CERN

Vacuum Systems
Lecture 5

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Outline

1. Beam-gas interactions

2. The LHC case

3. Some studies related to
LHC, HL-LHC, FCC etc. vacuum systems

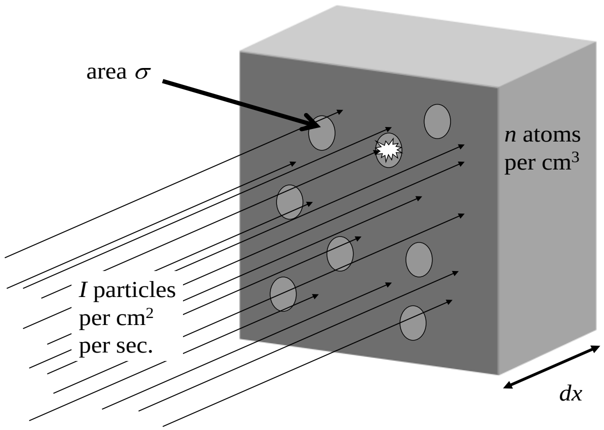
1. Beam-gas interactions

Cross section

- The cross section σ, is the probability the beam interacts with the atoms of target

- When a beam of intensity I, cross a target of thickness dx with a density of atoms n, the change in beam current is:

$$dI = -I\,\sigma\, n\, dx$$



- The cross section is a constant having the dimension of an area

- The unit is 1 barn = 10^{-28} m² = 10^{-24} cm²

- The beam moves at a speed v, thus the thickness of target traversed during the time dt equals: v dt

- using the previous equation, this gives:

$$\frac{dI}{dt} = -I\, n\, v\, \sigma$$

Beam residual gas interactions, SP Møller, CAS, CERN 99-05
Lifetime, cross-section and activation, P. Grasfström, CAS, CERN 2007-003

Life time

- The evolution of the beam current is given by the integration of the previous equation:

$$I = I_o\, e^{-\frac{t}{\tau}} \quad \text{with} \quad \boldsymbol{\tau = \frac{1}{n\,\sigma\,v}}$$

- During the interaction process, the beam current decrease exponentially with a time constant inversely proportional to the gas density and the cross section

- In a vacuum system, the beams interacted differently with the different gas species of density n_i according to their respective cross sections σ_i:

$$\tau_i = \frac{1}{n_i\,\sigma_i\,v}$$

- Summing up the interaction process on the different gas species gives:

$$\sum \frac{dI_i}{dt} = -Iv \sum n_i \sigma_i$$

- Thus:

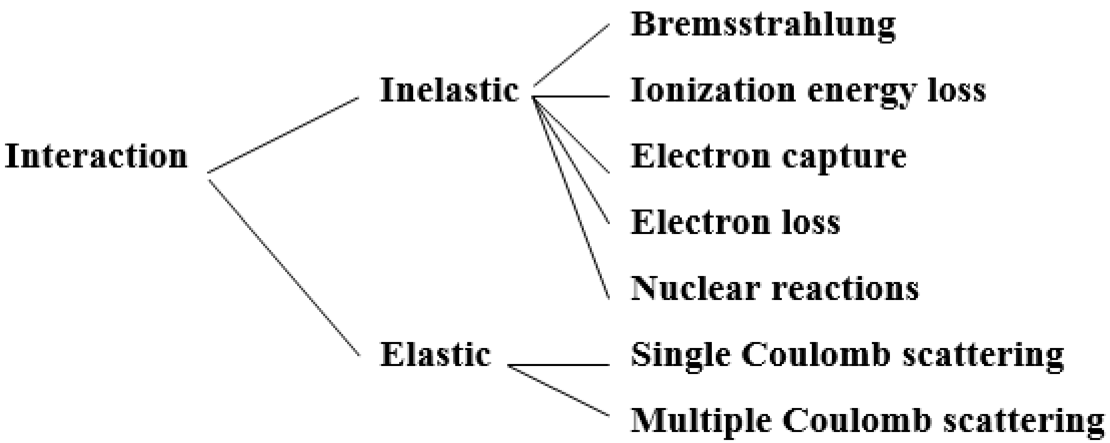
$$\frac{1}{\tau} = \sum \frac{1}{\tau_i}$$

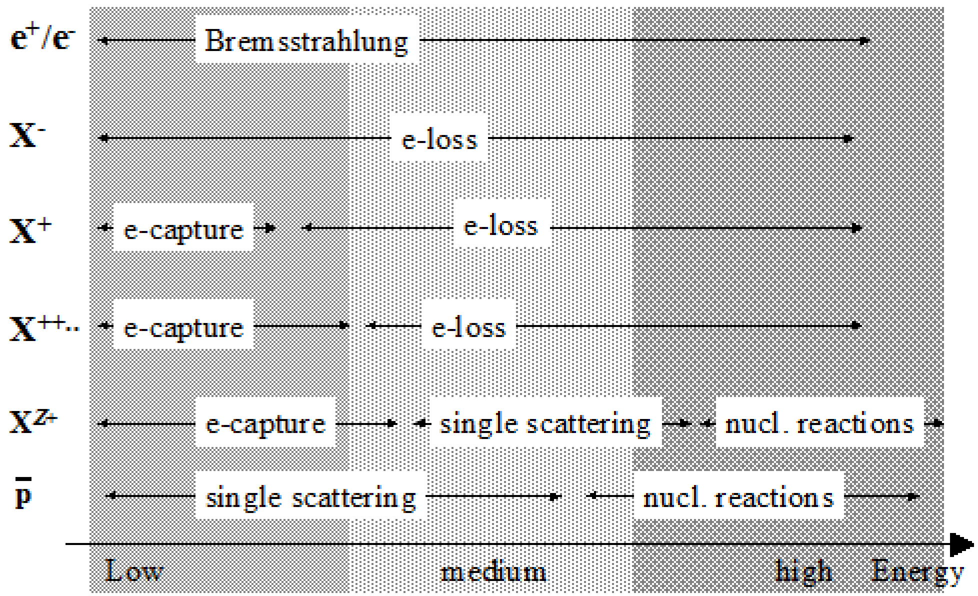
For a vacuum system: $$\frac{1}{\tau} = \frac{1}{\tau_{H2}} + \frac{1}{\tau_{CH4}} + \frac{1}{\tau_{H2O}} + \frac{1}{\tau_{CO}} + \frac{1}{\tau_{CO2}}$$

The vacuum life time must be much larger (*i.e.* >> 24 h) than other life times such as *e.g.* the particle loss due to the collisions

Beam-gas interactions

Complementary information





Beam residual gas interactions, SP Møller, CAS, CERN 99-05

Proton storage ring

- At high energy, the proton beam can interact with the nuclei of the atom. The scattered proton change its direction or loses so much energy that it is lost from the beam

- The nuclear scattering cross section increases with beam energy :

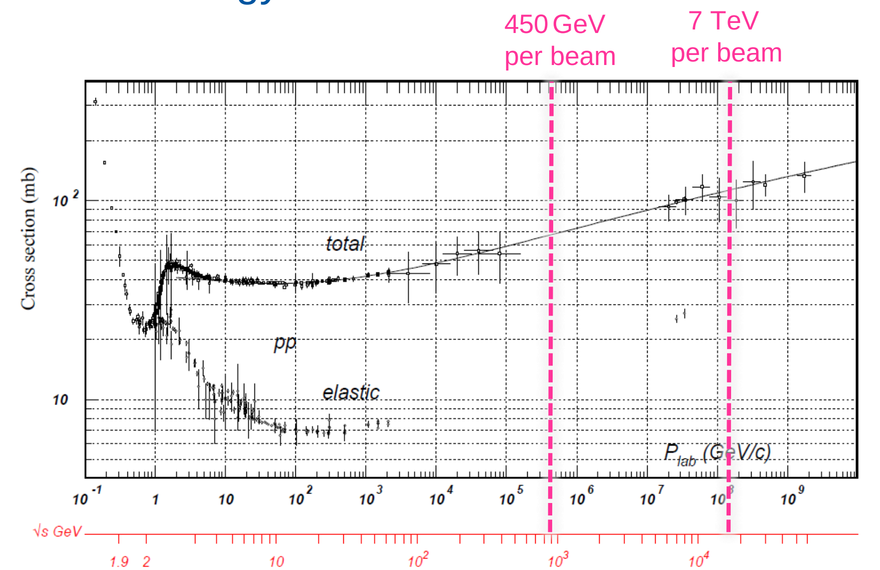
7 TeV values

Gas	A	σ(mb)	$\sigma_{rel,i}$
H_2	2	95	1
He	2	126	1.33
CH_4	16	566	5.96
H_2O	18	565	5.96
CO	28	854	8.99
N_2	14	820	8.63
O_2	32	924	9.73
CO_2	44	1317	13.86
Kr	84	2177	22.92
Xe	131	3231	34.01

$$\sigma_{rel,i} = \frac{\sigma_i}{\sigma_{H2}}$$

$$\sigma_{pA} = \sigma_{pp} A^{0.7}$$

H	σ(mb)
450 GeV	32.5
7 TeV	47.5
50 TeV	65



Total and elastic cross sections for pp collisions as a function of laboratory beam momentum and total centre of mass energy

- In a vacuum system, it is convenient to express the gas density in H_2 equivalent as if there were one specie of gas.

$$n_{H2\,eq} = \sum n_i \, \sigma_{rel,i}$$

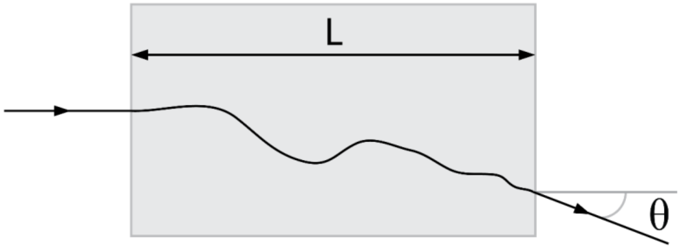
Proton storage ring

Complementary information

- A single Coulomb scattering event is due to the elastic scattering via electro-magnetic forces of an incoming particle on a nuclei.

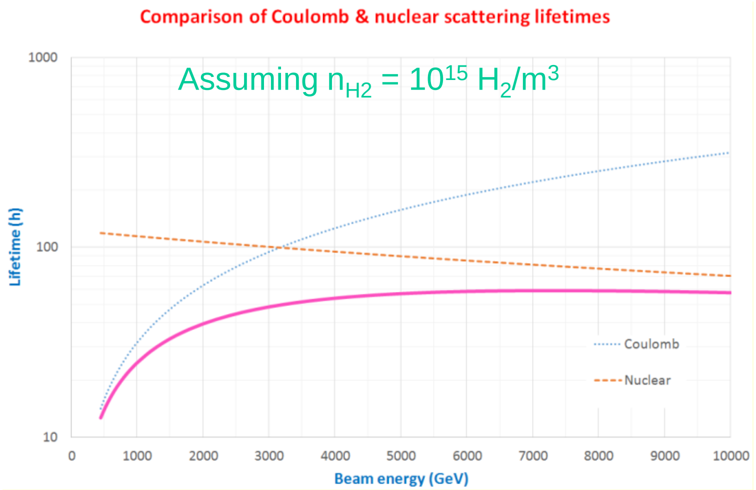
- Multiple Coulomb scattering is due to the successive events of small angle scattering which leads to the gradual blow up of the beam emittance, ε and thus its dimension transverse σ.

$$\sigma = \sigma_0 \, e^{-\frac{t}{\tau_m}}$$



- The multiple scattering characteristic time, τ_m, is directly proportional to the beam momentum

$$\tau_m[hour] = 1.13\ 10^{22} \frac{\varepsilon}{G\langle\beta\rangle} \frac{p^2}{n} \propto \frac{p^2}{\gamma} \propto p$$



Gas	Mass	Gas Factor
H_2	2	21.10
He	4	39.45
CH_4	16	370.86
H_2O	18	593.10
CO	28	900.66
N_2	28	884.60
O_2	32	1144.00
Ar	40	2709.26
CO_2	44	1472.66

- With:
G the gas factor,
n the gas density (molecules/m^3)
P the particle momentum (GeV/c)
<β> the average beta function (m)
$\varepsilon = \varepsilon_0/\gamma$ the beam emittance (m rad)

- The nuclear cross section dominates above 3 TeV

Electron storage ring

Complementary information

- The beam life time depends on 4 scattering cross sections

$$\sigma = \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4$$

$$\tau = \frac{1}{n\,\sigma\,c}$$

- Nuclear elastic scattering:

$$\sigma_1 = 1.305\ 10^{-35}\,\frac{Z^2}{E^2}\left[\left(\frac{\langle\beta_H\rangle}{a}\right)^2 + \left(\frac{\langle\beta_V\rangle}{b}\right)^2\right]$$

With:
σi cross section in m²
Z atomic number (i.e. 6 for C)
E the beam energy (GeV)
a semi-horizontal chamber dimension (m)
b semi-vertical chamber dimension (m)
<β> Average beta in H and V plane (m)
$\varepsilon_{RF} = \chi_{RF}$ E is the maximum allowable energy spread in the RF (χ_{RF} <<1)

- Nuclear inelastic scattering:

$$\sigma_2 = 3.09\ 10^{-31}\,Z^2\,ln\left(\frac{183}{Z^{\frac{1}{3}}}\right)\left[ln\left(\frac{1}{X_{RF}}\right) - \frac{5}{8}\right]$$

- Elastic scattering from electrons surrounding the nucleus of the residual gas:

$$\sigma_3 = 2.55\ 10^{-32}\,\frac{Z}{X_{RF}\,E}$$

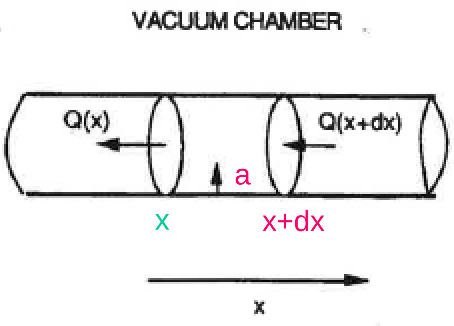
- Inelastic scattering from electrons surrounding the nucleus of the residual gas:

$$\sigma_4 = 3.09\ 10^{-31}\,Z\left[ln\left(\frac{4.89\ 10^3\ E}{X_{RF}}\right) - 1.4\right]\left[ln\left(\frac{1}{X_{RF}}\right) - \frac{5}{8}\right]$$

Gas flow in an elemental chamber

- We assume an elemental vacuum chamber pipe of length dx, with specific conductance c, into which gas desorbs at a rate a.
- The gas flow, Q, through the elemental chamb

$$Q = -c\,\frac{dP}{dx}$$



- The change of gas density in the volume element Vdx between x and x+dx is:

$$V dx \frac{dP}{dt} = +a dx + c\left[\frac{dP}{dx}\right]_{x+dx} - c\left[\frac{dP}{dx}\right]_{x}$$

$$V\frac{dP}{dt} = a + c\left[\frac{d^2P}{dx^2}\right]$$

- In steady state condition (dP/dt =0), we have:

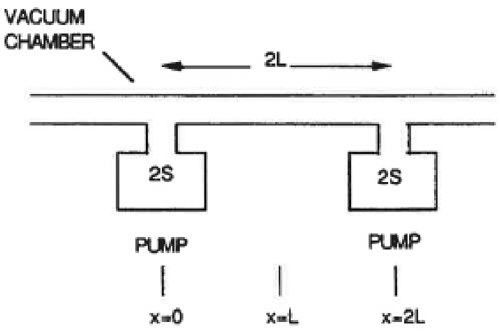
$$\frac{d^2P}{dx^2} = -\frac{a}{c}$$

- Which solution is a parabolic function.

Vacuum system design, A.G. Mathewson, CAS, CERN 94-041

Simple machine

- We assume a simple machine with pumps of speed 2S, regularly spaced by a distance 2L.



- boundary conditions:

$$\left[\frac{dP}{dx}\right]_{x=L} = 0 \quad \text{and} \quad P(0) = P(L) = \frac{a\,L}{S}$$

- So:

$$\boxed{P(x) = \frac{aL}{S} + \frac{aL}{c}x - \frac{a}{2c}x^2}$$

- The maximum pressure is given by:

$$P_{max} = \frac{aL}{S} + \frac{aL^2}{2c}$$

- The average pressure is given by:

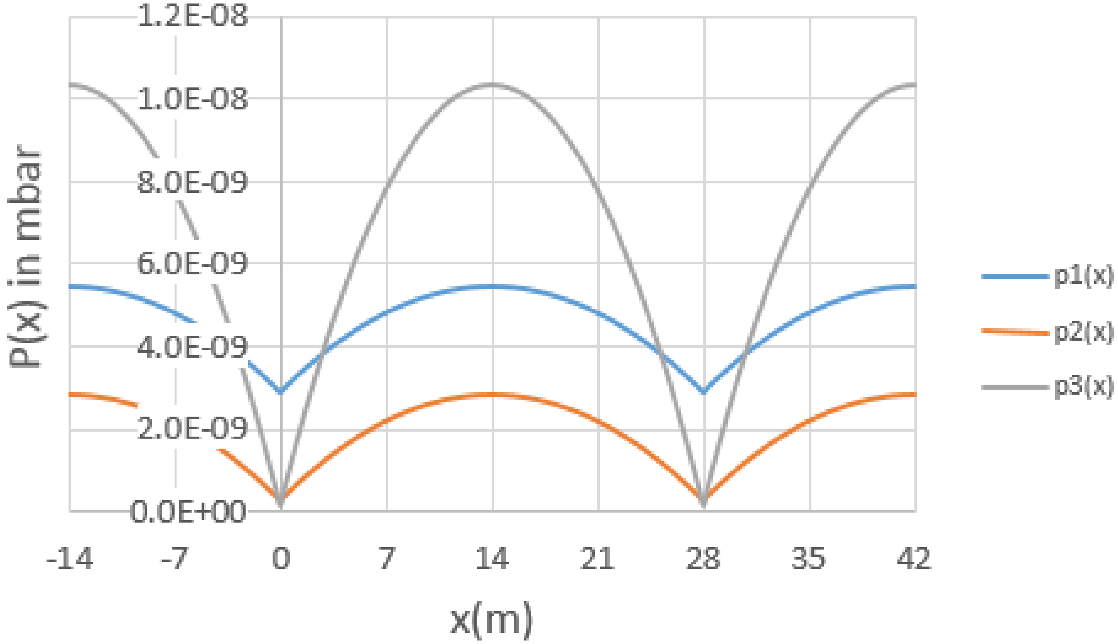
$$P_{av} = \frac{1}{2L}\int_0^{2L} P(x)dx = aL\left[\frac{1}{S} + \frac{L}{3c}\right]$$

Vacuum system design, A.G. Mathewson, CAS, CERN 94-041

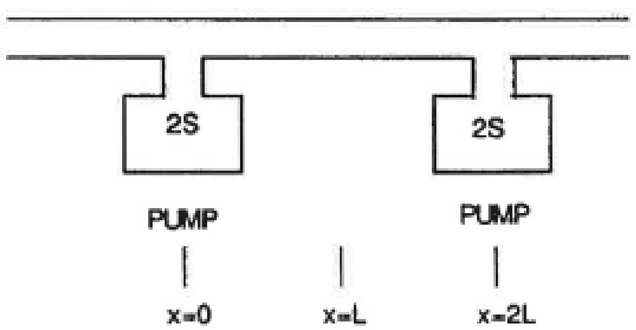
Simple machine: application

- P is the gas pressure (mbar)
- V is the volume per unit of length (l m^{-1})
- c is the specific conductance of the tube (l s^{-1} m)
- a is the gas desorption per unit length of tube (mbar l s^{-1} m^{-1})
- 2L is the distance between the pumps (m)
- 2S is the pumping speed (l s^{-1})

	P1(x)	P2(x)	P(3)
D (cm)	**10**	**10**	**5**
c (l s^{-1} m)	121	121	15.1
2S (l s^{-1})	30	300	300
P_{max} (mbar)	6 10^{-9}	3 10^{-9}	1 10^{-8}
P_{av}(mbar)	**3 10^{-9}**	**2 10^{-9}**	**7 10^{-9}**

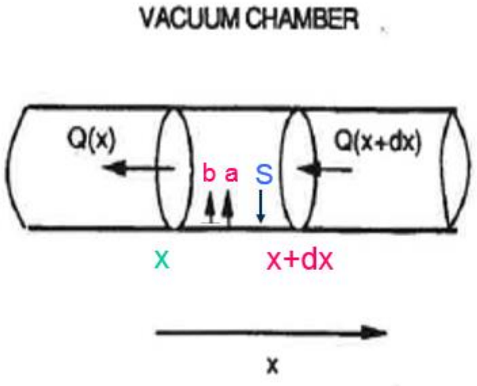


The average pressure is dominated by the conductance



Simple machine with distributed pumping, s

$$V\frac{dP}{dt} = a + (b - s)P + C\frac{d^2P}{dx^2}$$



- Where:

  a is the linear outgassing rate (includes thermal desorption and photon stimulated desorption) in Torr.l/s/m

  s is the linear pumping speed in l/s/m

  b is the ion induced desorption; b = 10^3 ησI/e in l/s/m

  I is the proton beam current in A

  C is the specific conductance of the vacuum chamber in l.m/s

  V is the volume per unit of length in l/m

- In quasi static conditions:

$$\frac{d^2P}{dx^2} = \left(\frac{s-b}{C}\right)P - \frac{a}{C}$$

- For long tubes $Cd^2P/dx^2 = 0$:

$$P_{inf} = \frac{a}{s-b}$$

- So the vacuum system is stable if s-b>0 *i.e.* s>b

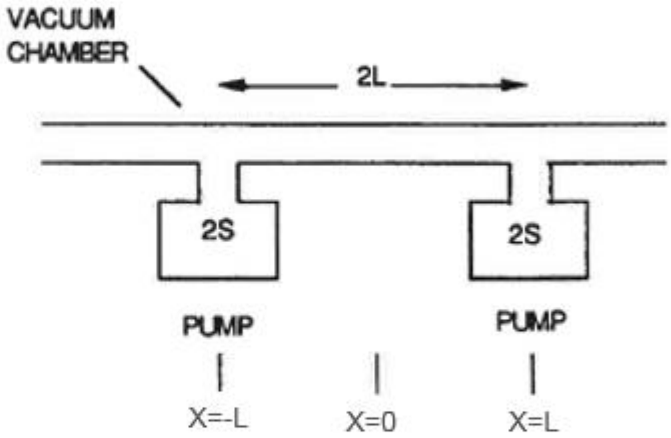
Simple machine with distributed pumping, s

- For short tubes $Cd^2P/dx^2 \neq 0$:

$$P(x) = Ae^{-\lambda x} + Be^{\lambda x} + \frac{a}{\lambda^2 C} \qquad \text{with} \qquad \lambda^2 = \frac{s-b}{C}$$

- With the following boundary conditions:

$$C\left[\frac{dP}{dx}\right]_{x=\mp L} = {}^{+}/_{-}\, P(\mp L)\ \ 2S$$



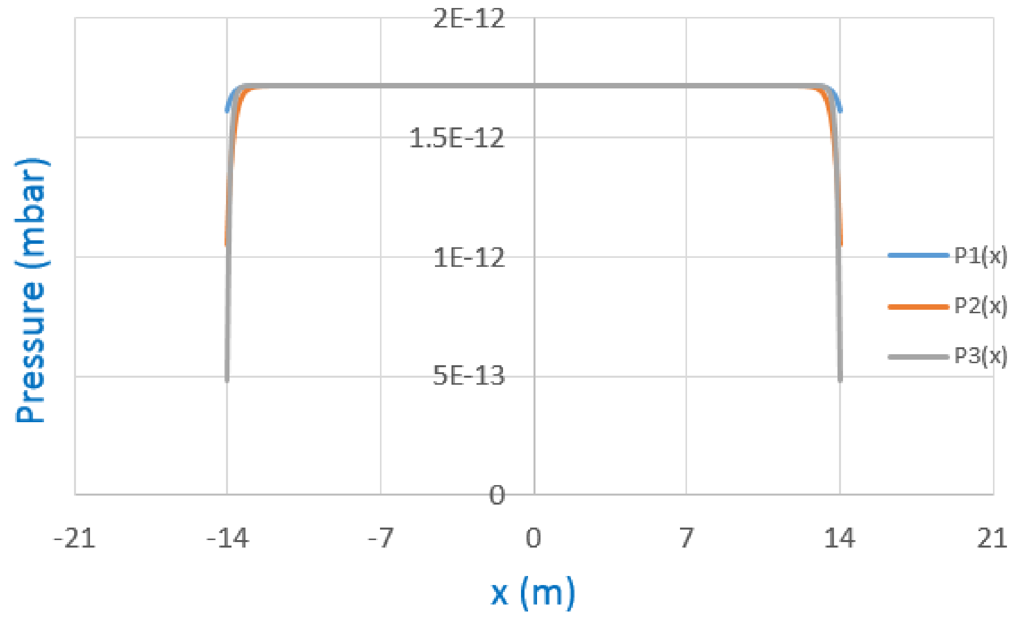
- It gives:

$$P(x) = P_{inf}\left(1 - \frac{\cosh(\lambda x)}{\cosh(\lambda L)\left(1 + \frac{C}{2S}\lambda \tanh(\lambda L)\right)}\right)$$

Simple machine with distributed pumping: application

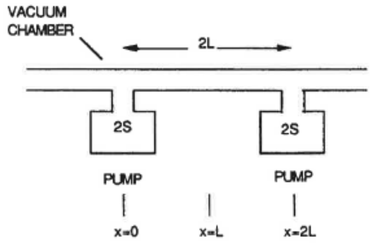
- P is the gas pressure (mbar)
- V is the volume per unit of length (l m^{-1})
- c is the specific conductance of the tube (l s^{-1} m)
- b is set to zero
- a is the gas desorption per unit length of tube (mbar l s^{-1} m^{-1})
- 2L is the distance between the pumps (m)
- 2S is the pumping speed (l s^{-1})

	P1(x)	P2(x)	P(3)
D (cm)	**10**	**10**	**5**
c (l s^{-1} m)	121	121	15.1
2S (l s^{-1})	30	300	300
a (mbar l /s / m)	3 10^{-9}	3 10^{-9}	1.5 10^{-9}
S (l s^{-1} m^{-1})	1834	1834	917
P_{inf}(mbar)	**2 10^{-12}**	**2 10^{-12}**	**2 10^{-12}**

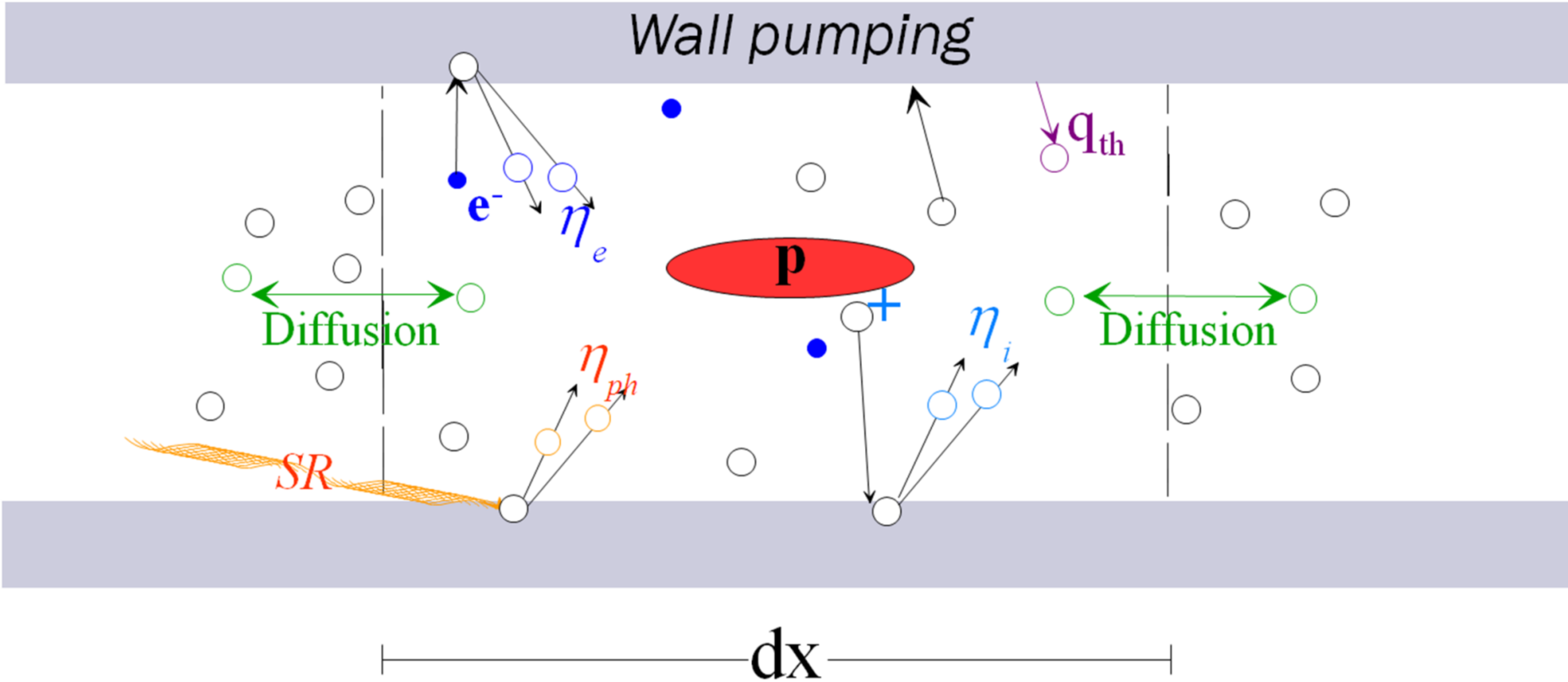


- 50 cm away from the pump, the pressure is independent of its pumping speed

The average pressure is dominated by the long tube pressure P_{inf}



VASCO : a code to study vacuum stability



The changing rate of the number of molecules per unit volume:

- Molecular diffusion
- Beam induced dynamic effects: ion, electron and photon induced molecular desorption.
- Gas pumping distributed along the beam pipe: NEG and Cryo
- Gas lumped pumping: Sputtered ion pumps

Gas Balance Equation

VASCO: Multi-gas code to calculate gas density profile in uhv system, A. Rossi. CERN LHC Project Note 341, 2004

$$V\frac{\partial n_g}{\partial t} = a\cdot D_g \cdot \frac{\partial^2 n_g}{\partial x^2} + \frac{I}{e}\sum_j \left\{\eta_{i,j^+\to g}\sigma_j^b \cdot n_j\right\} - \left(\frac{A\cdot v_g}{4}\cdot\alpha_g + C_g\right)\cdot n_g + \eta_{ph,g}\cdot\dot{\Gamma}_{ph} + \eta_{e,g}\cdot\dot{\Gamma}_e + A\cdot q_g$$

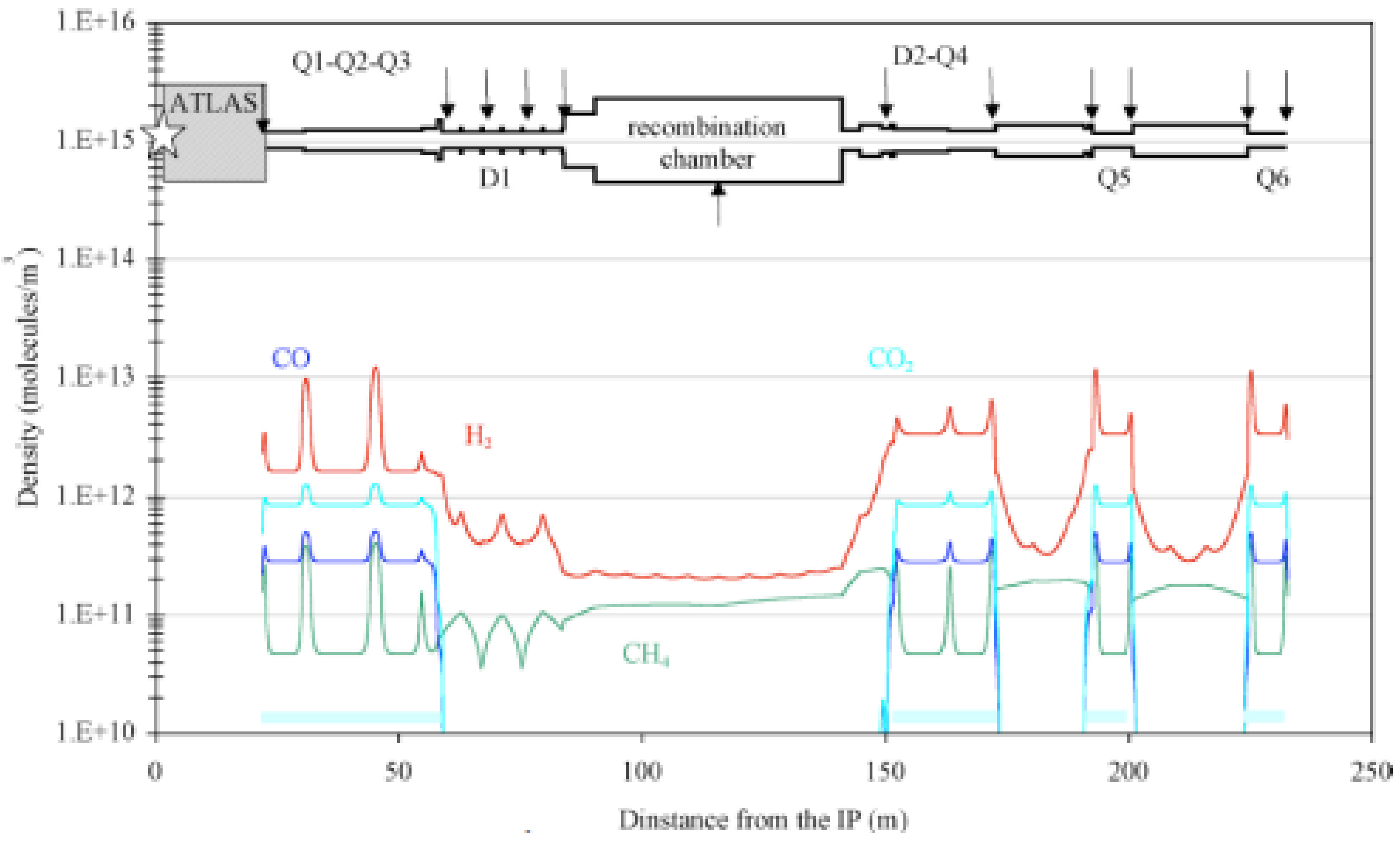
- *Time variation of particles in volume V*
- *Diffusion through surface a*
- *Ionization by beam and desorption by the ions*
- *Distributed pumping of NEG or Cryo*
- *Desorption by photons*
- *Desorption by electron*
- *Thermal desorption*

Multi Gas Model

MULTI GAS MODEL

- Dominant gas species present in a vacuum system: H_2, CH_4, CO and CO_2
- The “multi gas” model takes into account that each of the gas species, once ionized, can desorbs any species both from the wall beam pipes or the condensed gas layer in a cryogenic system
- The equation of each species depends on the gas densities of other species, and all the equations results inter-dependent

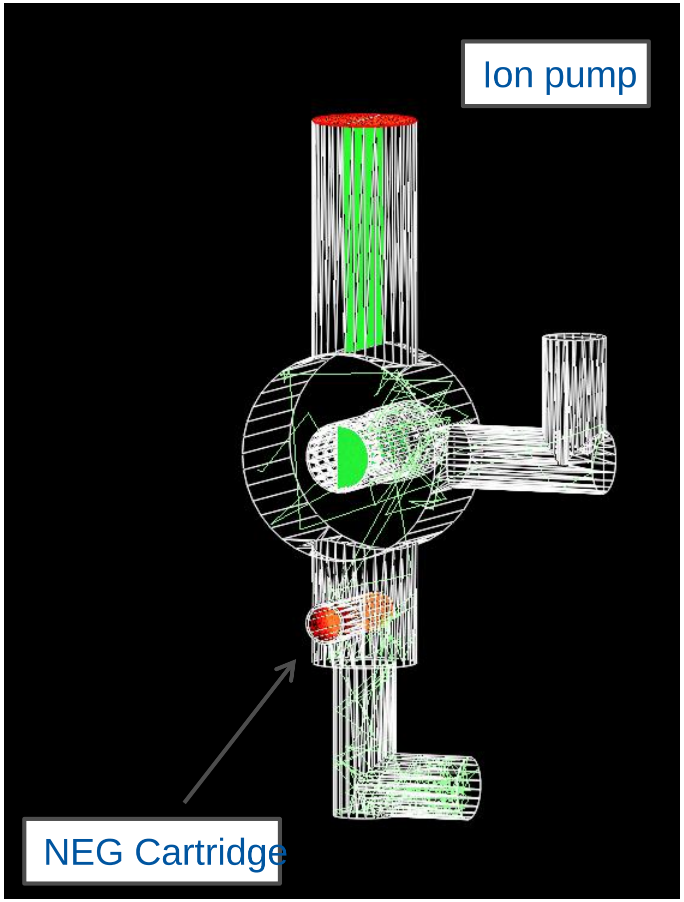
Gas density profile around ATLAS



A. Rossi, CERN LHC PR 783, 2004.

Gas density profile simulation: Molflow+

A Test-Particle Monte-Carlo Simulator for Ultra-High Vacuum systems



Simulation done with a flow of 1×10^{-8} mbar*l/s coming from the VAX insert

	Pressure in the beam line [mbar]	Pressure in the SVT gauge [mbar]
Ion Pump	2×10^{-8}	2×10^{-8}
Ion Pump + D400 NEG cartridge	6×10^{-9}	6×10^{-9}

Data from G.Bregliozzi – TE-VSC

For info: http://test-molflow.web.cern.ch/content/about-molflow

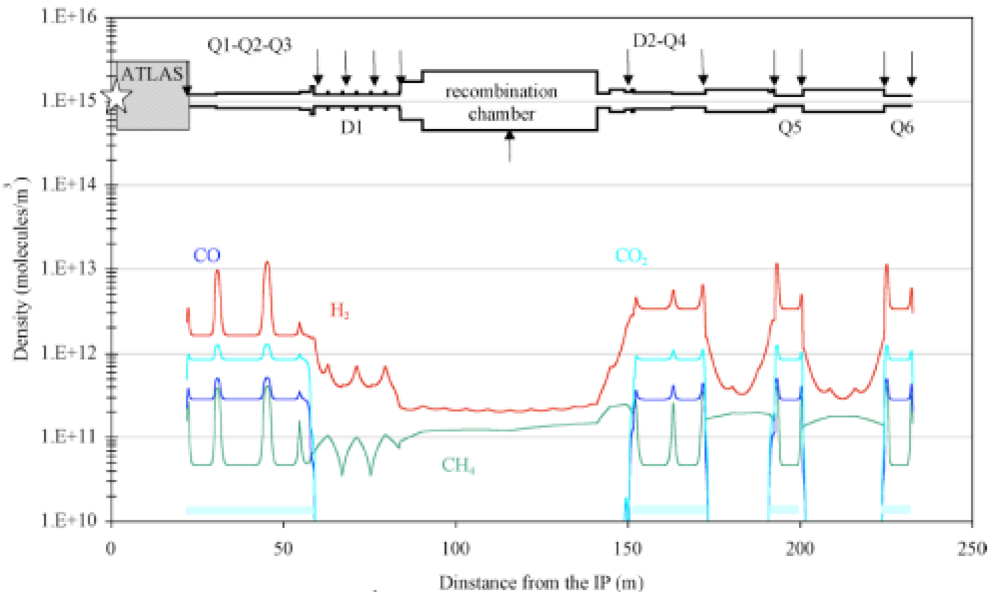
2. The LHC case

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.

LHC Current Parameters

Complementary information

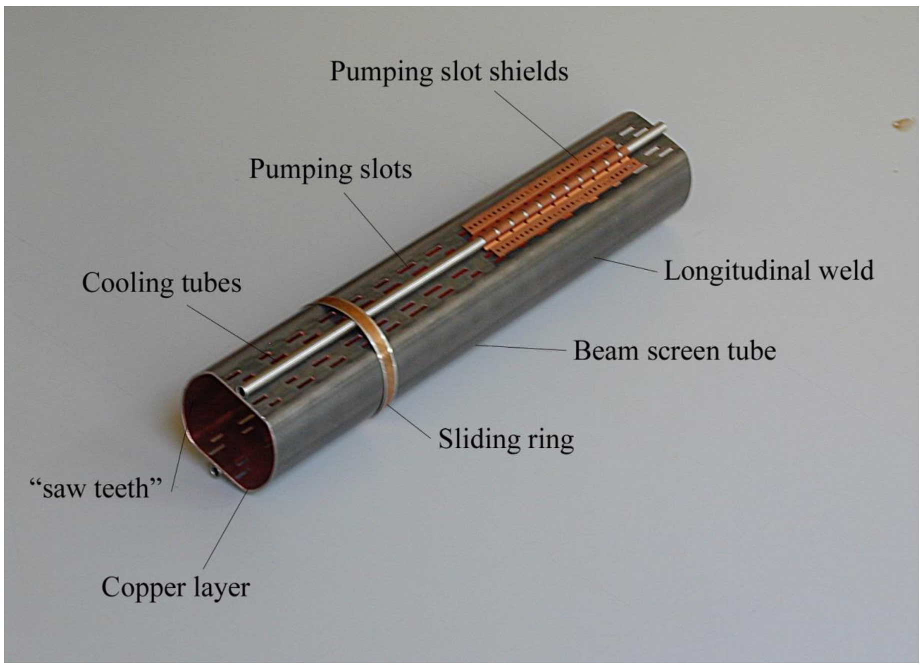
	Design		Commissioning				
	Nominal	Ultimate	2010	2011 (Fill 2256)	2012 (Fill 3250)	2015 (Fill 4569)	2016 (Fill 5045)
Energy [TeV]	7		3.5	3.5	4	6.5	6.5
Luminosity [x10^{34} $cm^{-2}.s^{-1}$]	1.0	2.3	0.02	0.36	0.75	0.6	**1.0**
Int. Luminosity [fb^{-1}/year]	80	120	0.0	5.9	23.3	4.2	16
Current [mA]	584	860	80	362	420	468	447
Proton per bunch [x10^{11}]	1.15	1.7	1.2	1.45	**1.6**	**1.15**	**1.19**
Number of bunches	2808		368	1380	1378	2244	2076
Bunch spacing [ns]	25		150 (75-50)*	50 (25)*	50 (25)*	**25**	**25**
Normalised emittance [μm.rad]	3.75		~ 3	~ 2.3	~ 2.2	~ 3	~ 3
β * [m]	0.55		3.5	1	0.6	0.8	**0.4**
Total crossing angle [μrad]	285		240	240	290	290	185
Critical energy [eV]	44.1		5.5		8.2	35.3	35.3
Photon flux [ph/m/s]	$1\ 10^{17}$	$1.5\ 10^{17}$	$0.06\ 10^{17}$	$0.3\ 10^{17}$	$0.4\ 10^{17}$	$0.8\ 10^{17}$	$0.8\ 10^{17}$
SR power [W/m]	0.22	0.33	0.002	0.01	0.02	0.13	0.13
Photon dose [ph/m/year]	$1\ 10^{24}$	$1.5\ 10^{24}$	$1\ 10^{21}$	$0.1\ 10^{24}$	$0.3\ 10^{24}$	$0.1\ 10^{24}$	$0.2\ 10^{24}$
Beam dose per year [A.h]	2800	4100	3	314	569	126	255

* During MD periods

New System: LHC Beam Screens Functionalities

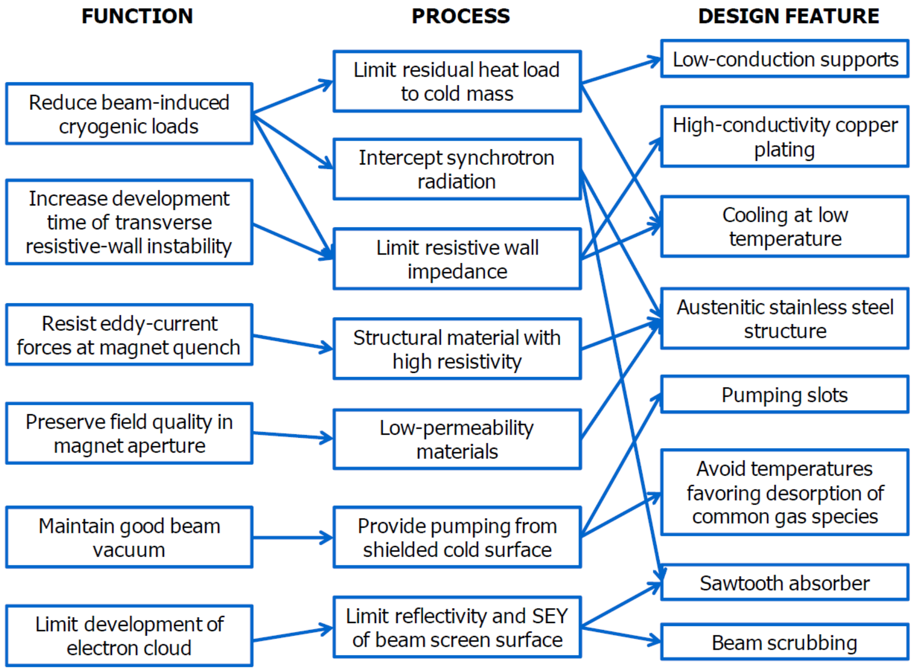
- An innovative and complex system, produced at several 10 km scale !

- Intercept the heat load induced by the circulating beam
- Operate between 5 and 20 K
- Pumping holes to control the gas density



Courtesy N. Kos CERN TE/VSC

Functional design map of beam screen



P. Lebrun et al.

Why Perforated Beam Screen ?

- SSC studies in 1994

V.V. Anashin *et al.* J. Vac. Sci.Technol. A. 12(5) , Sep/Oct 194

No perforations

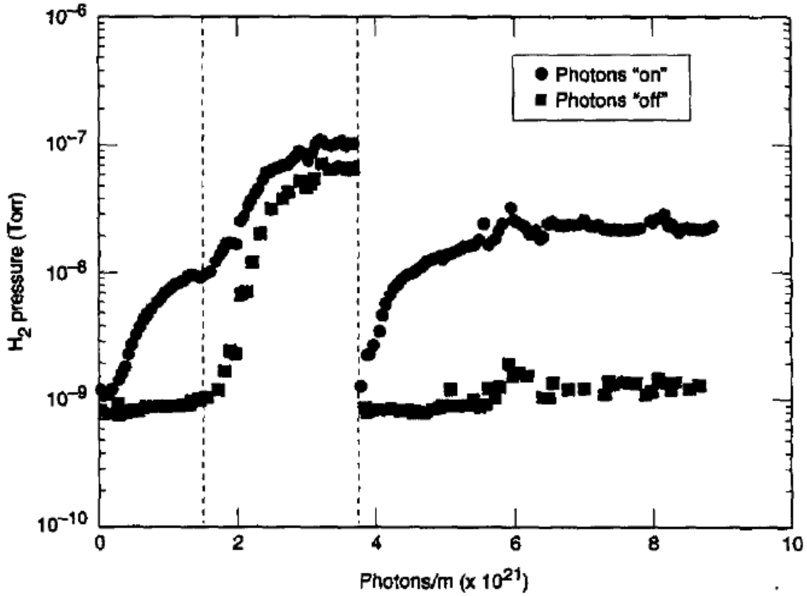


FIG. 1. Room-temperature RGA H_2 pressure measured at the center of the 4.2-K beam tube vs integrated photon flux with photons on and photons off. The raw pressure difference "on" minus "off" has been normalized to 1×10^{16} photons/m/s. The vertical dashed lines correspond to features discussed in the text.

With perforations

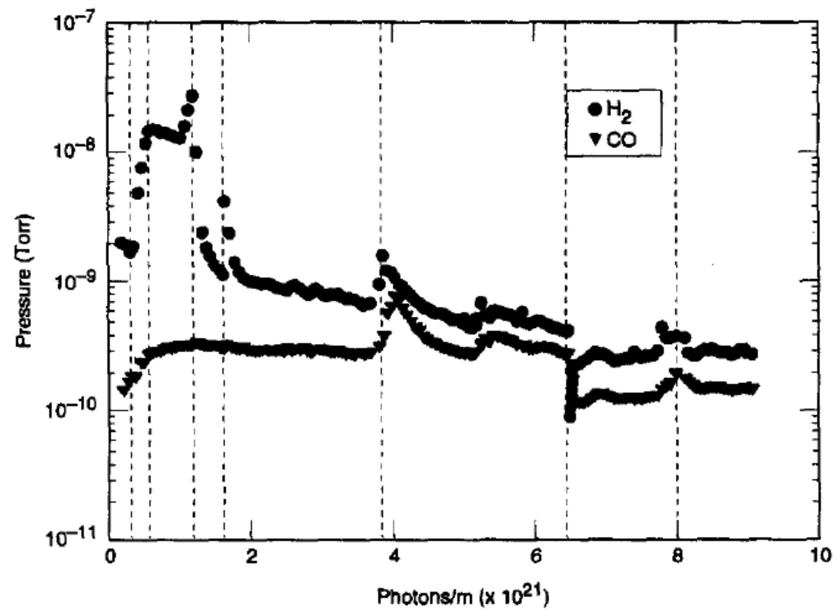


FIG. 2. Room-temperature RGA H_2 and CO dynamic pressures measured at the center of the liner configuration. Dynamic pressure is normalized to 1×10^{16} photons/m/s.

A **perforated** beam screen allows to control the gas density

Gas density & surface coverage equations

V.V. Anashin *et al.* J. Vac. Sci.Technol. A. 12(5) , Sep/Oct 194

$$V\frac{\partial n}{\partial t} = \eta_1\dot{\Gamma} + \eta'\dot{\Gamma} + \frac{A_w s}{\tau_w^t} - \sigma_w S_w * n - C * n + A_c D\frac{\partial^2 n}{\partial z^2}$$

$$A_w\frac{\partial s}{\partial t} = \eta_2\dot{\Gamma} + \sigma_w S_w * n - \frac{A_w s}{\tau_w^t} - \eta'\dot{\Gamma}\,.$$

- with:

n gas density, s surface coverage, V volume per unit length, A_w surface per unit length, A_cD axial diffusion term of molecules, σ sticking probability, S ideal speed per unit length, C beam screen holes pumping speed per unit length, tm sojourn time of physisorbed molecule, η desorption yield of chemisorbed molecules, η' recycling desorption yield of physisorbed molecules,

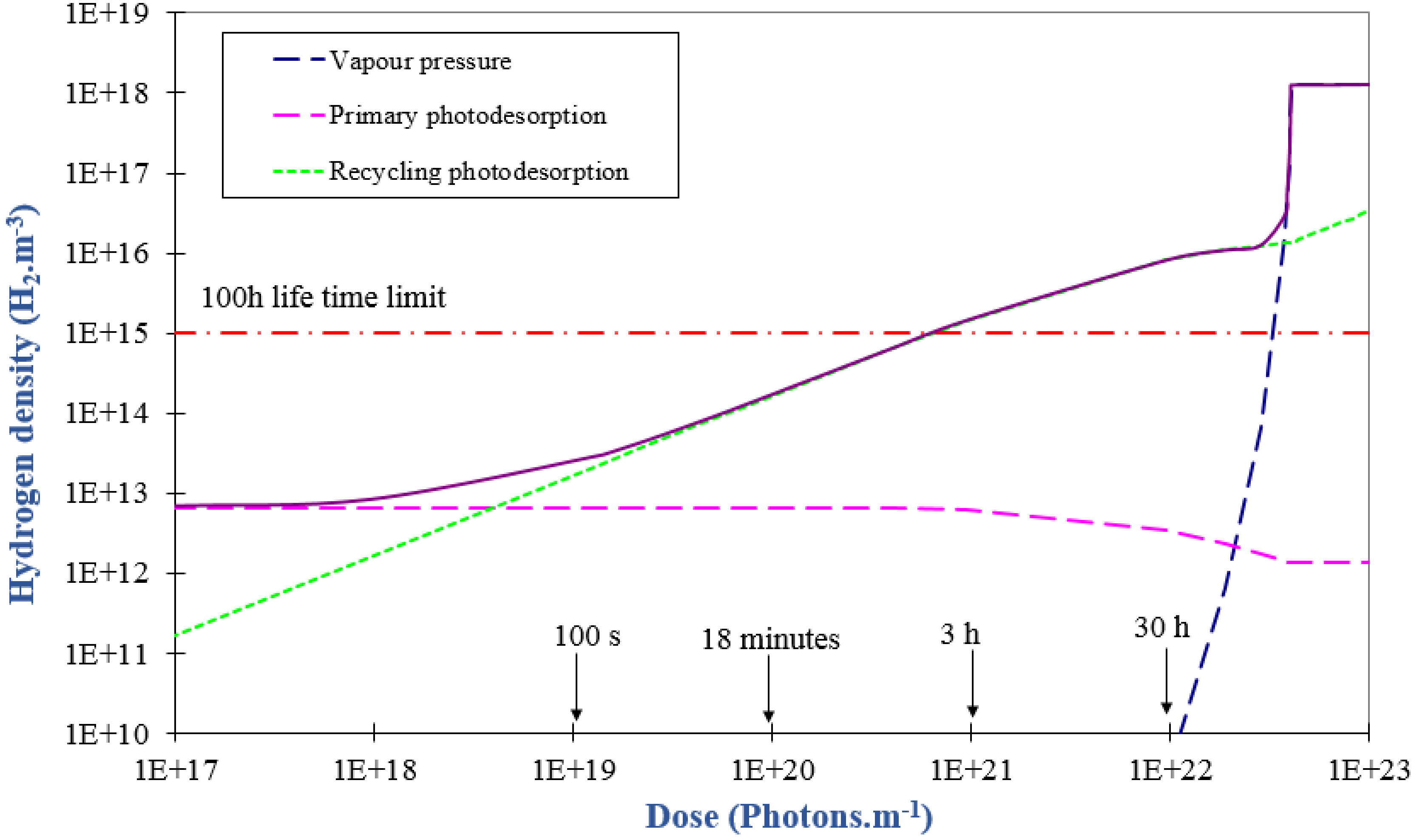
- Infinitely long tube ($A_cD=0$), without beam screen (C=0) and quasi static conditions:

$$n = \frac{\eta_1\dot{\Gamma}}{\sigma_w S_w} + \frac{\eta'\dot{\Gamma}}{\sigma_w S_w} + \frac{1}{\sigma_w S_w}\frac{A_w S}{\tau_w^t}$$

$$s = \frac{1}{A_w}\int_0^{\Gamma}(\eta_1 + \eta_2)d\Gamma$$

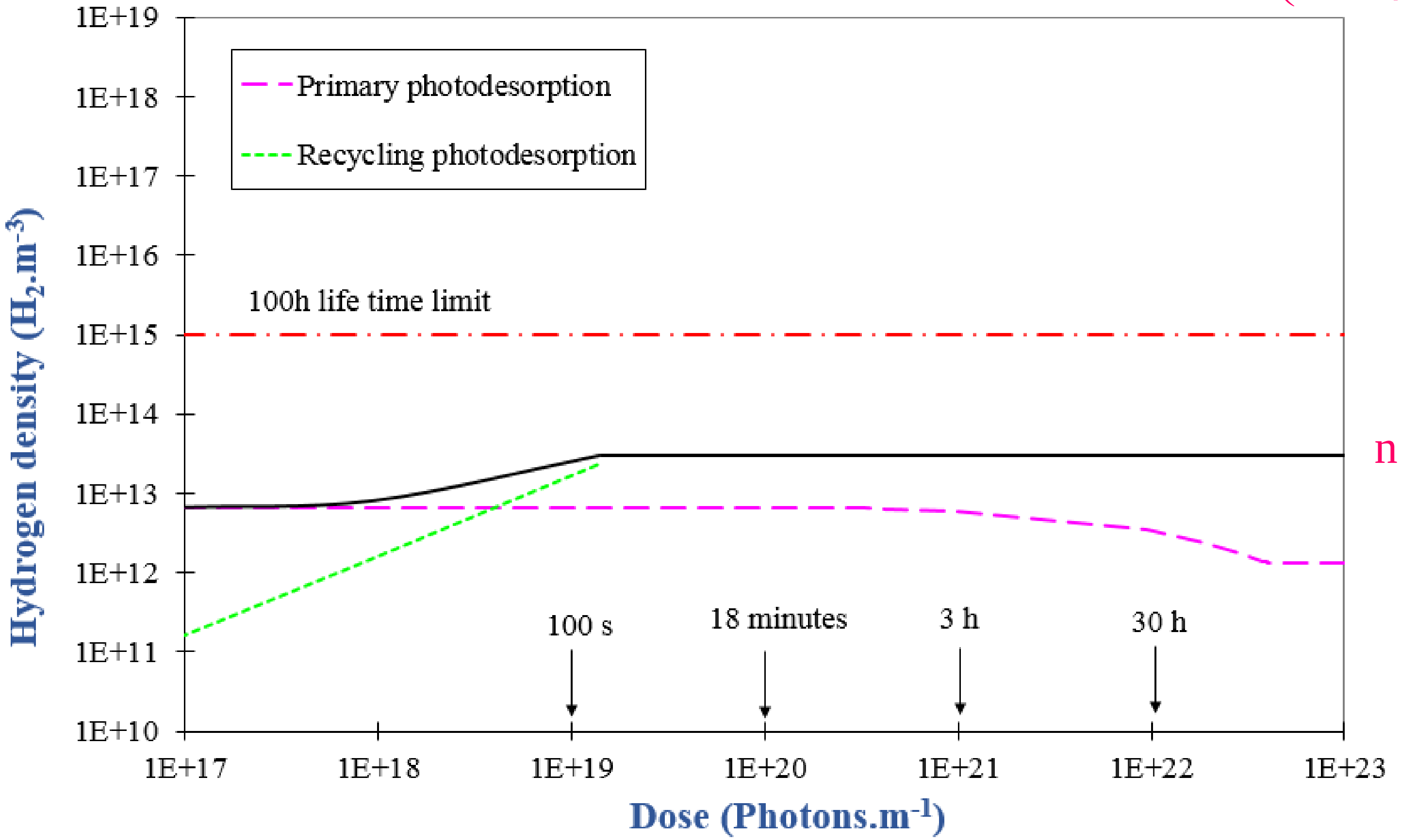
Increase with the surface coverage

Cryosorbing tube without holes



Perforated beam screen

- Infinitely long tube ($A_c D=0$), with a beam screen ($C \neq 0$) and quasi static conditions:
  - Equilibrium pressure $$n_{eq} = \frac{\eta \dot{\Gamma}}{C}$$
  - Equilibrium coverage $$\theta_{eq} = \left(\frac{\sigma S}{C} \frac{\eta}{\eta_0^{'}} \right) \theta_m$$

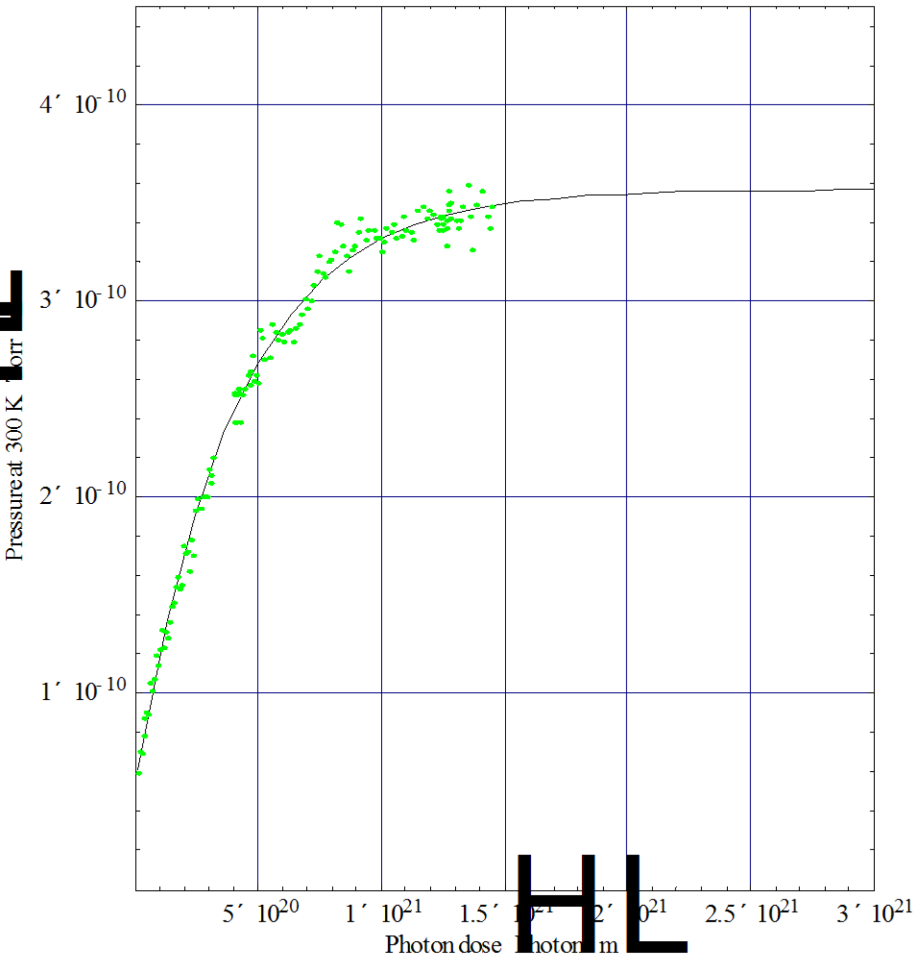


$$n_{eq} = \frac{\eta \dot{\Gamma}}{C}$$

A **perforated** beam screen allows to control the gas density

Fit to measured data at 10 K with 194 eV crit. energy

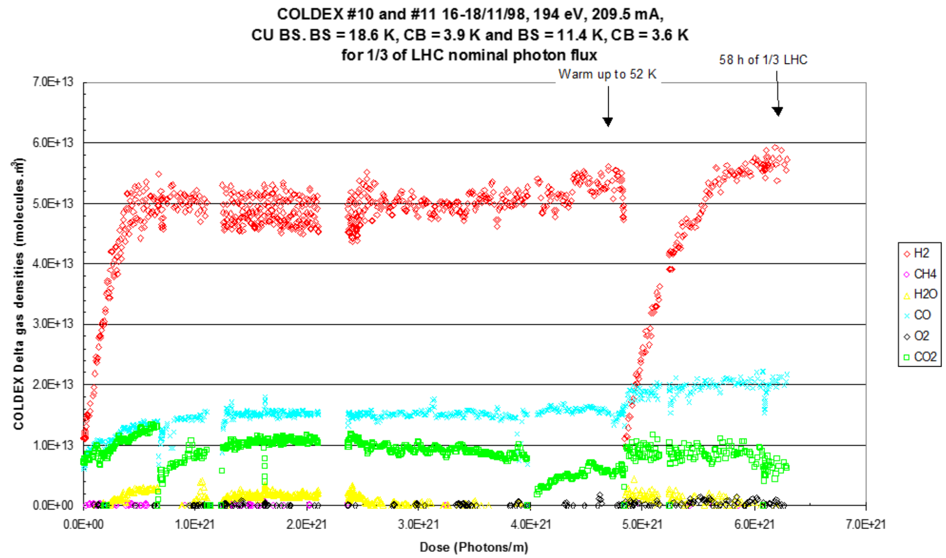
Complementary information



η = 2.6 10^{-4} H_2/ph

η' = 0.08 H_2/ph/monolayer

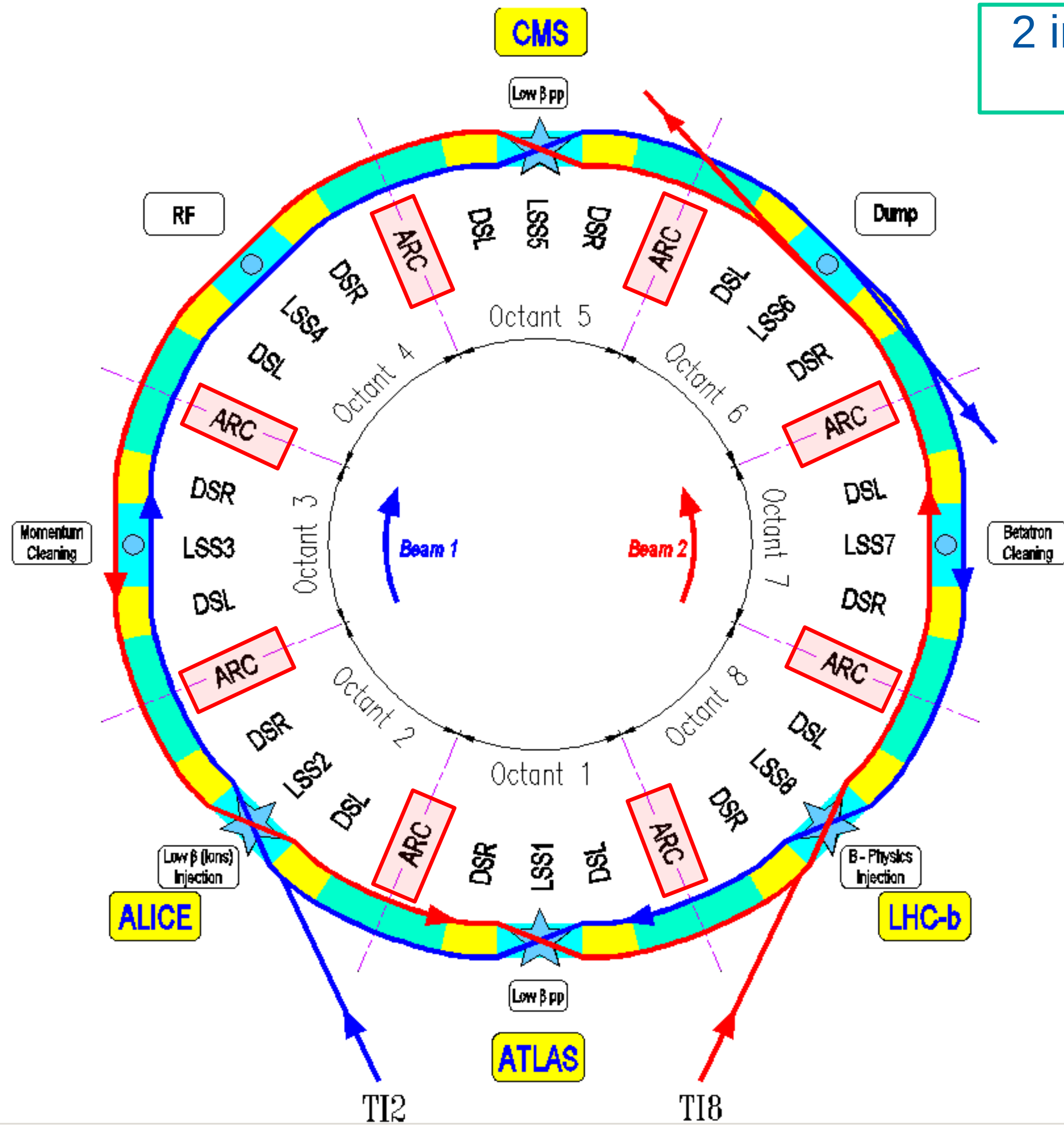
σ= 0.08

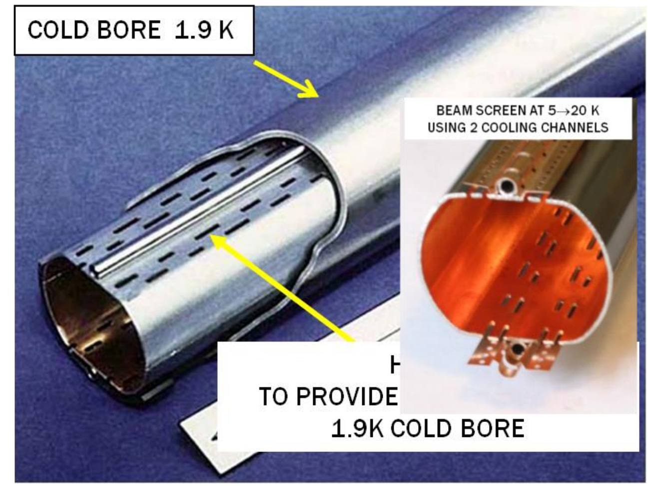


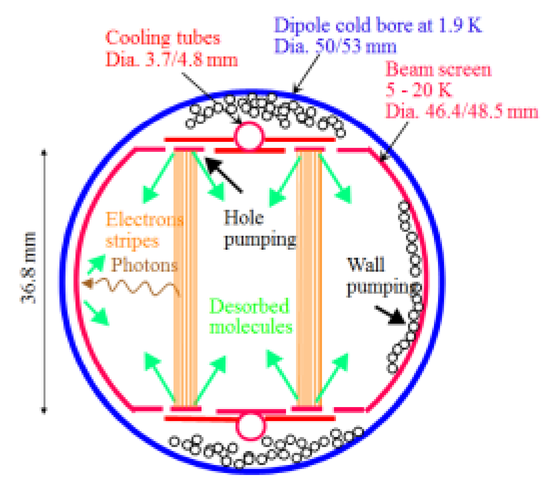
3.2 Arc Vacuum System

Cryogenic Beam Vacuum

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







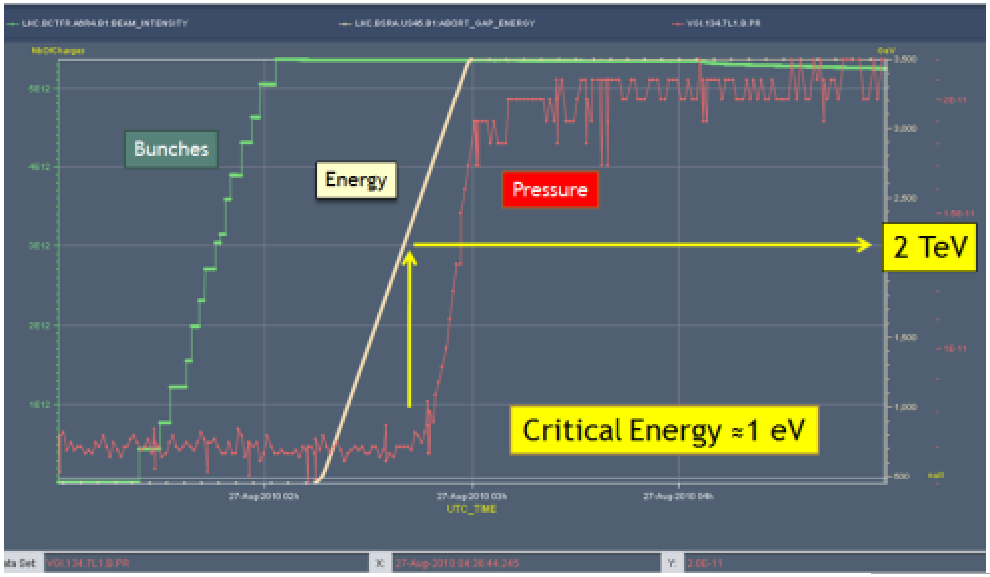
Arc : Some Numbers

Complementary information

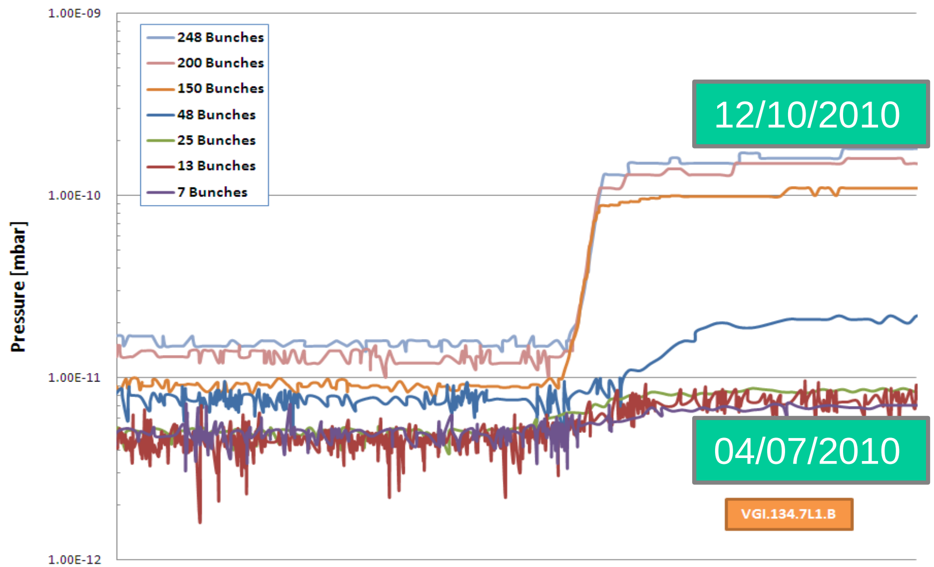
Item	Total
Vacuum sectors (cryogenic)	16
Vacuum sector valves	32
Roughing valves (arc)	844
Ion pumps	0
Bayard Alpert gauges	0
Penning gauges (arc)	108
Pirani gauges	108

Item	Length (m)
Unbaked Arc @ cryo T	~ 45 000

First Observation of Synchrotron Radiation: Aug-2010



- Pressure rise during the beam energy ramp
- At E= 2 TeV, Critical energy 1 eV, pressure starts to rise

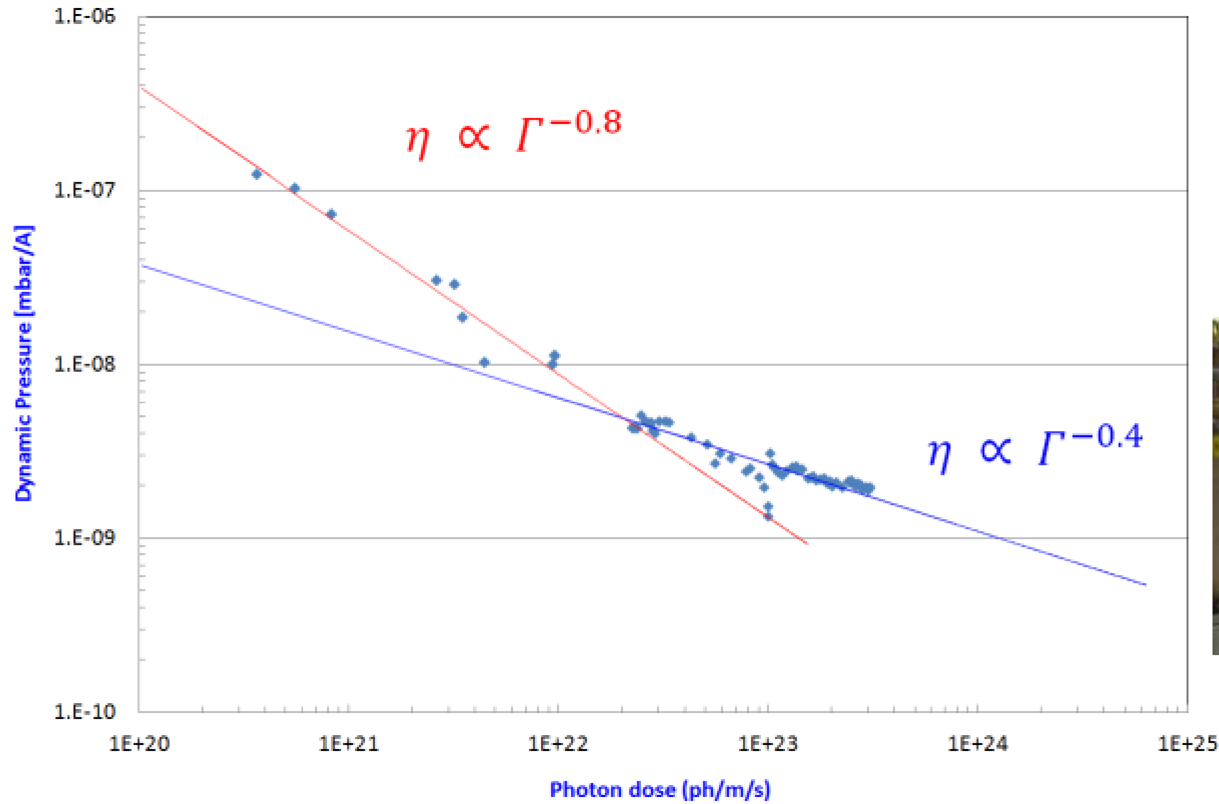


- Dynamic pressure increases with beam current
- DeltaP = 2 10^{-10} mbar

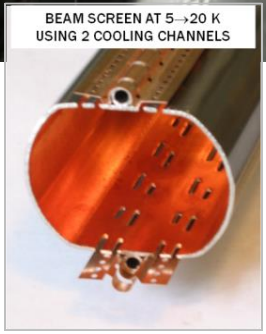
Beam Conditioning under SR

Complementary information

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



- 2 trends :
  - Room temperature
  - Cryogenic temperature



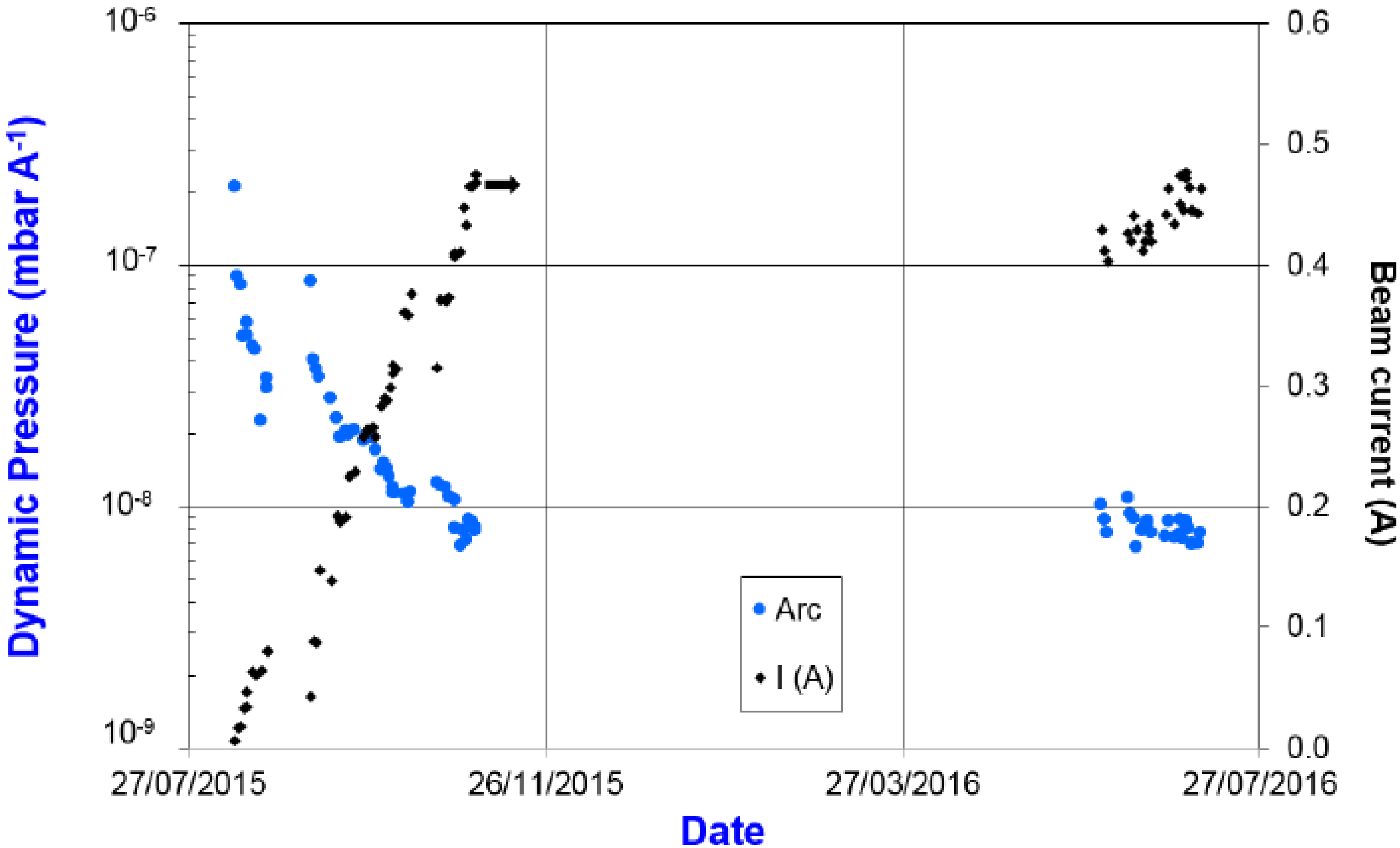
- Inside the arc, at 5-20 K, □P < 10^{-10} mbar (i.e. below detection limit)

- The photodesorption yield at cryogenic temperature is estimated to be < 10^{-4} molecules/photon

Beam conditioning in the LHC arcs

Complementary information

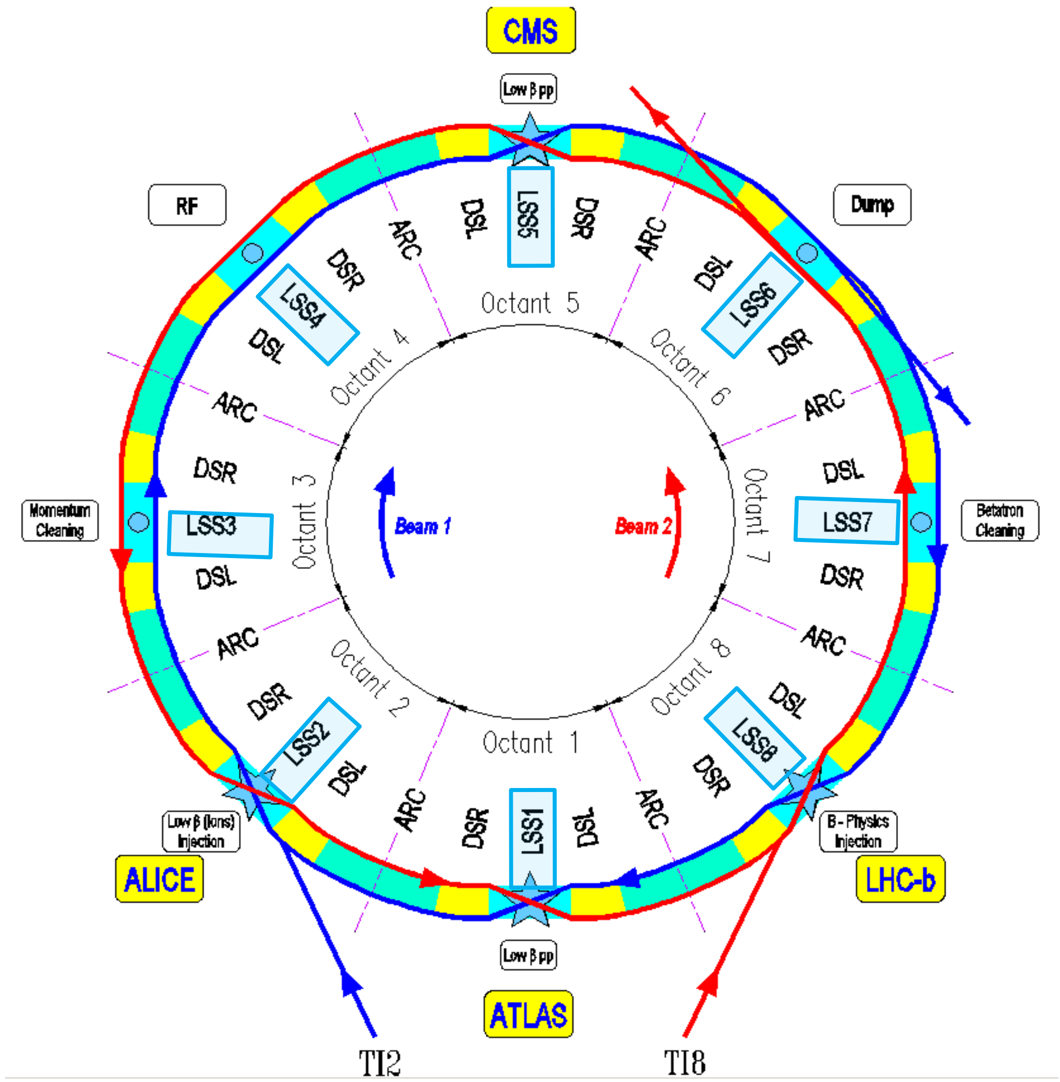
- Dynamic pressure reduction during LHC commissioning.



V. Baglin, Vacuum, 2016

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

LSS: Some Numbers

Complementary information

Component	Total
Vacuum sectors (cryogenic / RT)	84 / 185
Vacuum sector valves (all LHC)	295
Roughing valves (LSS)	309
Ion pumps (special /30 / 60 / 400 l/s)	12 / 550/ 168 / 49
Bayard Alpert gauges (LSS)	178
Penning gauges (LSS)	502
Pirani gauges (LSS)	289

Item in LSS	Length (m)	% wrt to total
SAM @ cryo T	~ 1 365	19
LSS @ RT baked	~ 1 000	14
LSS @ RT with baked NEG	~ 4 800	67
Total length under vacuum	7 227	100

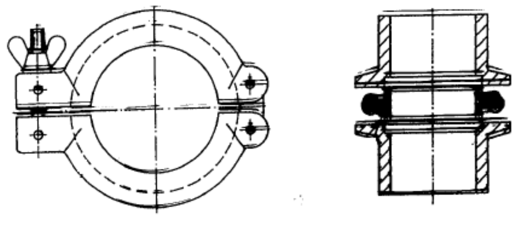
- ~ 85 % of the baked vacuum system is NEG coated

Flanges and Gaskets

Complementary information

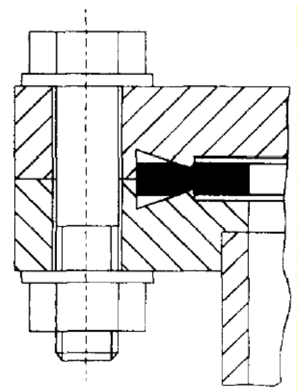
- For primary vacuum, elastomer seals and clamp flanges are used
- KF type components:

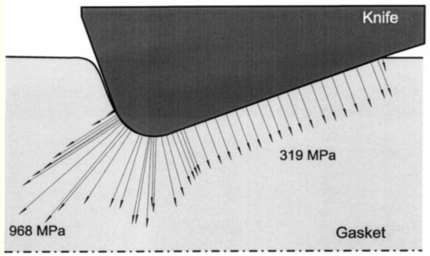
  Many fittings (elbows, bellows, T, cross, flanges with short pipe, reductions, blank flanges …)
  ISO diameters



- 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

Complementary information

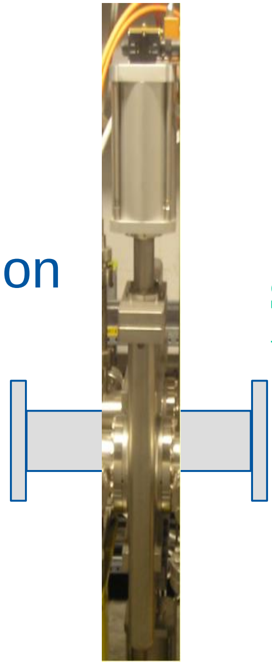
- Metallic tubes are preferred (low outgassing rate)
- Stainless steel is appreciated for mechanical reason (machining, welding)

Copper tubes

- Bellows are equipped with RF fingers (impedance)

- Valves are used for roughing and sectorisation

Roughing valve

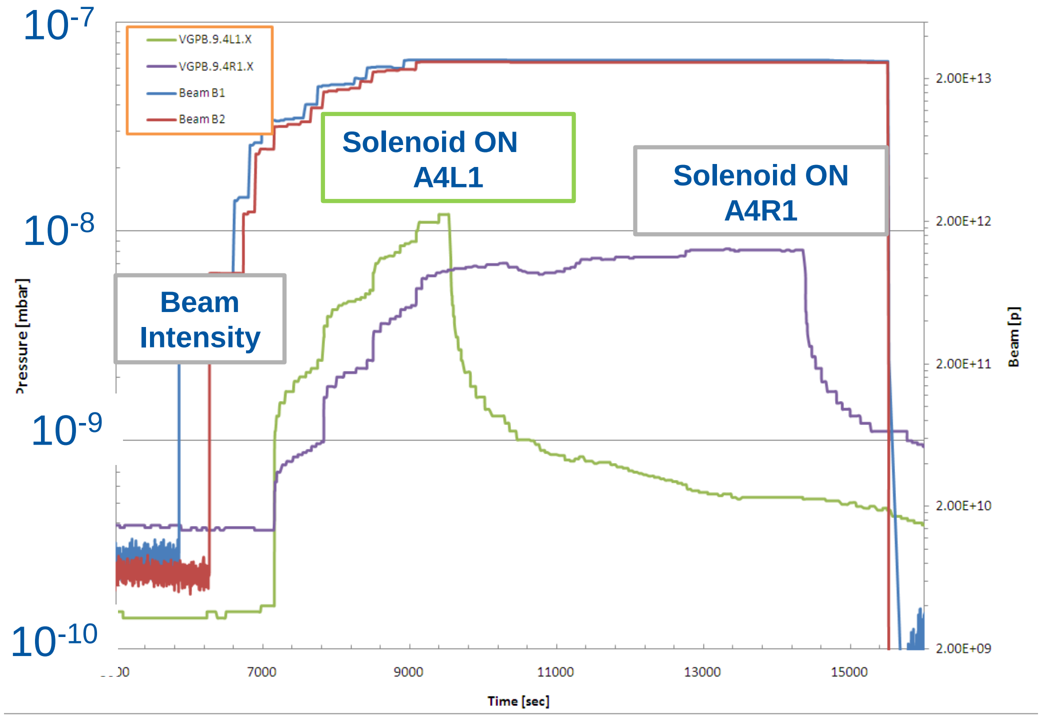


Sector valves

First Observation of Electron Cloud : 29-9-2010

- The position at 45 m from the IP is the longest unbaked area (operating at RT) in LHC, so the first candidate to trigger electron cloud ….

- Reduction of 1 order of magnitude when solenoids are ON

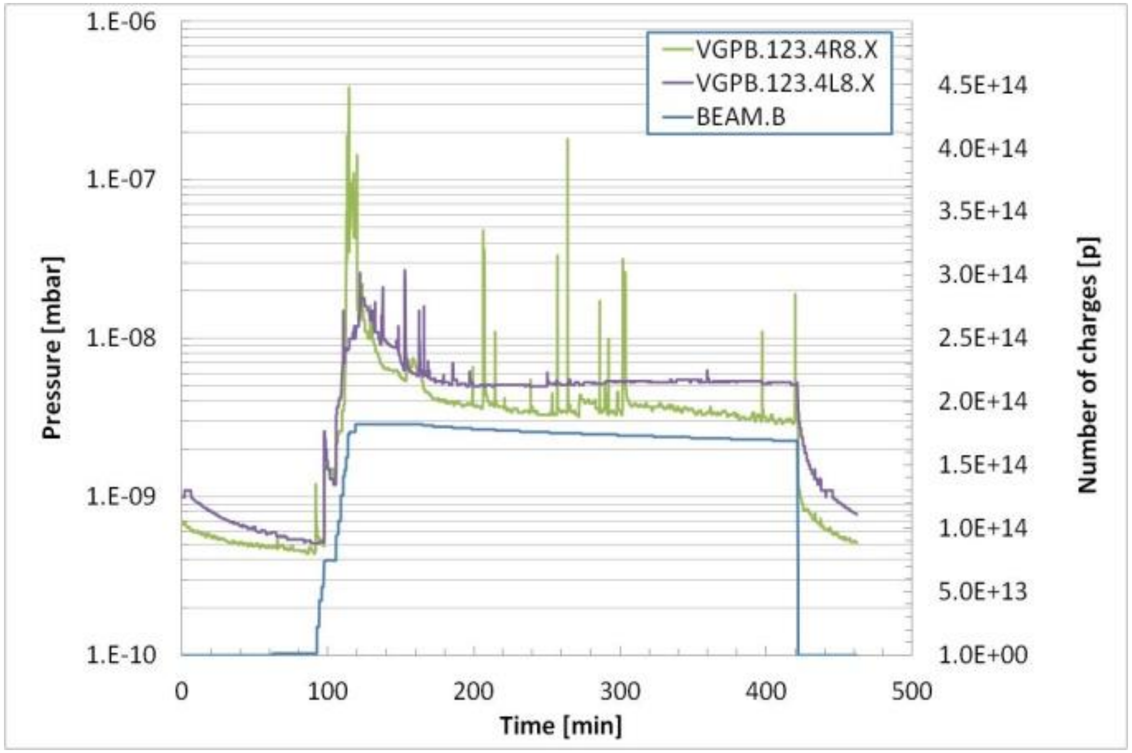


Magnetic field of solenoid≈ 20 Gauss

G. Bregliozzi *et al.*, IPAC San Sebastian, 2011

Appropriate mechanical design is vital

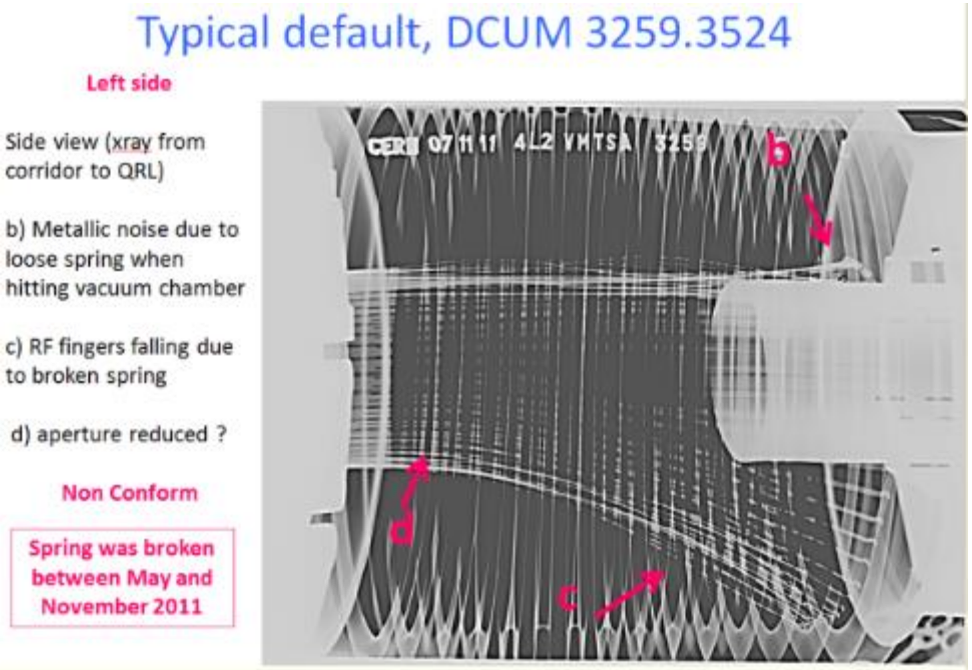
- Design extrapolated and not mechanically validated before installation in the ring
- Pressure spikes located beside inner triplets generated interlocks and background

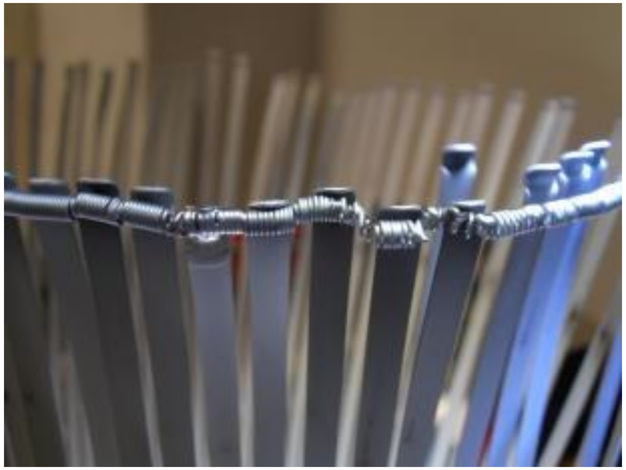


Observed Pressure spikes during a physics fill

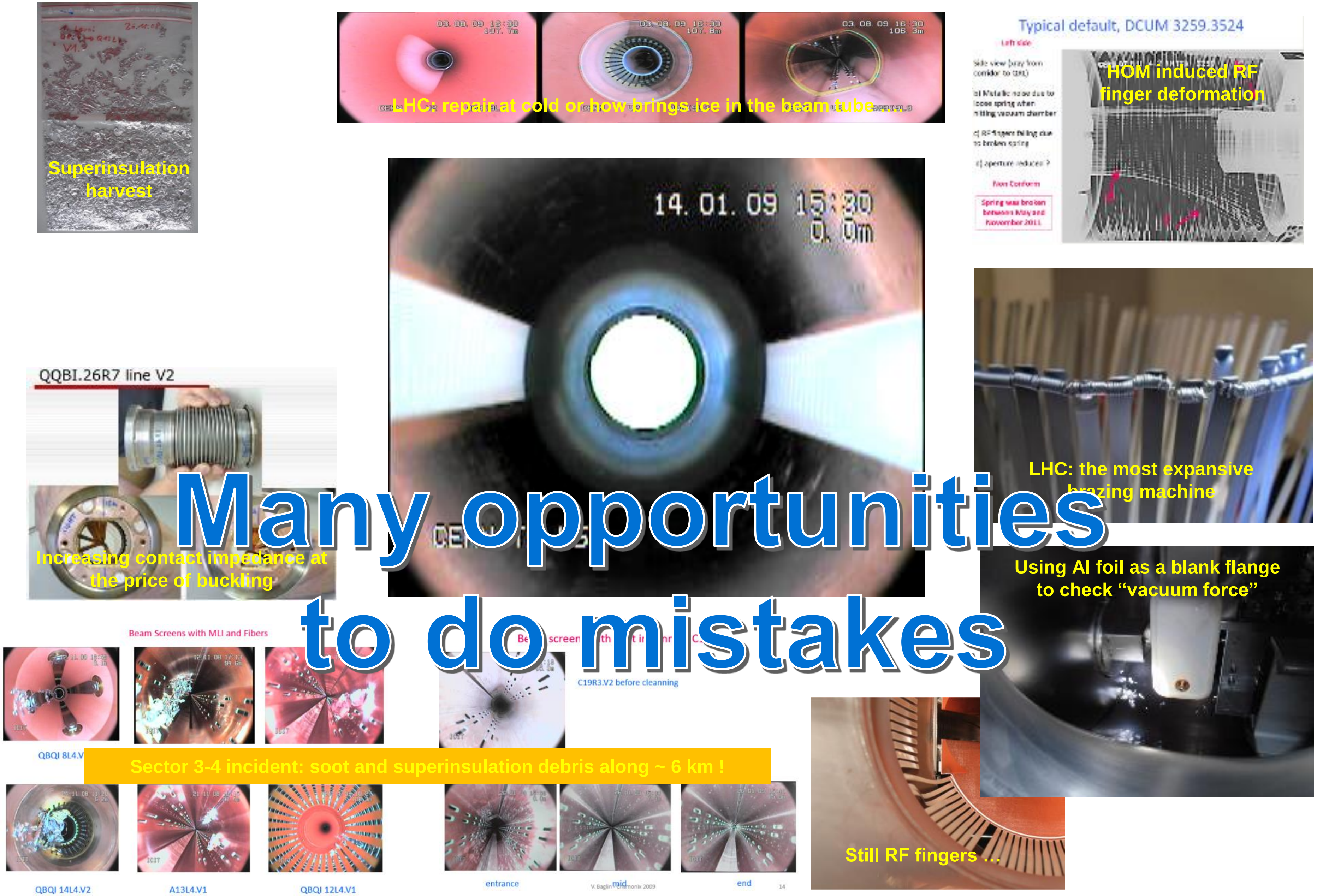
Vacuum Modules or what can you do with beam heating

- X-rays done in May showed a conform module, in November the module was broken
- The RF bridge was destroyed by the beam !
- 8 out of a total of 20 in LHC were damaged i.e. 40 %



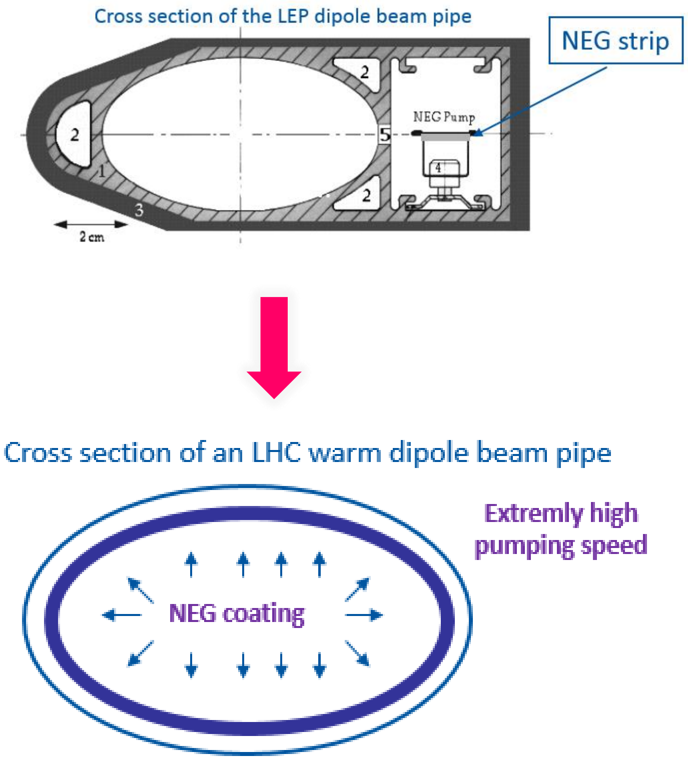


Many opportunities to do mistakes



New System: NEG film coating

- Invention of low activation temperature getter film
  => full pumping across the beam pipe
- Some vacuum chambers were constructed and getter coated …
- ~ 1 200 vacuum chambers produced



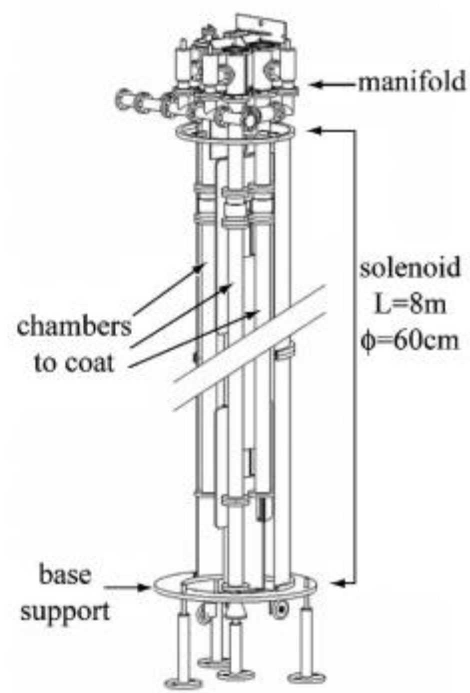
C. Benvenuti *et al.*

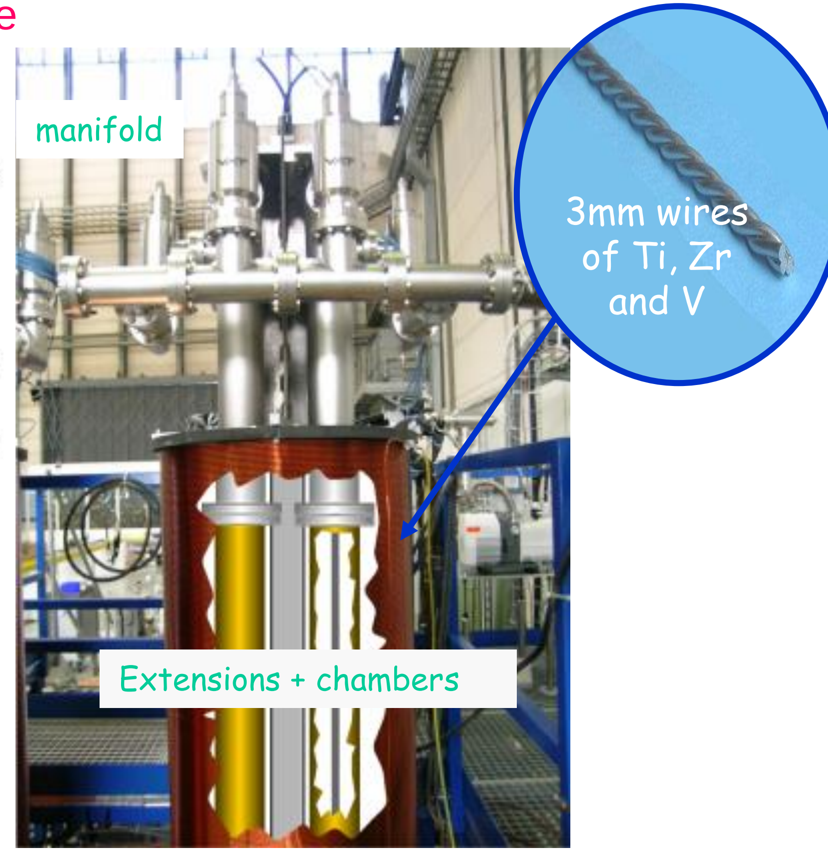
Courtesy R.Veness and P. Chiggiato

LSS Coating System

Complementary information

- 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
- Performances are valided by XPS on witness sample

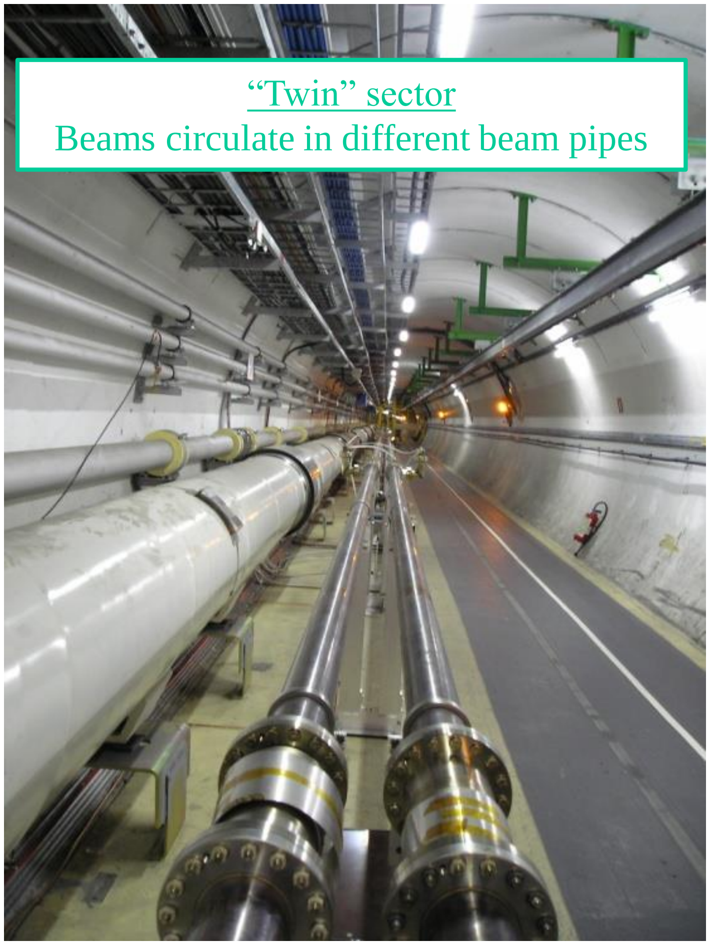


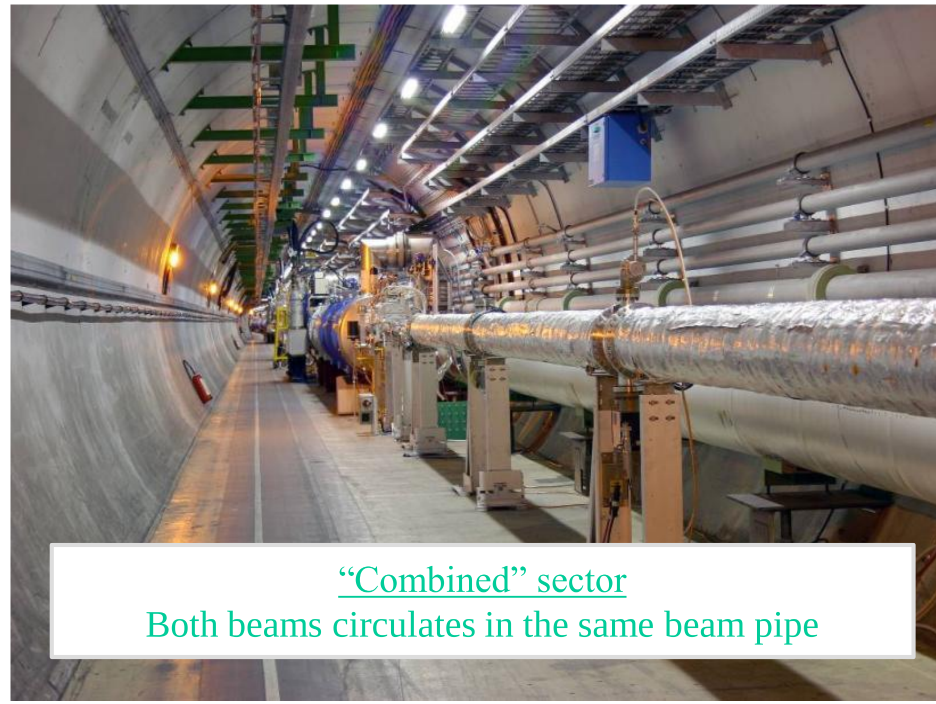


P. Costa Pinto, P. Chiggiato / Thin Solid Films 515 (2006) 382-388

Room Temperature Vacuum System

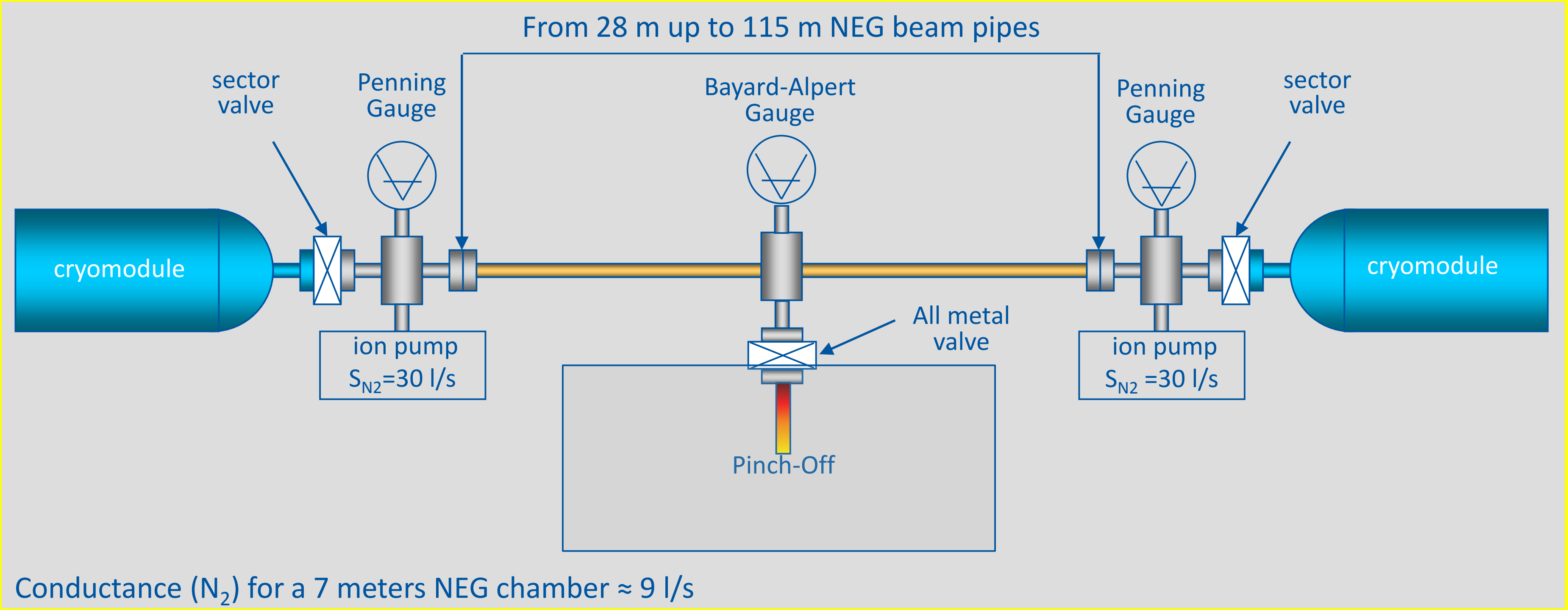
- ….. and installed inside the LHC tunnel
- to bring the separated beams from the arcs into a single beam pipe for the experiments (held at room temperature !)





Room Temperature Vacuum Sectors

- 185 vacuum sectors at RT
- From 1 m till 150 m long
- Contains : kickers, septum, collimators, masks, beam instrumentation
- Separation of baked from cryogenic unbaked vacuum sectors



Room Temperature Vacuum Sectors

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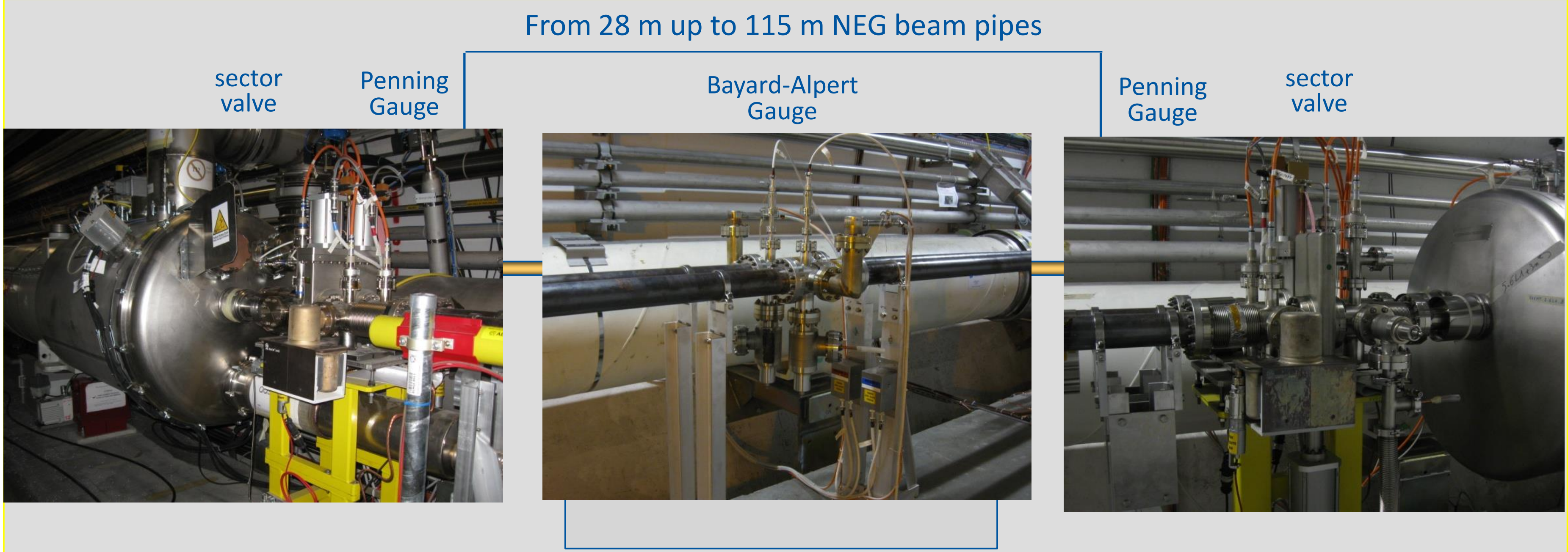


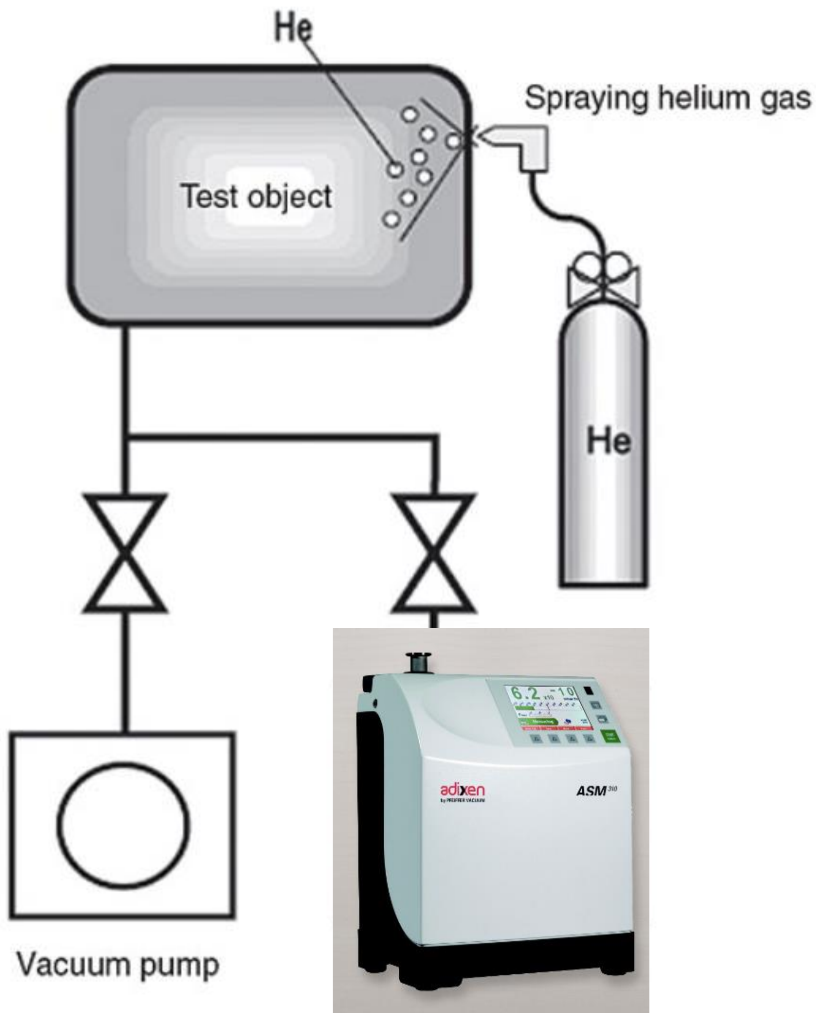
Conductance (N_2) for a 7 meters NEG chamber ≈ 9 l/s

Principle of leak detection

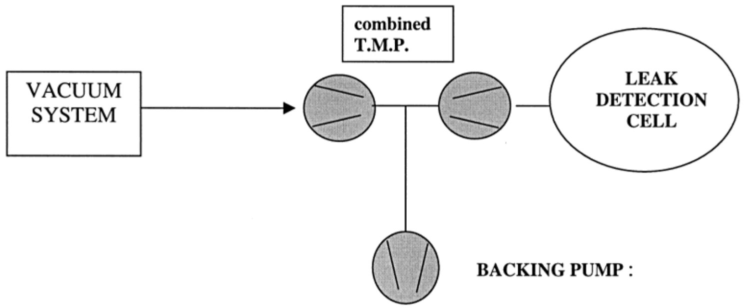
- Detection method : He is sprayed around the test piece and a helium leak detector (*i.e.* a RGA tune to He signal) is connected to the device under test.

Design in LHC:

leak rate < 10^{-9} mbar.l/s for a vacuum sector so the leak rate per component < 10^{-10} mbar.l/s



He leak detector



Counter flow method

Leak Detection

Complementary information

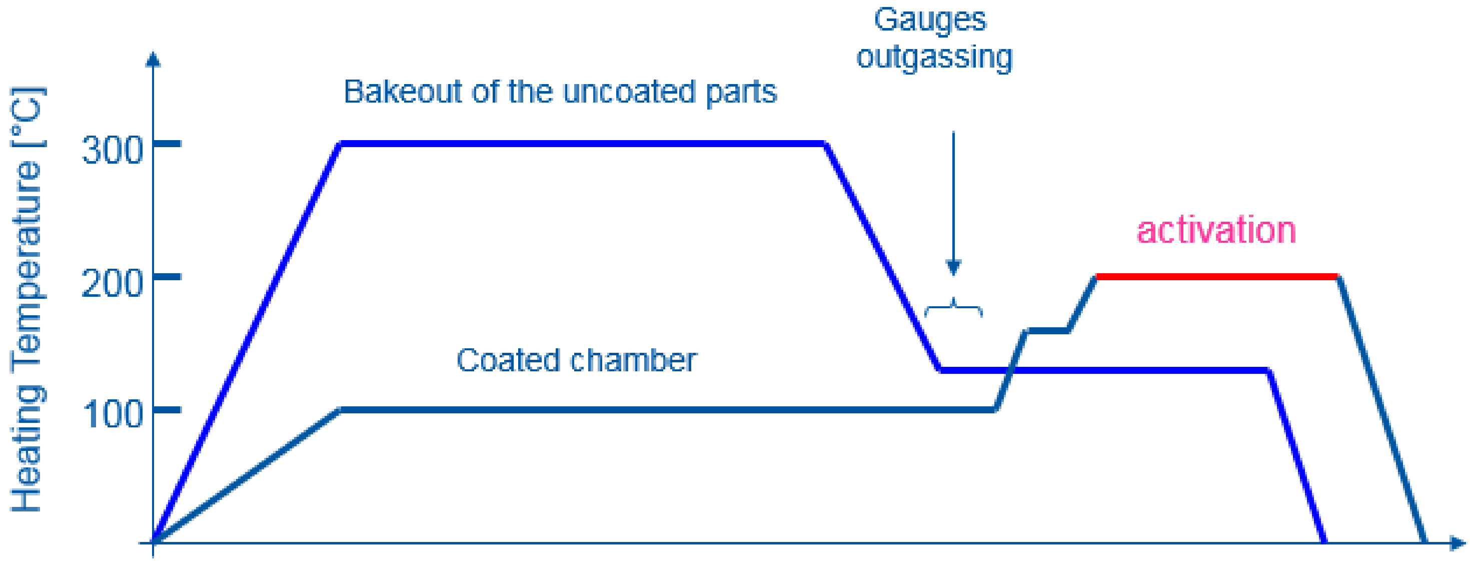
- The vacuum system of an accelerator must be leak tight !

- 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.
- As a result of virtual leaks, the leak detection sensitivity limit in the concerned vacuum sector is altered

- 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

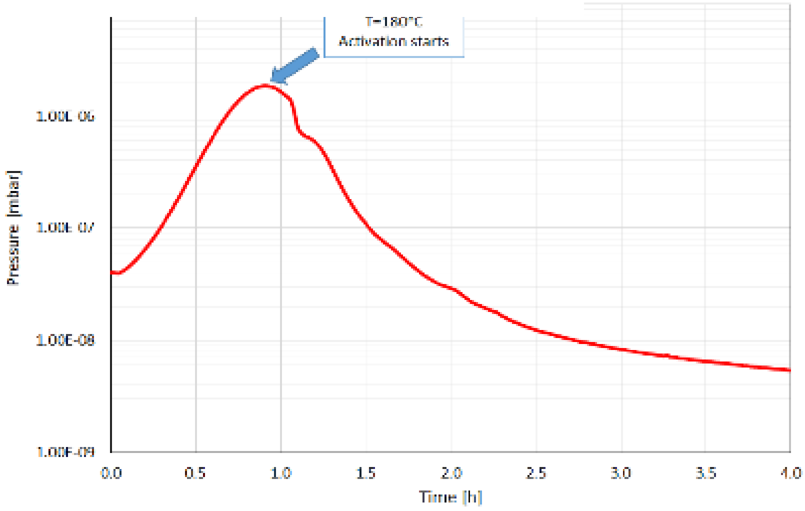
Commissioning of the NEG coated vacuum system



Courtesy G. Bregliozzi, P. Chiggiato

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

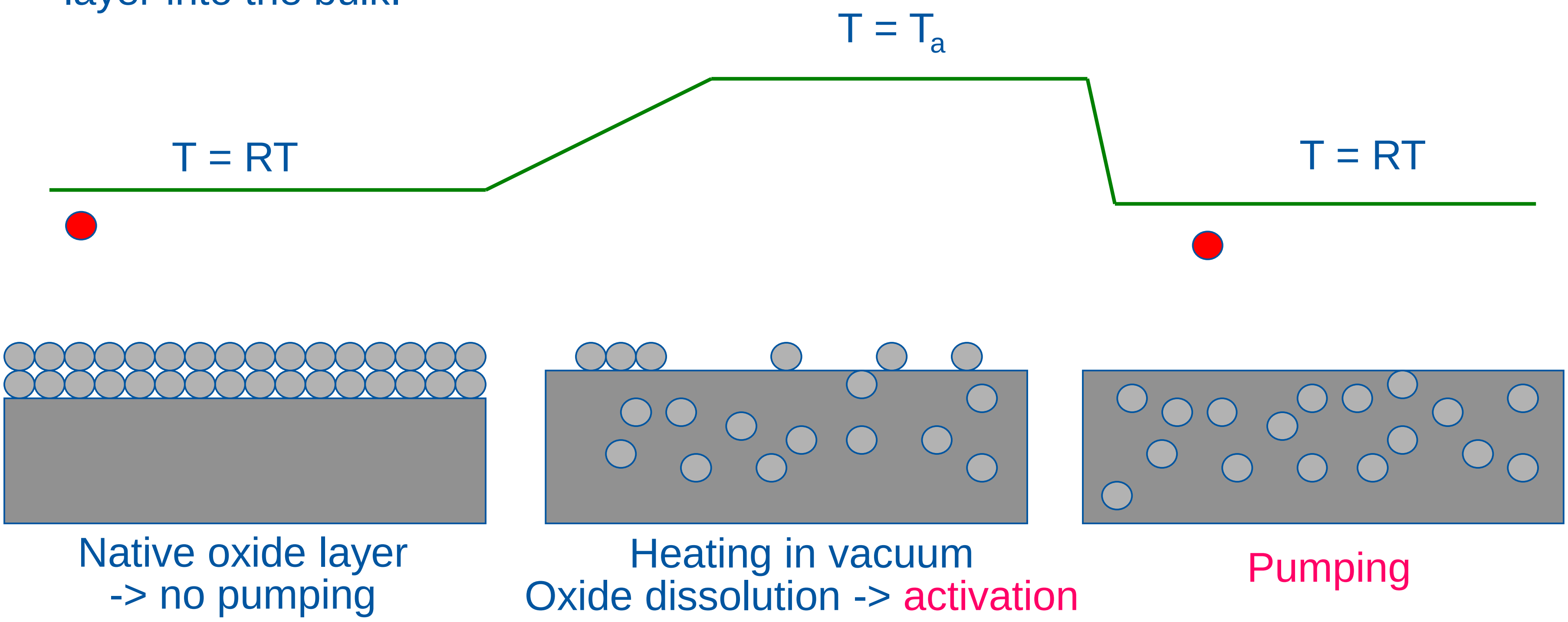
- Acceptance criteria rely on :
  - Temperature monitoring during activation
  - Aperture pumping speed measurement
  - Residual gas analysis
  - Leak rate below ~ 10^{-9} mbar.l/s



Courtesy G. Bregliozzi, V. Bencini

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.

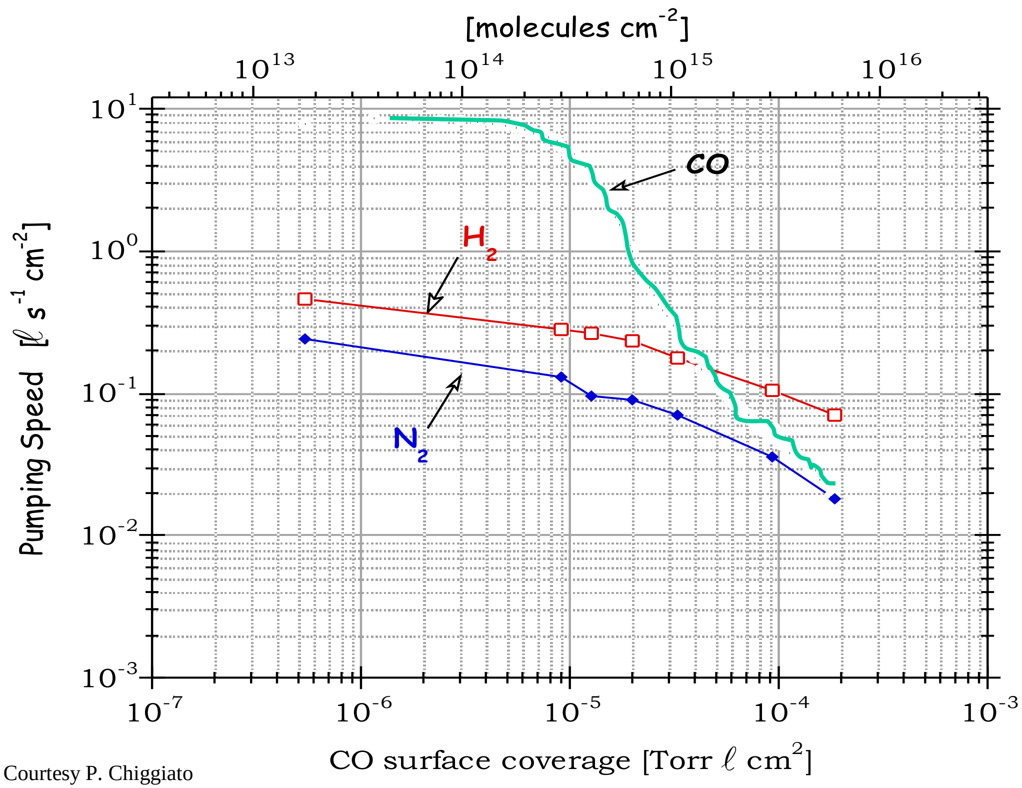


- NEGs pump most of the gas except rare gases and methane at room temperature

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

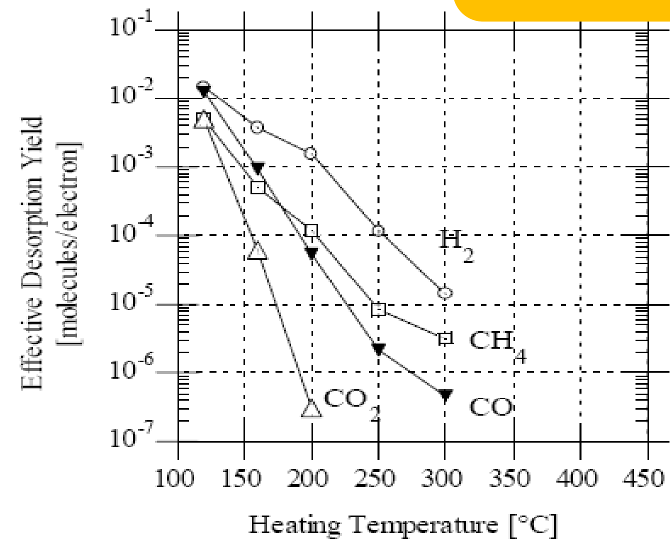
- But : limited capacity and fragile coating sensitive to pollutant (hydrocarbons, Fluor …)

TiZrV Vacuum Performances

Complementary information

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

ESD Y



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

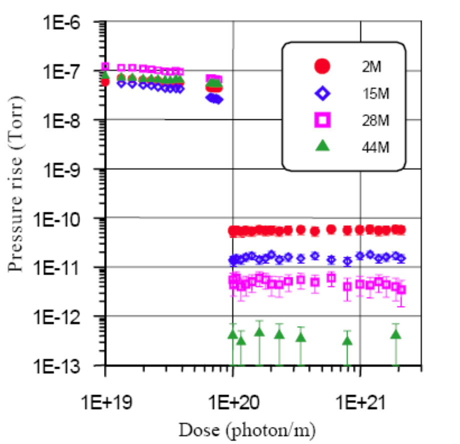


Figure 2: Pressure rise measured in the centre of the TiZrV coated test chamber before activation ($<1\cdot10^{20}$ photons/m) and after activation ($>1\cdot10^{20}$ photons/m).

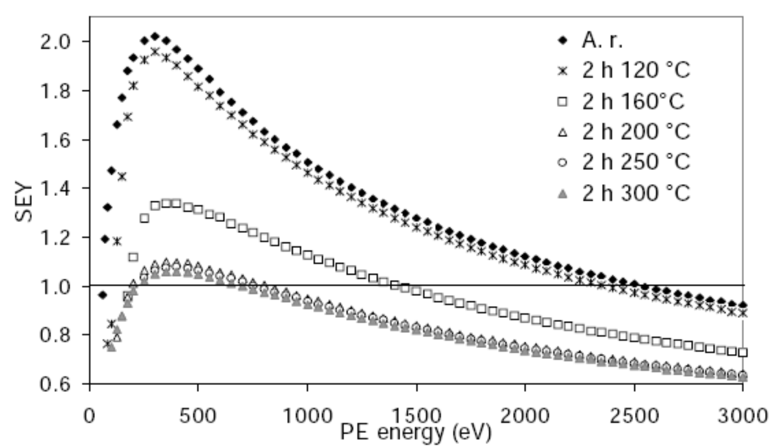
PSD Yields

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

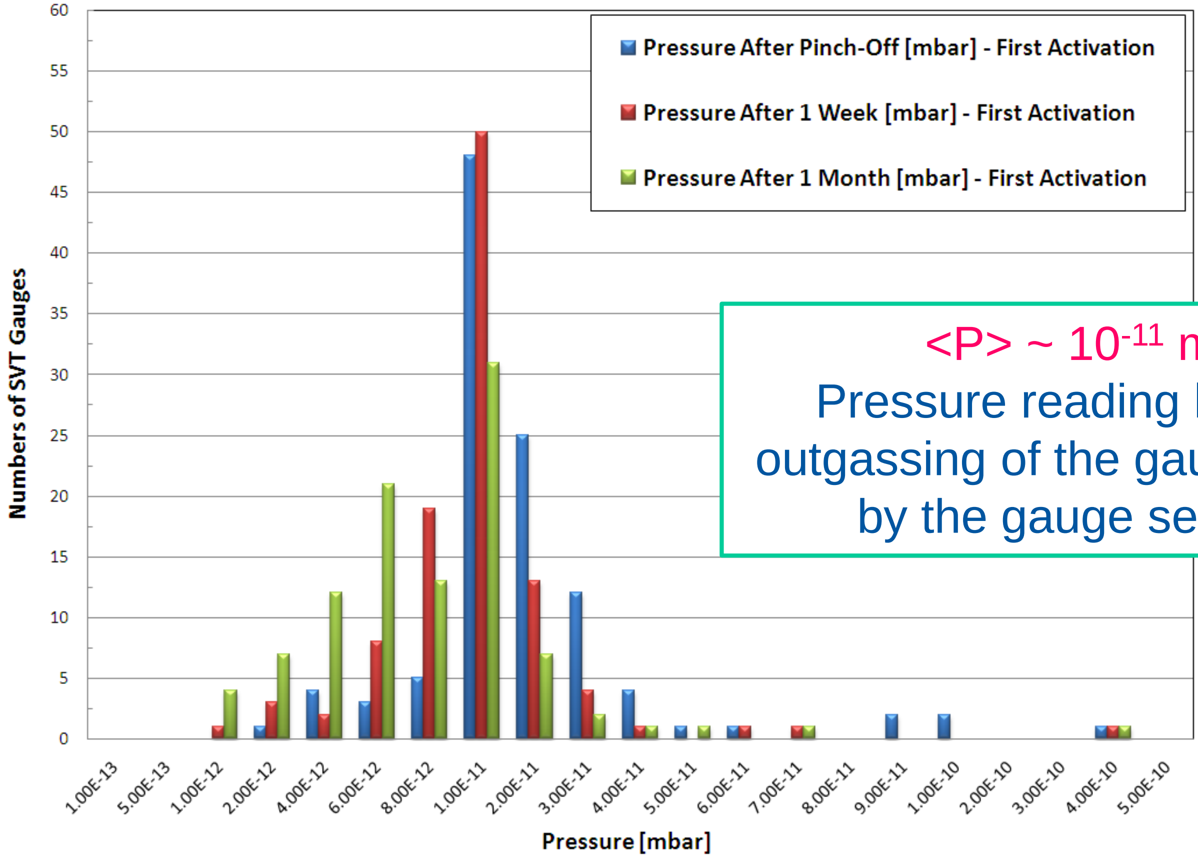
Secondary Electron Yield



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

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

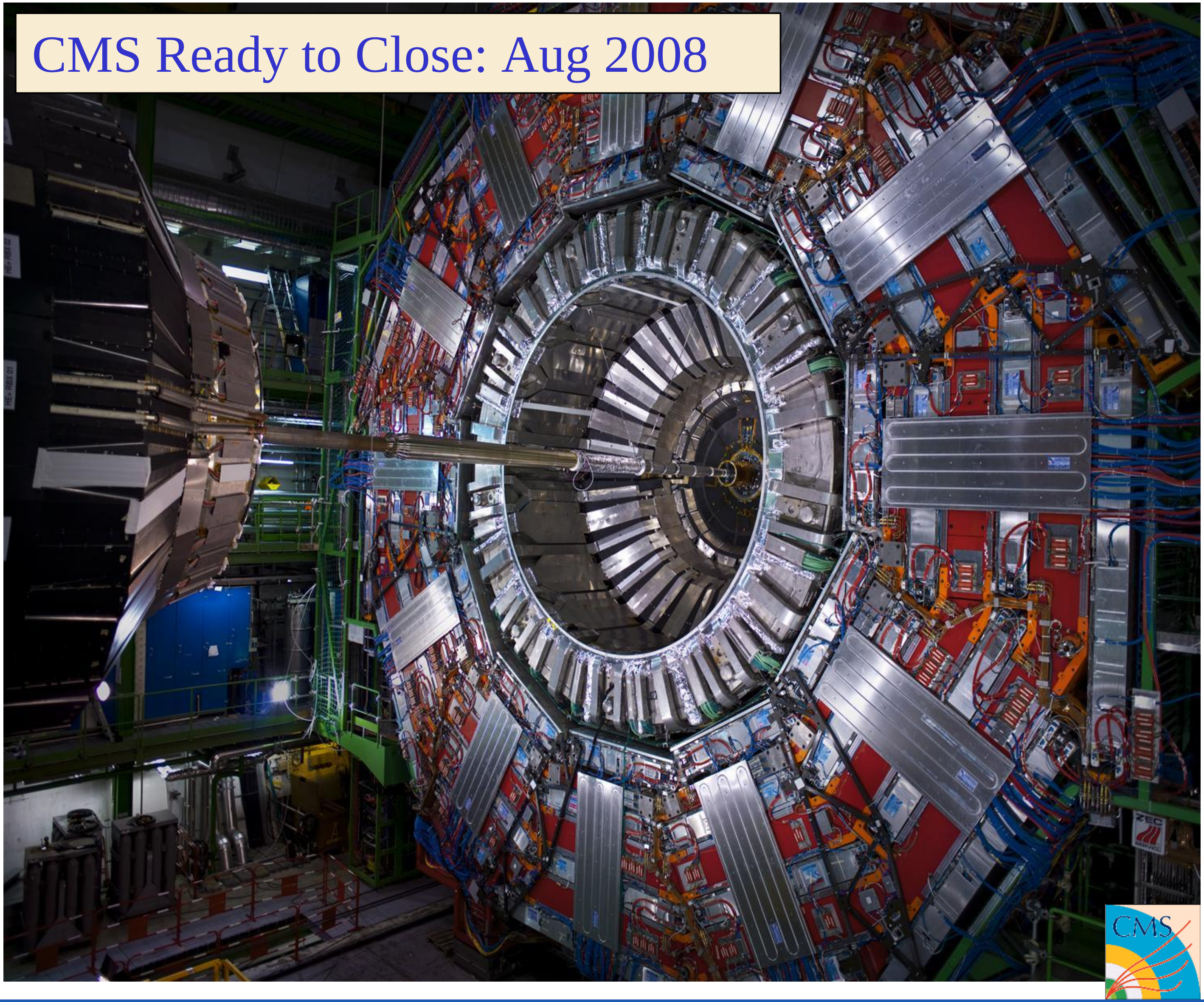
Ultimate Vacuum Pressure Distribution after NEG Activation of the LHC Room Temperature Vacuum Sectors



<P> ~ 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

And of Course … Through the LHC Experiments



Beam Pipe Installation in ATLAS Before Closure

LHC Experimental Areas

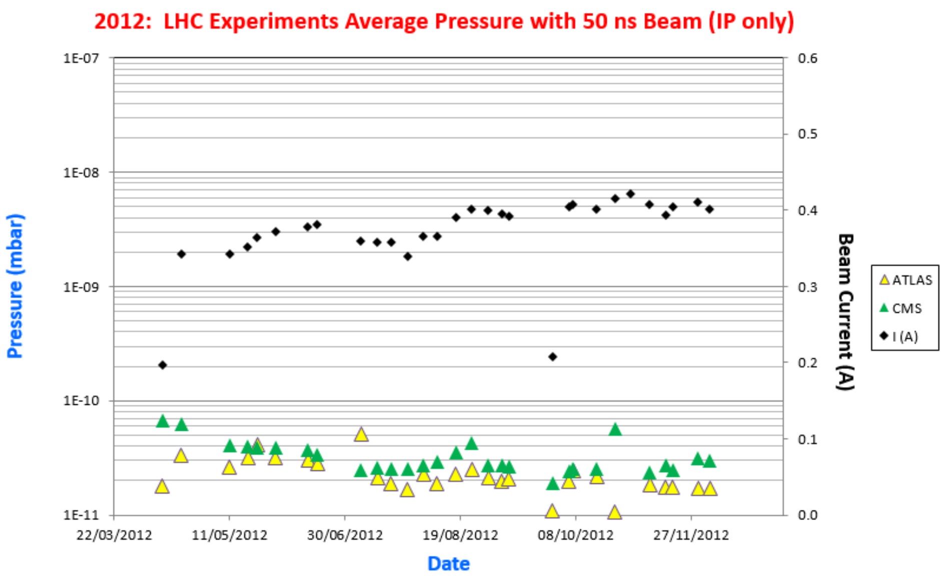
Complementary information

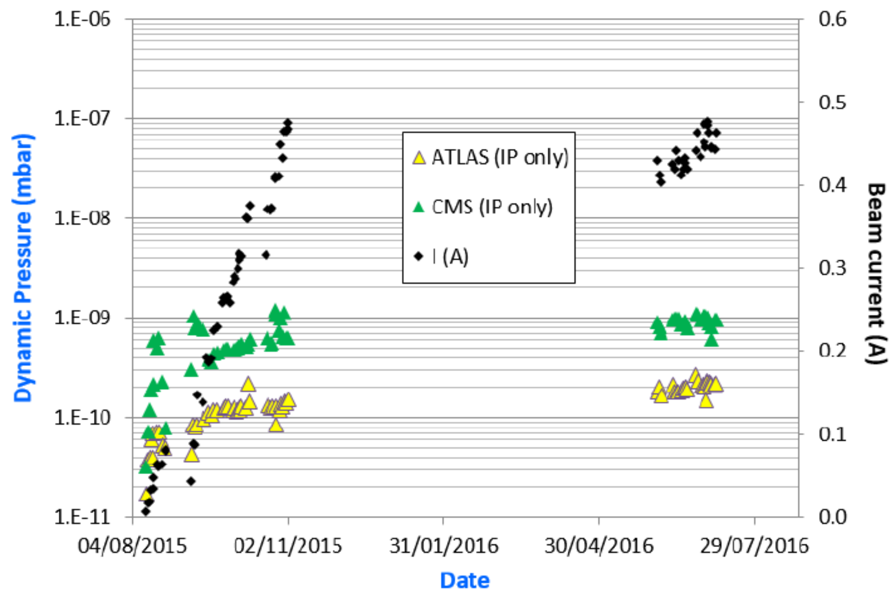
- NEG coated vacuum system
  => Large pumping speeds, low SEY and desorption yields

- <$P_{\text{LHC Experiments}}$> ~ 5 10^{-10} mbar => with 25 ns bunch spacing and 450 mA
  => No background issues: within specifications

- <$P_{\text{LHC Experiments}}$> with 50 ns beams
  ~ 5 10^{-10} mbar in 2011 at 375 mA
  ~ 3 10^{-11} mbar in 2012 at 400 mA

- <$P_{\text{LHC Experiments}}$> with 25 ns beams
  ~ 5 10^{-10} mbar in at 450 mA and 25 ns bunch spacing





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

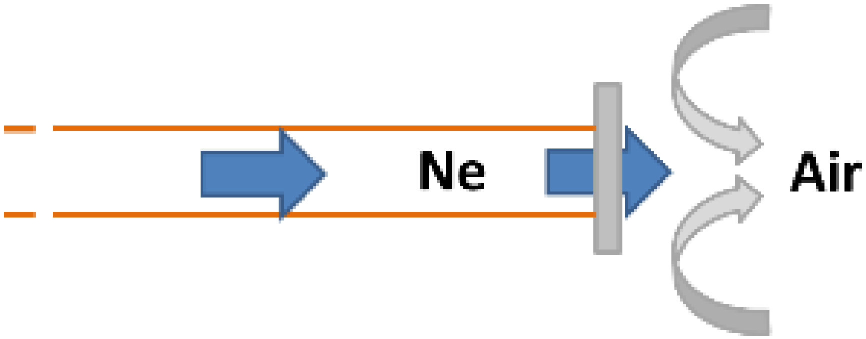
Standard Intervention: Bake out + Activation

Usually a **3 weeks** intervention (typical of any baked vacuum system) depending on the sector complexity:

- Venting the sector to air
- Mechanical intervention
- Pumping and leak detection
- Bakeout installation
- Bakeout and NEG activation
- Bakeout removal

Fast Repair: Ne venting

- 5 days intervention
- Ne flow to reduce air back streaming
- This method avoids the NEG saturation (remember Ne is an inert gas).

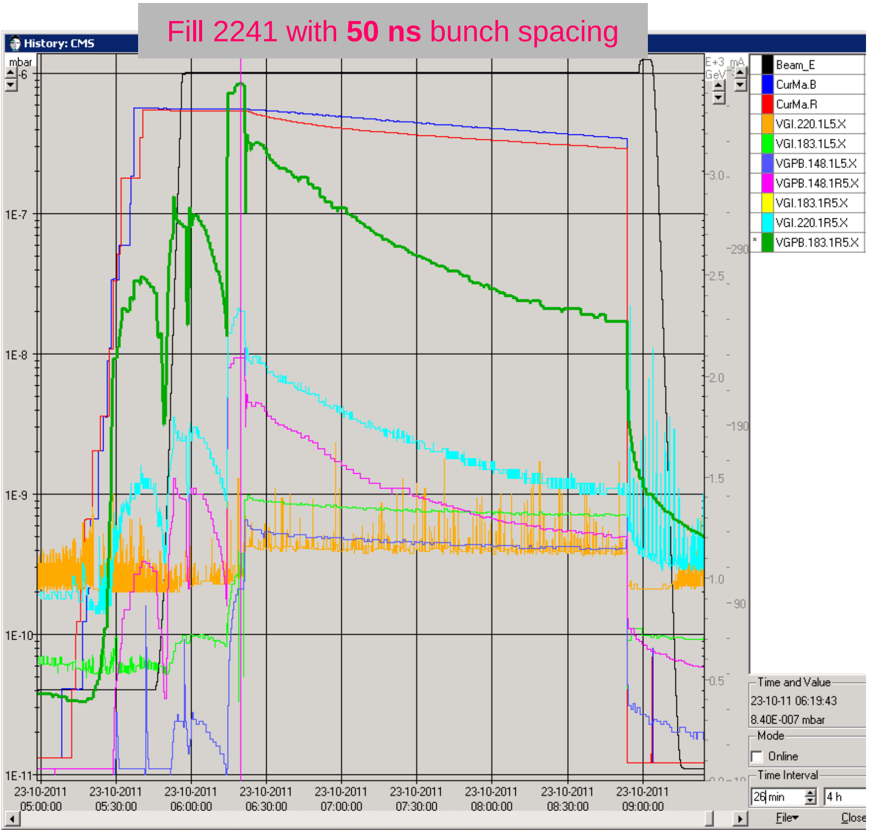


Neon trolley

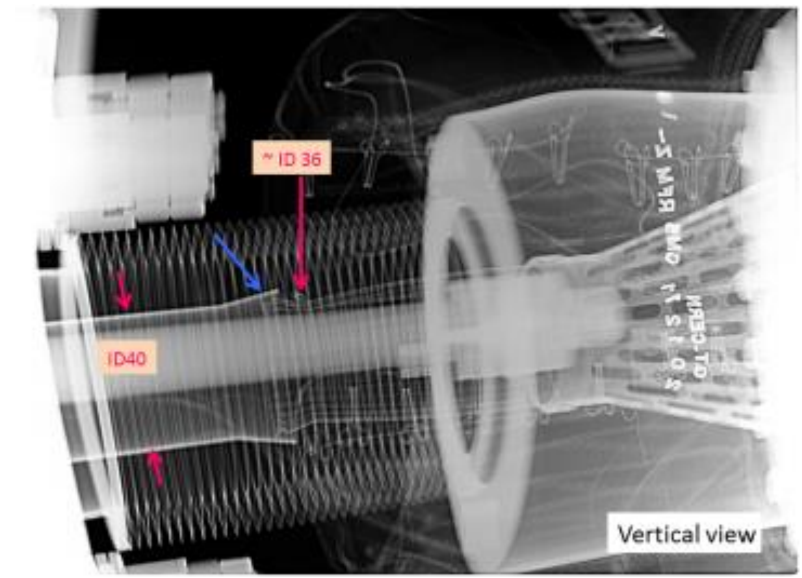
2011: Pressure spikes in right side of CMS

- In 2011, frequent pressure spikes, some up to 10^{-6} mbar, were observed at CMS, 18 m, right side.

- When the local pressure was above 10^{-8} mbar, CMS background was larger than 100 % thereby reducing the detector capability



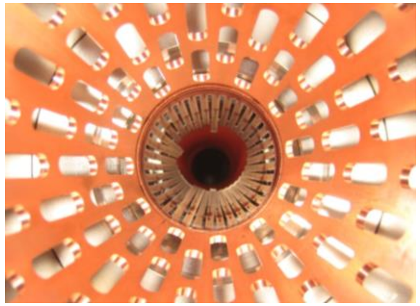
Typical Observation

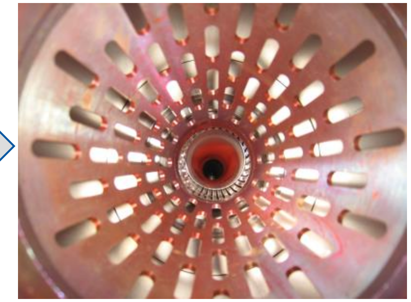


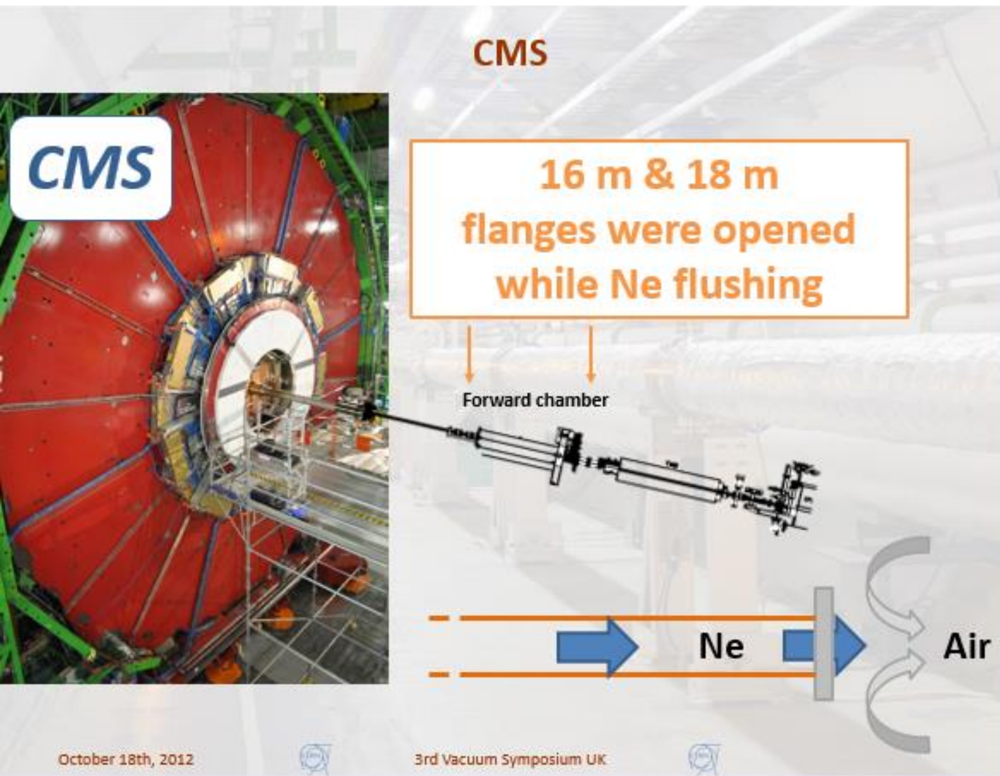
Courtesy J-M. Dalin EN-MME

Ne venting to save the 2012 CMS Run !

- Vacuum system performance recovered even following the dismounting of 2 m long vacuum chambers



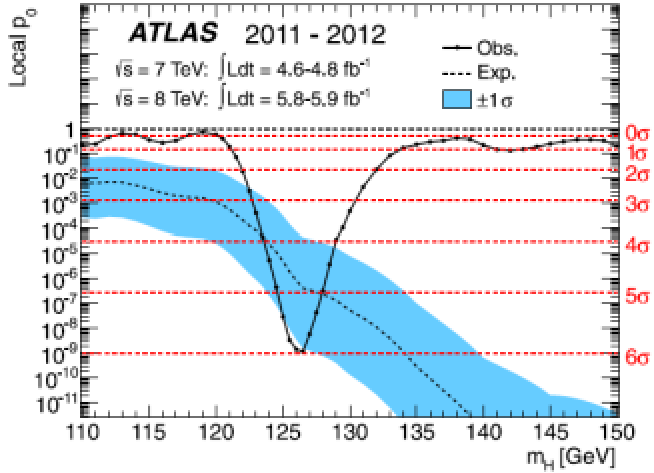


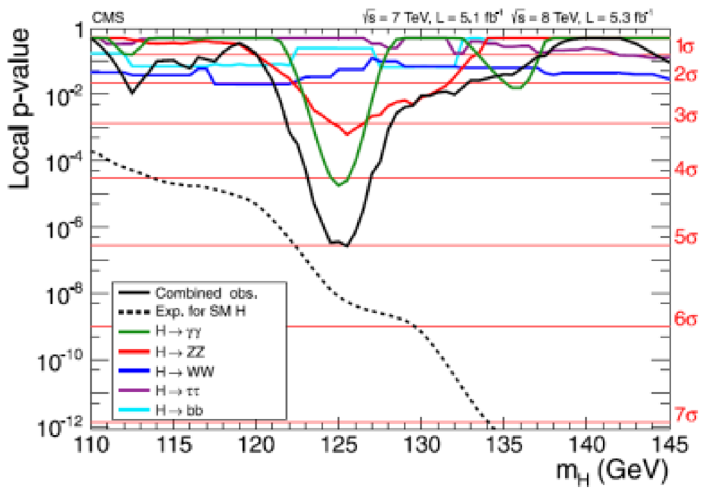


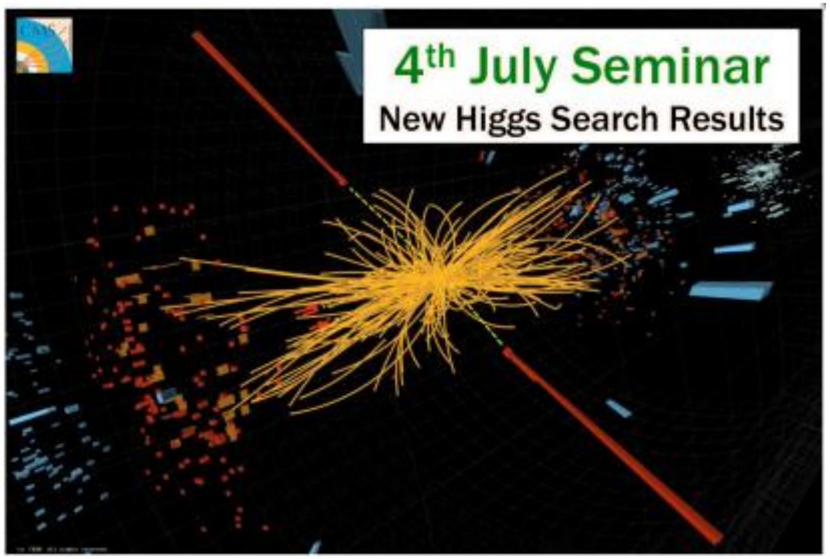
January 2012

4th July 2012: SM BEH Boson Discovery

ATLAS and CMS discovered a new boson in the mass region ~ 125-126 GeV/c^2



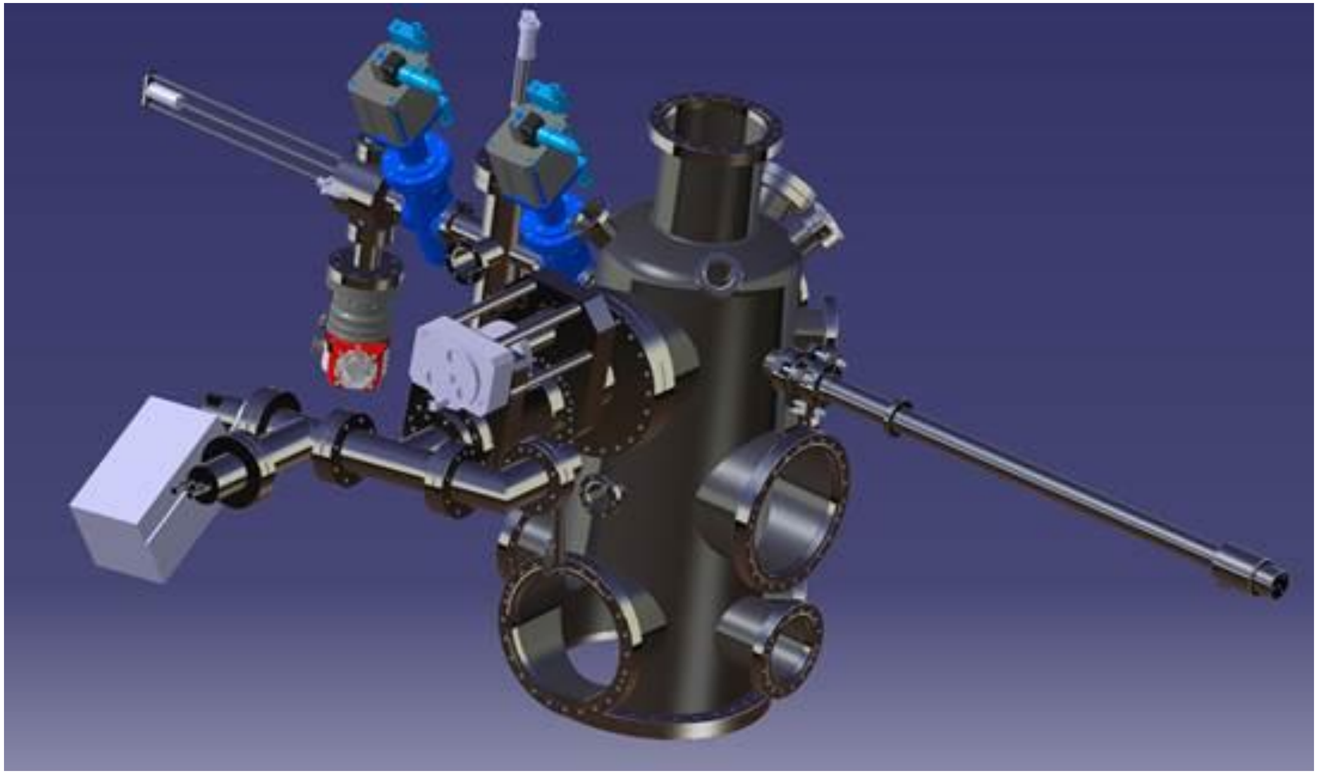




3. Some studies related to LHC, HL-LHC, FCC etc. Vacuum systems

Laboratory

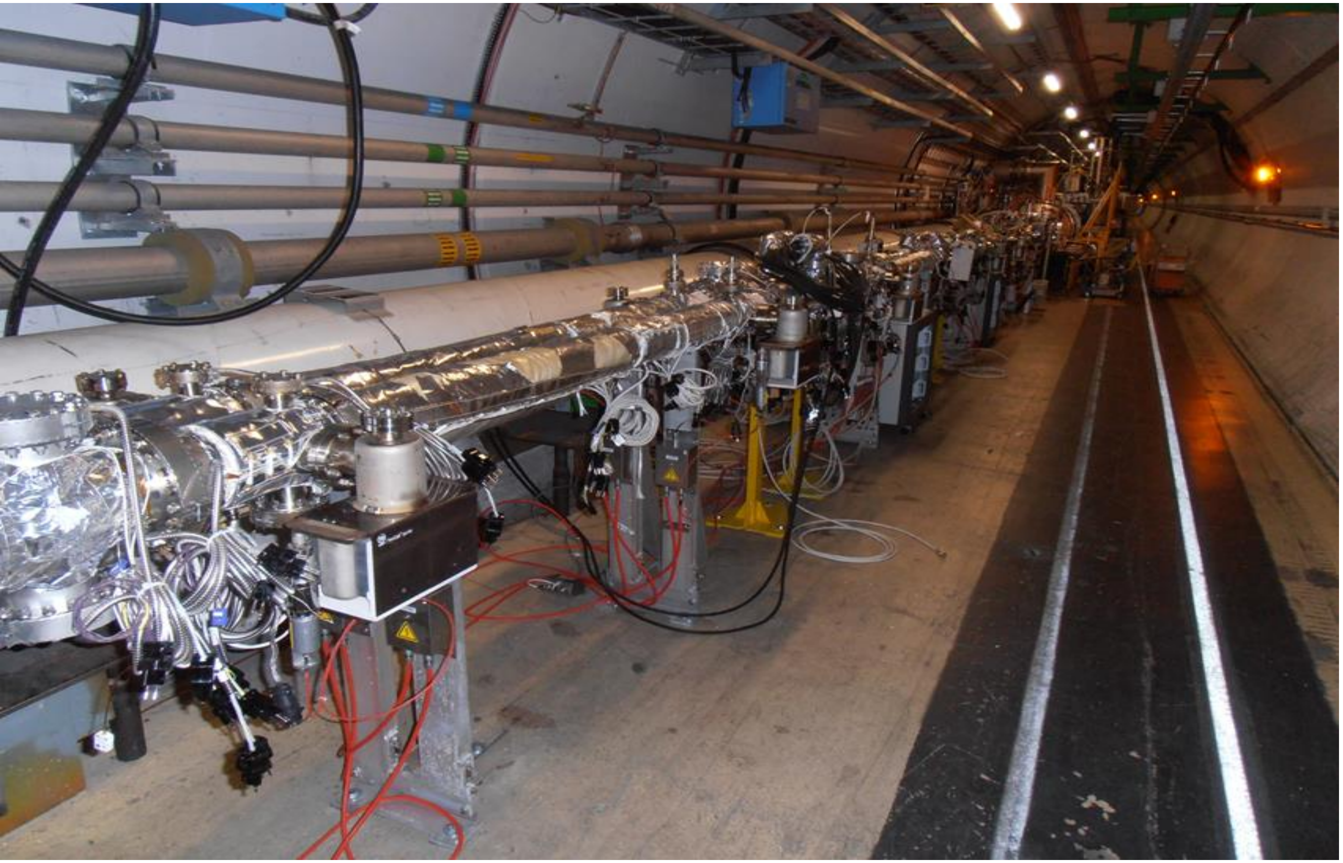
- Studies at cryogenic temperature down to 10 K
- Load lock system
- Isotherm, TDS, sticking coefficient, beam induced desorption from electrons, ions etc.



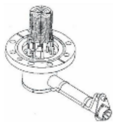
Vacuum pilot sector

- Total and partial pressure, photoelectron current, electron cloud flux pick-ups, calorimetry etc. for electron cloud characterisation

- Liners can be modified : Cu, NEG, a-C coating, Laser Engineered Samples etc.



VQM



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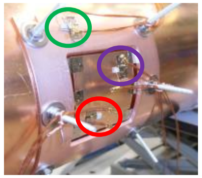
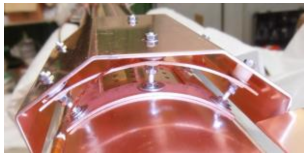


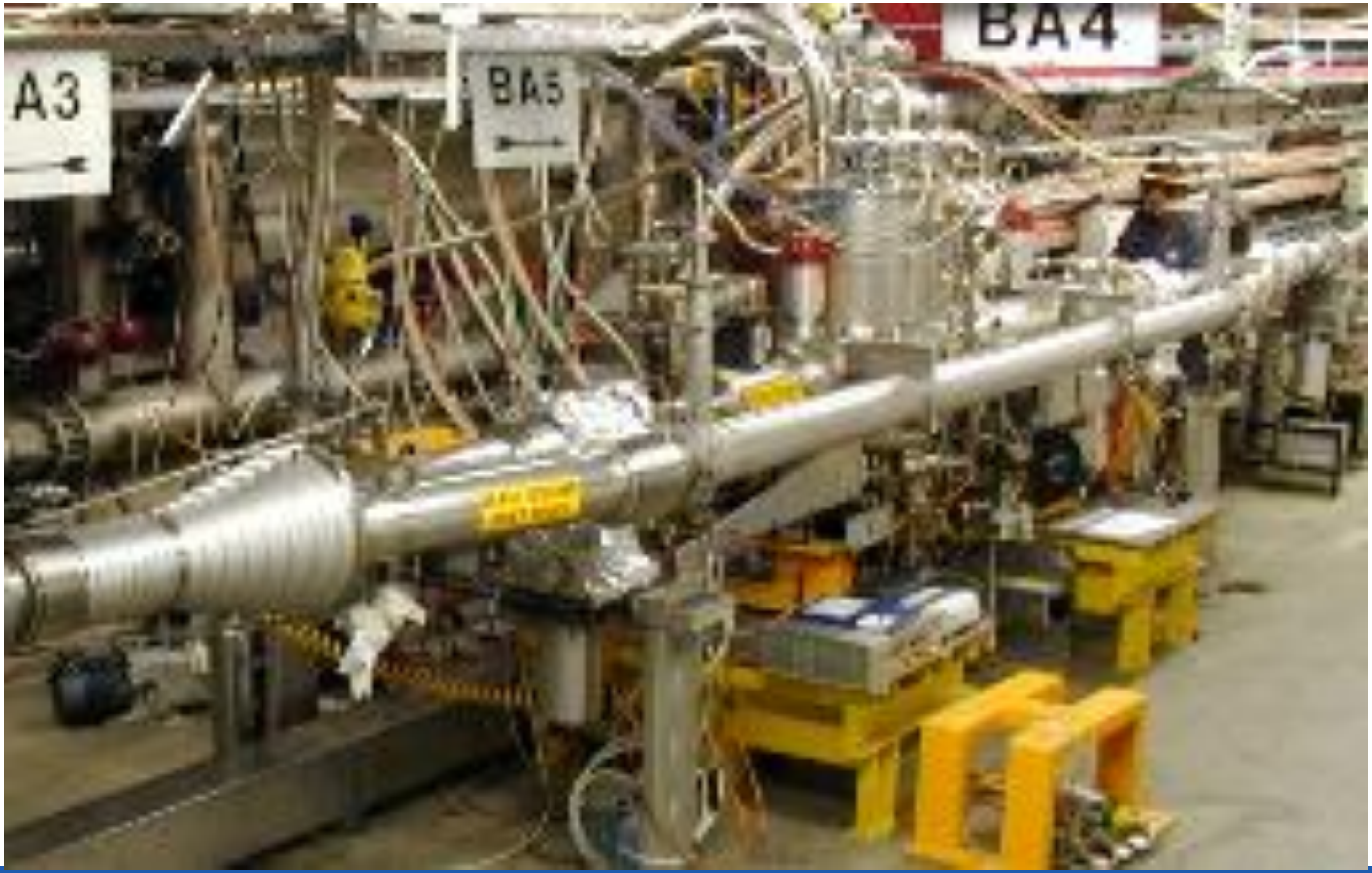
Heat load



Electron collection

COLDEX: A Bench to Study Electron Cloud

- A system to simulate a LHC type vacuum system: perforated beam screen with cold bore
- BS ~ 5 to 100 K, CB ~ 3 to 5 K
- Pressure measurement, gas composition, calorimetric measurement, current measurement



How LESS surfaces are behaving?

Lecture 5 summary

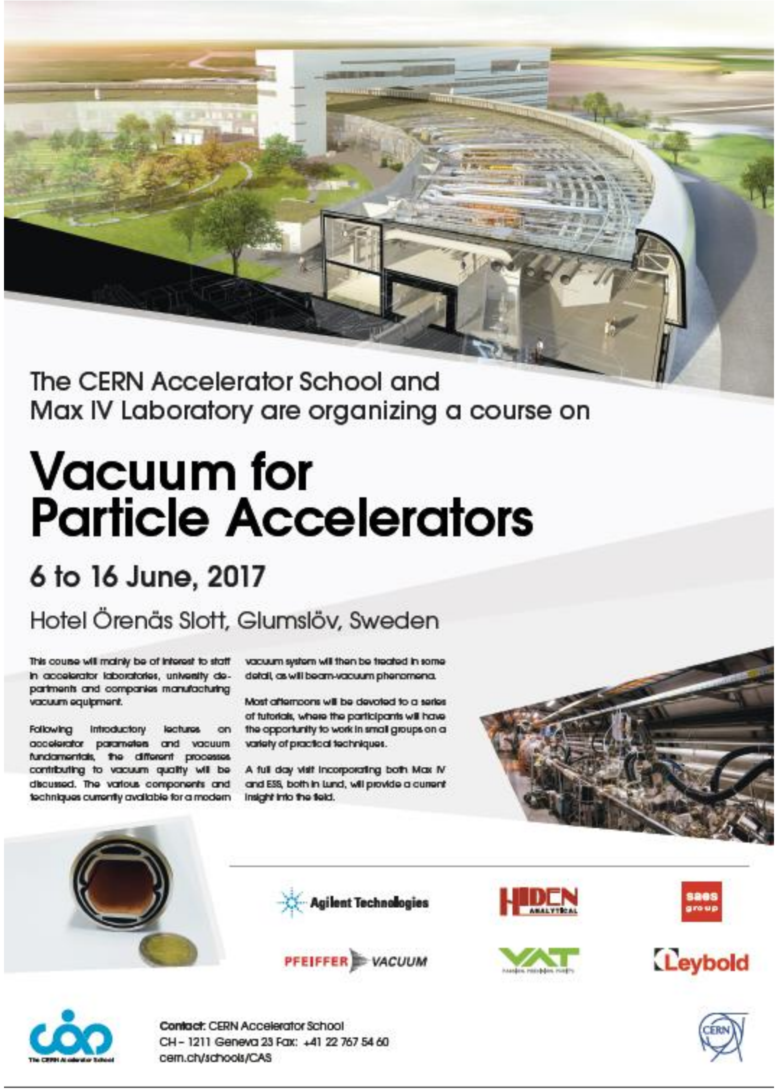
- The vacuum life time is an accelerator is driven by elastic & inelastic interactions
- Accelerator vacuum systems can be modeled by simple sets of equations
- Accurate pressure profiles can be computed
- Accelerators operate as designed but there is always room for mistakes!
- Smart solutions have to be developed for specific issues
- Laboratory studies are needed to properly design a machine

WE NEED YOU!

CAS School on Vacuum for Particle Accelerators

6 to 16 June 2017

Hotel Orenas Slott, Glumslov, Sweden



http://cas.web.cern.ch/cas/Lund2017/Lund-advert.html

Programme

- 30 lectures:
  - Overview of the field
- 5 tutorials:
  - Residual gas analysis
  - Leak detection, pumping
  - Computation
  - Mechanical eng.
  - Impedance for vac. sys.
- 2 Visits & 2 seminars:
  - MAX IV the 4th Generation SR source.
  - European Spallation Source (ESS).
- Industrial exhibition
- 1 Excursion

DRAFT PROGRAMME FOR VACUUM FOR PARTICLE ACCELERATORS
6-16 June, 2017, Lund, Sweden

Time	Tuesday 6 June	Wednesday 7 June	Thursday 8 June	Friday 9 June	Saturday 10 June	Sunday 11 June	Monday 12 June	Tuesday 13 June	Wednesday 14 June	Thursday 15 June	Friday 16 June
08:30 09:20	ARRIVAL DAY	Opening Talks	Materials & Properties IV: Outgassing P. Chiggiato	Getter Pumps E. Maccallini	Vacuum for Thermal Insulation of Cryogenic Equipment P. Cruikshank	EXCURSION	Surface Characterisation R. Valizadeh	Transport to Max IV Lab	Controlling Particles/Dust in Vacuum Systems L. Lilje	Vacuum Design Aspects H. Reich-Sprenger	DEPARTURE DAY
09:30 10:20		Introduction to Machine Parameters P. Tavares	Vacuum Gauges I K. Jousten	Ion Pump Technology for Particle Accelerators M. Audi	Vacuum Gauges II K. Jousten		Interactions between Beams and Vacuum System Walls R. Cimino	**Seminar** Max IV Laboratory M. Grabski	Beam Induced Radioactivity & Radiation Hardness F. Cerutti	Manufacturing & Assembly for Vacuum Technology S. Mathot	
		COFFEE	COFFEE	COFFEE	COFFEE		COFFEE	COFFEE	COFFEE	COFFEE	
11:00 11:50		Fundamentals of Vacuum Technology E. Al Dmour	Mechanical Vacuum Pumps H. Barfuss	Introduction to Cryogenics S. Claudet	Beam Induced Desorption O. Malyshev		Surface Cleaning & Finishing M. Taborelli	**Seminar** ESS Spallation Source Vacuum System M. Juni Ferreira	Radiation Damage and its Consequence M. Brugger	The Real Life of Operation V. Baglin	
12:00 13:00		Impedance & Instabilities R. Wanzenberg	Computation for Vacuum System of Accelerators R. Kersevan	Cryo-pumping V. Baglin	Beam-Gas Interaction M. Ferro Luzzi		Thin-Film Coating P. Costa Pinto	Lunch	Control & Diagnostic P. Gomes	Challenges for Vacuum Technology of Future Accelerators J. Jimenez	
		LUNCH	LUNCH	LUNCH	LUNCH		LUNCH		LUNCH	LUNCH	
14:30 15:20		Materials & Properties I: Introduction S. Sgobba	Tutorial	Tutorial	Tutorial		Tutorial	Visit to M ax IV 15:00	Tutorial	Tutorial Work	
15:30 16:20		Materials & Properties II: Thermal & Electrical Characteristics S. Calatroni	Tutorial	Tutorial	Tutorial		Tutorial	15:00 Visit to ESS	Tutorial	Closeout	
		TEA	TEA	TEA	TEA		TEA		TEA	TEA	
17:00 17:50		Materials & Properties III: Mechanical Behaviour C. Garion	Tutorial Work	Tutorial Work	Tutorial Work		Tutorial Work		Tutorial Work	Closing Remarks	
19:30	Buffet	**Dinner**	**Dinner**	**Dinner**	**Dinner**	**Dinner**	**Dinner**	**Dinner**	**Dinner**	**Special Dinner**	

Some References

- Cern Accelerator School, Vacuum technology, CERN 99-05
- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03
- Vacuum system design, A.G. Mathewson, CERN-94-01
- 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.
- Vacuum Technology, A. Roth. Elsevier Science
- Handbook of accelerator physics and engineering, World Scientific, 2013

Some Journals Related to Vacuum Technolgy

- Journal of vacuum science and technology
- Vacuum

Thank you for your attention !!!

CERN