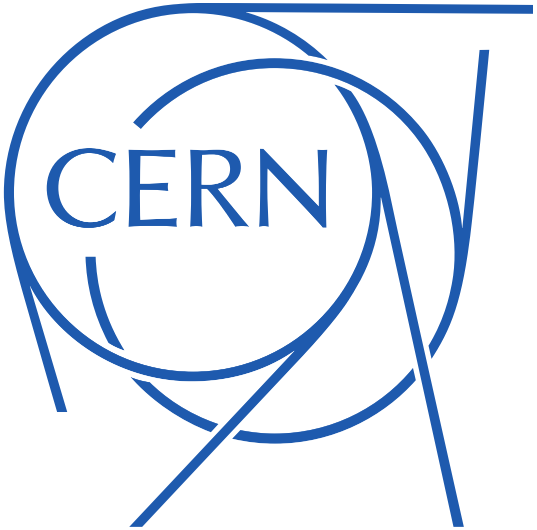
CERN

Vacuum Systems

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Outline

1. Vacuum Basis
2. Vacuum Components
3. Vacuum with Beams : LHC Example

1. Vacuum Basis

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

As a consequence of the « vacuum force » …

Ø (mm)	**16**	**35**	**63**	**80**	**100**	**130**	**150**	**212**
kg	2	10	32	52	81	137	182	363

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)

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

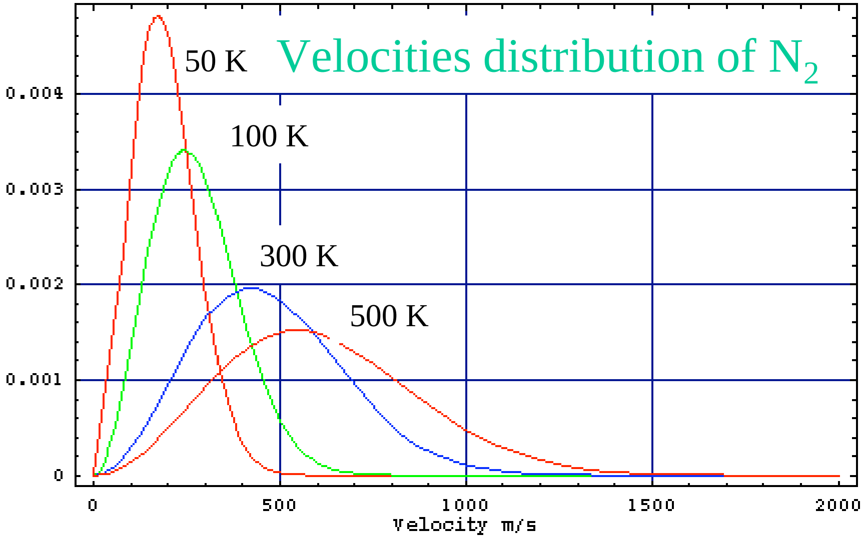
- The distribution of velocities, dn/dv, follows a Maxwell-Boltzmann function

- 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

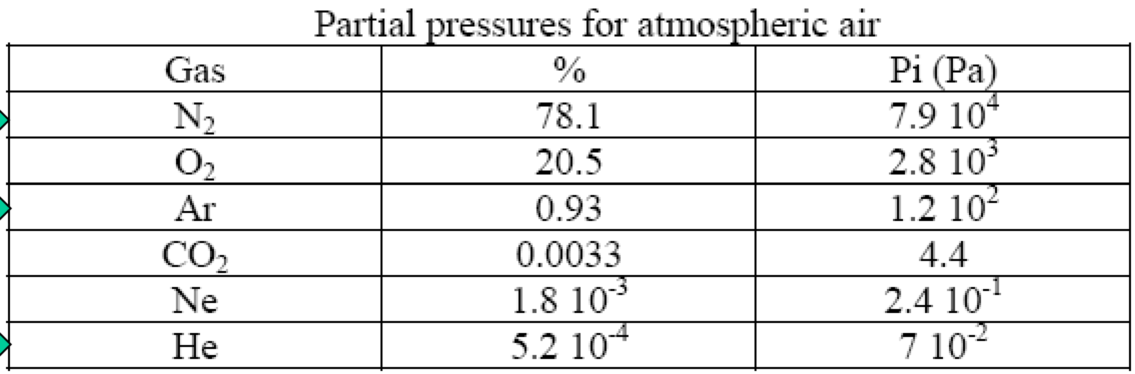


Total Pressure and Partial Pressure

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

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

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



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

Traces

Mean Free Path

- It is the path length that a molecules traverse between two successive 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 :

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

- At atmospheric pressure, λ = 70 nm
- At 1 Torr, λ = 50 µm
- At 10^{-3} Torr, λ = 5 cm
- At 10^{-7} Torr, λ = 500 m
- At 10^{-10} Torr, λ = 500 km

Increasing mean free path when decreasing pressure

Turbulent and Viscous Flows

- When pumping down from atmospheric pressure, the physics is caracterised by different flow regimes. 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 atmospheric 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 (1-10^{-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

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

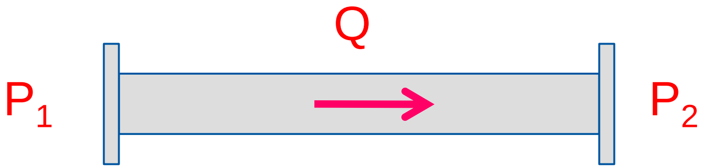
Molecular flow is the main regime of flow to be used in vacuum technology

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

Conductance

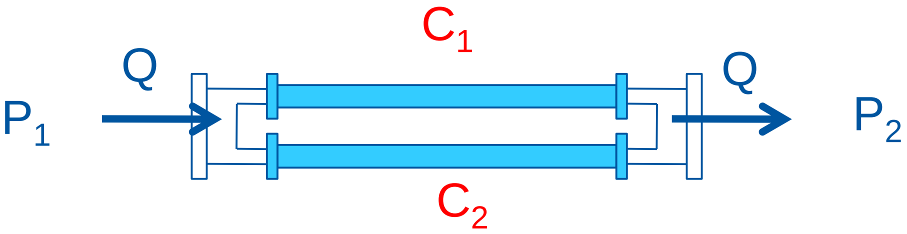
- It is defined by the ratio of the molecular flux, Q, to the pressure drop along a vacuum vessel. It is a function of the shape of the vessel, the nature of the gas and its temperature.

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



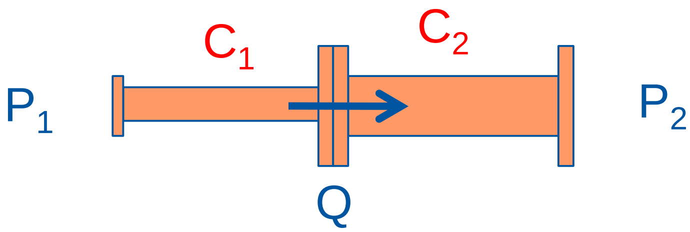
- Adding conductances in parallel

$$C = C_1 + C_2$$



- 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 $\rightarrow$ $$\boxed{S = \frac{Q}{P}}$$

mbar

- S range from 10 to 20 000 l/s

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

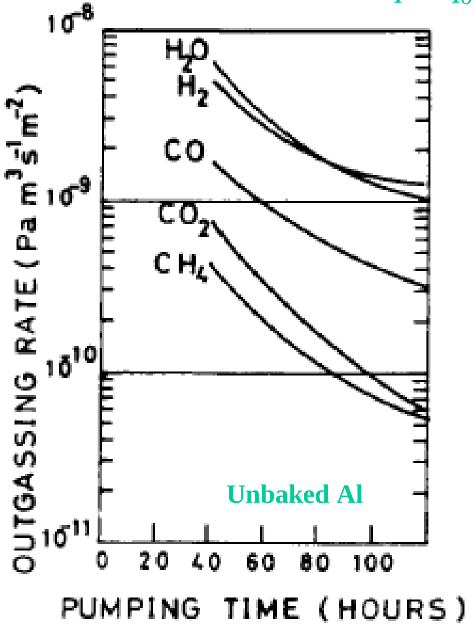
3 orders of magnitude for pumping
vs
10 orders of magnitude for outgassing

Outgassing MUST be optimised to achieve UHV

Outgassing

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

Metallic surfaces $q \sim q_0/t$

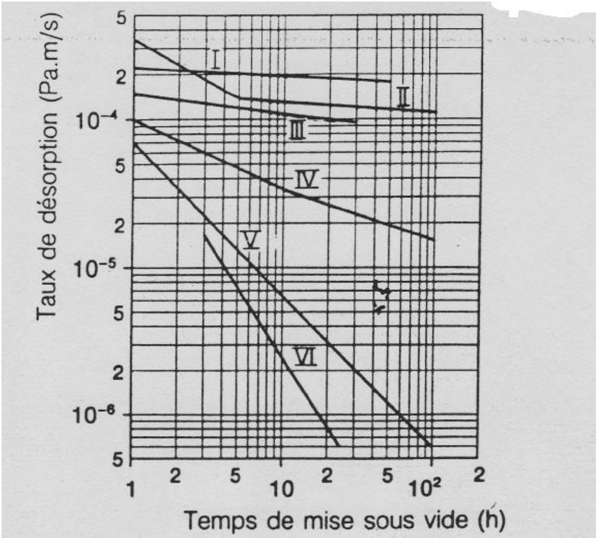


A.G. Mathewson *et al.*
J.Vac.Sci. 7(1), Jan/Fev 1989, 77-82

x 5 000

→

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



Lexan MR 400 (polycarbonate)
genre *Plexiglas* (polyméthacrylate de méthyle)
Ertacétal noir (polyacétal)
Téflon (polytétrafluoréthylène) après 15 h d'étuvage à 100 °C
(épaisseur de 10 mm)

Good Vacuum Design :

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

Cleaning Methods

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

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

  Degreasing with an alkaline detergent at 50°C in an ultrasonic bath
  Running tap water rinse
  Cold demineralised water rinse by immersion
  Rinse with alcohol
  Dry with ambient air

cuves for beam screens

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

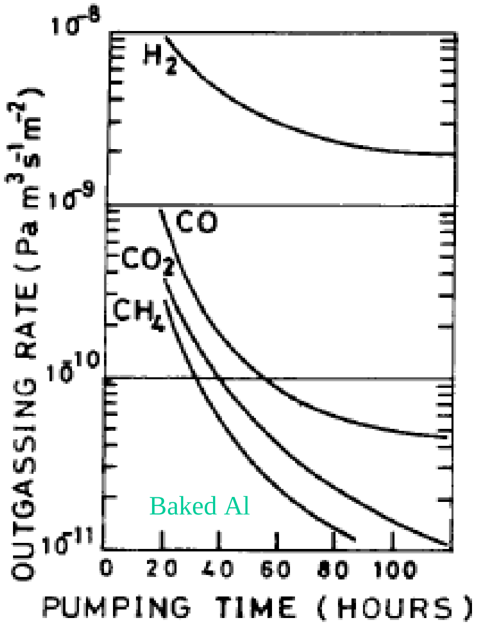
Length: 6 m
Diameter: 1 m
Maximum charge weight: 1000 Kg
Ultimate pressure: 8 10^{-8}Torr
Pressure at the end of the treatment: high 10^{-6} Torr

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

- Wear gloves to handle the material

In Situ Bake Out

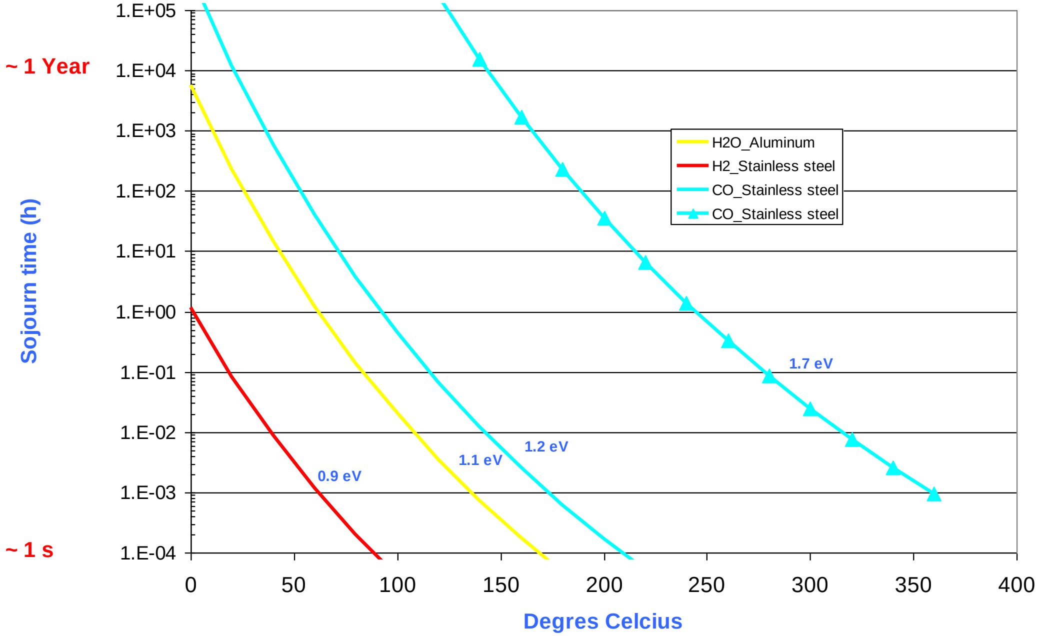
- The outgassing rate of unbaked surfaces is dominated by H_20.
- A bake-out above 150 degrees increase the desorption rate of H_2O and reduce the H_2O sojourn time in such a way that H_2 become the dominant gas



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 50 h of pumping (Torr.l/s/cm^2)

	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

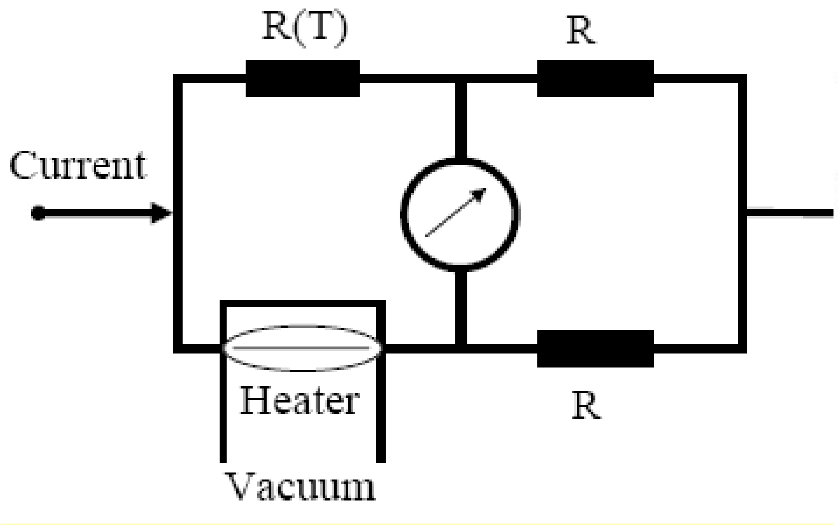
2. Vacuum Components

Pirani Gauge

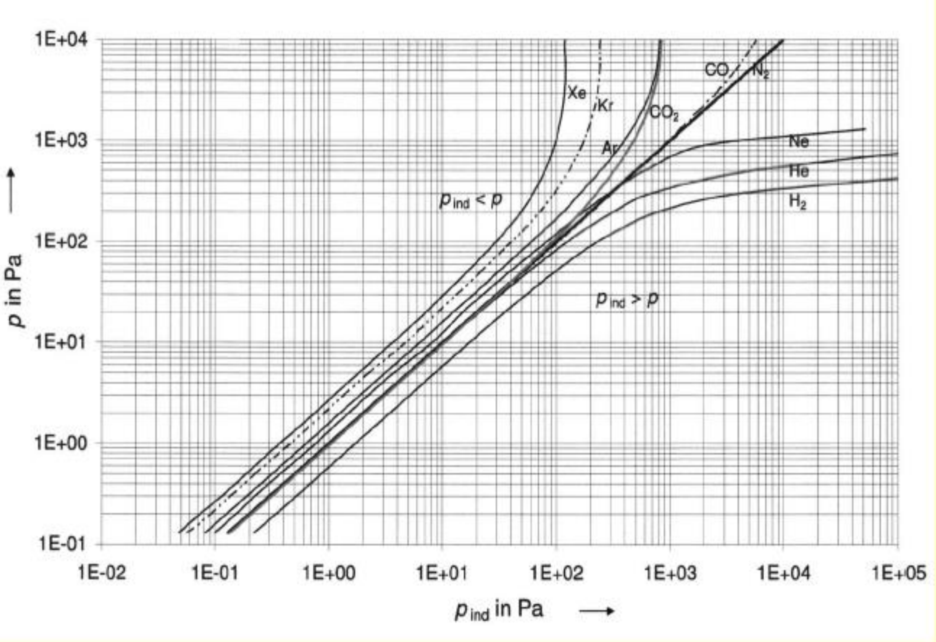
- Pirani gauges are commonly used in the range 1 atm -10^{-4} mbar.

- 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

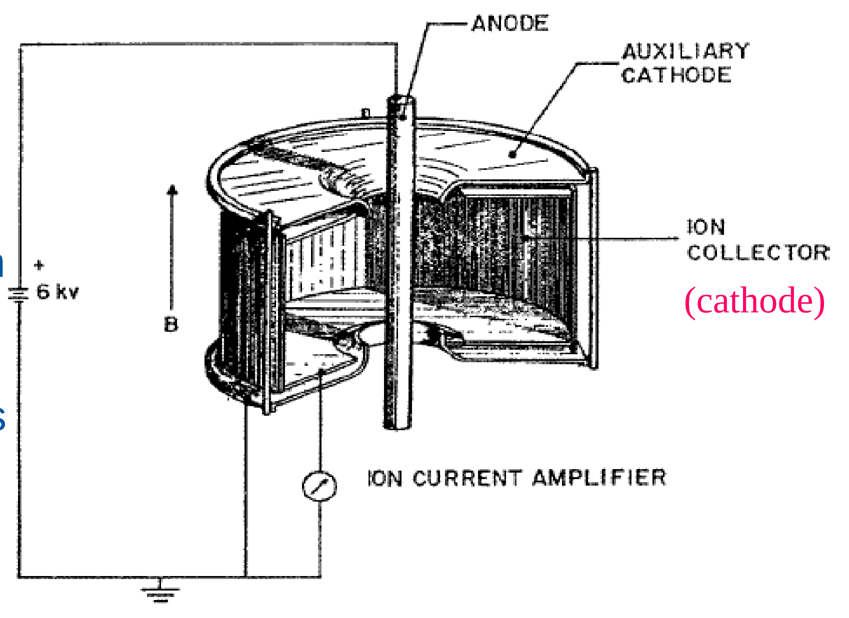
- The operating principle is based on the measurement of a discharge current in a Penning cell which is a function of pressure : $I^+ = P^n$, n is close to 1

- 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

- WARNING : leakage current on the HV cables simulates a higher pressure



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

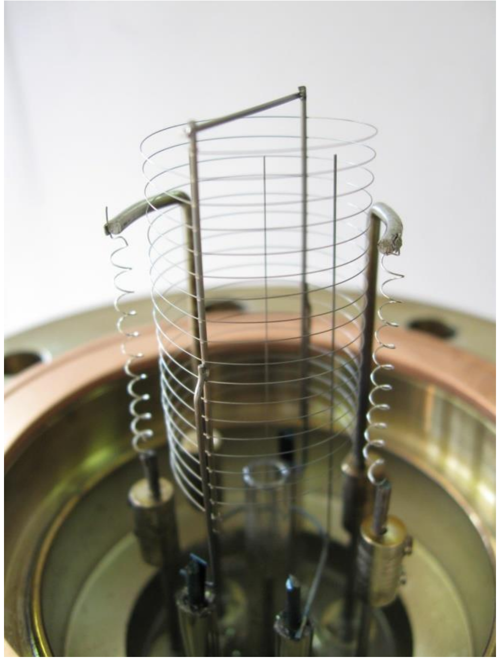
Bayard-Alpert Gauge

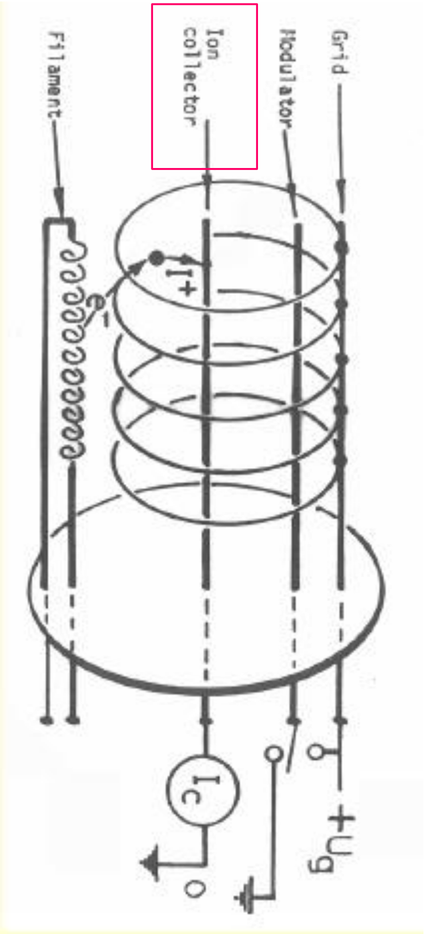
- Bayard-Alpert gauges are used for vacuum measurement purposes in the range 10^{-5} -10^{-12} mbar.

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

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

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





- The gauge needs to be calibrated

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

Residual Gas Analysers

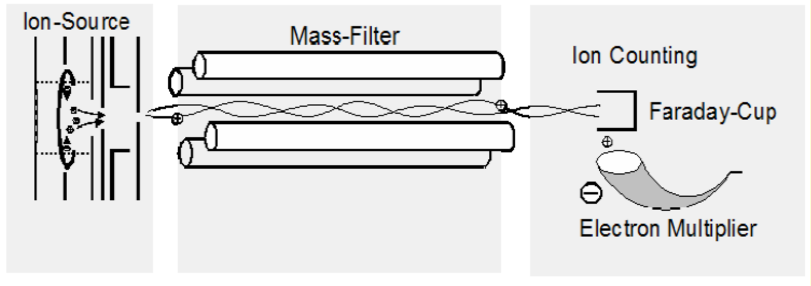
- Residual Gas Analysers are used in the range 10^{-4} -10^{-12} mbar. Their purpose is to do gas analysis

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

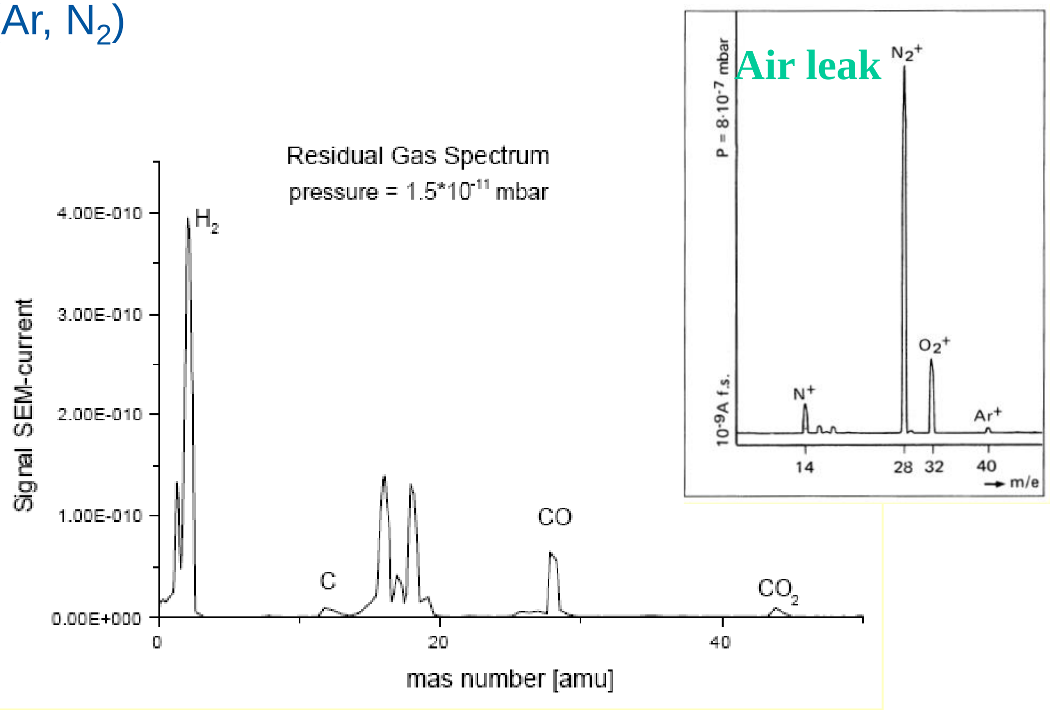
- It is a delicate instrument which produces spectrum sometimes difficult to analyse

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

- The RGA needs to be calibrated



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



Primary Pumps

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

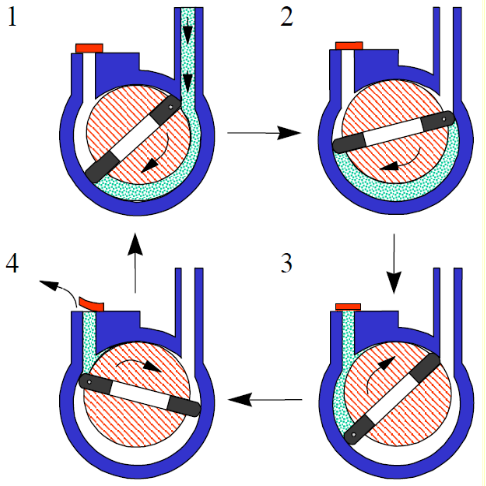
- They are usually used as a backing pump of turbomolecular pumps

- Two categories : dry and wet pumps.

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

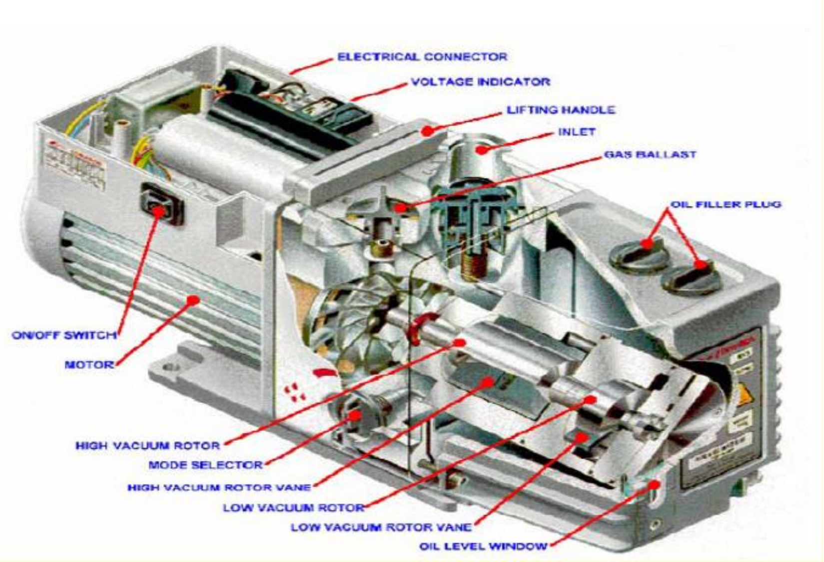
- Wet pumps are operating with oil which acts as a sealing, a lubricant, a heat exchanger and protects parts from rust and corrosion

Oil Sealed Rotary Vane Pump



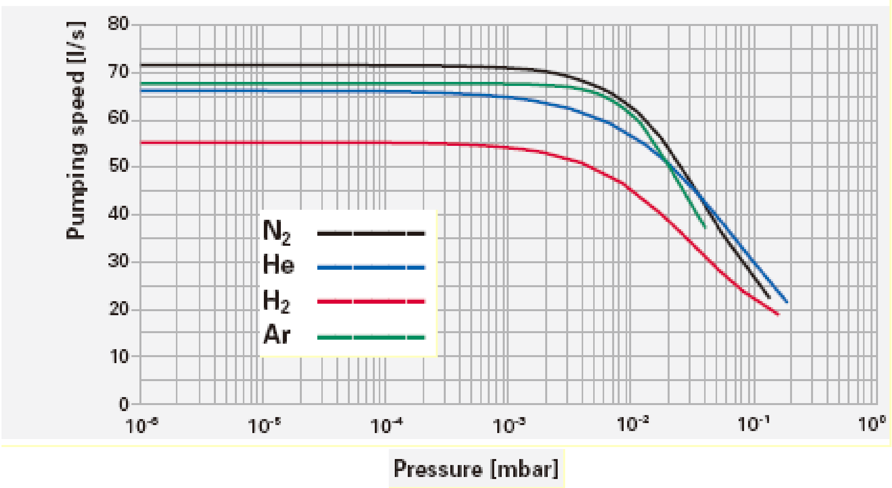
1 Inlet exposed
2 Trapped volume
3 Compression
4 Exhaust

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

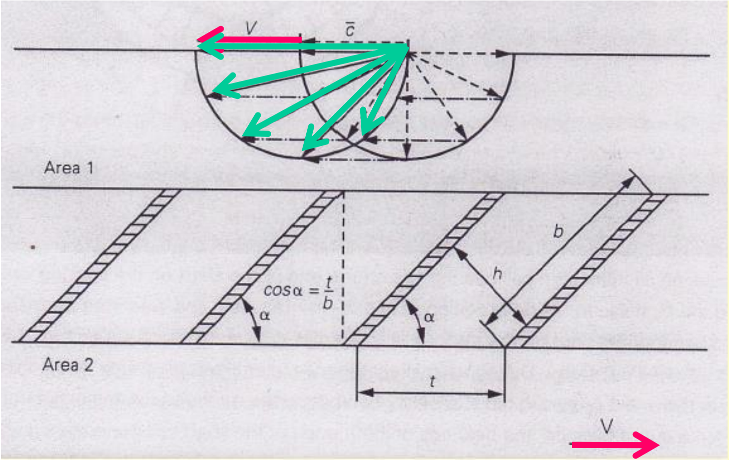


Turbomolecular Pump

- 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)

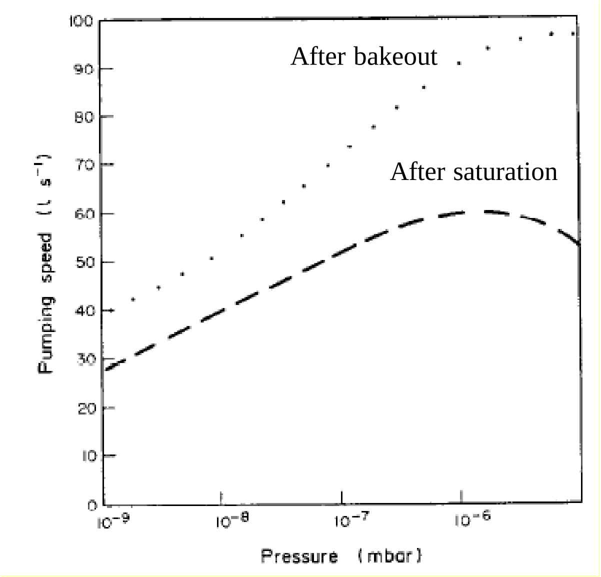


- The compression ratio (P_{inlet}/P_{outlet}) increase exponentially with $\sqrt{M}$: “clean” vacuum without hydrocarbons. So, the oil contamination from the primary pump is avoided

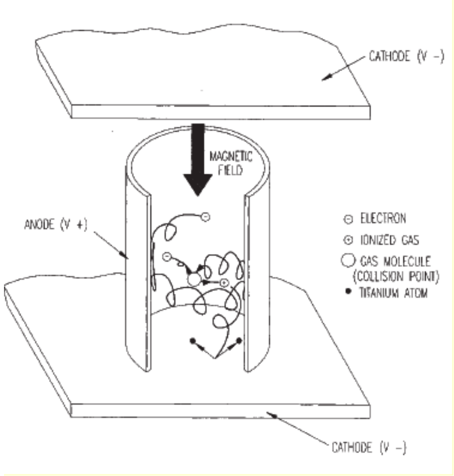
Sputter Ion Pump

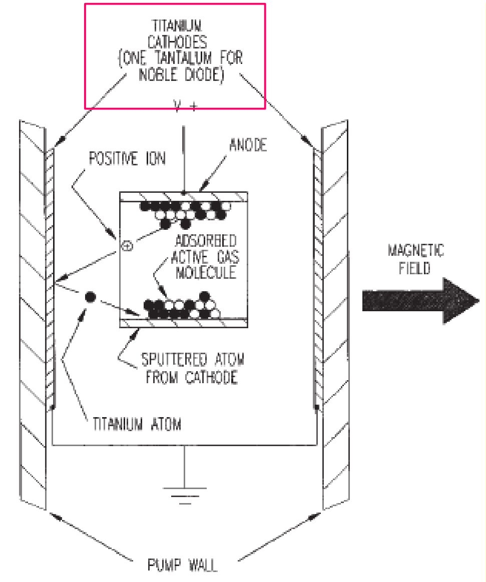
- This pump operate in the range 10^{-5} -10^{-11} mbar. It is used to maintain the pressure in the vacuum chamber of an accelerator.
- Their pumping speed range from 1 to 500 l/s

- 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 buried or implanted onto the cathode.
- Advantage : like for a Penning gauge, the collected current is proportional to the pressure. It is also used for interlocking.



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

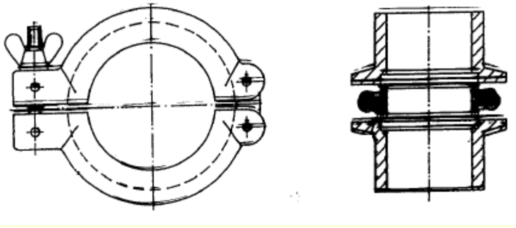




Flanges and Gaskets

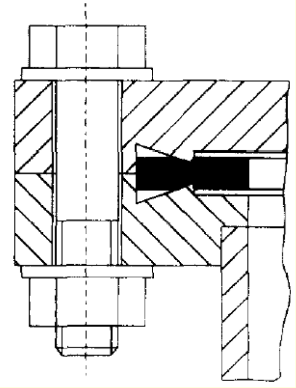
- For primary vacuum, elastomer seals and clamp flanges are used
- KF type components:

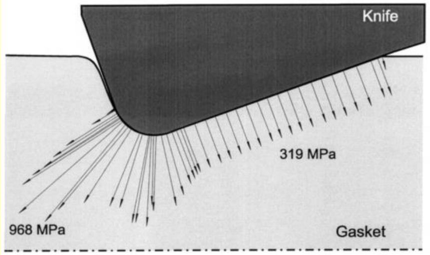
  Many fittings (elbows, bellows, T, cross, flanges with short pipe, reductions, blank flanges …)
  ISO diameters



- 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





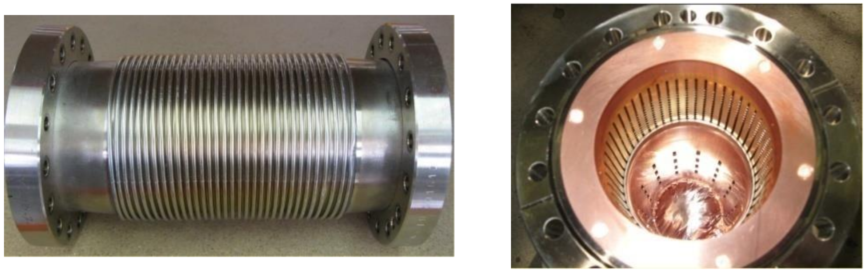
P. Lutkiewicz, C. Rathjen.
J.Vac.Sci. 26(3), May/Jun 2008, 537-544

Tubes, Bellows, Valves

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

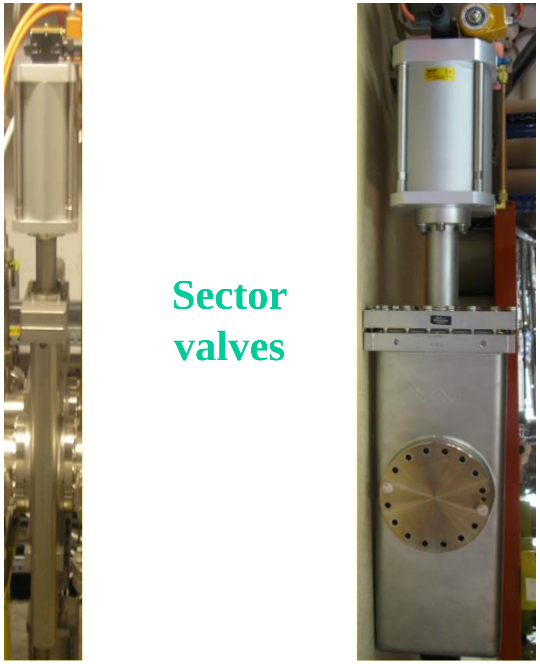
Copper tubes

- Bellows are equipped with RF fingers (impedance)



- Valves are used for roughing and sectorisation

Roughing valve



Sector valves

Leak Detection

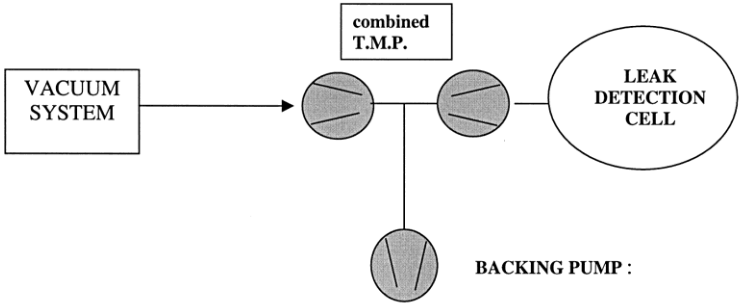
- The vacuum system of an accelerator must be leak tight !

- 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 or corrosion

- 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

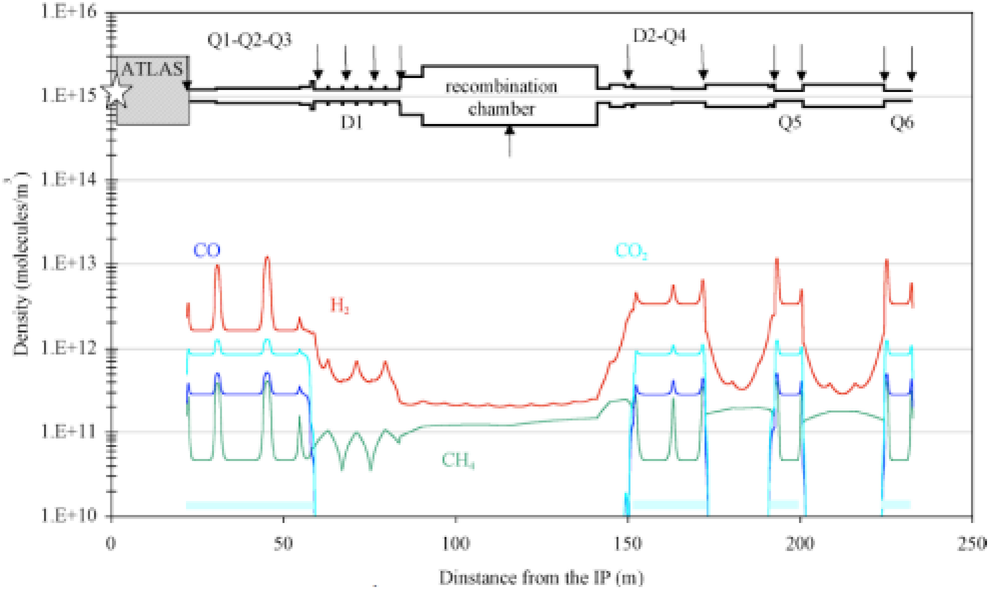
3. Vacuum with Beams : LHC Example

Design value : a challenge with circulating beams

- Life time limit due to nuclear scattering ~ 100 h
  - n ~ 10^{15} H_2/m3
  - $<P_{arc}> < 10^{-8}$ mbar H_2 equivalent
  - ~ 80 mW/m heat load in the cold mass due to proton scattering

$$\tau = \frac{1}{\sigma \, c \, n} \qquad P_{cold\, mass} = \frac{I\, E}{c\, \tau}$$

- Minimise background to the LHC experiments



	H2_eq / m3	mbar
$<LSS_{1\ or\ 5}>$	~ 5 10^{12}	10^{-10}
<ATLAS>	~ 10^{11}	10^{-11}
<CMS>	~ 5 10^{12}	10^{-10}

A. Rossi, CERN LHC PR 783, 2004.

Why a Challenge?

Because, the static pressure increases by several orders of magnitude due to the dynamics effects related to the presence of a beam

(next 4 slides are just a flavor of the main phenomena which are taking place in an accelerator)

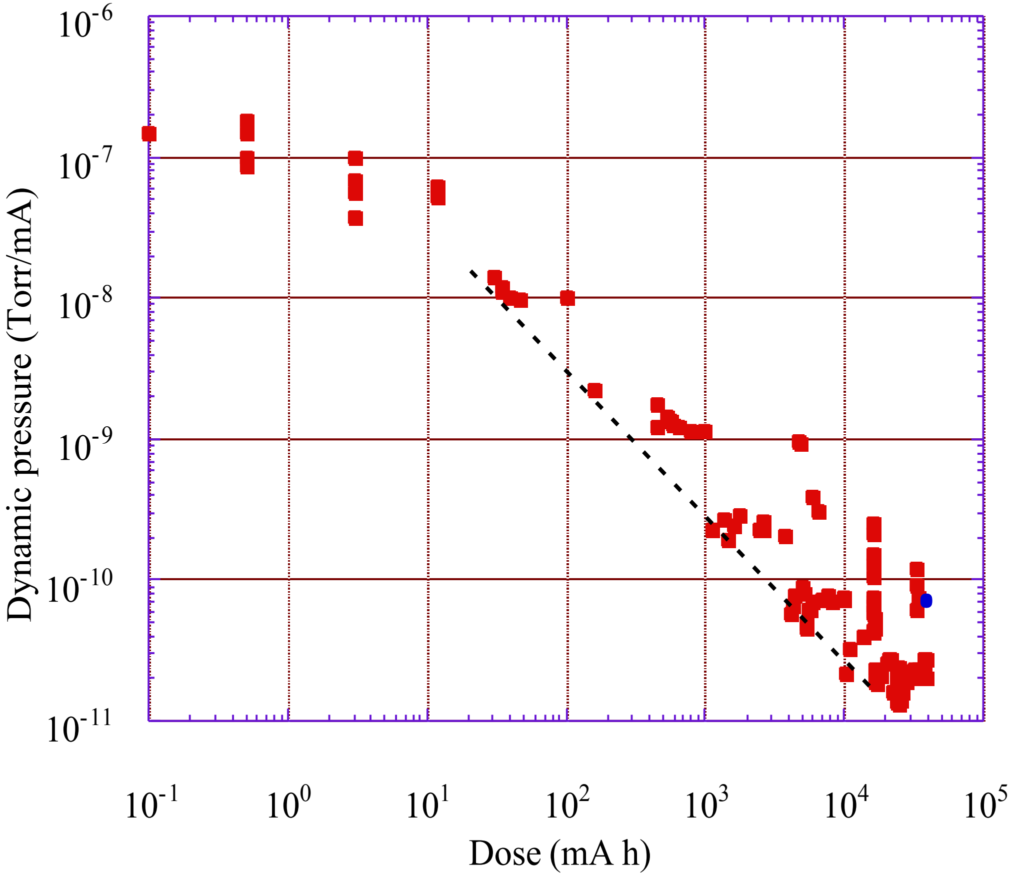
3.1 Dynamic Effects

Photon Stimulated Desorption

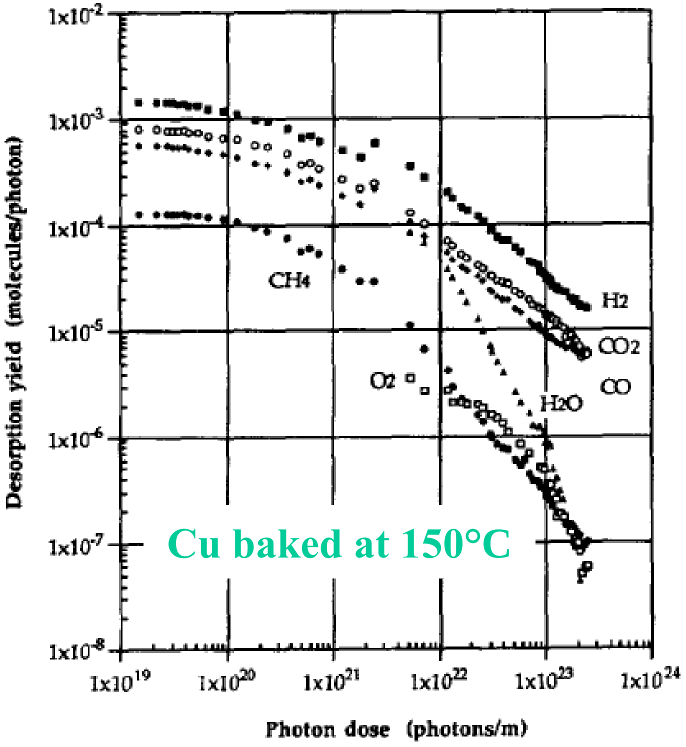
- Synchrotron radiation induce gas desorption : SR machine, LEP, LHC
- Heat load and gas load
- η_{photon} is the photon desorption yield

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

Beam cleaning during the first period of LEP



O. Gröbner. Vacuum 43 (1992) 27-30



Cu baked at 150°C

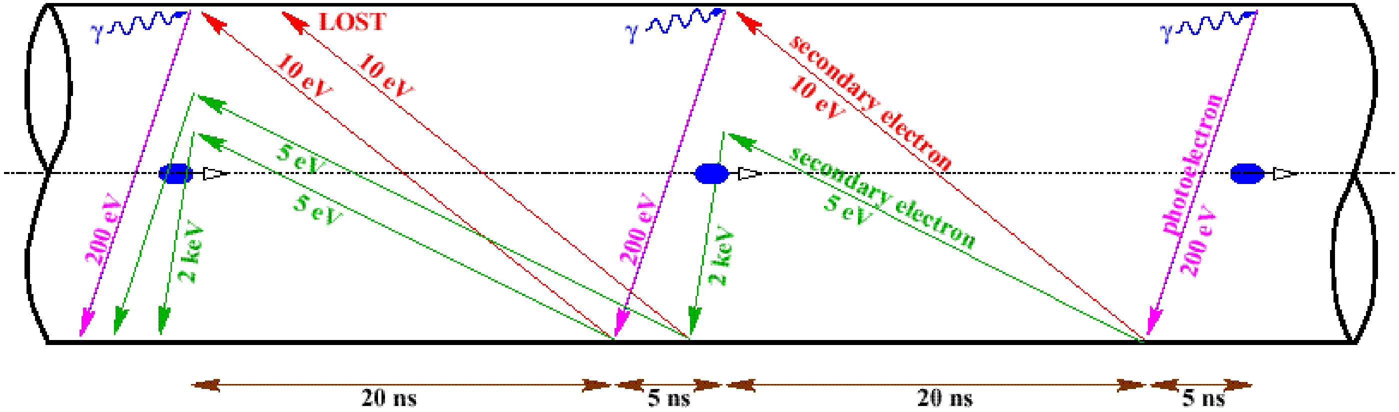
O. Gröbner *et al.*
J.Vac.Sci. 12(3), May/Jun 1994, 846-853

Electron Cloud : the Mechanism

- In modern machine with dense bunches and large positive current : KEK-B, PEP-II, SPS, RHIC, Dafne, LHC, SuperKEKB …
- Emittance growth, gas desorption and heat load in cryogenic machine

- Key parameters :
  - bunch structure & current
  - vacuum chamber dimension
  - magnetic field
  - secondary electron yield
  - photon electron yield
  - electron and photon reflectivities
  - …

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

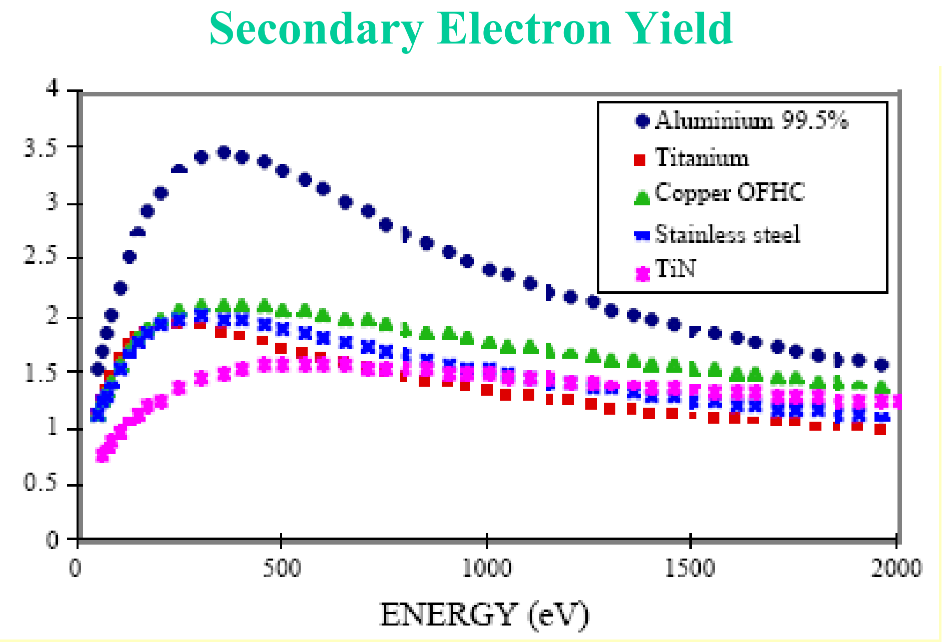


Schematic of electron-cloud build up in the LHC beam pipe.

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

Electron Cloud : the Recipes

- 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 reflectivity …)
  - Adapt the bunch structure or the chamber geometry to reduce multiplication
  - …



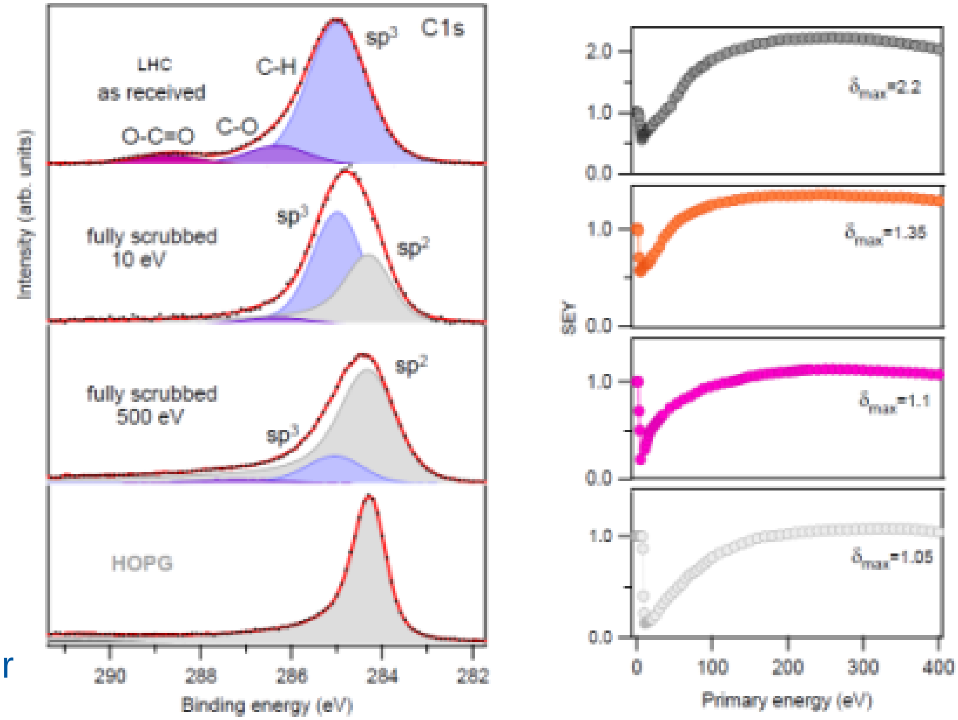
N. Hilleret *et al.*, LHC Project Report 433 2000, EPAC 00

Beam Induced Multipacting along the Beam Pipe

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

} Operational parameters

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



HOPG : highly oriented pyrolitic graphite

- Mitigations:
  - NEG coating with low SEY (~ 1.1)
  - Beam scrubbing to reduce SEY :

    Modification of C1s core level

    Conversion sp^3 => sp^2

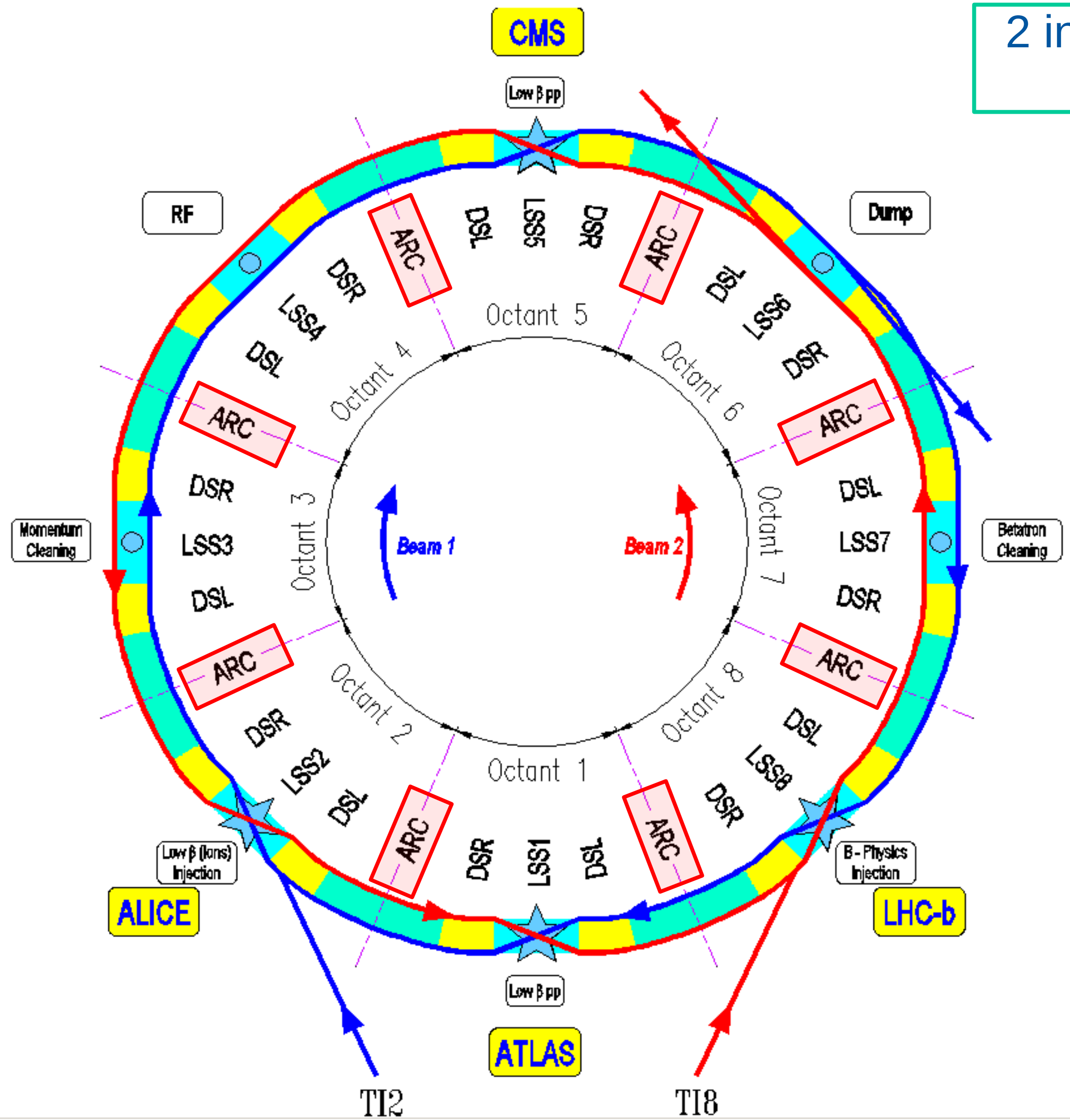
    High energy electrons increase the number of graphitic like C-C bounds
  - Monitored by ESD reduction

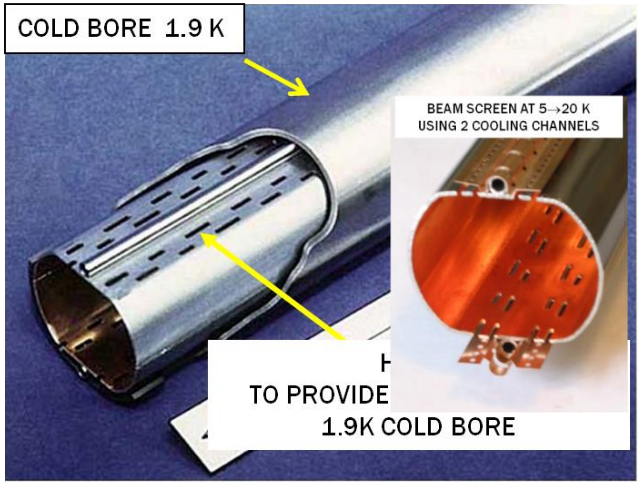
$$\boxed{P = \frac{Q + \eta_{Electrons}\dot{\Gamma}_{Electrons}}{S}}$$

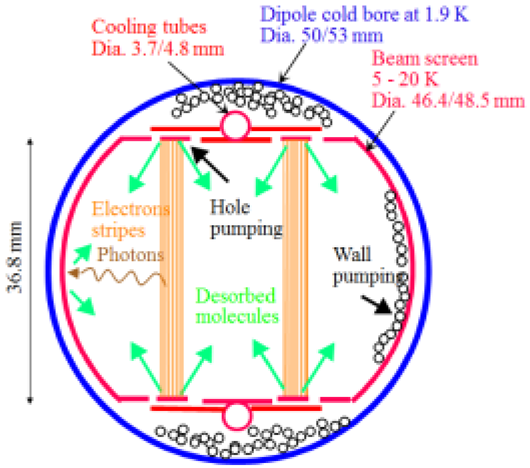
3.2 Arc Vacuum System

Cryogenic Beam Vacuum

2 independent beam pipes per arc:
8 arcs of 2.8 km each

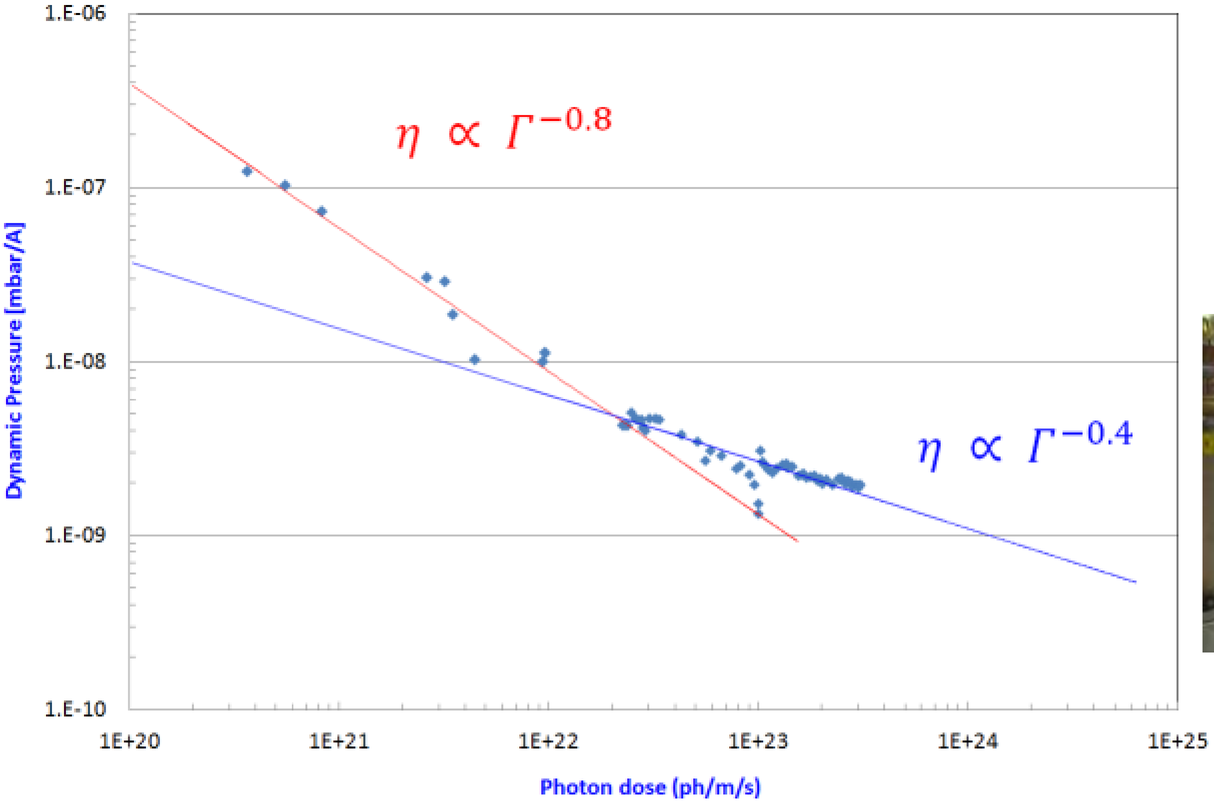






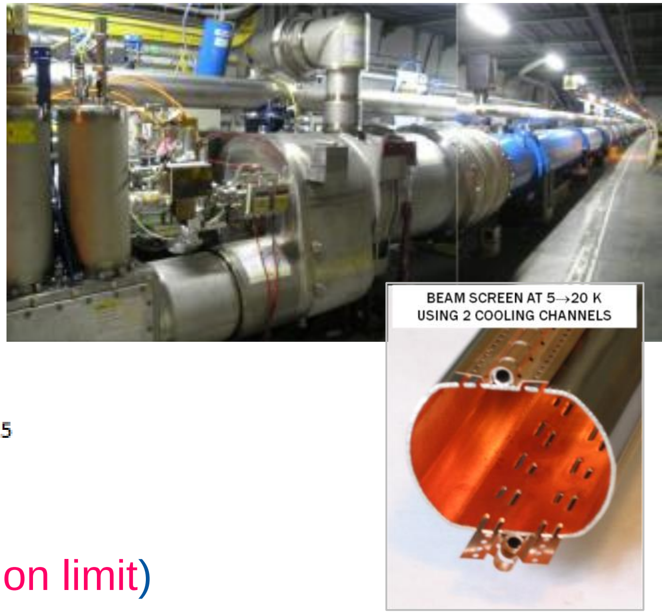
Beam Conditioning under SR

- Arc extremity’s vacuum gauges : unbaked Cu and cryogenic beam screen
- Reduction by 2 orders of magnitude since October 2010



V. Baglin. Vacuum 138 (2017) 112-119

- 2 trends :
  - Room temperature
  - Cryogenic temperature



- Inside the arc, at 5-20 K, deltaP < 10^{-10} mbar (*i.e.* below detection limit)
- The photodesorption yield at cryogenic temperature is estimated to be < 10^{-4} molecules/photon

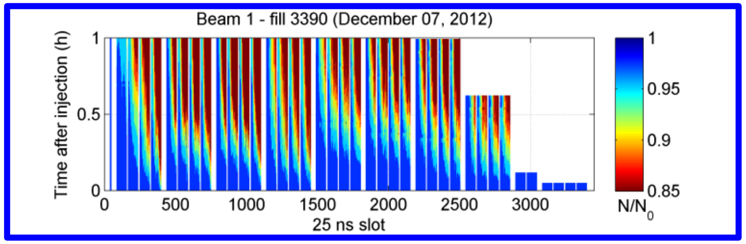
Beam Scrubbing

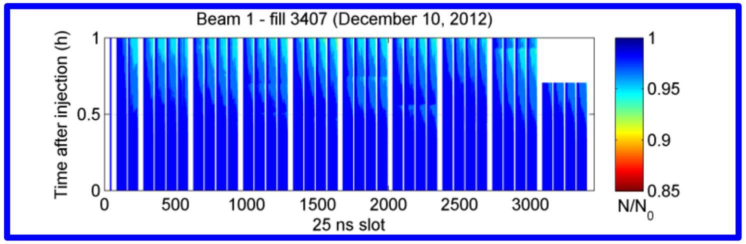
- “Scrubbing” periods are required during LHC commissioning. Particularly during bunch spacing reduction and beam intensity increase

- Increase of beam life time with time

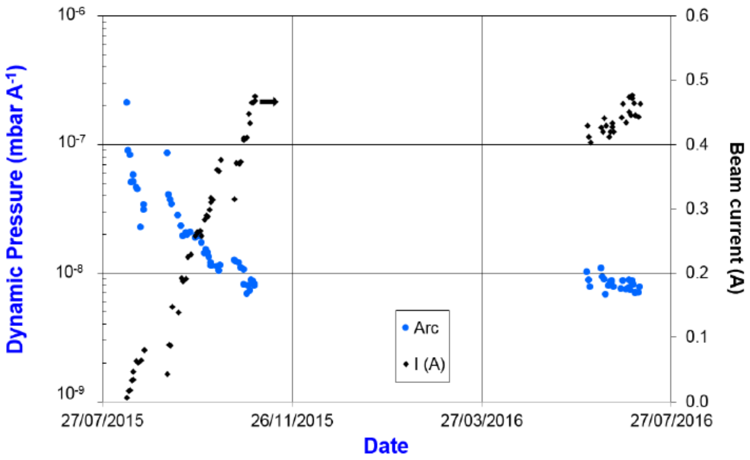
- Strong pressure reduction in a short time

- Heat load reduction with time

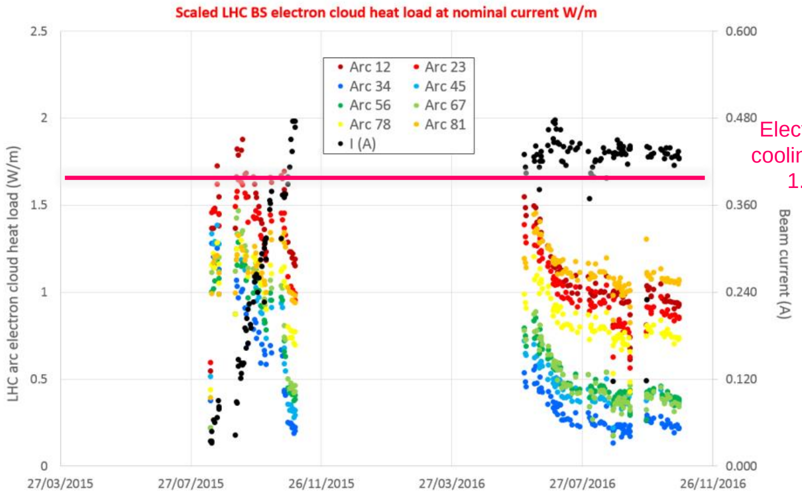




Courtesy G. Rumolo



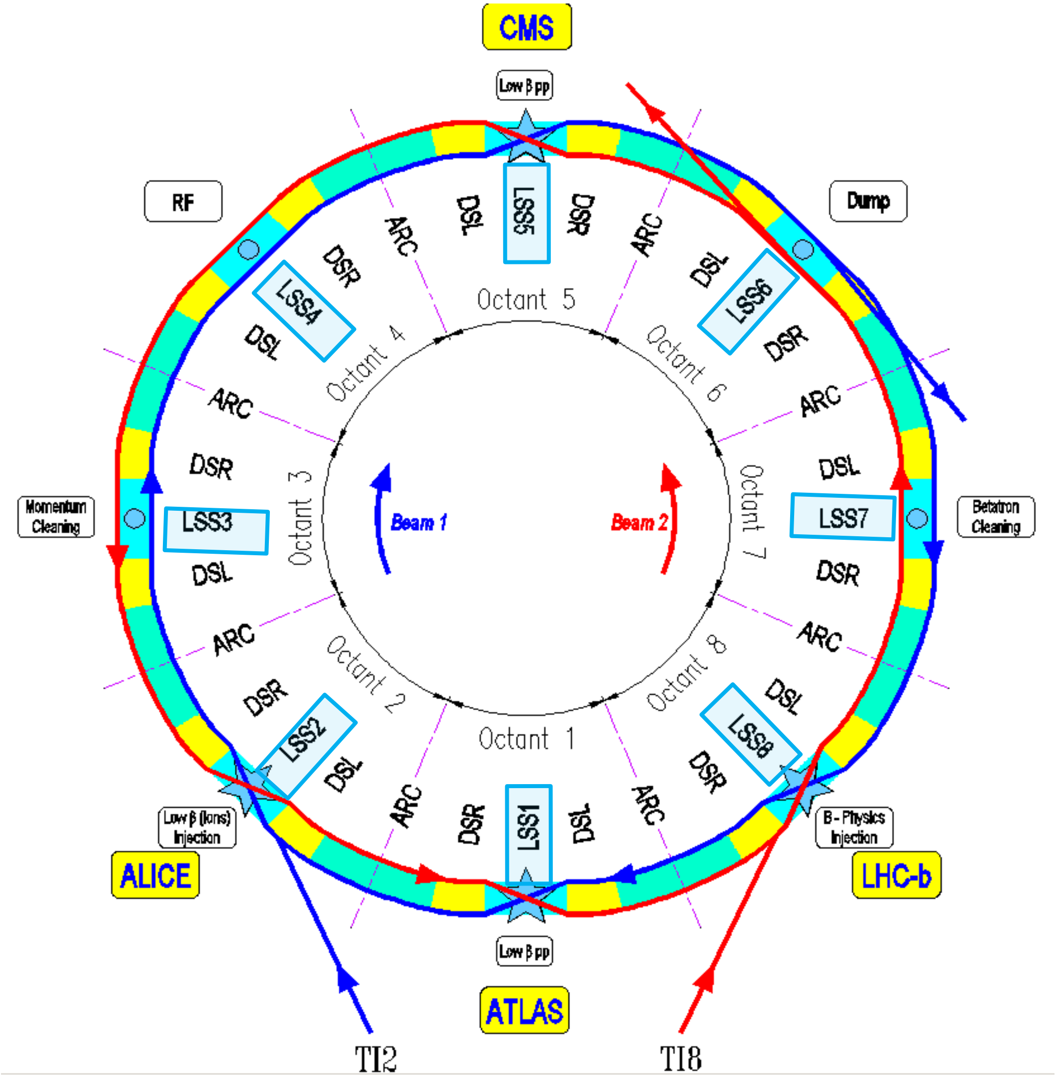
V. Baglin. Vacuum 138 (2017) 112-119



Electron cloud cooling capacity 1.6 W/m

3.3 RT Vacuum System

Room Temperature Beam Vacuum



6 km of RT beam vacuum in the long straight sections

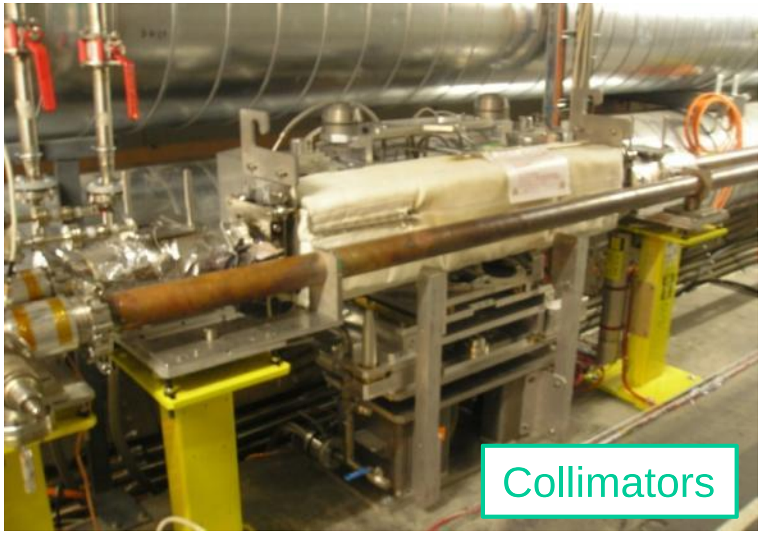
Extensive use of NEG coatings

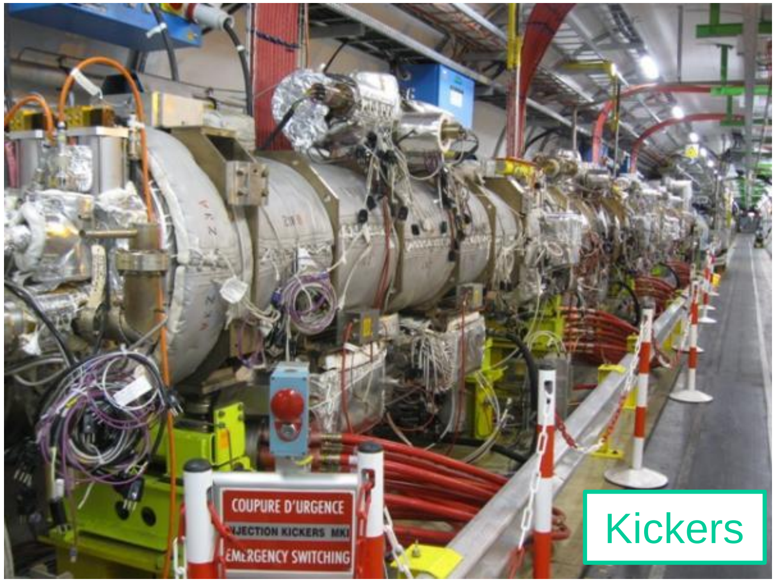
Pressure $<10^{-11}$ mbar after vacuum activation

Standard Components Installed Inside LSS

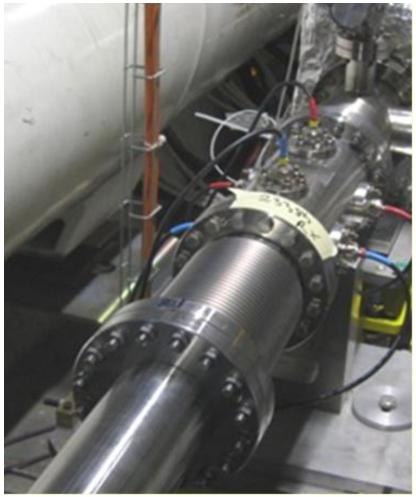
- Warm magnets, kickers, septum, collimators, beam instrumentation …


Warm magnets


Collimators

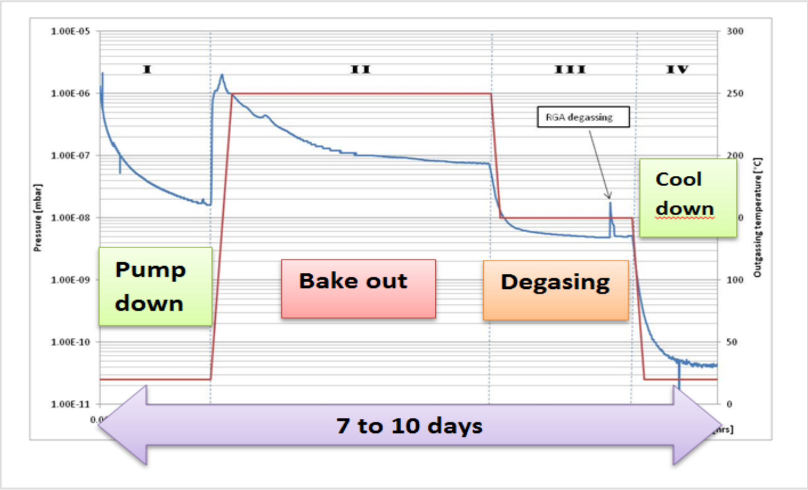


Kickers


Beam Instrumentations

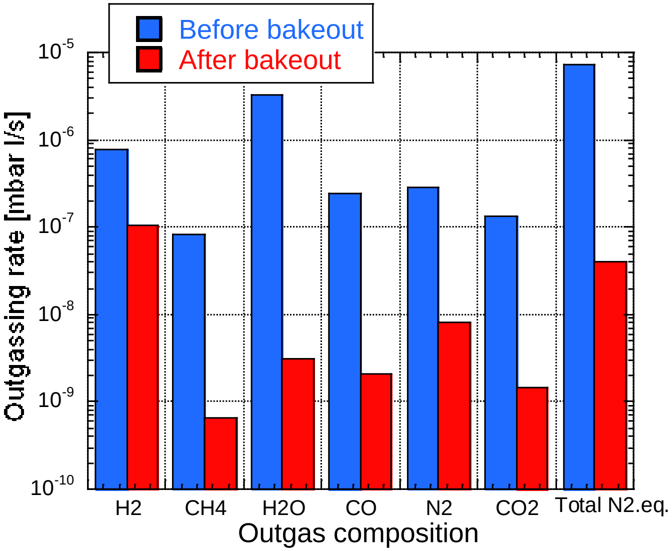
Vacuum Acceptance Tests

- Prior installation more than 2300 LSS's equipments have been baked and validated at the surface :
  - leak detection
  - residual gas composition
  - total outgassing rate



G. Cattenoz *et al.* IPAC'14, Dresden 2014

- Example : studies for LHC collimators
  - outgassing rate
  - impact on getter coated vacuum chambers



Status	Q (mbar l /s)
Unbaked	$7\ 10^{-6}$
1st bake-out	$7\ 10^{-8}$
2nd bake-out	$5\ 10^{-8}$
3rd bake-out	$4\ 10^{-8}$

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

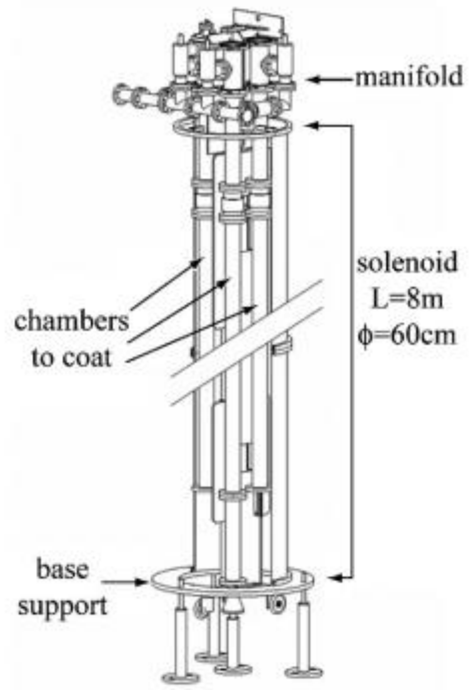
Room Temperature Vacuum System

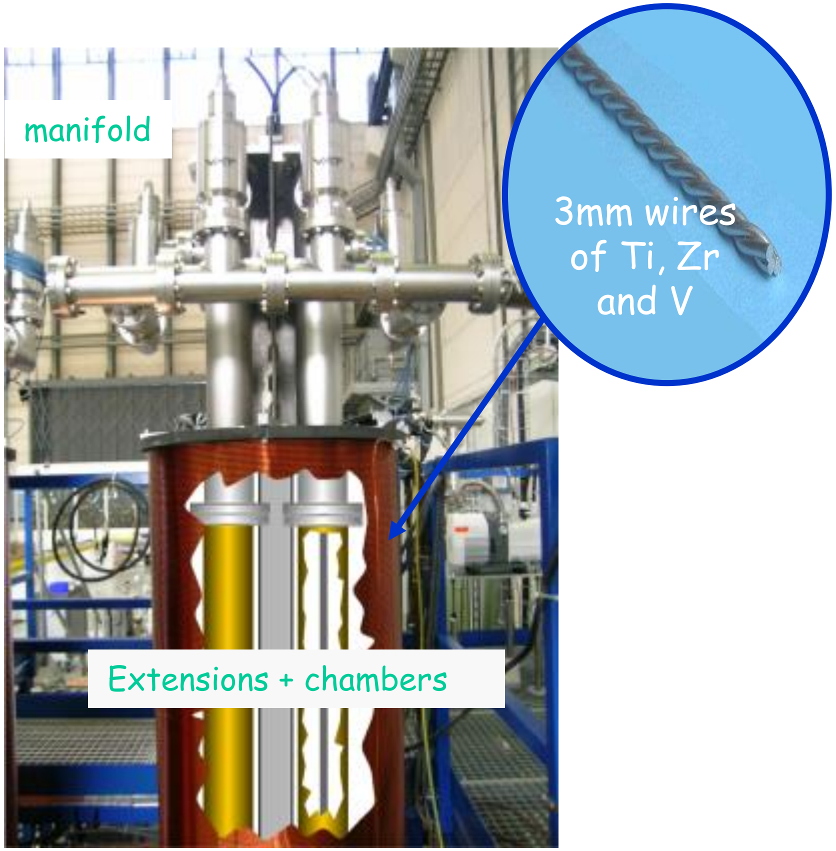
- ~ 1 µm thick, Non Evaporable Getter TiZrV coated vacuum chambers ensure the required vacuum performances for LHC
- Some vacuum chambers were constructed and getter coated …

Courtesy R.Veness and P. Chiggiato TE-VSC

LSS Coating System

- Ti-Zr-V is coated by magnetron sputtering with Kr gas
- ~ 1 µm thick
- All room temperature vacuum chamber including the experimental beam pipe are coated with Ti-Zr-V

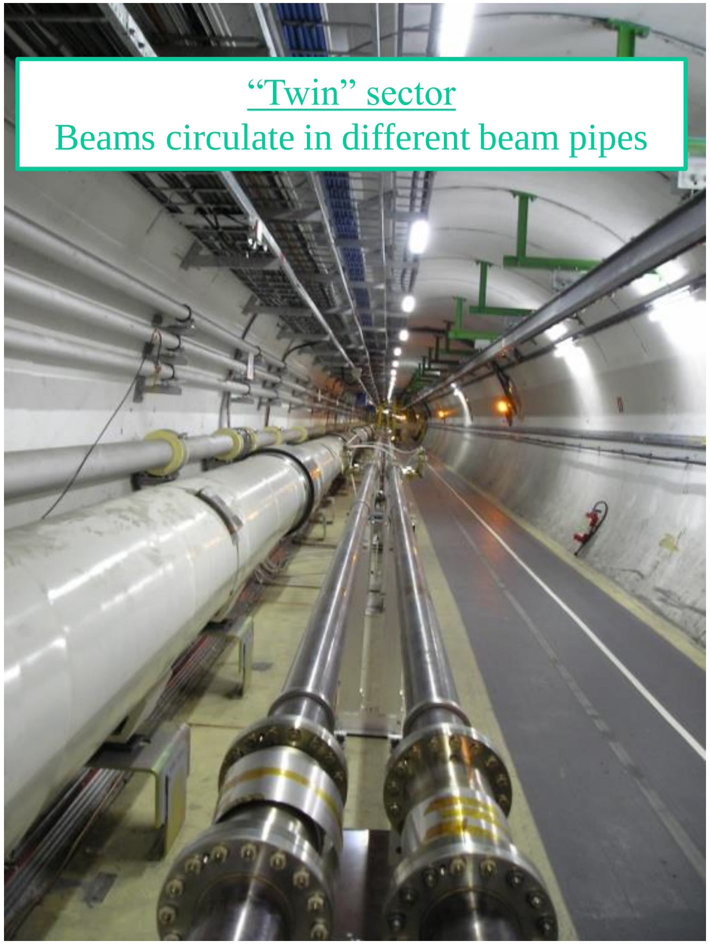




P. Costa Pinto, P. Chiggiato / Thin Solid Films 515 (2006) 382-388

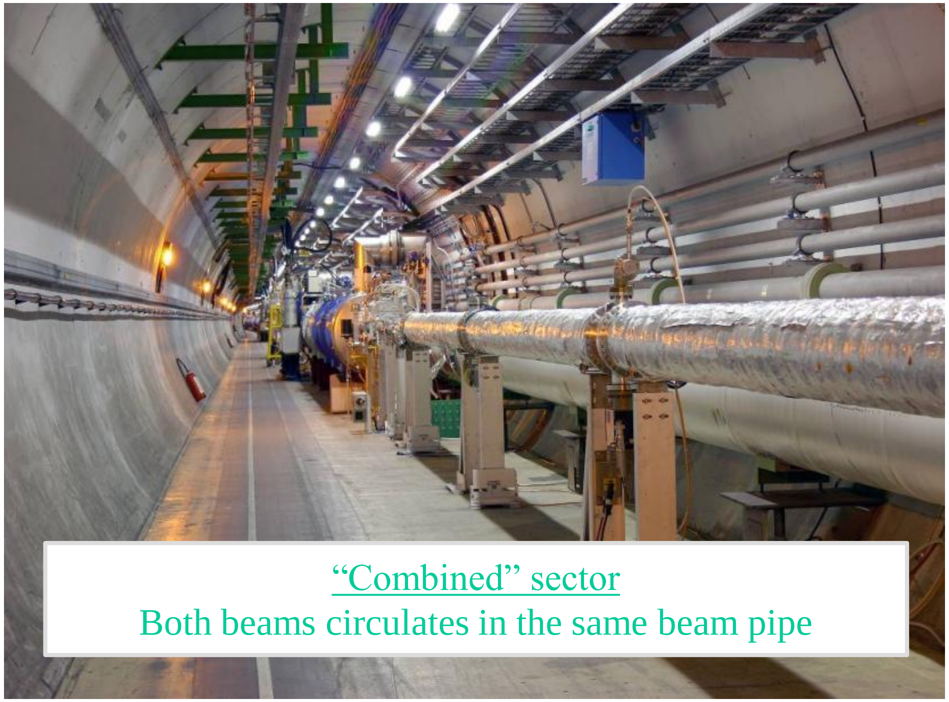
Room Temperature Vacuum System

- ….. and installed inside the LHC tunnel
- to bring the separated beams from the arcs into a single beam pipe for the experiments (held at room temperature !)



“Twin” sector

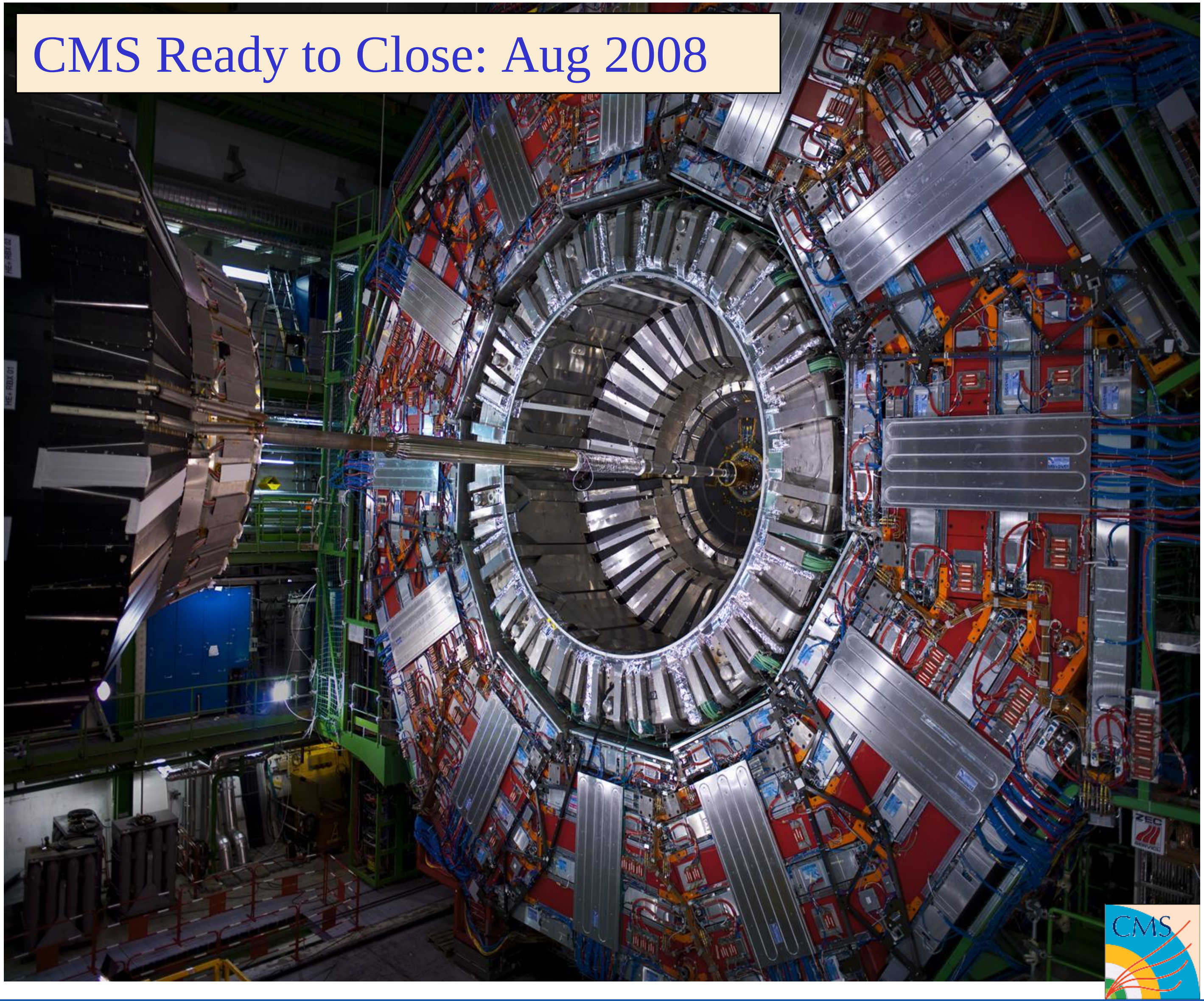
Beams circulate in different beam pipes



“Combined” sector

Both beams circulates in the same beam pipe

And of Course … Through the LHC Experiments

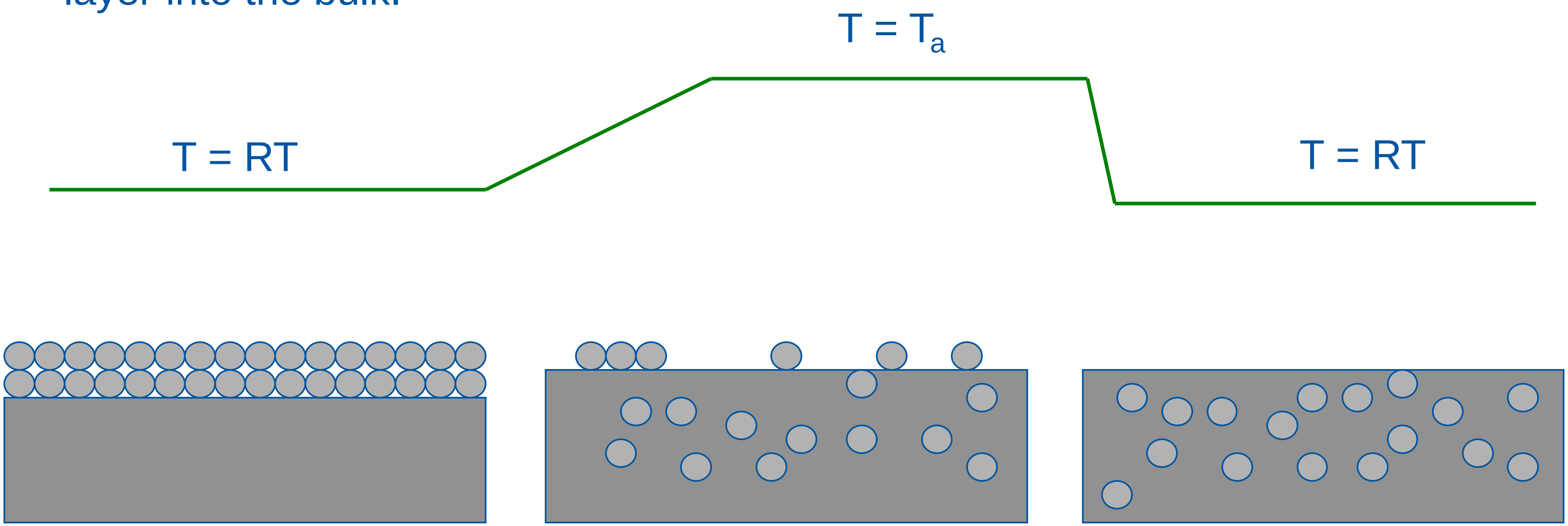


CMS Ready to Close: Aug 2008

Beam Pipe Installation in ATLAS Before Closure

Non-Evaporable Getter (NEG)

- Getters are materials capable of chemically adsorbing gas molecules. To do so their surface must be clean. For Non-Evaporable Getters a clean surface is obtained by heating to a temperature high enough to dissolve the native oxide layer into the bulk.



Native oxide layer
-> no pumping

Heating in vacuum
Oxide dissolution -> activation

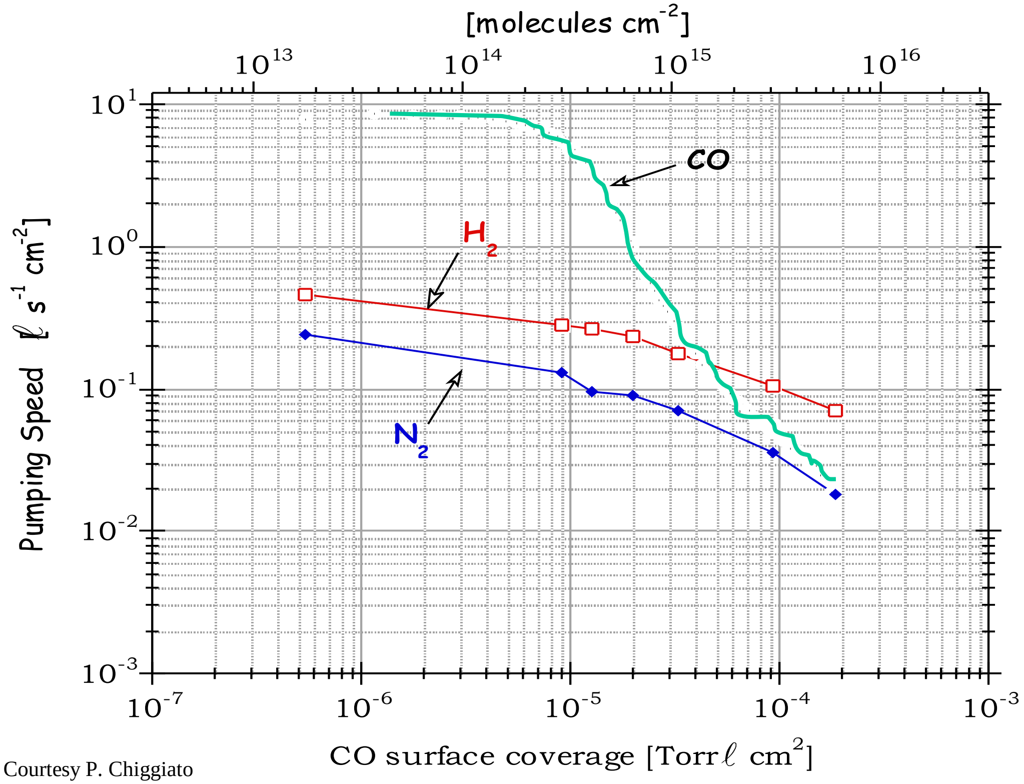
Pumping

- NEGs pump most of the gas except rare gases and methane at room temperature

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

TiZrV Vacuum Performances

Pumping Speed



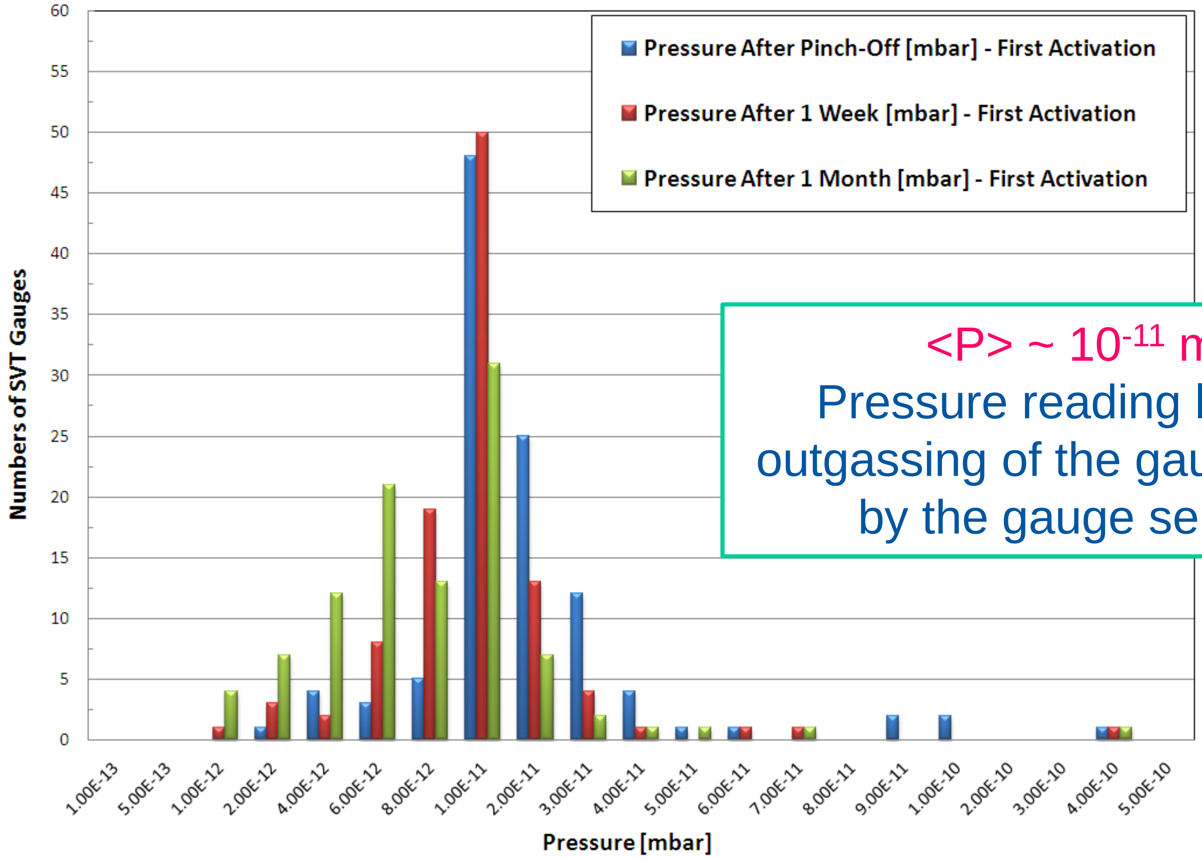
Courtesy P. Chiggiato

- Very large pumping speed : ~ 250 l/s/m for H_2, 20 000 l/s.m for CO
- Very low outgassing rate

- But : limited capacity and fragile coating sensitive to pollutant (hydrocarbons, Fluor …)

Room Temperature Vacuum System : Static Pressure $< 10^{-11}$ mbar

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



$<P> \sim 10^{-11}$ mbar

Pressure reading limited by outgassing of the gauge port and by the gauge sensitivity

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

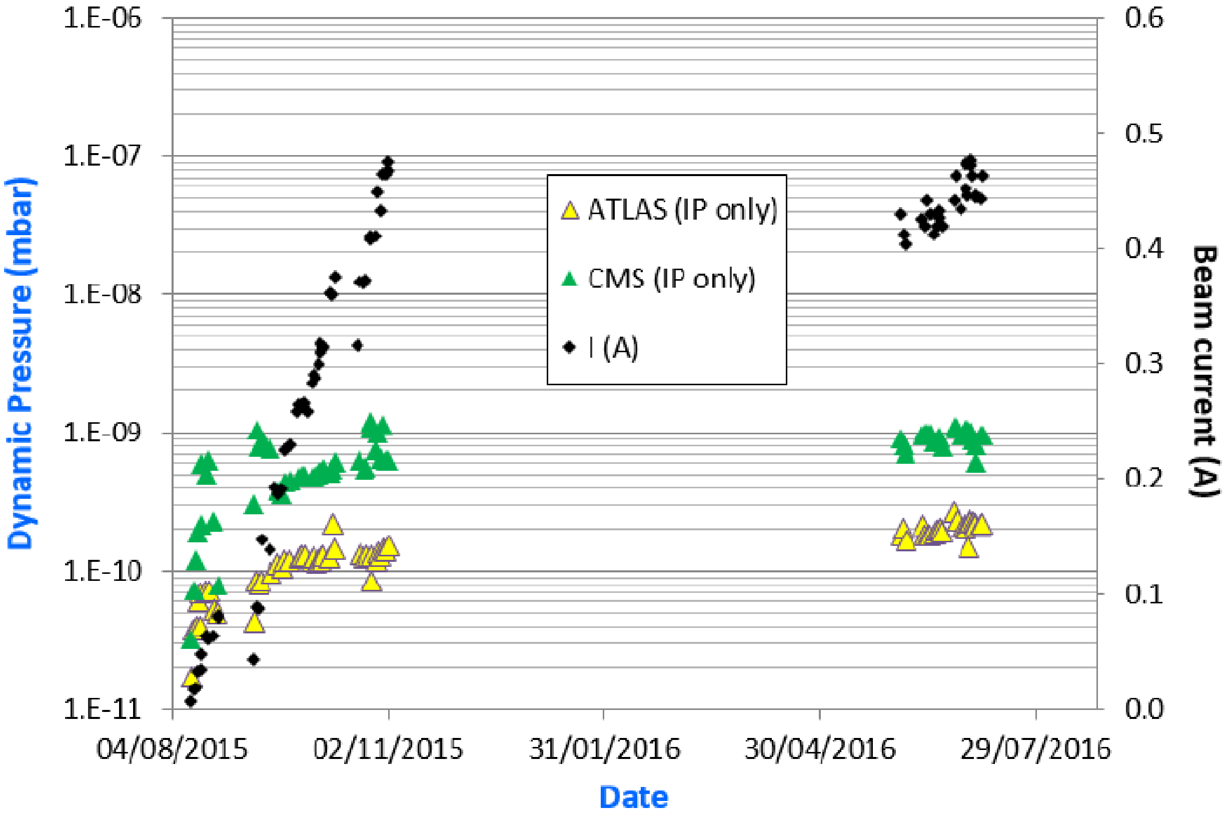
LHC Experimental Areas

- NEG coated vacuum system

  => Large pumping speeds, low SEY and desorption yields

- $\langle P_{\text{LHC Experiments}} \rangle \sim 5\ 10^{-10}$ mbar => with 25 ns bunch spacing and 450 mA

  => No background issues: within specifications



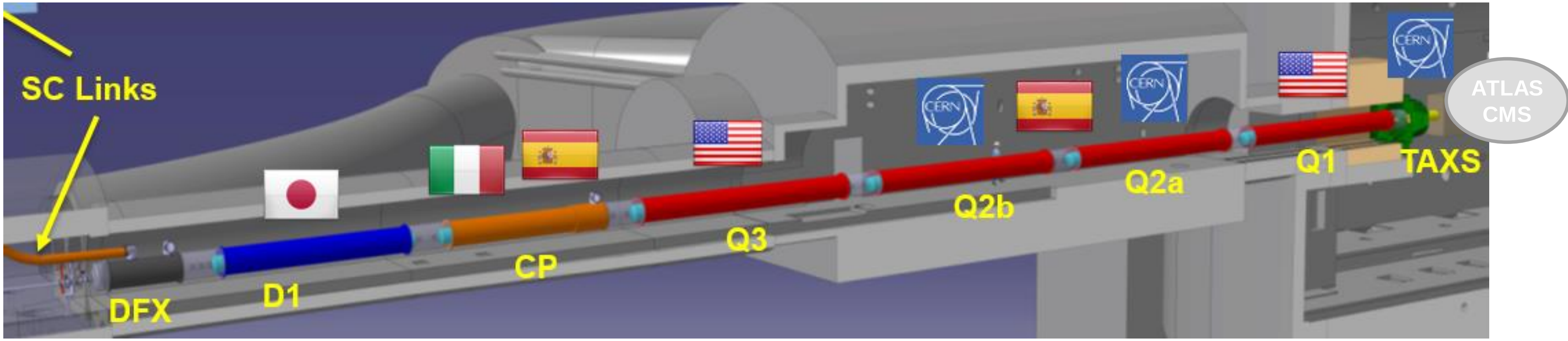
V. Baglin. Vacuum 138 (2017) 112-119

3.4 What about the future?

HL-LHC

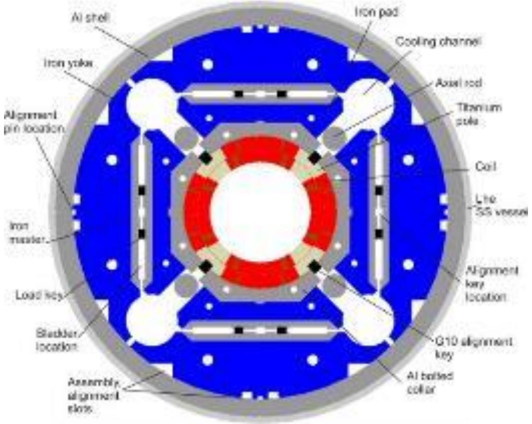
NEW focussing quadrupole and merging dipole

- Decrease beta (*i.e* beam size) at collision point (beta*) from 55 cm to 15 cm



- All superconducting magnets at 1.9 K with a beam screen at 5-20 K or 60-80 K

- Q1, Q2, Q3, CP (corrector package)
    - Nb_3Sn (new technology)
    - 150 mm ID, gradient = 130 T/m, peak field 11.5 T
- D1, D2
    - NbTi (classical technology)
    - 150 mm, 5.6 T



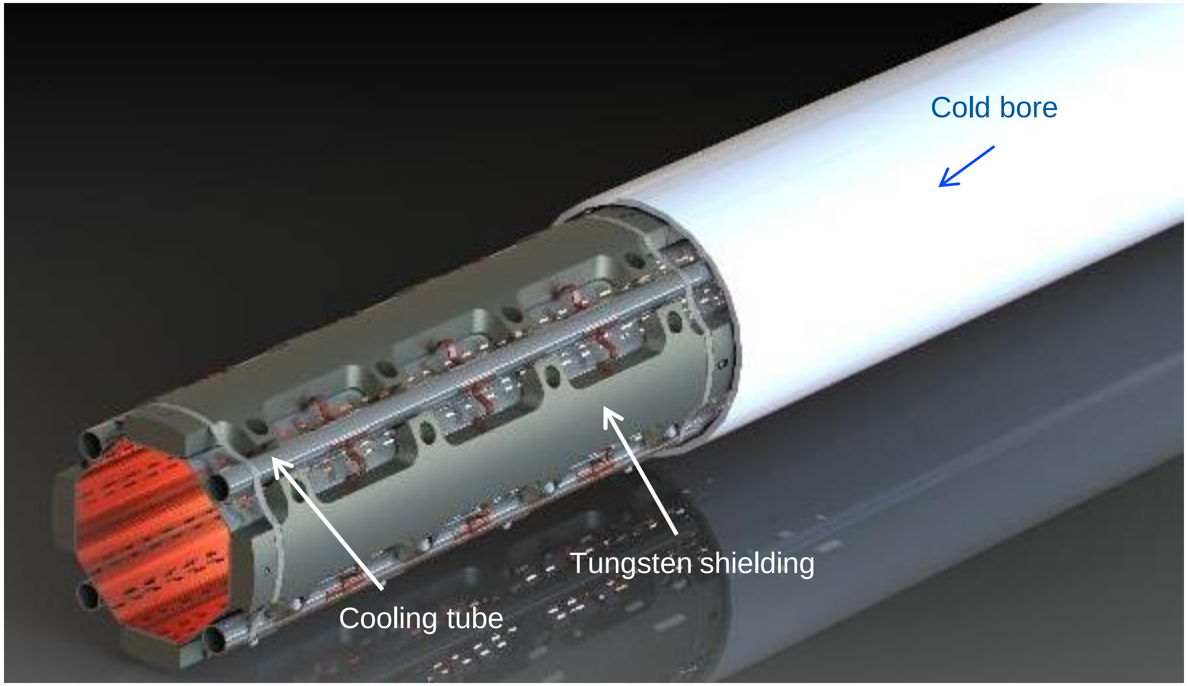
Shielded Triplet Beam Screens

- Triplets beam screens are shielded with tungsten to intercept the debris produced at the interaction point, protecting thus the cold mass

- Nominal heat load on the beam screen = 15 W/m

- Four cooling tubes extract the beam induced heating and maintain the beam screen temperature along the Triplet string in the 40-60 K temperature range

- Carbon coated beam screen wall to mitigate electron multipacting



Some References

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- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03

- Cern Accelerator School, Vacuum for particle accelerators, 6-16/2017, Sweden

- The physical basis of ultra-high vacuum, P.A. Redhead, J.P. Hobson, E.V. Kornelsen. AVS.

- Scientific foundations of vacuum technique, S. Dushman, J.M Lafferty. J. Wiley & sons. Elsevier Science.

- 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 Technolgy

- Journal of vacuum science and technology

- Vacuum

Thank you for your attention !!!

Spare slides

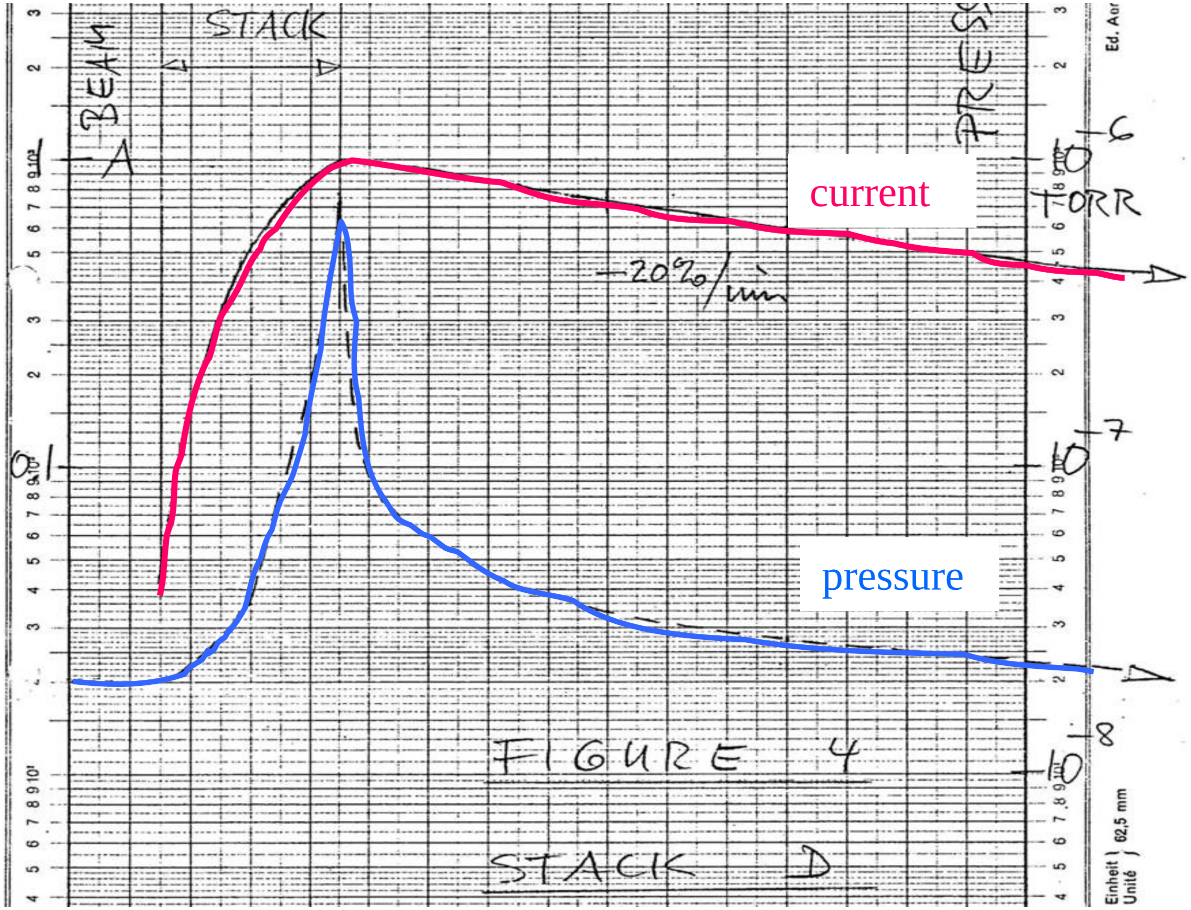
Vacuum Instability : the Effect

- 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



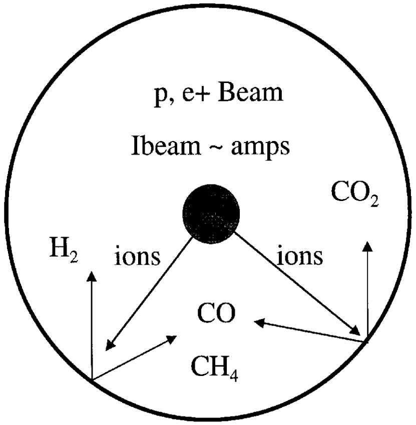
First documented pressure bump in the ISR

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

Vacuum Instability : Mechanism and Recipe

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

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

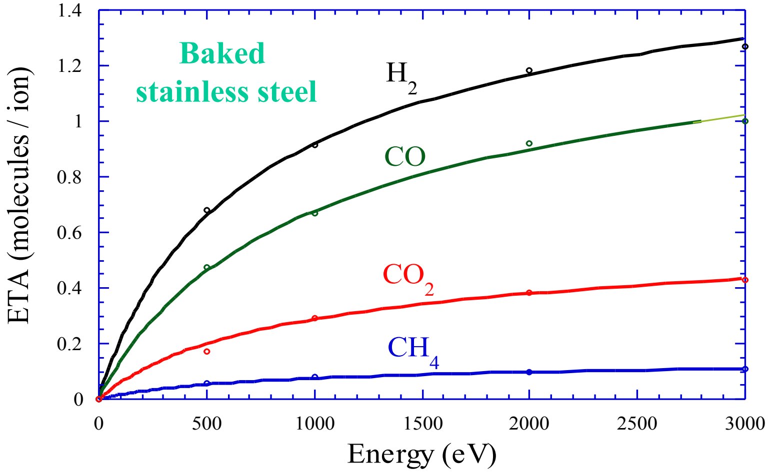


- When the beam current approach the **critical current**, the pressure increases to infinity

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

- Recipe:

Reduce η_{ion}
Increase pumping speed



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

LHC Beam Screen Stability

- A minimum pumping speed is provided thanks to the beam screen's holes

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

	H_2	CH_4	CO	CO_2
$(\eta I)_{\text{crit}}$ [A]	1300	80	70	35

Courtesy N. Kos CERN TE/VSC

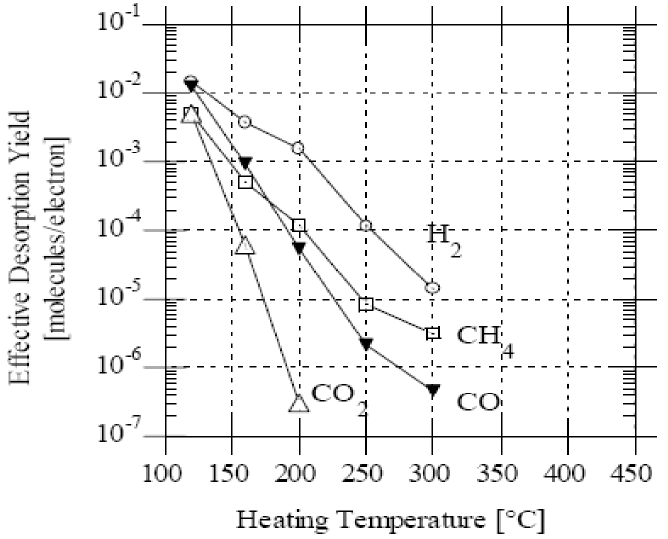
- Beam screen's holes provide **room for LHC upgrades** …..

- NB : In the long straight sections, vacuum stability is provided by TiZrV films and ion pumps which are less than 28 m apart

TiZrV Vacuum Performances

- Very low stimulated desorption yield
- SEY ~ 1.1 => very low multipacting
- But : limited capacity and fragile coating sensitive to pollutant (hydrocarbons, Fluor …)

ESD Yields



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

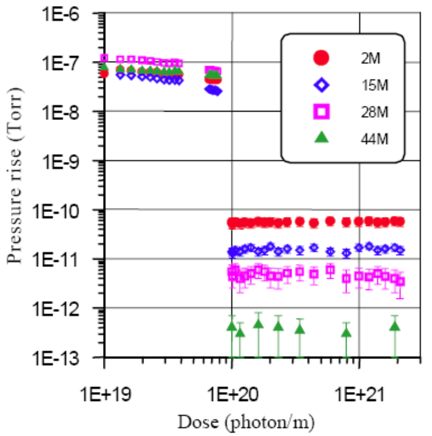
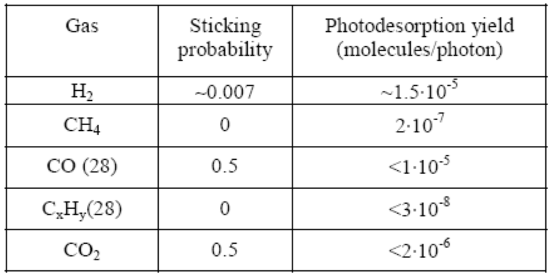


Figure 2: Pressure rise measured in the centre of the TiZrV coated test chamber before activation ($<1\cdot10^{20}$ photons/m) and after activation ($>1\cdot10^{20}$ photons/m).

PSD Yields

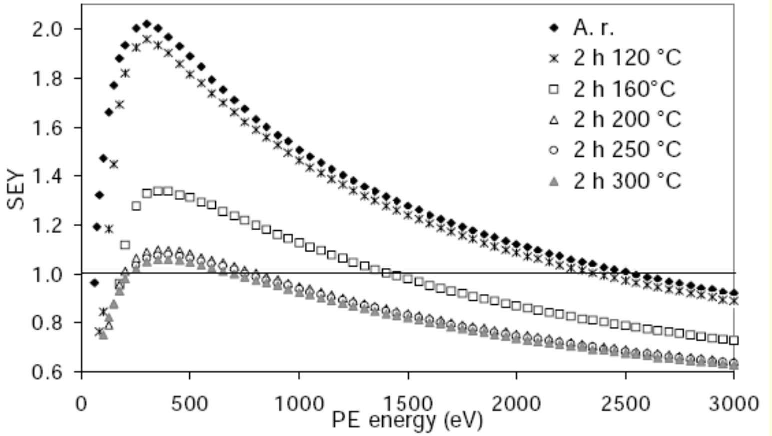
Table 2: Summary of results from the activated test chamber



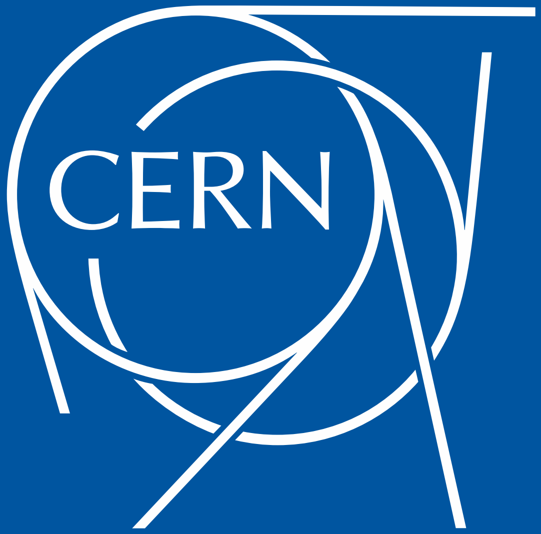
Gas	Sticking probability	Photodesorption yield (molecules/photon)
H_2	~0.007	$\sim1.5\cdot10^{-5}$
CH_4	0	$2\cdot10^{-7}$
CO (28)	0.5	$<1\cdot10^{-5}$
C_xH_y(28)	0	$<3\cdot10^{-8}$
CO_2	0.5	$<2\cdot10^{-6}$

V. Anashin *et al.* EPAC 2002

Secondary Electron Yield



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


CERN