Vacuum in Accelerators

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What does it mean ?

From

Units

till

LHC

Vacuum in Accelerators

Outline

1. Vacuum Basis

2. Vacuum Components

3. Vacuum with Beams : LHC Case

1. Vacuum Basis

Units

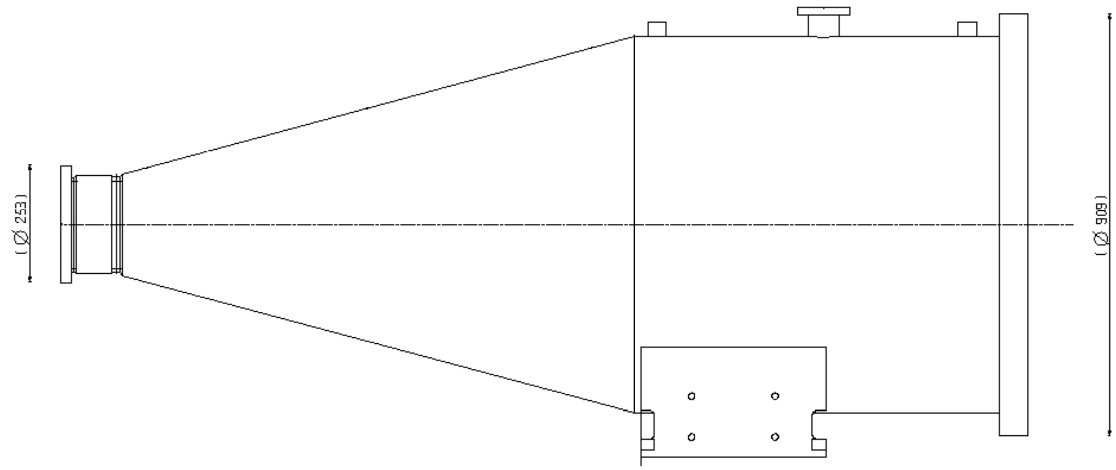
- The pressure is the force exert by a molecule per unit of surface : 1 Pa = 1 N/m^2

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

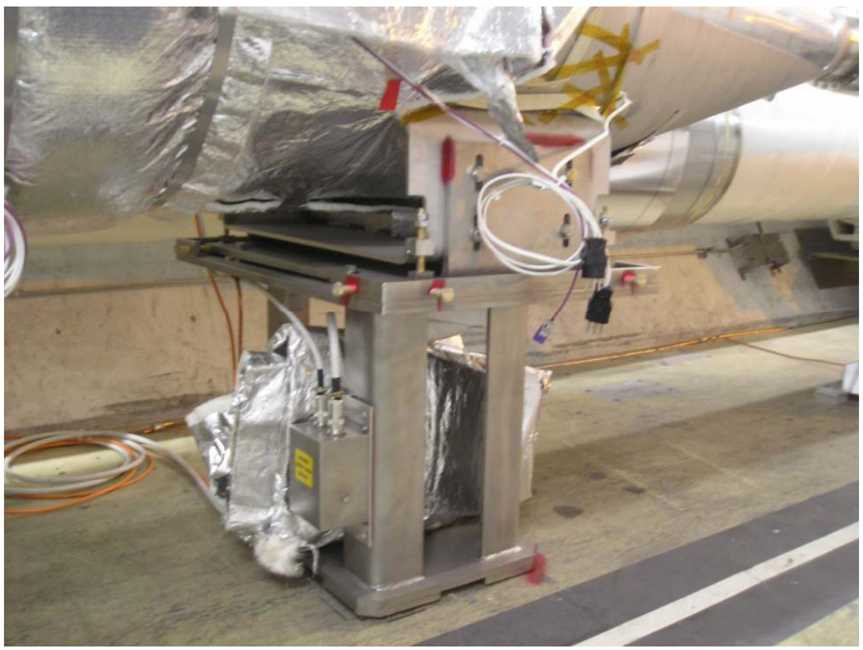
As a consequence of the « vacuum force » …

Work with the Mechanical Design Office !

0.5 tonne



6.6 tonnes



Otherwise…

Little Problem (you don't need a "good" vacuum) !

- Case of the CERN ISR in the 70's : spontaneous breaking of the a bellow (due to a bad design or due to a fixed point not well attached ?)

- But still possible nowadays even with modern computing tools …

- Case of the QRL's bellows in the LHC, due to a bad design (too small corrugation high)

Ideal Gas Law

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

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

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

Relates gas density and pressure

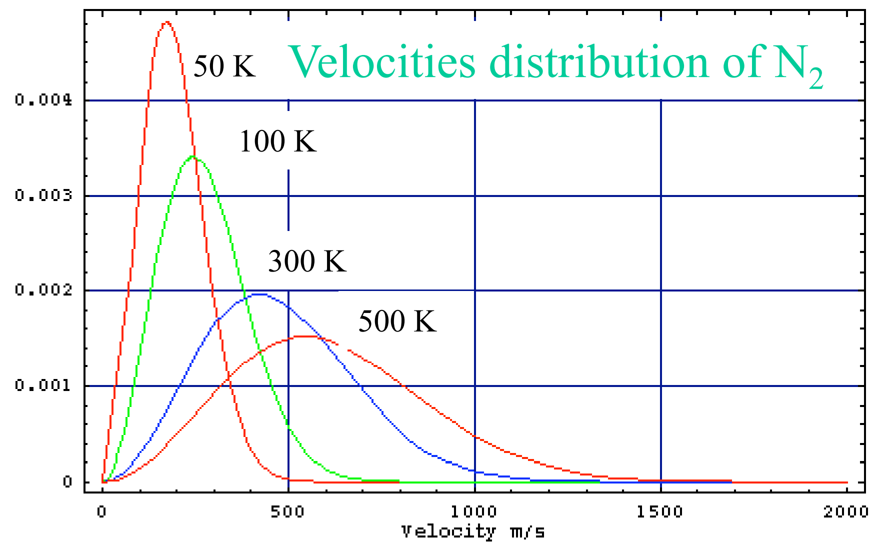
- The distribution of velocities, dn/dv, follows a Maxwell-Boltzmann function

- 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



Total Pressure and Partial Pressure

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

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

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

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 succesives impacts with other molecules. It depends of the pressure, of the temperature and of the molecular diameter.

- It increases linearly with temperature

- For air at room temperature :

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

- At atmospheric pressure, λ = 70 nm

- At 1 Torr, λ = 50 µm

- At 10^{-2} Torr, λ = 0. 5 cm

- At 10^{-6} Torr, λ = 50 m

Turbulent and Viscous Flows

- When pumping down from athmospheric pressure, the physics is caracterised by different flow regims. It is a function of the pressure, of the mean free path and of the components dimensions.

- Reynold number, Re :
  - if Re > 2000 the flow is turbulent
  - it is viscous if Re < 1000

$$\mathrm{Re} = \frac{\mathrm{Q}[Torr.l/s]}{0.089\mathrm{D}[cm]}$$

- The turbulent flow is established around the athmospheric pressure

- In the low vacuum (10^3-1 mbar), the flow is viscous. The flow is determined by the interaction between the molecules themselves. The flow is laminar. The mean free path of the molecules is small compared to the diameter of the vacuum chamber

$$\text{Viscous flow} : \overline{\mathrm{P}}\,\mathrm{D} > 0.5\,[Torr.cm]$$

Transition and Molecular Flows

• In the medium vacuum ($1\text{-}10^{-3}$ mbar), the flow is transitional. In every day work, this range is transited quickly when pumping down vacuum chambers. In this regime, the calculation of the conductance is complex. A simple estimation is obtained by adding laminar and molecular conductances.

• 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 diameter. The molecular interactions do not longer occurs. Molecules interact only with the vacuum chamber walls

$$\text{Molecular flow}: \overline{P}\,D < 1.5\,10^{-2}\ [Torr.cm]$$

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.

God made the bulk:
The surface was invented by the devil

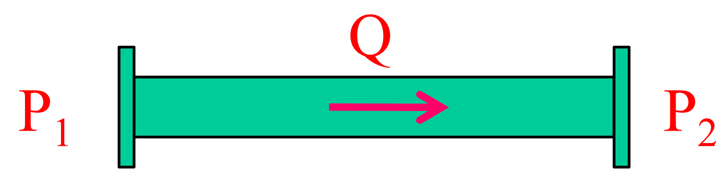
Wolfgang Pauli

When expressing the complexity of a surface

Conductance

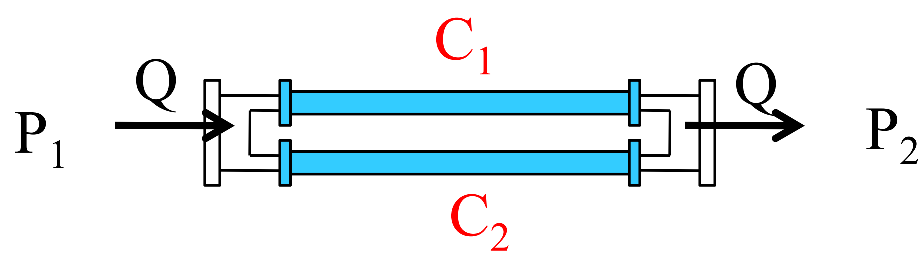
- It is defined by the ratio of the molecular flux, Q, to the pressure drop along a vacuum vessel. It is a function of the shape of the vessel, the nature of the gas and its temperature.

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



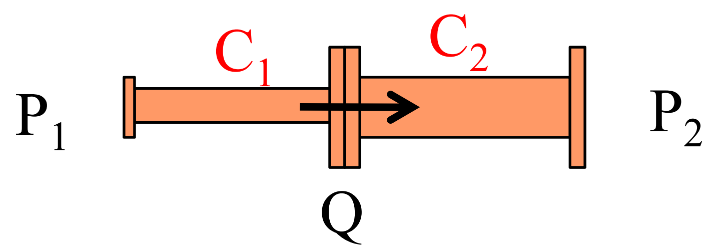
- Adding conductances in parallel

$$C = C_1 + C_2$$



- Adding conductances in series

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



Conductance Calculus in Molecular Regime

- **For an orifice :**

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

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

Pumping Speed

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

mbar.l/s

l/s $\boxed{S = \dfrac{Q}{P}}$

mbar

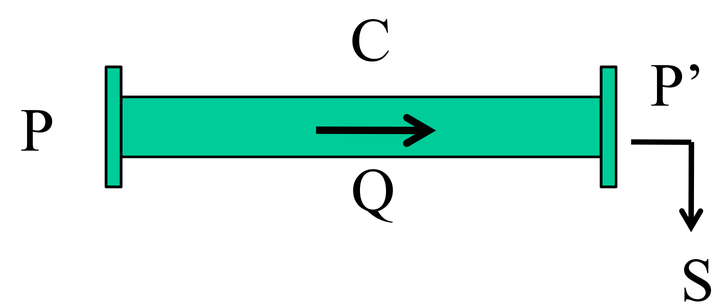
- Coupling of a pump and of a vacuum chamber :

$$\begin{cases} Q = C\,(P - P') \\ Q = P'S \end{cases}$$

$$\Leftrightarrow S_{eff} = \frac{Q}{P} = \frac{C\,S}{C + S}$$

if $C >> S$, $S_{eff} \sim S$

if $C << S$, $S_{eff} \sim C$



Example :

Consider a turbomolecular pump of 400 l/s (CHF 10 000) to evacuate a 10 cm diameter tube of 2 m long.

S = 400 l/s ; C = 60 l/s so $S_{eff} \sim$ 50 l/s ….

... you sould have use a smaller pump since you are conductance limited !

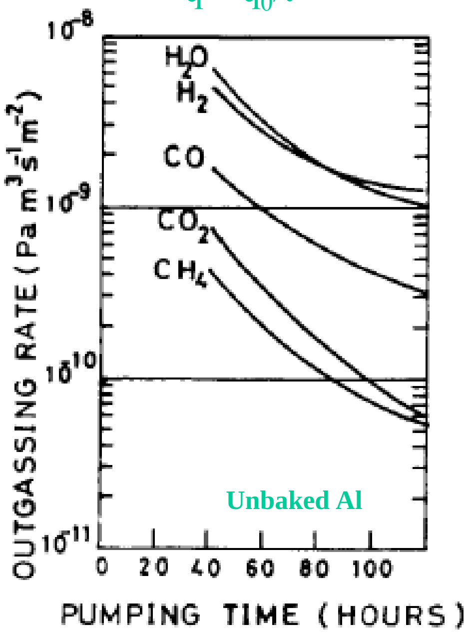
S = 60 l/s (CHF 5 000) ; C = 60 l/s so $S_{eff} \sim$ 30 l/s

Outgassing

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

Metallic surfaces

$q \sim q_0/t$

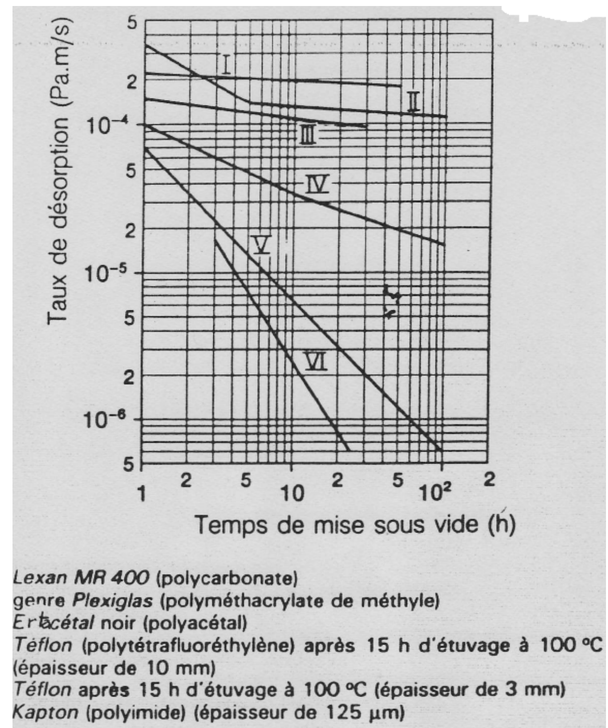


A.G. Mathewson *et al.*
J.Vac.Sci. 7(1), Jan/Fev 1989, 77-82

x 5 000

Plastic surfaces

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



Good Vacuum Design :

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

Cleanning Methods

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

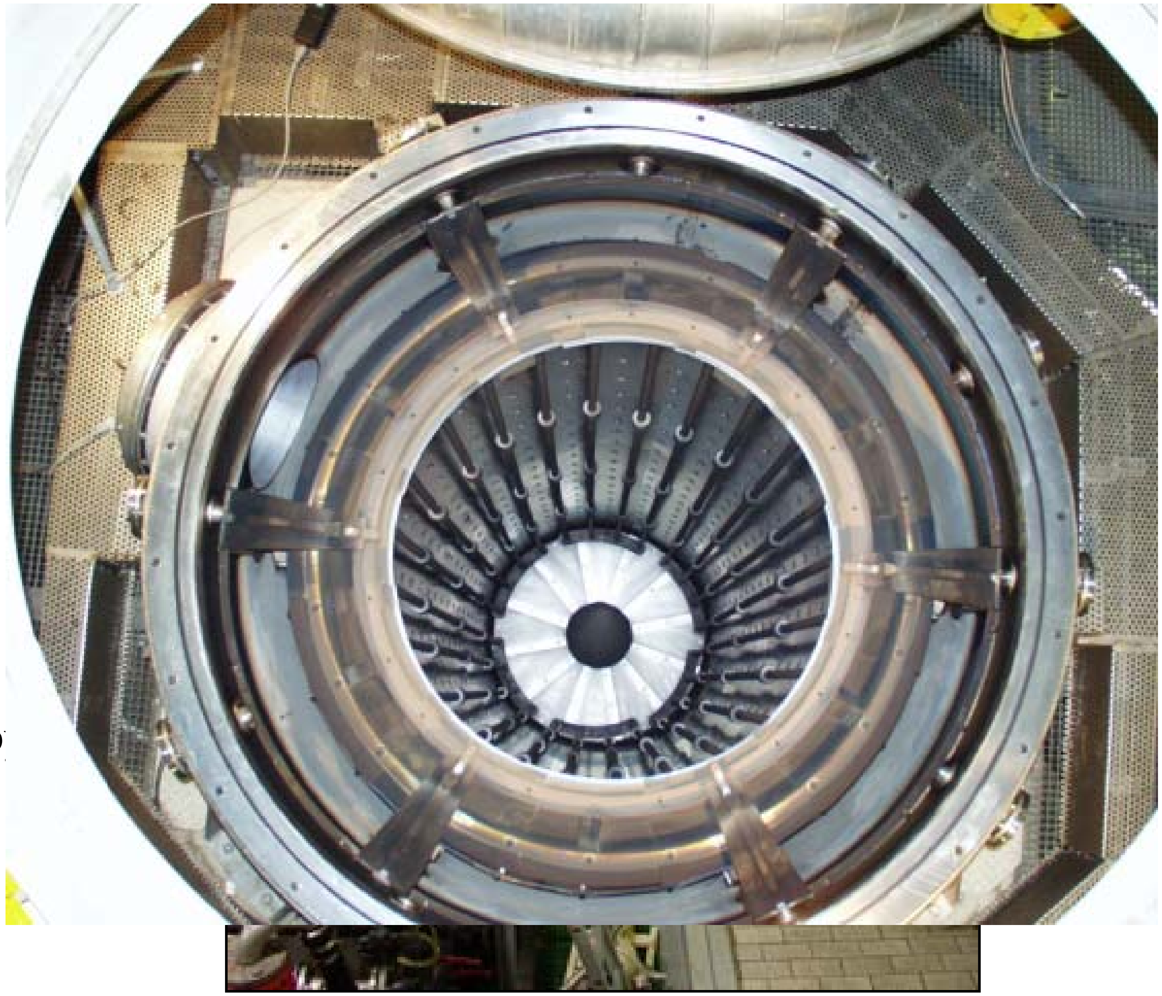
- Chemical cleaning is used to remove gross contamination such as grease, oil, finger prints.
- Example of CERN LHC beam screens :

  Degreasing with an alkanile detergent at 50°C in an ultrasonic bath
  Running tap water rinse
  Cold demineralised water rinse by immersion
  Rinse with alcool
  Dry with ambiant air

- Vacuum firing at 950°C is used to reduce the hydrogen content from stainlees 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 b

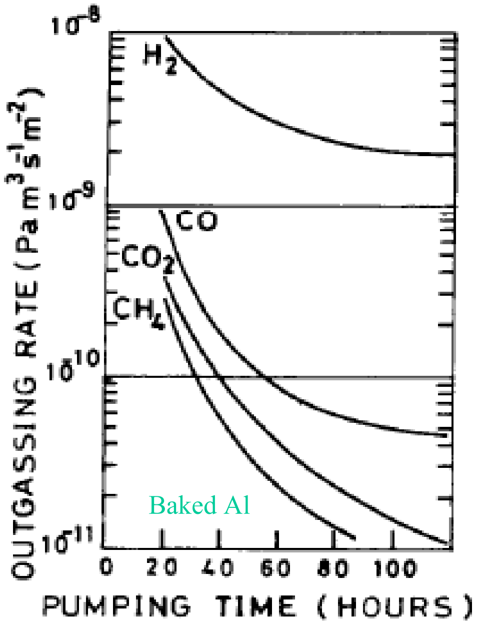


- Wear gloves to handle the material

cuves for beam screens

Bake-out

- The outgassing rate of unbaked surfaces is dominated by H_20. A bake-out above 150 degrees increase the desorption rate of H_2O and reduce the H_2O sojourn time in such a way that H_2 become the dominent gas



A.G. Mathewson *et al.*
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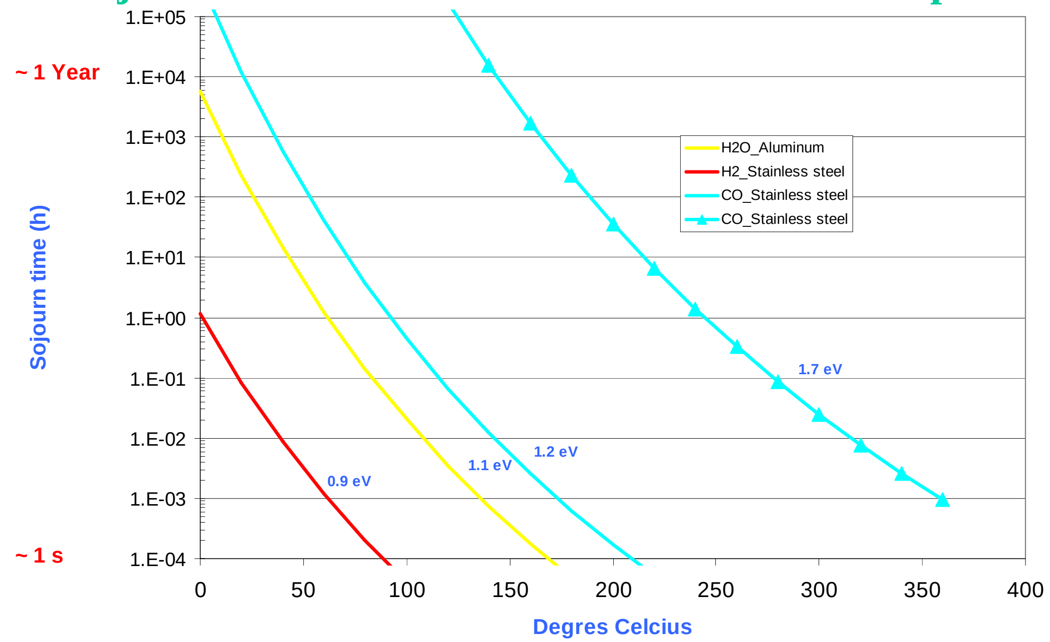
Sojourn time of a molecule as a function of temperature



Stainless steel after 50 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

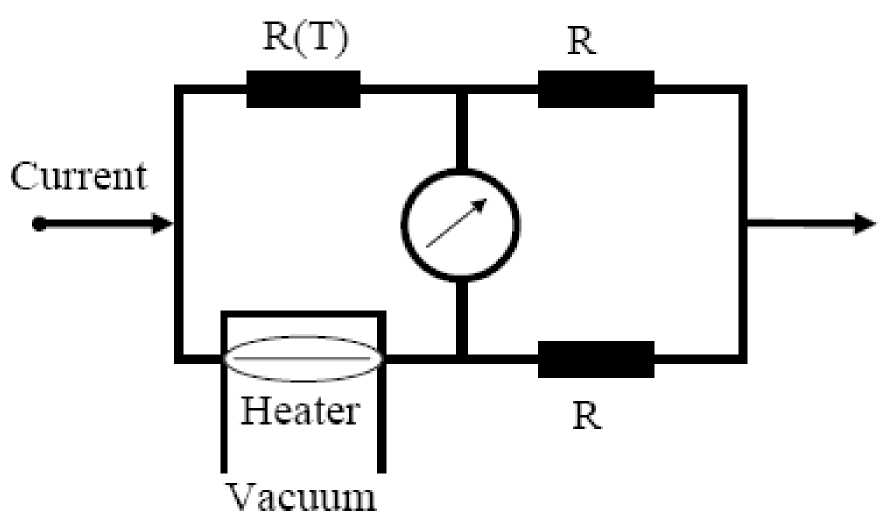
2. Vacuum Components

Pirani Gauge

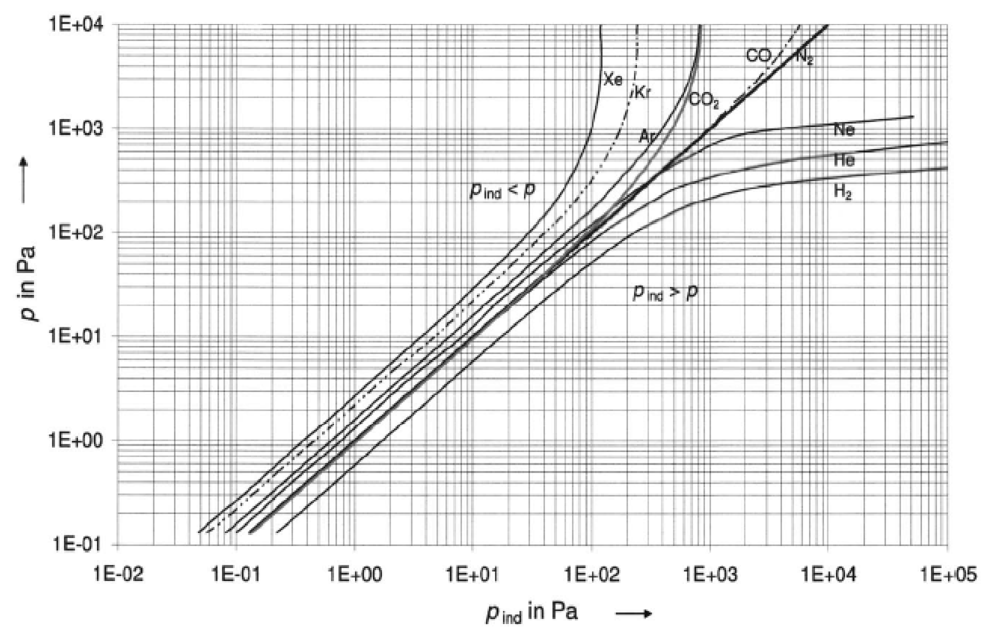
• Pirani gauges are commonly used in the range 1 atm -10^{-4} mbar.

• 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 (~ 120°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

Penning Gauge

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

• It is 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

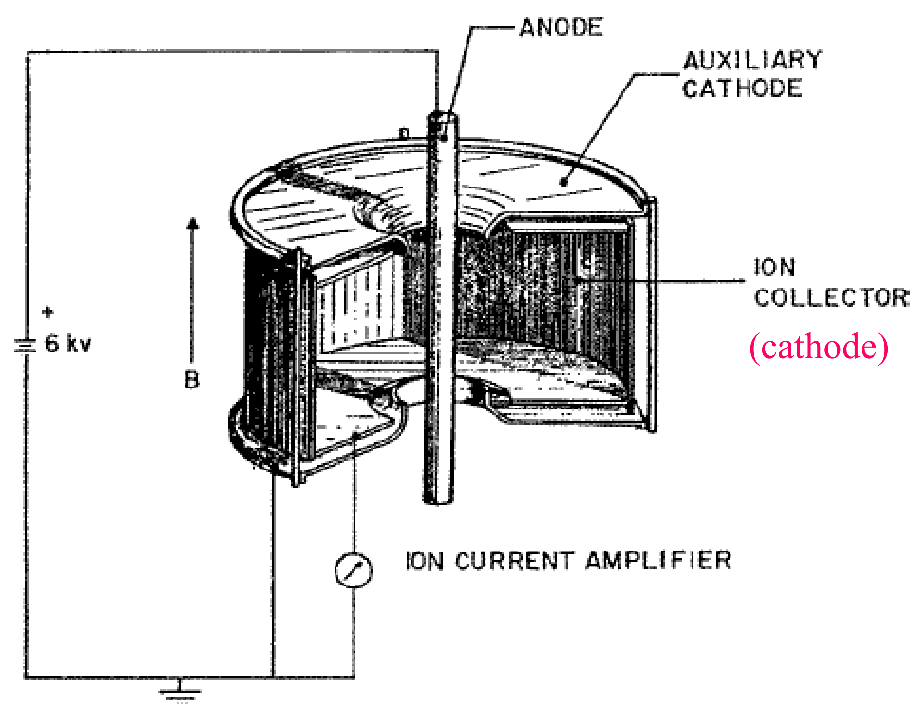
•At high pressure the discharge is unstable due to arcing.

• 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



P. Redhead. J.Vac.Sci. 21(5), Sept/Oct 2003, S1-S5

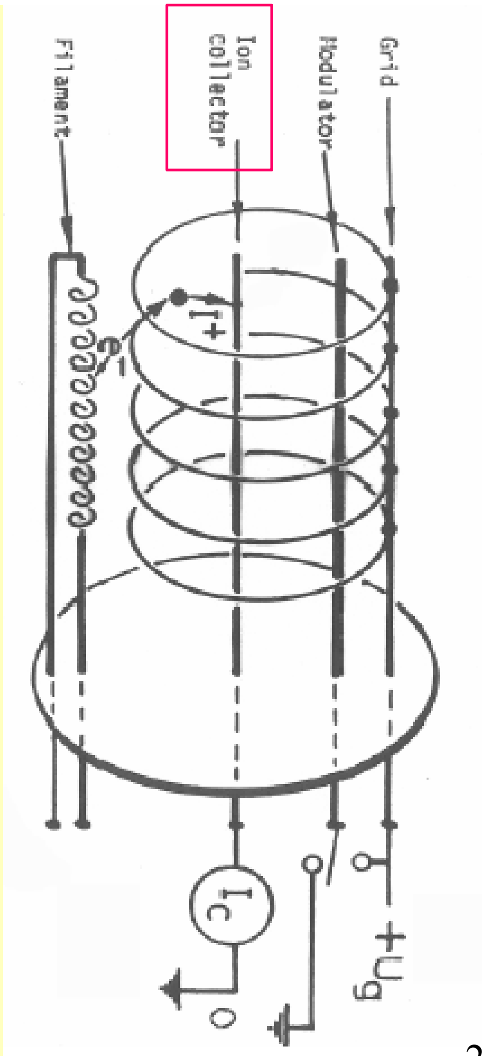
Bayard-Alpert Gauge

- 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 oscilations inside the grid and ionise the molecules of the residual gas. Ions are then collected by an electrode.

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

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



- The gauge needs to be calibrated

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

Residual Gas Analysers

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

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

- It is a

- It can

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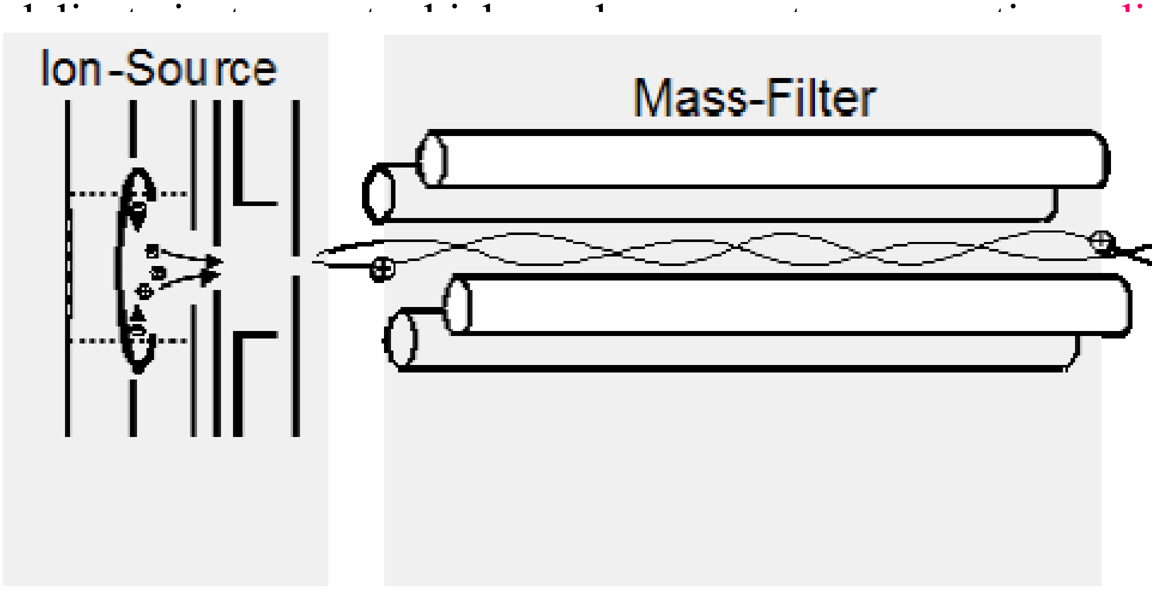
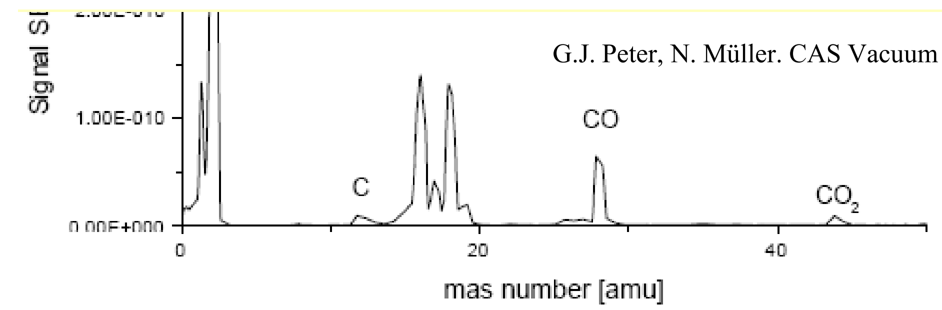
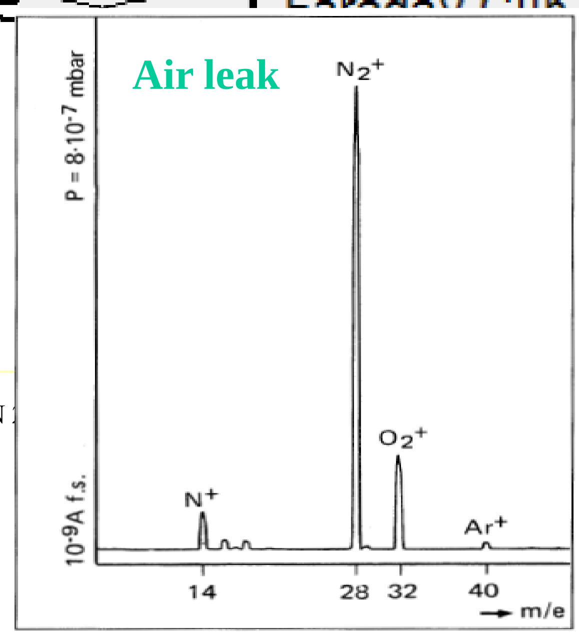






Primary Pump

- Are used to pump down from atmosphere down to 10^{-2} mbar with a speed of a few m^3/h

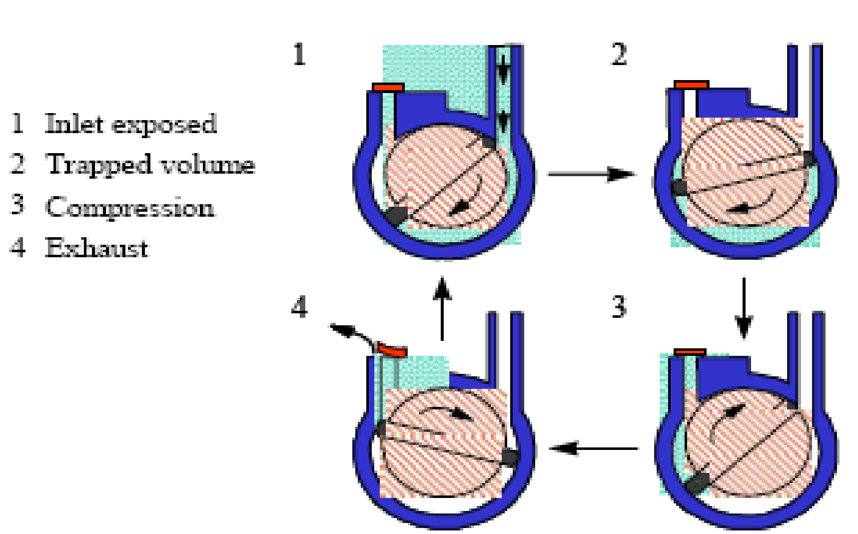
- They are usualy used as a baking pump for turbomolecular pumps

- Two categories : dry and wet pumps.

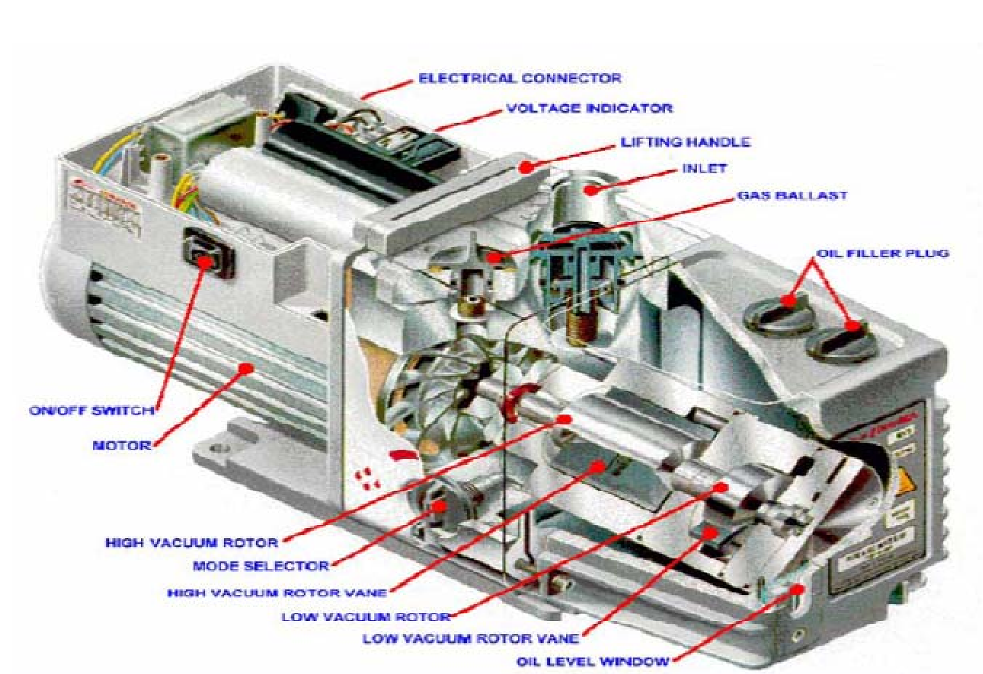
- Dry pumps are expensive and need additional cooling (water)

- Wet pumps are operating with oil wich acts as a sealing, a lubricant, a heat exchanger and protects parts from rust and corrosion

Oil Sealed Rotary Vane Pump

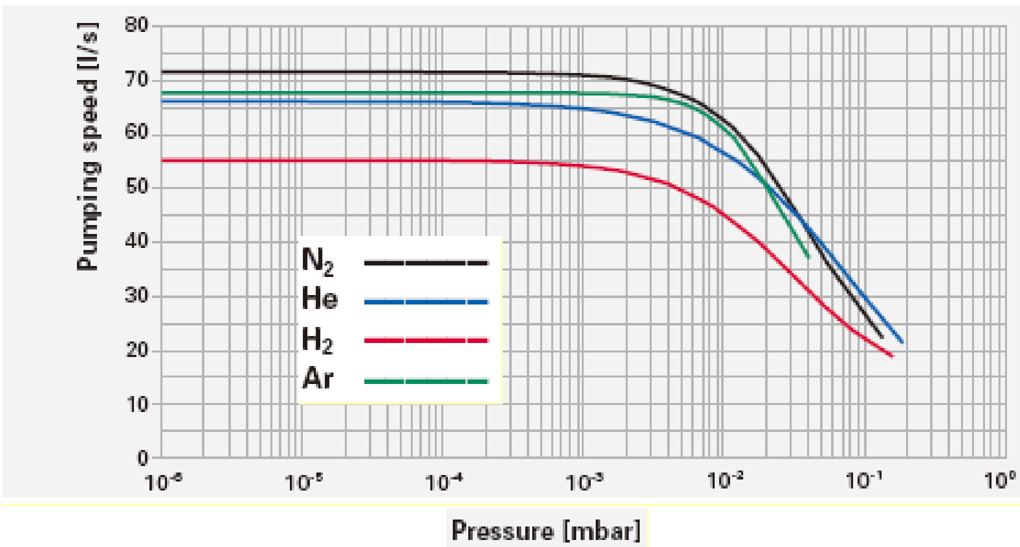


A.D. Chew. CAS Vacuum in accelerators CERN 2007-003

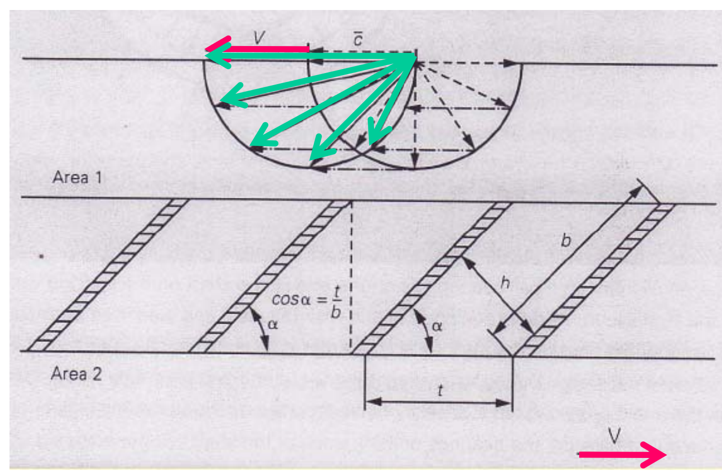


Turbomolecular Pump

- This pump operates in the molecular regime and is used to pump down an accelerator vacuum system. Usually, it is installed with its primary pump on a mobile trolley : it can be removed after valving off
- Its ultimate pressure can be very low : 10^{-11} mbar
- Its pumping speed range from 10 to 3 000 l/s



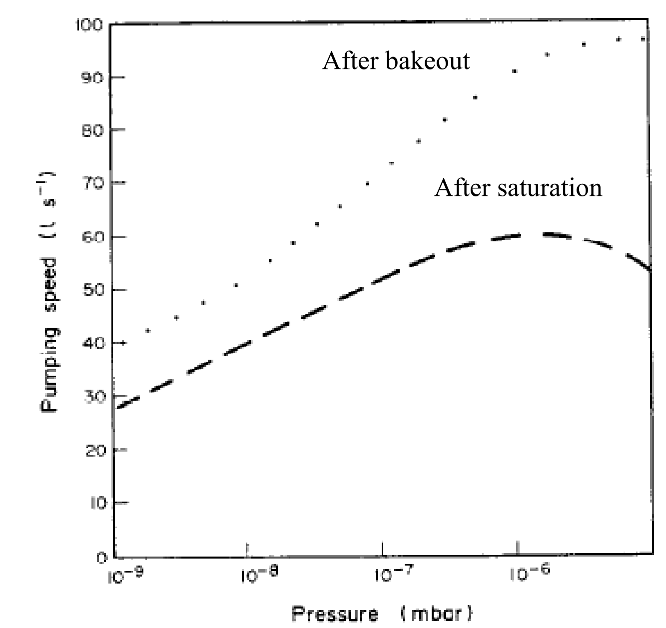
- The pumping mechanism is based on the transfer of impulse. When a molecule collide a blade, it is adsorbed for a certain lenght of time. After re-emission, the blade speed is added to the thermal speed of the molecules. To be significant, the blade speed must be comparable to the thermal speed hence it requires fast moving surfaces (~ 40 000 turns/min)



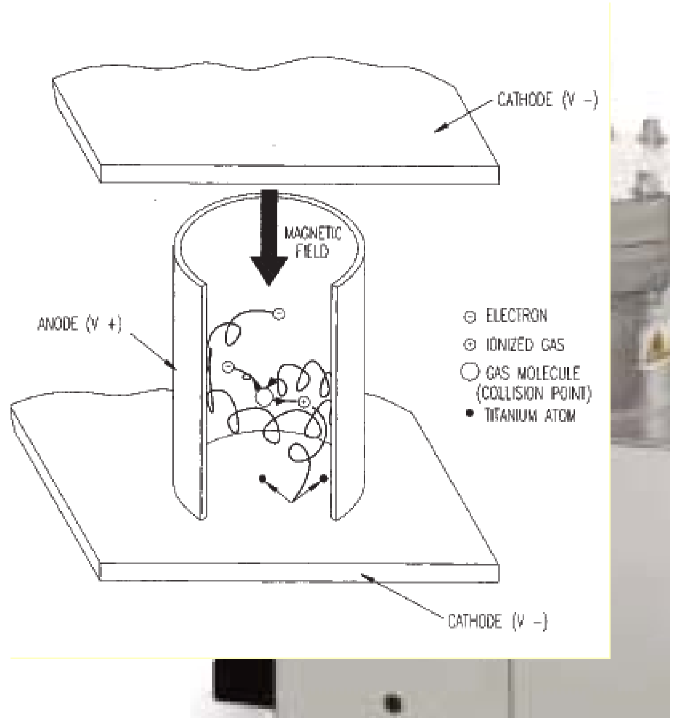
- The compression ratio (P_{inlet}/P_{outlet}) increase exponentially with $\sqrt{M}$: “clean” vacuum without hydrocarbons. So, the oil contamination from the primary pump is avoided

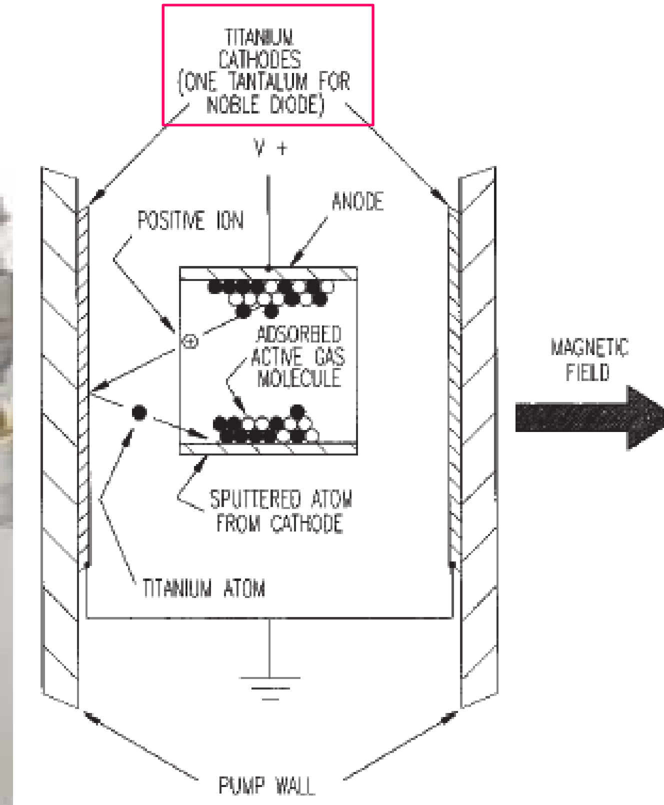
Sputter Ion Pump

- This pump operate in the range 10^{-5} -10^{-11} mbar. It is used to maintain the pressure in the vacuum chamber of an accelerator.
- Its pumping speed range from 1 to 500 l/s



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





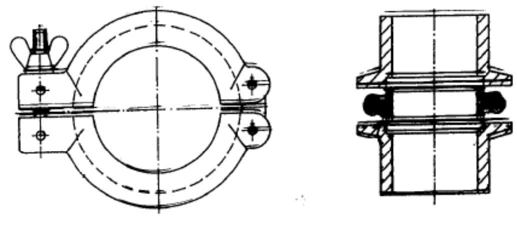
- When electrons spiral in the Penning cell, they ionised molecules. Ions are accelerated towards the cathode (few kV) and sputter Ti. Ti, which is deposited onto the surfaces, forms a chemical bounding with molecules from the residual gas. Noble gases and hydrocarbons, which does not react with Ti,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

Flanges and Gaskets

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

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

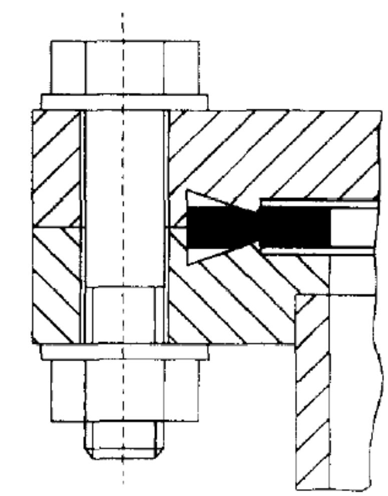
    ISO diameters

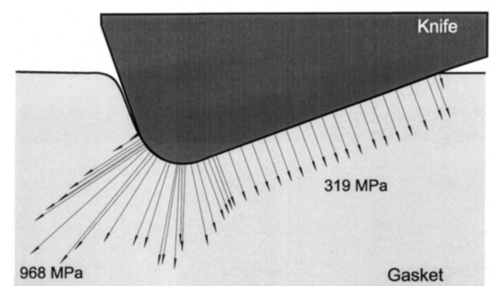


- For ultra high vacuum, metalic gaskets and bolds flanges are used
- Conflat® Type components :

    Copper gaskets, blank flanges, rotable flanges, welding flanges, elbows, T, crosses, adaptators, zero length double side flanges, windows …

    ISO diameters





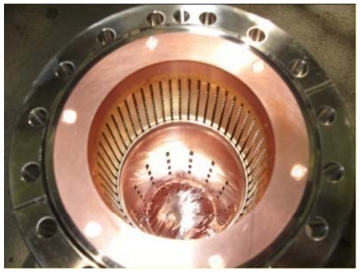
P. Lutkiewicz, C. Rathjen.
J.Vac.Sci. 26(3), May/Jun 2008, 537-544

Tubes, Bellows, Valves

- Metallic tubes are preffered (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

Roughing valve

Sector valves

Leak Detection

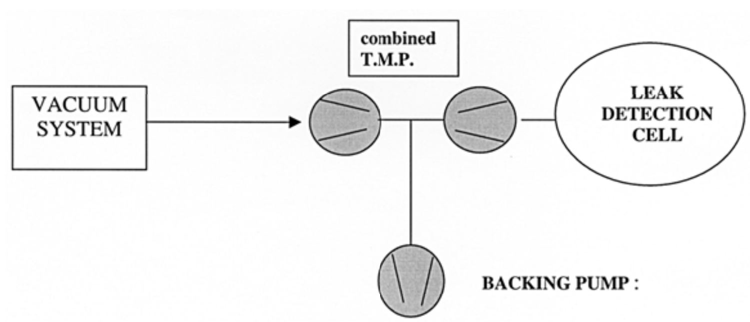
• The vacuum system of an accelerator must be leak tight !

• All vacuum components must follow acceptance tests (leak detection, bake out, residual gas composition and outgassing rate) before installation in the tunnel

• Virtual leaks, due to a closed volume, must be eliminated during the design phase. Diagnostic can be made with a RGA by measuring the gas composition before and after venting with argon.

• Leaks could appear :
  - during components constructions at welds (cracks or porosity)
  - due to porosity of the material
  - during the assembly and the bake-out of the vacuum system (gaskets)
  - during beam operation due to thermal heating

• Detection method : He is sprayed around the test piece and a helium leak detector (*i.e.* a RGA tune to He signal) is connected to the device under test.



Counter flow method

3. Vacuum with Beams : LHC

Desesperated Time ….

- Despited all the precautions taken before …

- The vacuum ingeneer becomes desesperated after the passage of the first (significant !) beam in his beautyfull (and expensive) vacuum system

Ma come è possibile????

- Because, the static pressure increases by several orders of magnitude due to dynamics effects

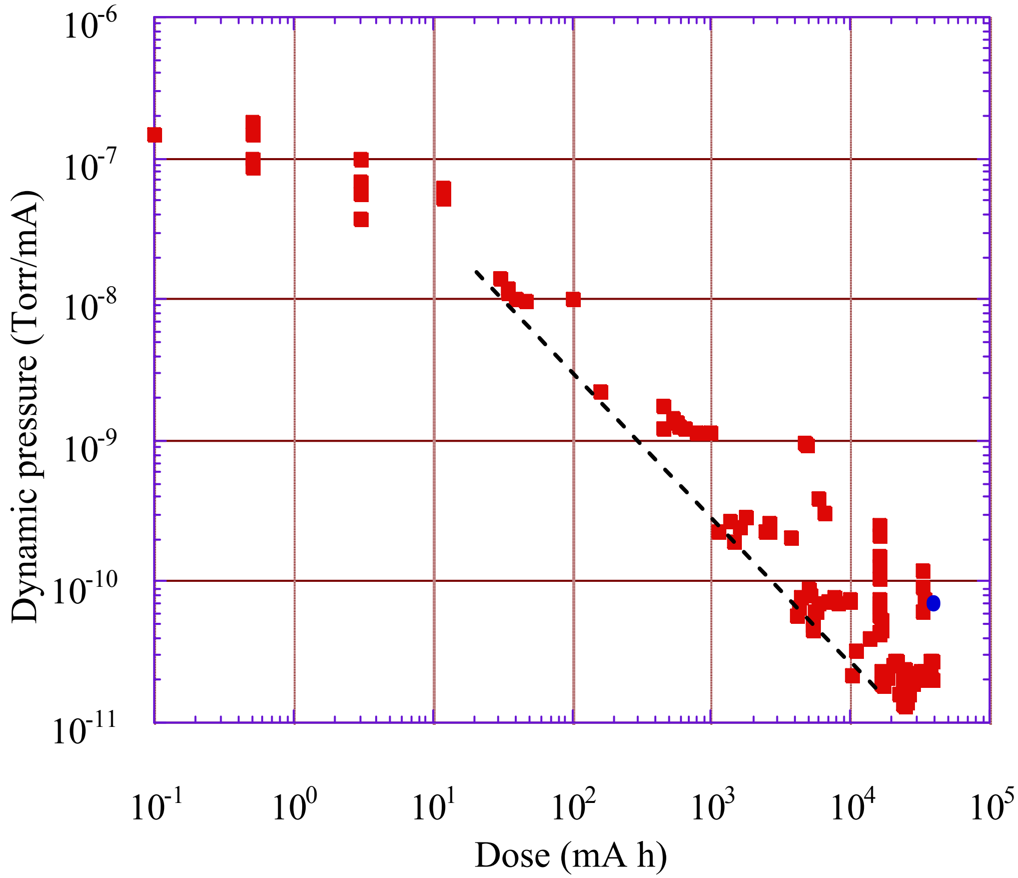
HOW is it Possible ?

Photon Stimulated Desorption

- Synchrotron radiation induce gas desorption : SR machine, LEP, LHC
- Heat load and gas load

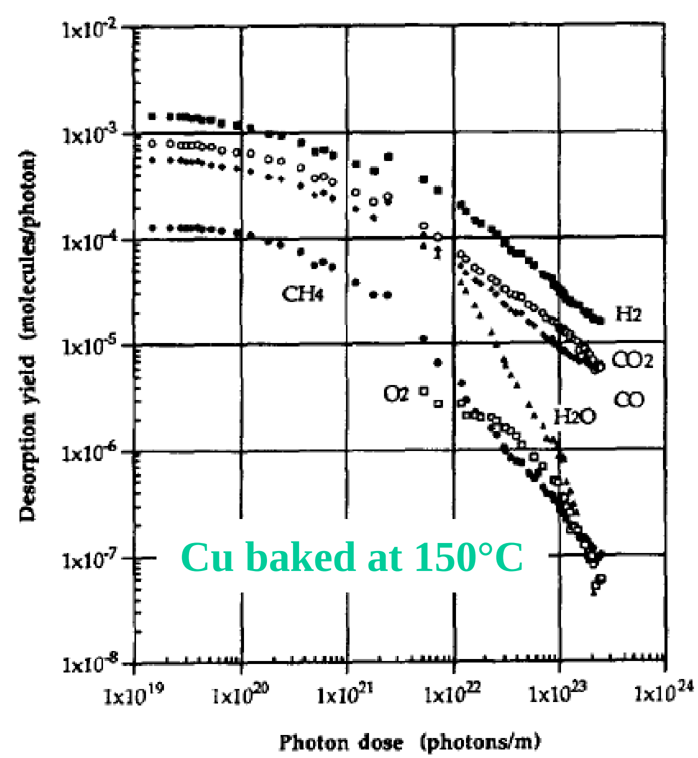
- η_{photon} is the photon desorption yield

Beam cleaning during the first period of LEP



O. Gröbner. Vacuum 43 (1992) 27-30

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

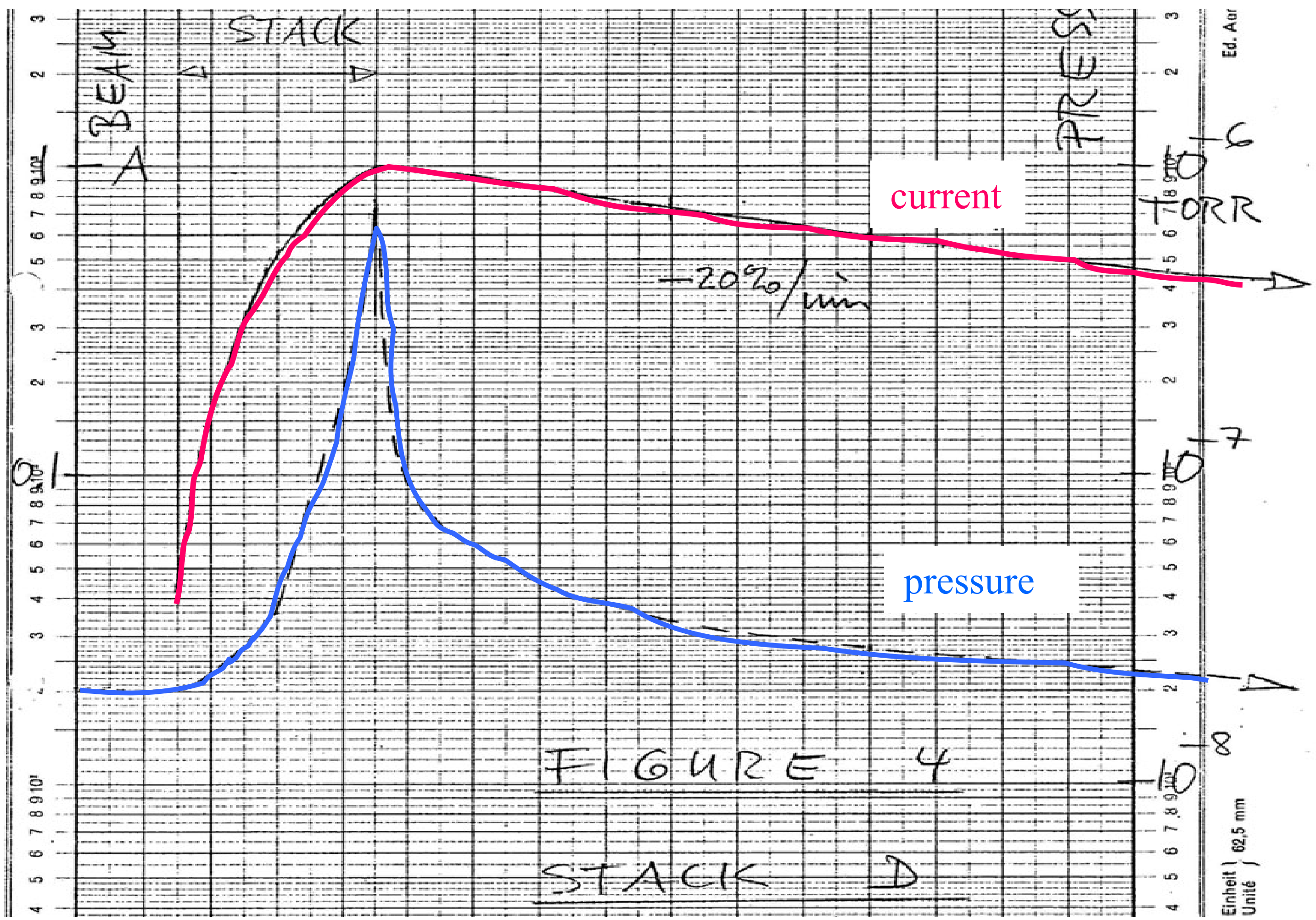


O. Gröbner *et al.*
J.Vac.Sci. 12(3), May/Jun 1994, 846-853

Vacuum Instability : the Effect

- In circular machine with large proton current : ISR, LHC

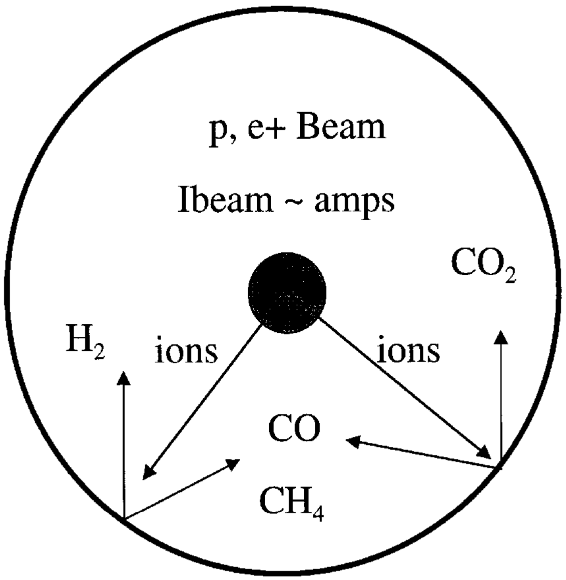
- Beam current stacking to 1 A
- Pressure increases to 10^{-6} Torr (x 50 in a minute)
- Beam losses



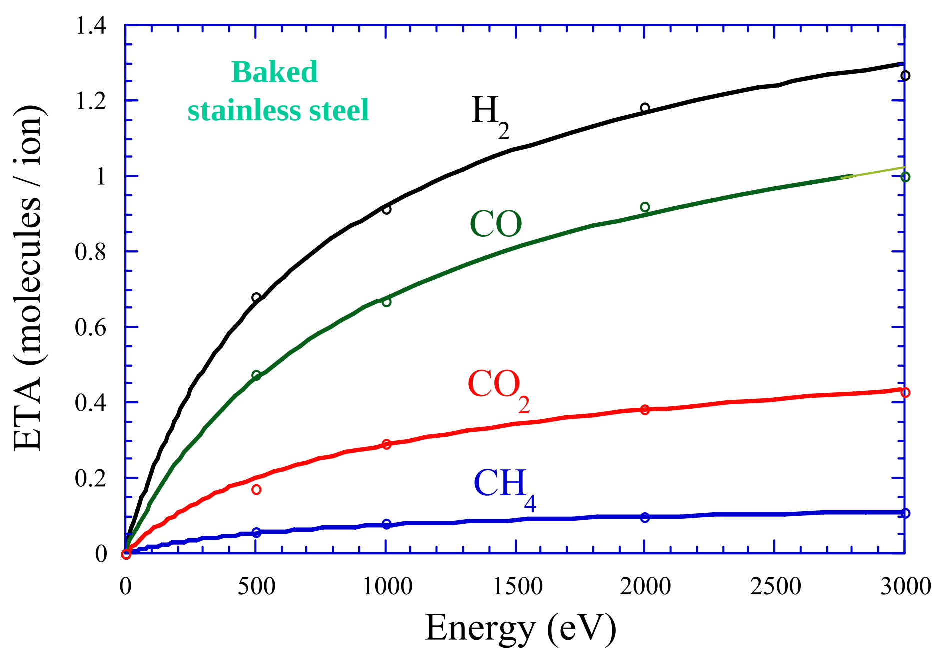
First documented pressure bump in the ISR
E. Fischer/O. Gröbner/E. Jones 18/11/1970

Vacuum Instability : Mecanism and Recipy

• Reduction of the effective pumping speed, S_{eff}



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



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

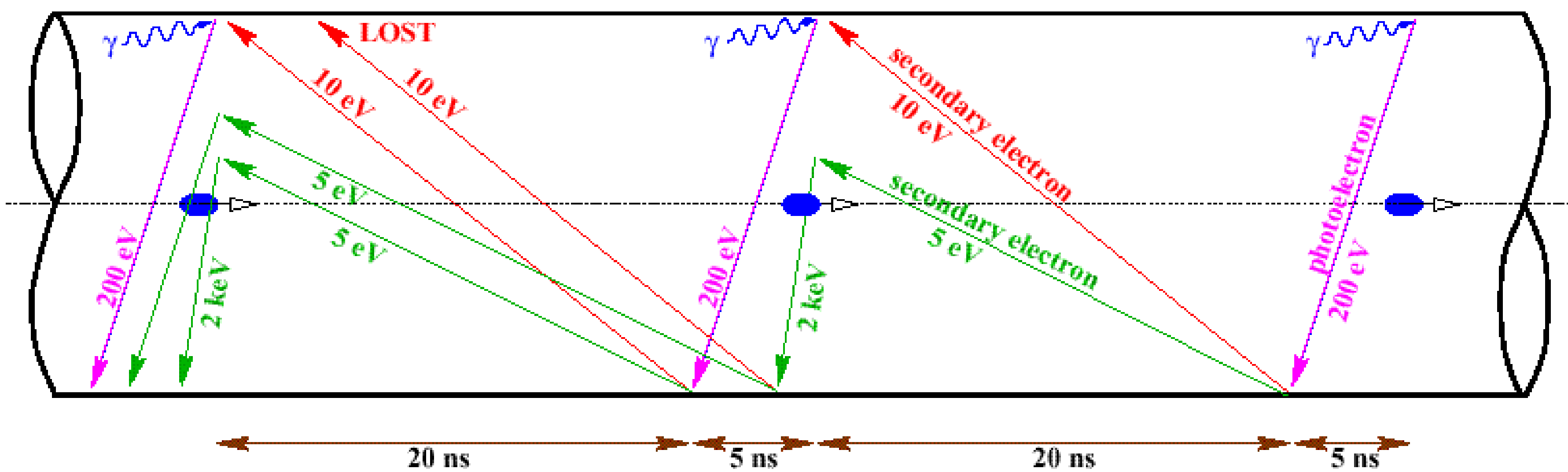
• Solution :

Reduce η_{ion}

Electron Cloud : the Mecanism

- In modern machine with dense bunches and large positive current : KEK-B, PEP-II, SPS, RICH, LHC …
- Emittance growth, gas desorption and heat load in cryogenic machine
- Key parameters :
  - bunch structure
  - vacuum chamber dimmension
  - secondary electron yield
  - photon electron yield
  - electron and photon reflectivities
  - …

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



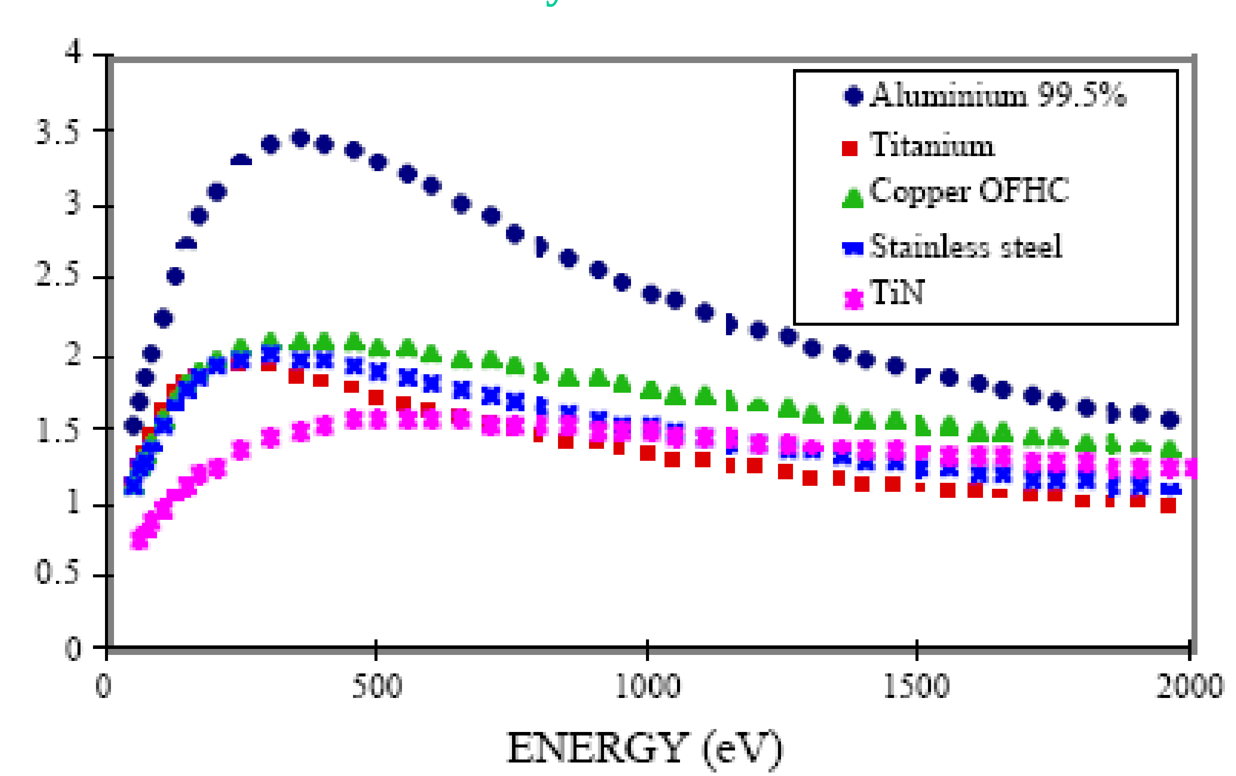
Schematic of electron-cloud build up in the LHC beam pipe.

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

Electron Cloud : the Recipies

- Play with the key parameters
- Reduce photoelectron yield (perpendicular vs grazing incidence)
- Reduce secondary electron yields (scrubbing, TiZrV coatings, carbon coatings, geometry ..)
- Reduce the amount of electrons in the system (solenoid magnetic field, clearing electrodes, material reflectivities …)
- Adapt the bunch structure or the chamber geometry to reduce multiplication
- …

Secondary Electron Yield

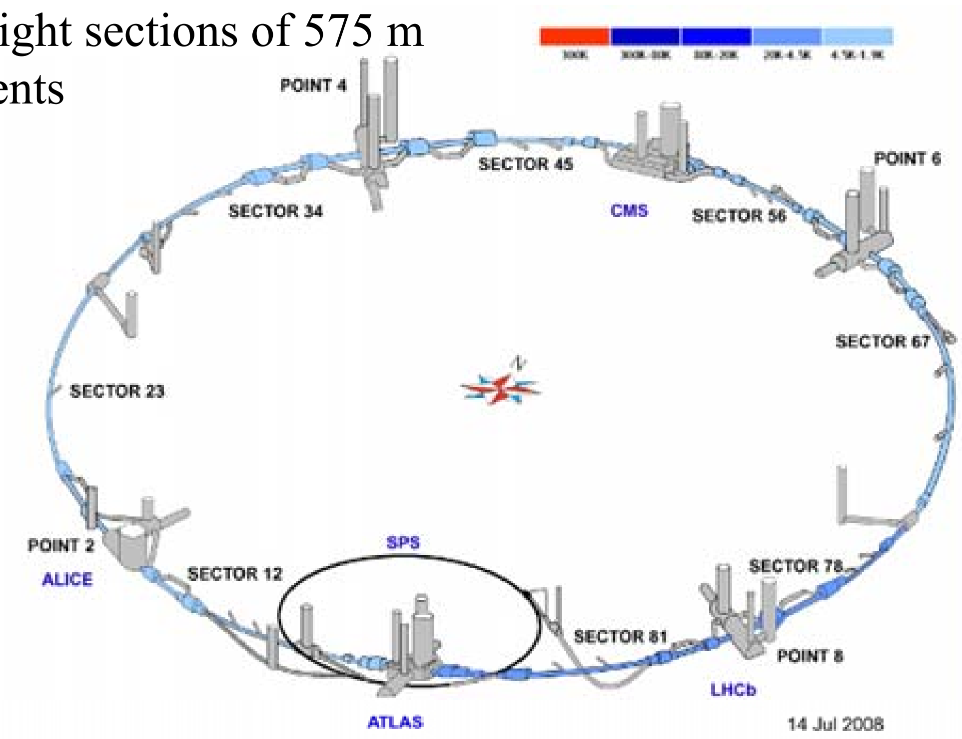


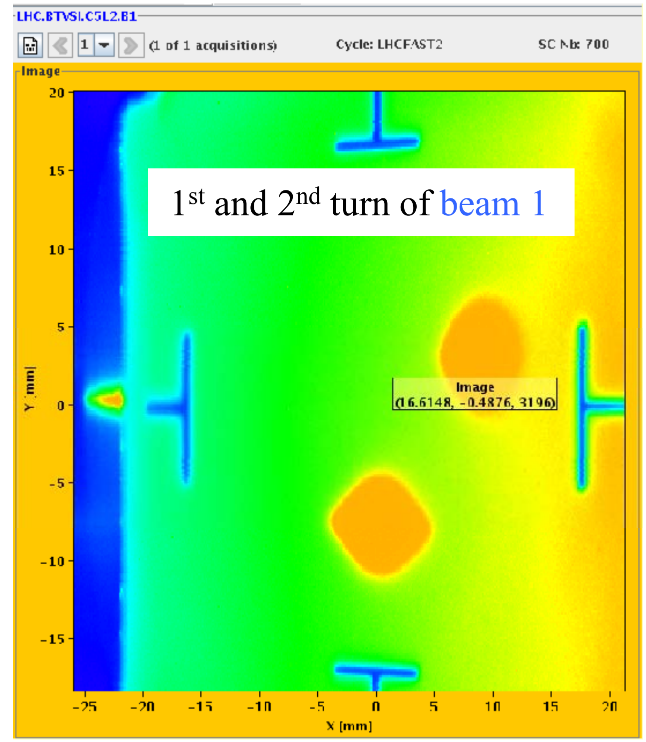
N. Hilleret *et al.*, LHC Project Report 433 2000, EPAC 00

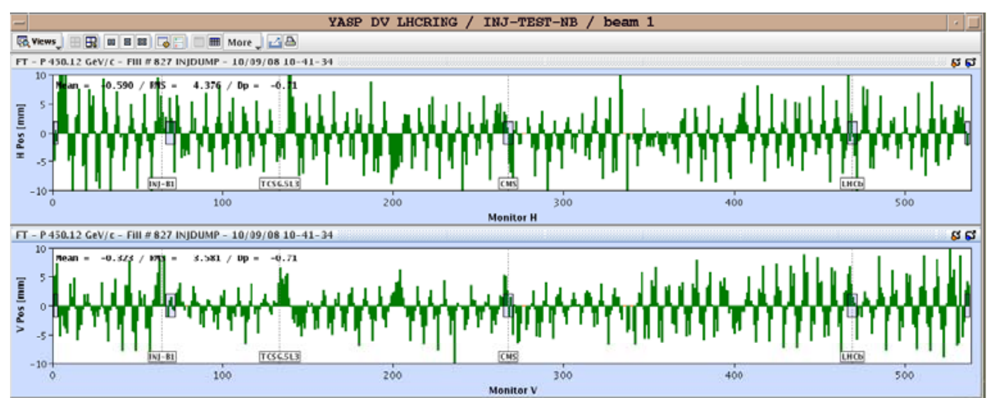
The CERN Large Hadron Collider (LHC)

1^{st} beam 10^{th} of September 2008

- 26.7 km circumference
- 8 arcs of 2.8 km
- 8 long straight sections of 575 m
- 4 experiments
- 7 TeV





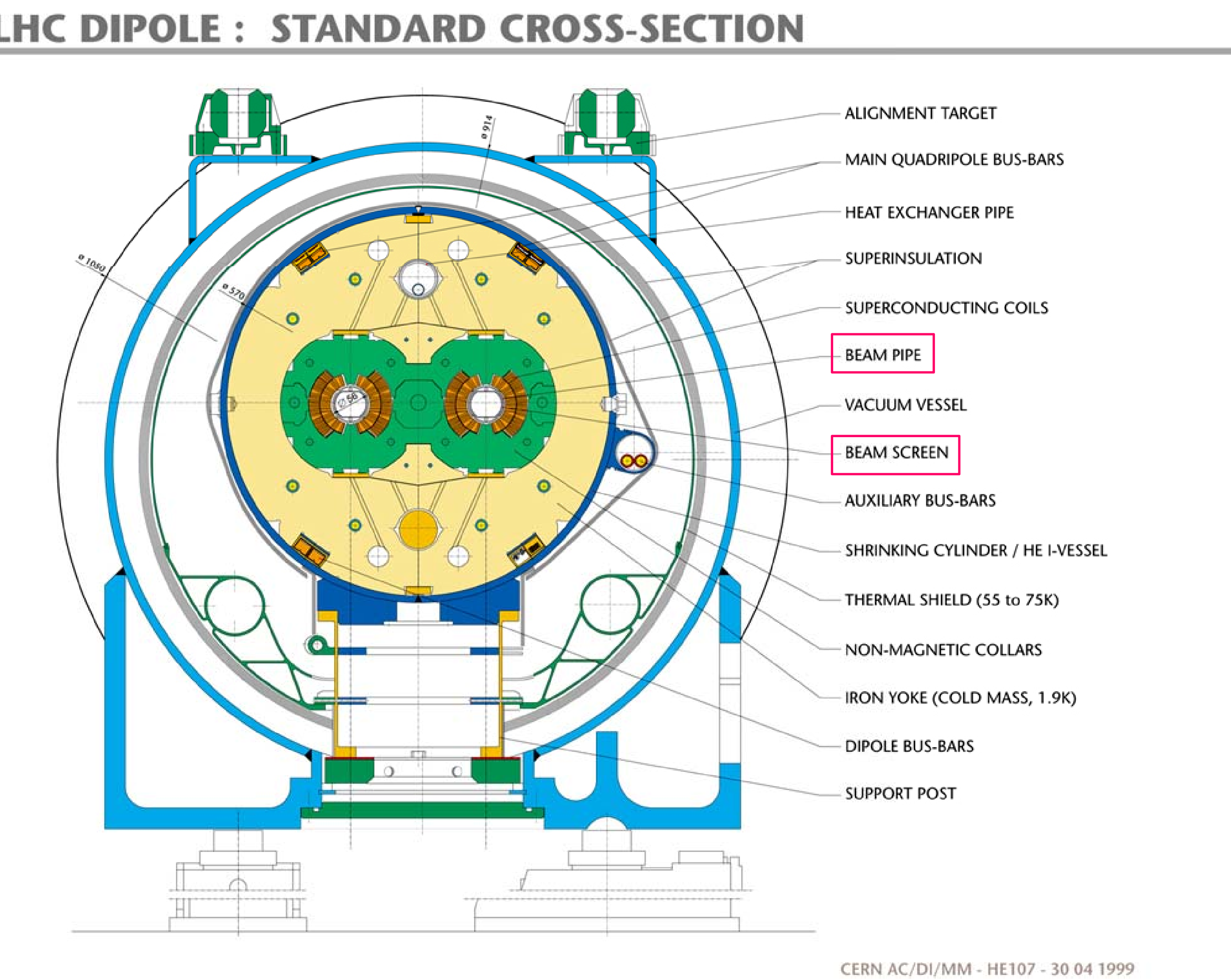


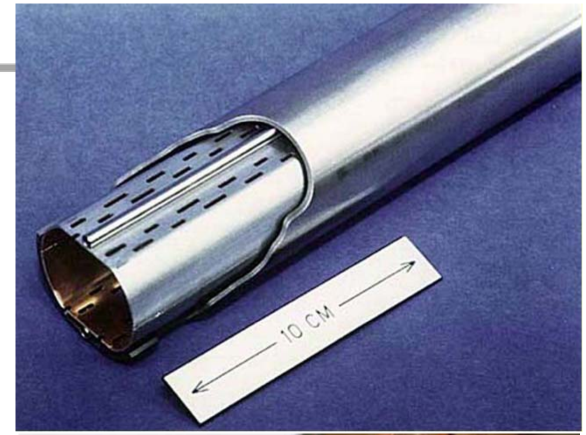
H and V trajectories of beam 1

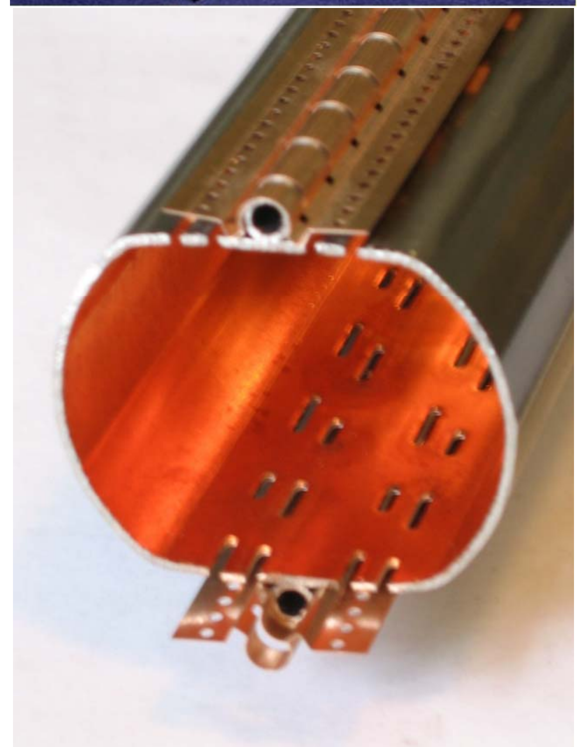
LHC Dipole Vacuum System

LHC Dipole Vacuum System

- Cold bore (CB) at 1.9 K which ensures leak tightness
- Beam screen (BS) at 5-20 K which intercepts thermal loads and acts as a screen







LHC Vacuum System Principle

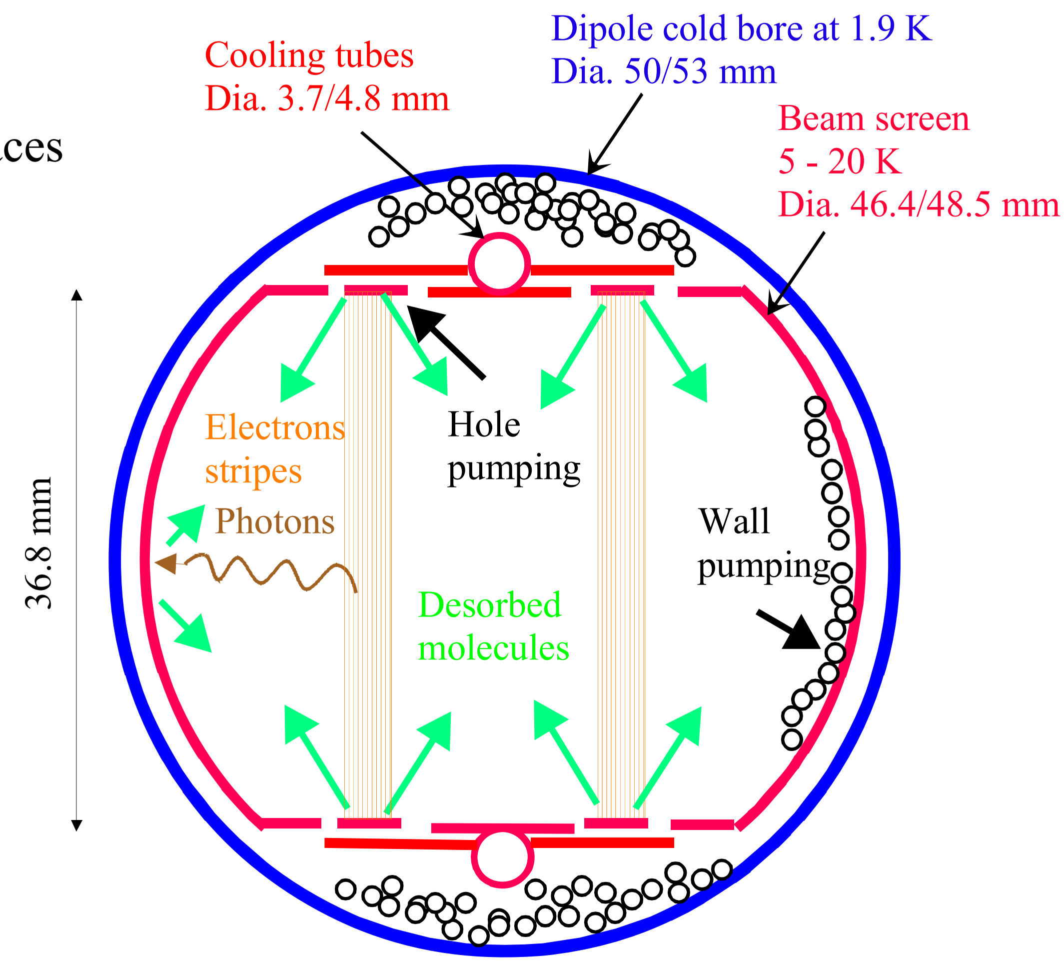
- Molecular desorption stimulated by photon, electron and ion bombardment
- Desorbed molecules are pumped on the beam vacuum chamber
- 100 h beam life time (nuclear scattering) equivalent to ~ 10^{15} H_2/m^3 (10^{-8} Torr H_2 at 300 K)

In cryogenic elements

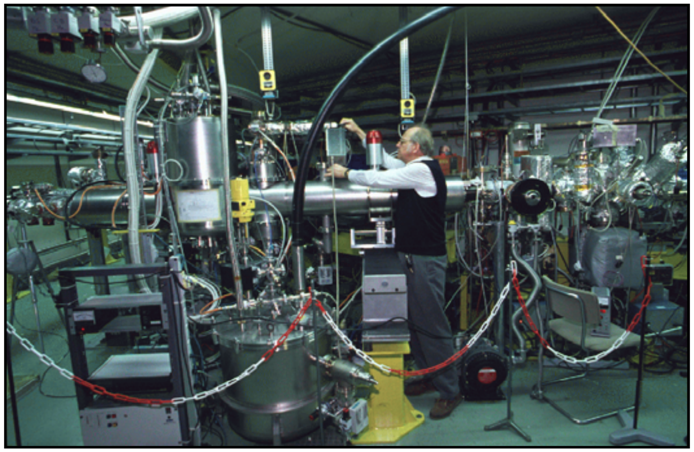
- Molecular physisorption onto cryogenic surfaces (weak binding energy)

- Molecules with a low recycling yield are first physisorbed onto the beam screen (CH_4, H_2O, CO, CO_2) and then onto the cold bore

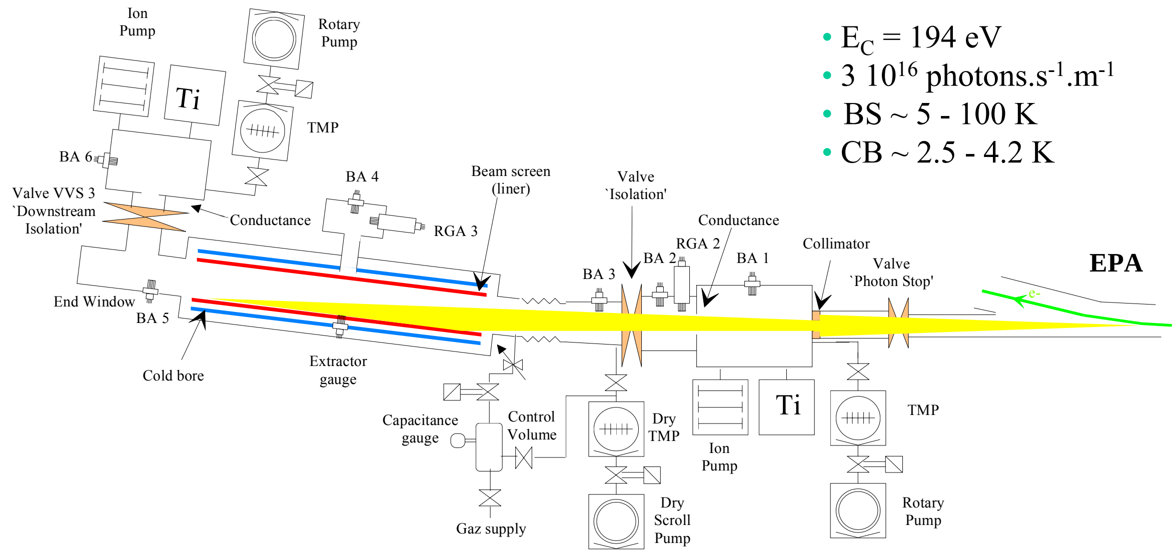
- H_2 is physisorbed onto the cold bore



LHC Vacuum System Principle : Demonstration



- E_C = 194 eV
- 3 10^{16} photons.s^{-1}.m^{-1}
- BS ~ 5 - 100 K
- CB ~ 2.5 - 4.2 K

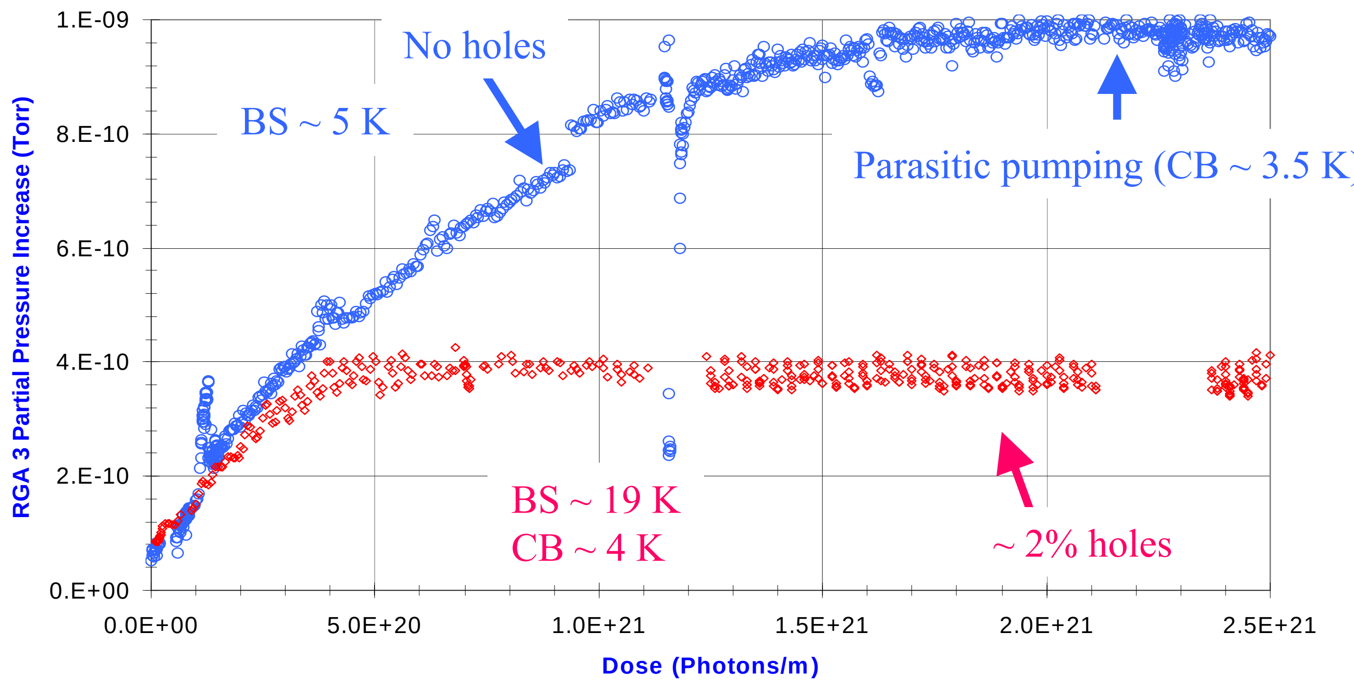


- Equilibrium pressure

$$n_{eq} = \frac{\eta \dot{\Gamma}}{C}$$

- Equilibrium coverage

$$\theta_{eq} = \left(\frac{\sigma S}{C} \frac{\eta}{\eta_0'} \right) \theta_m$$



V. Baglin *et al.* EPAC'00, Vienna 2000.

Room Temperature Vacuum System

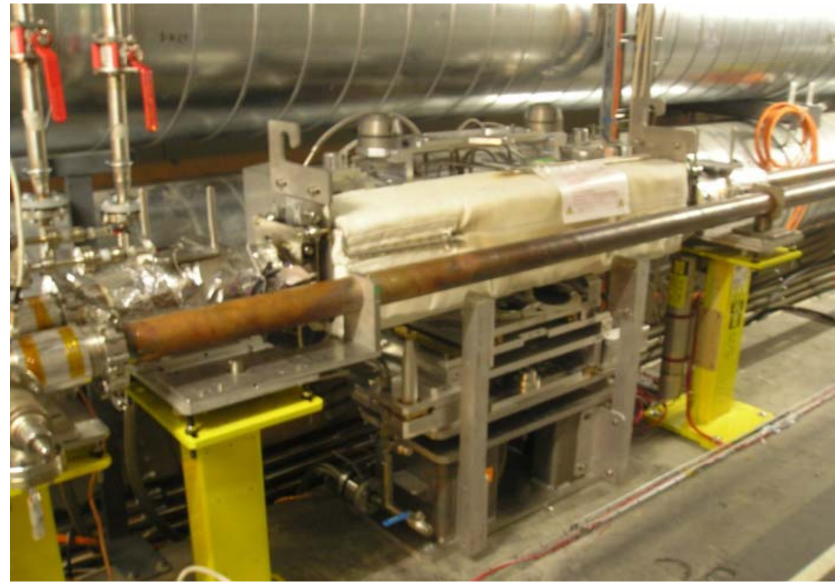
- ~ 1 μm thick, Non Evaporable Getter TiZrV coated vacuum chambers ensure the required vacuum performances for LHC
- Some vacuum chambers were constructed and getter coated …

Courtesy R.Veness AT/VAC and P. Chiggiato TS-MME

Room Temperature Vacuum System

- ….. and installed inside the LHC tunnel

Vacuum chambers

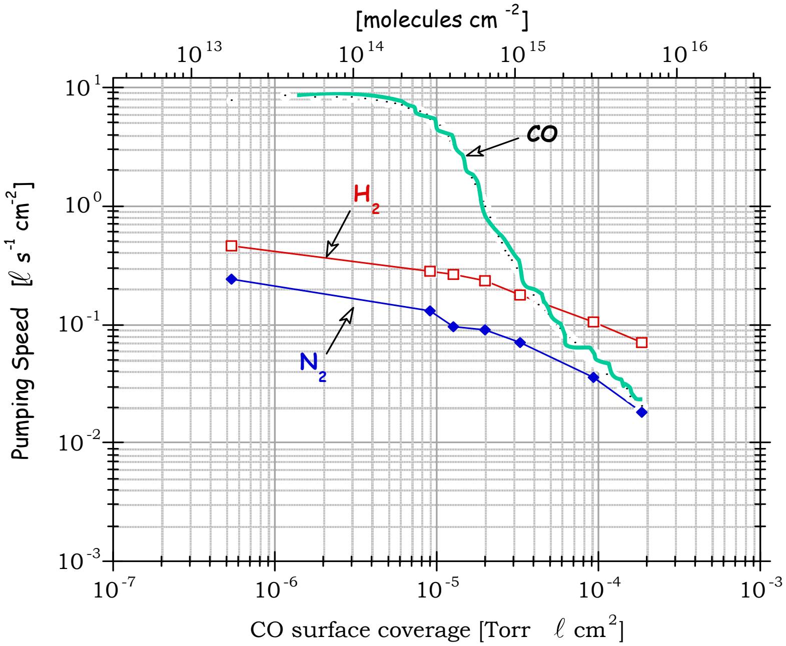


Collimators

Warm magnets

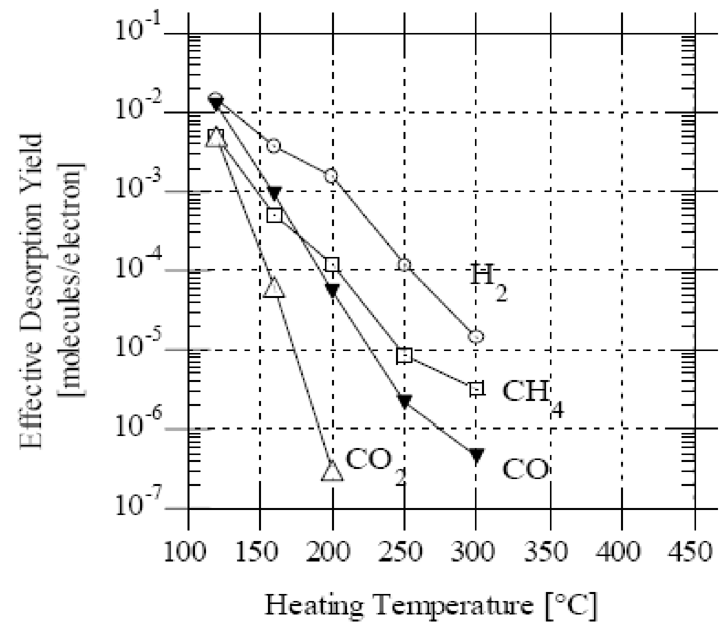
TiZrV Vacuum Performances

Pumping Speed



Courtesy P. Chiggiato TS/MME

ESD Yields



C. Benvenuti *et al.* J.Vac.Sci.Technol A 16(1) 1998

PSD Yields

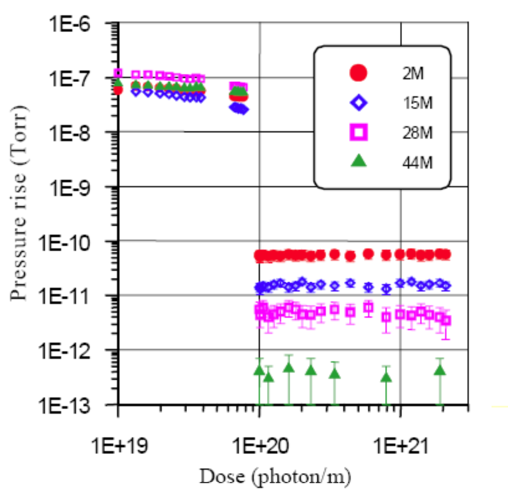


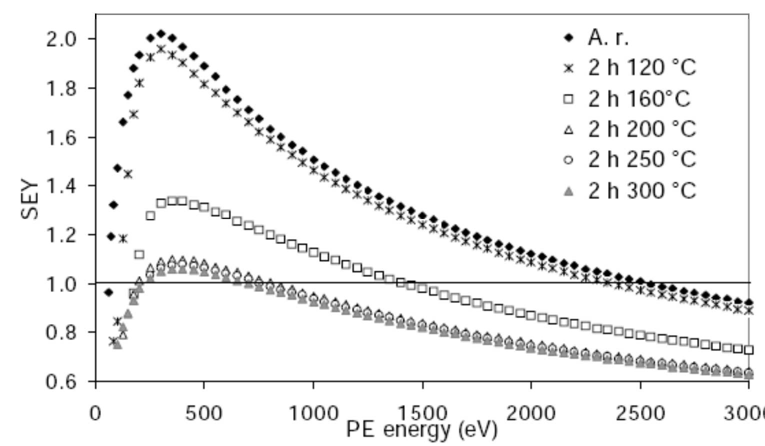
Figure 2: Pressure rise measured in the centre of the TiZrV coated test chamber before activation ($<1\cdot10^{20}$ photons/m) and after activation ($>1\cdot10^{20}$ photons/m).

Table 2: Summary of results from the activated test chamber

Gas	Sticking probability	Photodesorption yield (molecules/photon)
H_2	~0.007	$\sim1.5\cdot10^{-5}$
CH_4	0	$2\cdot10^{-7}$
CO (28)	0.5	$<1\cdot10^{-5}$
C_xH_y(28)	0	$<3\cdot10^{-8}$
CO_2	0.5	$<2\cdot10^{-6}$

V. Anashin *et al.* EPAC 2002

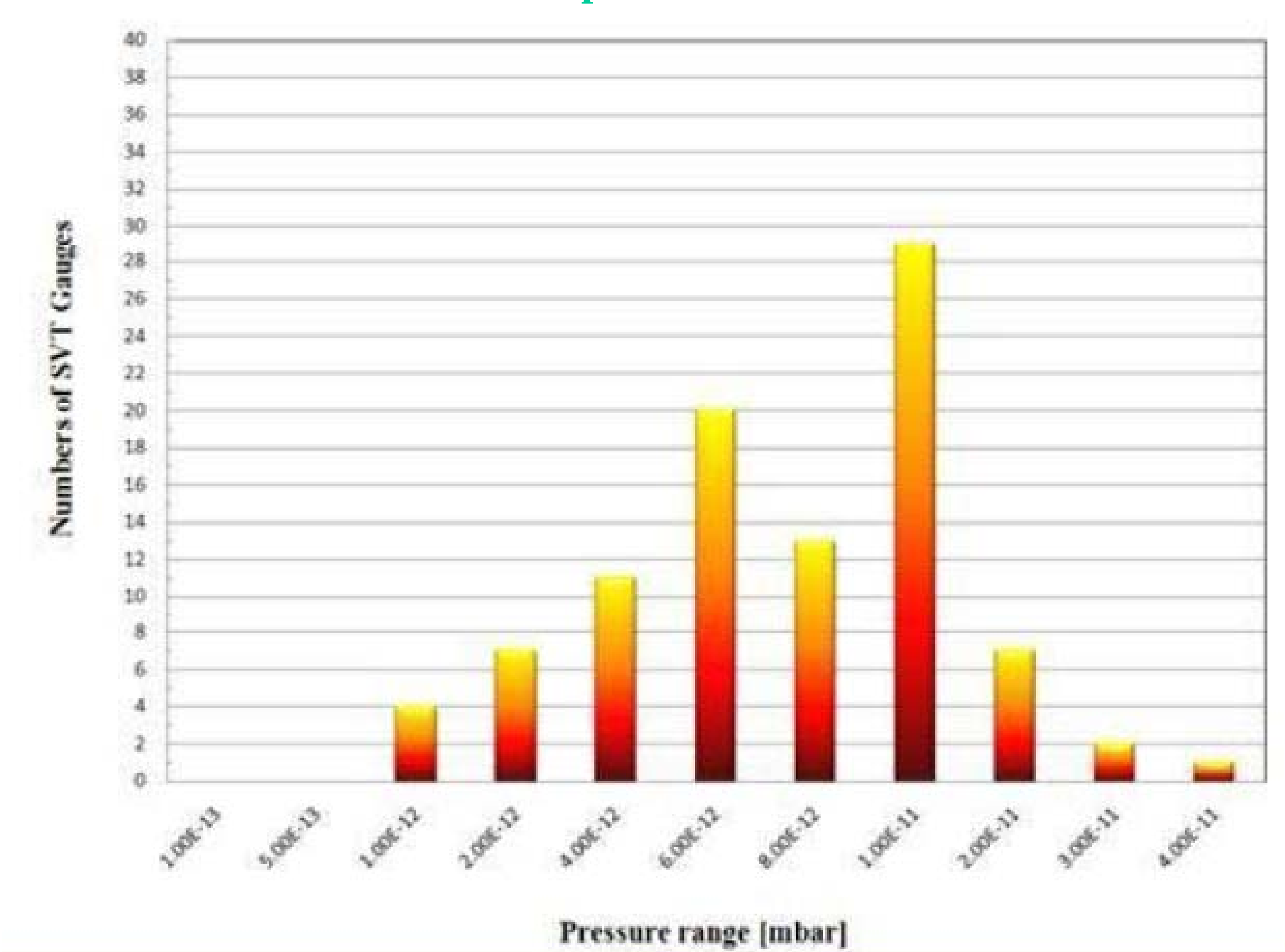
Secondary Electron Yield



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

Room Temperature Vacuum System : Demonstration

Ultimate Vacuum Pressure Distribution after NEG Activation of the LHC Room Temparture Vacuum Sectors



G. Bregliozzi *et al.* EPAC'08, Genoa 2008

Thank you for your attention !!!

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- Les calculs de la technique du vide, J. Delafosse, G. Mongodin, G.A. Boutry. Le vide.
- Vacuum Technology, A. Roth. Elsevier Science.

Some Journals Related to Vacuum Technology

- Journal of vacuum science and technology
- Vacuum