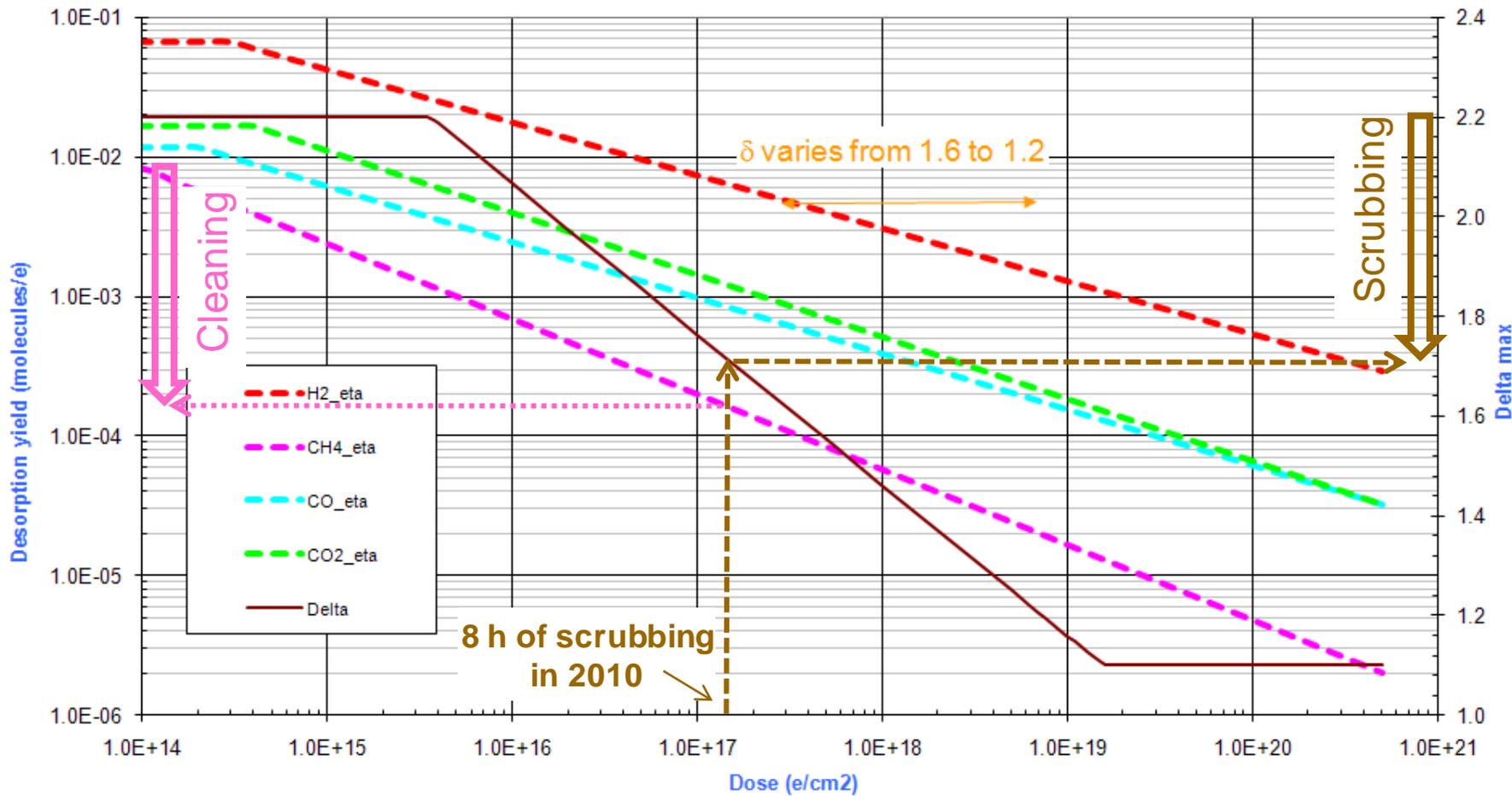
Pressure signature



The LHC Case

LHC relies on Vacuum Cleaning & Beam Scrubbing...

Expected decrease η and δ (calculations)



Final remarks (1/2)

- Beam lifetime depends on nature of residual gas (ionisation cross-section)
 - Most of radiation resistant sensors provide total pressure indications...
 - Computation of Beam-gas effects need conversion to gas densities...
- Beam-induced dynamic effects dominate by far for high energy and intensity accelerators
 - Shall be considered at the design stage since mitigations are always difficult and expensive to retrofit...
- Thermal outgassing is a slow effect (few seconds) and depends on local Conductance
 - Fast effects are Beam-induced effects!



Final remarks (2/2)

- Performance depends more on the design and on material choices than on the pumping scheme
 - Reminds that outgassing of materials range within orders of magnitude as pumping gets limited by Conductance...
- An optimised vacuum engineering is essential
 - To minimise Vacuum-induced forces
 - Unexpected displacements and buckling...
 - To make more efficient Vacuum Cleaning and Coatings, Leak detections, Installation, Survey and Maintenance...
- Selecting the Vacuum instrumentation depends on:
 - Pressure range and local configuration
 - External constraints
 - Radiation: only passive gauges can stand radiations
 - Magnetic field: study in a case by case
 - Cable length (case of most of the accelerators)



The end... Questions?



Cryogenics

Vacuum

Survey

Machine protection

The Boss

Operation with Beams

Some References

- **Books**

- CAS CERN Accelerator School, Vacuum in accelerators, CERN 2007-03
- CAS CERN Accelerator School, Vacuum Technology, Edited : S. Turner. CERN 1999-05
- The physical basis of ultra-high vacuum, P.A. Redhead, J.P. Hobson, E.V. Kornelsen. AVS.
- Foundations of Vacuum Science and Technology, Edited J.M. Lafferty, John Wiley & Sons, 1998
- Vacuum Technology, A. Roth. Elsevier Science.
- Handbook of Accelerator Physics and Engineering, A. W. Chao, M. Tigner, World Scientific, 1998
- Les calculs de la technique du vide, J. Delafosse, G. Mongodin, G.A. Boutry. Le vide.
- American Vacuum Society Classics,
- American Institute of Physics, 1993
- Scientific foundations of vacuum technique, S. Dushman, J.M Lafferty. J. Wiley & sons. Elsevier Science.

- **Journals**

- VACUUM
- Journal of Vacuum Science and Technology (A)
- Nuclear Instruments and Methods (Section A)



Additional Slides



Dr. José Miguel JIMENEZ
CERN, Technology Department
Head of the Vacuum, Surfaces and Coatings group



Instrumentation & Pumping

Pumps – Summary (1/3)

	Advantages	Disadvantages
TMP	<ul style="list-style-type: none">- No memory effects- Constant pumping speed for pressures lower than 10^{-3} mbar- Pumping speed independent of total gas load- Starts working at high pressures (molecular regime)	<ul style="list-style-type: none">- Mechanical fragility- Risk of contamination from the backing pump- Need of venting anytime the pump is stopped- Need of valve on the main flange- Intrinsic limitation in ultimate pressure of H_2- Possible vibrations- Maintenance
SIP	<ul style="list-style-type: none">- Clean pumping- No maintenance- No vibrations- Installation in any orientation- Relatively long lifetime- Relatively low cost- Limited but high H_2 capacity- The pump current gives a pressure reading	<ul style="list-style-type: none">- Low capture probability- Gas Selectivity and limited capacity- Memory effects (in particular for rare gases)- Ignition in 10^{-5} mbar range- Bulky- Difficult starting for old pumps- Production of charged particles in particular at start-up- Field emission problems for old pumps- Fringing magnetic field- Safety issue: high voltage

Instrumentation & Pumping

Pumps – Summary (2/3)

	Advantages	Disadvantages
NEG pumps	<ul style="list-style-type: none">- Clean vacuum- High pumping speed for reactive gases- With SIP, extremely low vacuum can be achieved- High gas capacity for porous NEG- Low cost- Electrical power needed only for activation; it works in case of power cut- No maintenance- No vibration	<ul style="list-style-type: none">- Selective pumping (no pumping of rare gases and methane)- H₂ embrittlement if regeneration is not applied- Formation of dust particles is not excluded- Safety issue: pyrophoric, it burns when heated in air at high temperature



Instrumentation & Pumping

Pumps – Summary (3/3)

	Advantages	Disadvantages
Cryopumps	<ul style="list-style-type: none"> - Very large pumping speed for all gases - Clean vacuum - High pumping capacity - Limited selectivity 	<ul style="list-style-type: none"> - Cost and maintenance - Relatively large volume needed (including refrigerator) - Gas release in case of power cut - Reduced pumping efficiency for H₂ for high quantity of gas adsorbed: regeneration needed - Need of valve on the main flange
Sublimation Pumps	<ul style="list-style-type: none"> - Clean vacuum - High pumping speed for reactive gases - With SIP, extremely low vacuum can be achieved - Low cost - Electrical power only for sublimation; it works in case of power cut - Limited maintenance (filament change) - No vibration 	<ul style="list-style-type: none"> - Very limited capacity - Need frequent sublimations at high pressure - Ti film peel-off for high sublimation rates - Selective pumping (no pumping of rare gases and methane) - Risk of leakage current in high voltage insulators - Ideal for low pressure applications