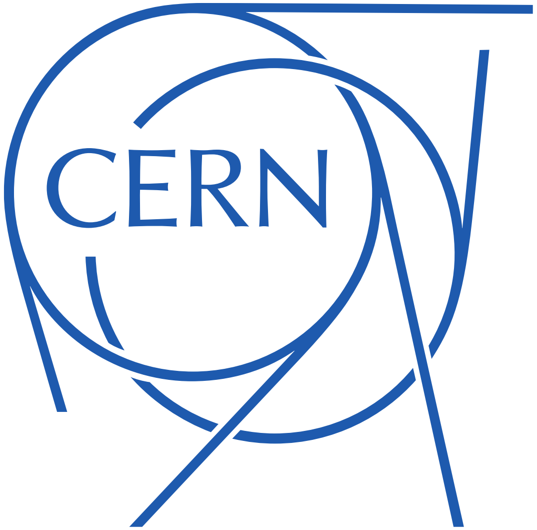

CERN

Vacuum Systems
Slot 8

V. Baglin

CERN TE-VSC, Geneva

Joint Universities Accelerator School

https://indico.cern.ch/event/1470062/timetable/?view=standard#day-2025-02-17

Outline

1. Beam-gas interactions
2. Pressure profiles
3. The LHC case
4. Summary

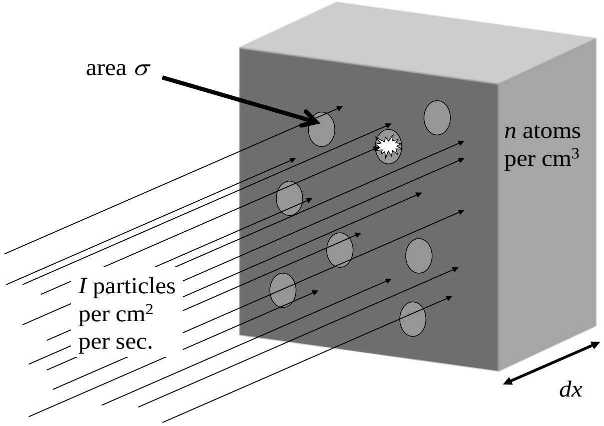
1. Beam-gas interactions

Cross section

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

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

$$\boxed{dI = -I\,\sigma\,n\,dx}$$



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

- The unit is **1 barn = 10^{-28} m^2 = 10^{-24} cm^2**

- 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:

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

A real barn…

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

Life time

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

$$\boxed{I = I_o\, e^{-\frac{t}{\tau}}}$$

with life time $\boldsymbol{\tau = \frac{1}{n\,\sigma\,v}}$

- 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 beam interacts differently with the different gas species of density n_i according to their respective cross sections σ_i: (NOTA BENE: $\boldsymbol{\tau_i}$ is in SECONDS)

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

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

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

- Thus:

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

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 *e.g.* the particle loss due to the collisions etc.

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:

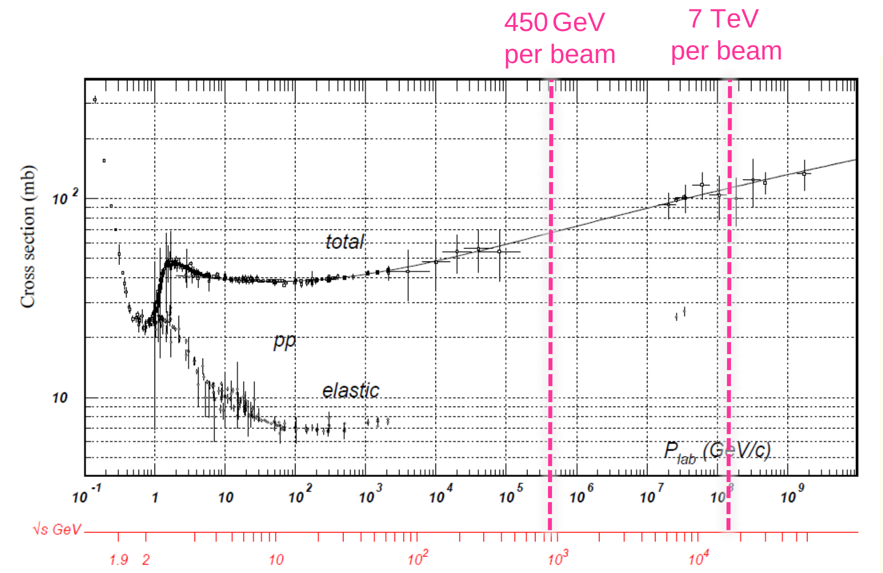
7 TeV values

Gas	Z	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

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

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

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 only one gas specie.

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

Application: LHC vacuum life time

- In the LHC, the vacuum life time is defined by nuclear scattering set to be >100 h:
  - The corresponding H_2 gas density is:

$$n_{H2} = \frac{1}{\tau\ \sigma_{H2}\ c} = \frac{1}{3.6\ 10^5 \times 95\ 10^{-31} \times 3\ 10^8} = \ 10^{15}\ H_2 \cdot m^{-3}$$

  - *i.e.* 4 10^{-8} mbar

- Assuming the residual gas composition is dominated by CO, this would correspond to:

$$n_{CO} = \frac{n_{H2}}{\sigma_{rel,i}} = \frac{10^{15}}{8.99} = \ 10^{14}\ CO \cdot m^{-3}$$

  - *i.e.* 4 10^{-9} mbar

Exercise: Assume a gas mixture of H_2 and CO, with 2 10^{14} $H_2 \cdot m^{-3}$ and 5 10^{13} $CO \cdot m^{-3}$ *i.e.* a total pressure of 10^{-8} mbar, what would be the vacuum life time?

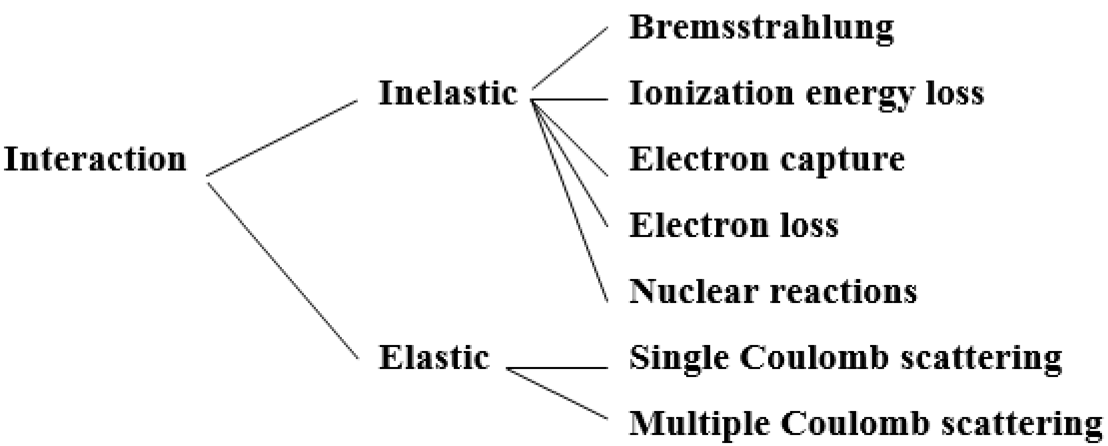
- compute the **equivalent H2 gas density**:

$$n_{H2\ eq} = n_{H2} + n_{CO}\ \sigma_{rel,co} = 2\ 10^{14} + 8.99\ \times 5\ 10^{13} = 6.4\ 10^{14}$$

- compute the vacuum lifetime in hours:

$$\tau_i = \frac{1}{n_i\ \sigma_i\ v} \qquad \tau = \frac{1}{3600}\frac{1}{n_{H2eq}\ \sigma_{H2}\ c} = \frac{1}{3600}\frac{1}{6.4\ 10^{14} \cdot 95\ 10^{-31} \cdot 3\ 10^8} = 150\ h$$

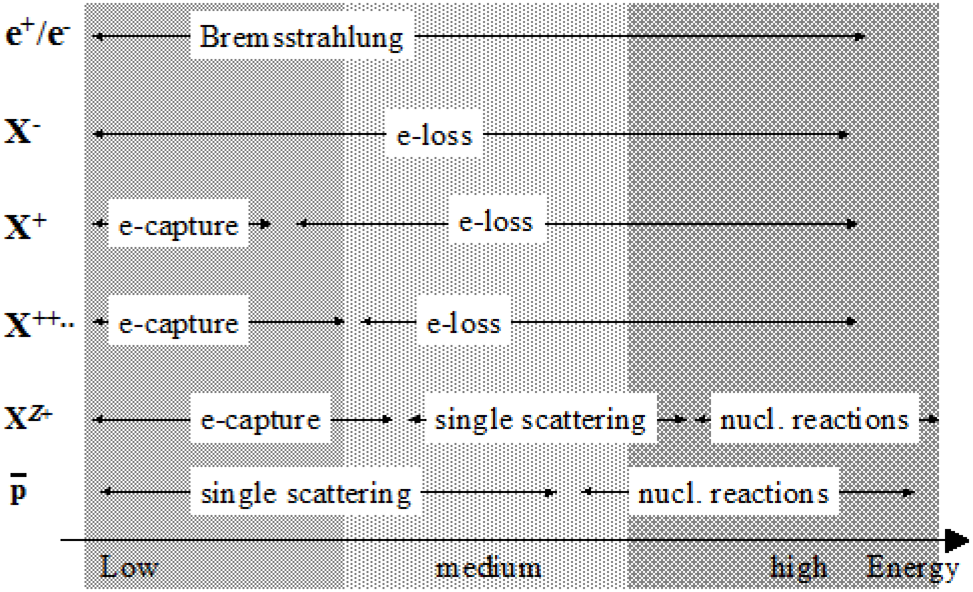
Beam-gas interactions



Interaction

Inelastic
- Bremsstrahlung
- Ionization energy loss
- Electron capture
- Electron loss
- Nuclear reactions

Elastic
- Single Coulomb scattering
- Multiple Coulomb scattering



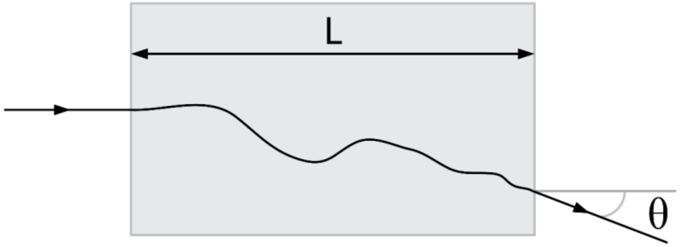
Beam residual gas interactions, SP Møller, CAS, CERN 99-05

Proton storage ring

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

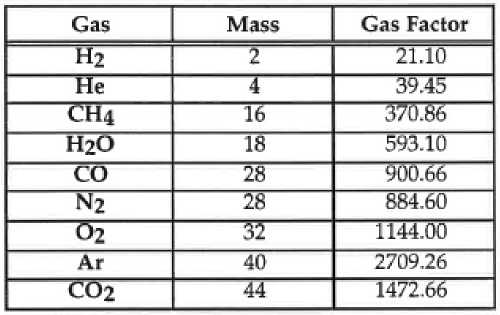
- Multiple Coulomb scattering is due to a series of small angle scattering events which lead to the gradual blow up of the beam emittance, ε and thus its transverse dimension σ.

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



- 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:

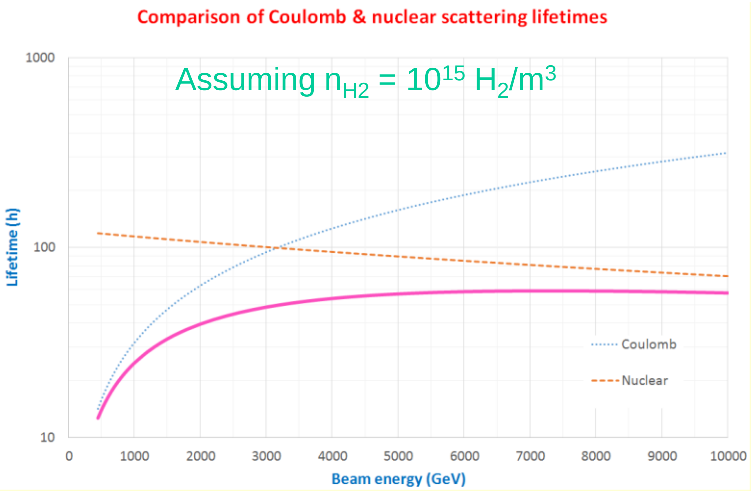
G the gas factor,

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)



Assuming $n_{H2} = 10^{15}\ H_2/m^3$

- The nuclear cross section dominates above 3 TeV

Electron storage ring

- The beam life time depends on 4 scattering cross sections

$$\boxed{\sigma = \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4} \qquad \tau = \frac{1}{\mathrm{n}\,\sigma\,\mathrm{c}}$$

- Nuclear elastic scattering:

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

- Nuclear inelastic scattering:

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

With:
σi cross section in m^2
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)

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

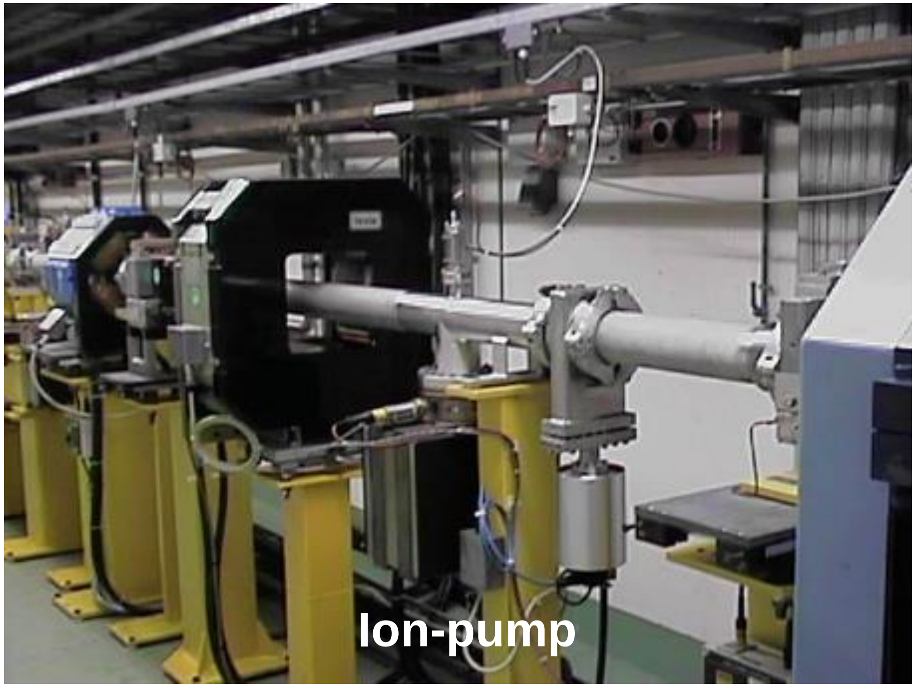
$$\sigma_3 = 2.55\ 10^{-32}\,\frac{Z}{\mathrm{X}_{RF}\,E}$$

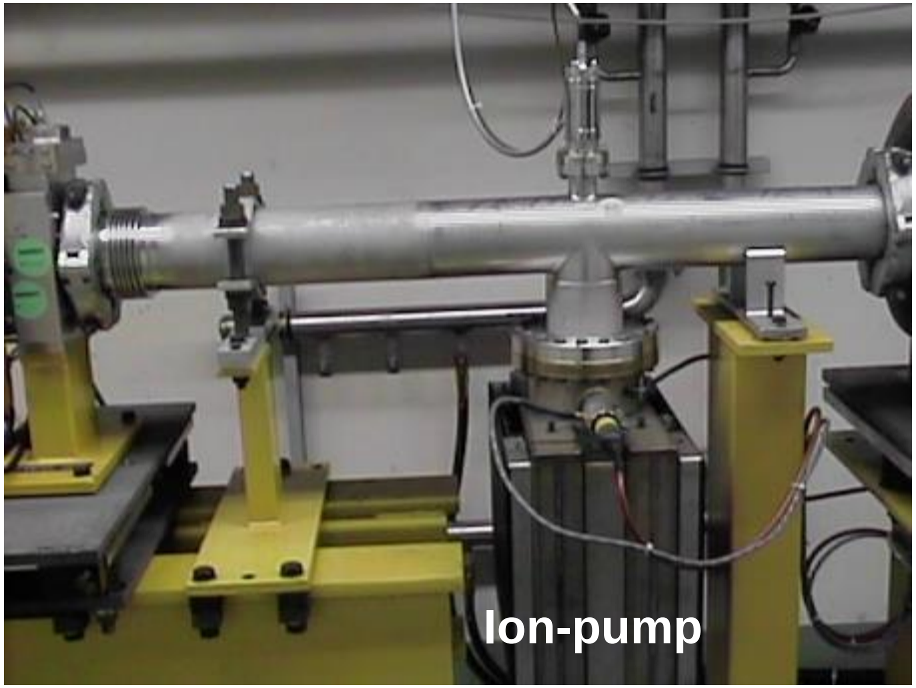
- Inelastic scattering from electrons surrounding the nucleus of the residual gas:

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

2. Pressure profiles

A lumped pumping system





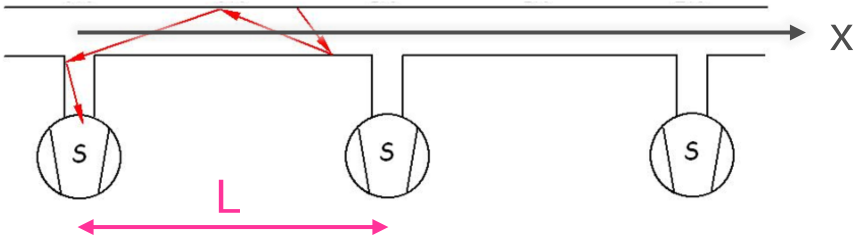
CERN Electron Positron Accumulator, 1998

Gas flow in an elemental chamber

- We then consider a chamber of uniform cross-section, of **specific surface A [cm^2/m]**, **specific outgassing rate of q [mbar·l/s/cm^2]**, with equal pumps (**pumping speed S [l/s]** each) evenly **spaced at a distance L in [m]**. **Q is the gas throughput in [mbar·l/s]**. The specific conductance is ***c*** **[l·m/s]**; **AqL = Q_{tot} [mbar·l/s]**

- The following equations can be written:

$$\begin{cases} Q(x) = -c\,\dfrac{dP(x)}{dx} \\ \dfrac{dQ(x)}{dx} = Aq \end{cases}$$



- Differentiating the first one and substituting in the second one we obtain:

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

- Which solution is a parabolic function (second order polynomial)
- The boundary conditions allow us to determine the two integration constants:

$$\begin{cases} \left[\dfrac{dP}{dx}\right]_{x=L/2} = 0 \\ P(0) = P(L) = \dfrac{Aq\,L}{S} \end{cases}$$

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

Simple machine

- So:

$$\boxed{P(x) = \frac{Aq}{2c}(Lx - x^2) + \frac{AqL}{S}}$$

- The maximum pressure is given by:

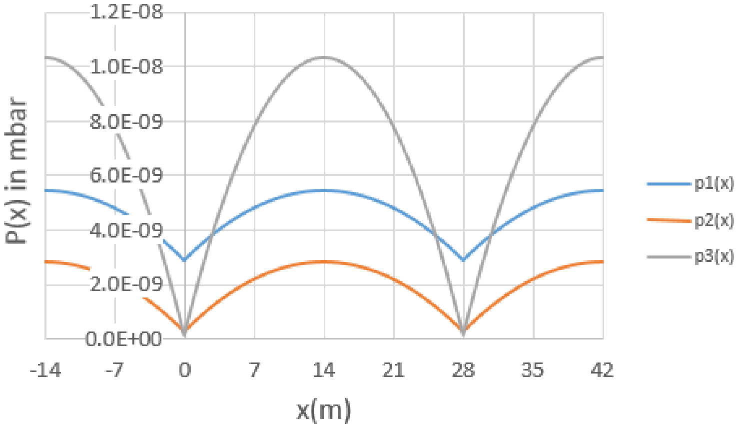
$$P_{max} = AqL\left(\frac{1}{S} + \frac{1}{8c}\right)$$

- The average pressure is given by:

$$P_{av} = \frac{1}{2L}\int_0^{2L} P(x)dx = AqL\left[\frac{1}{S} + \frac{L}{12c}\right]$$

The average pressure is dominated by the conductance

	P1(x)	P2(x)	P(3)
D (cm)	**10**	**10**	**5**
c (l s^{-1} m)	121	121	15.1
S (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}**

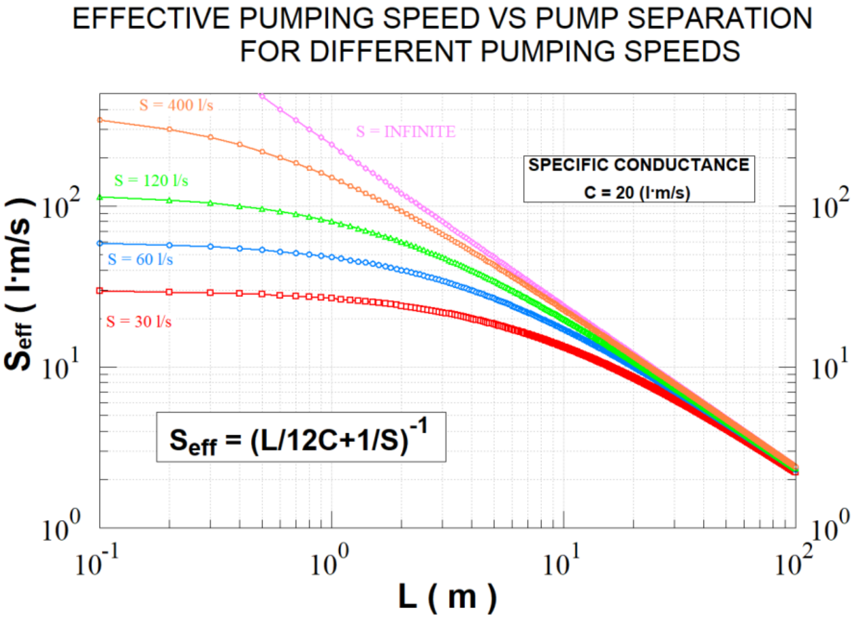


Vacuum system design, A.G. Mathewson, CAS, CERN 94-041

Simple machine

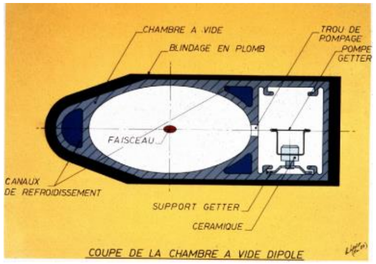
- Recalling AqL = Q and P = Q/S, we have

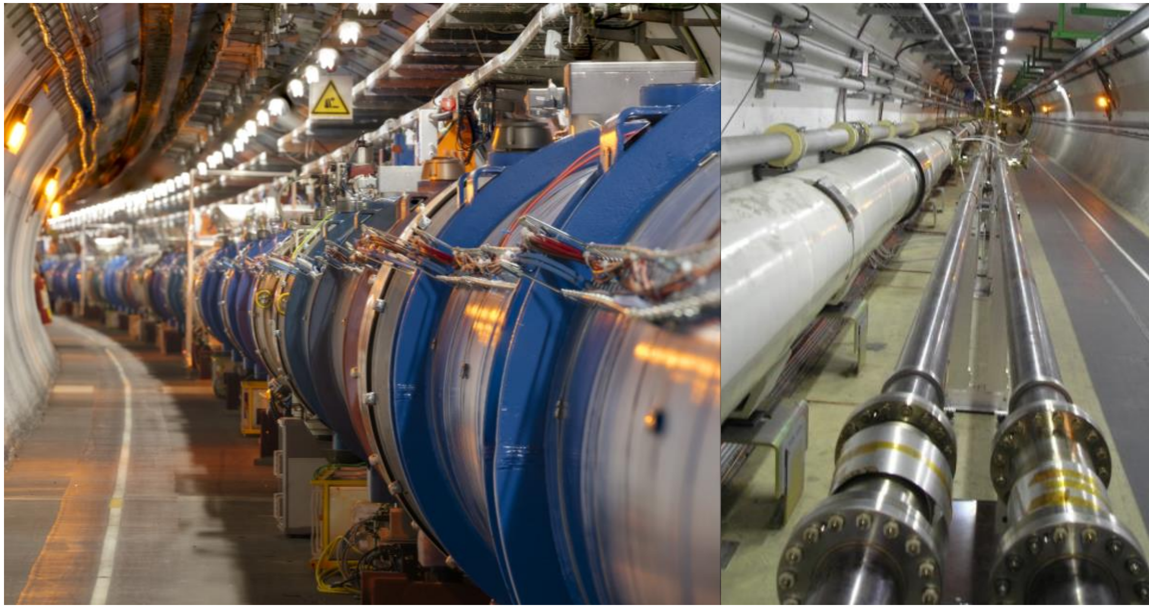
$$S_{eff} = \left(\frac{1}{S} + \frac{1}{12c}\right)^{-1}$$



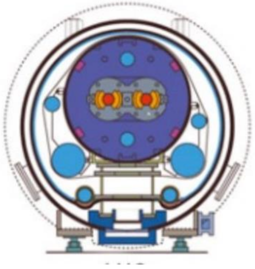
Some distributed pumping system

LEP beam pipe



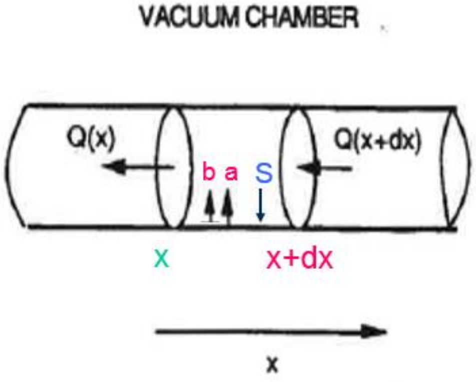


LHC Cryogenic and RT beam pipes with 1-2μm-thick NEG-coating (Ti-Zr-V)



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 (distributed) 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 $Cd^2P/dx^2 = 0$:

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

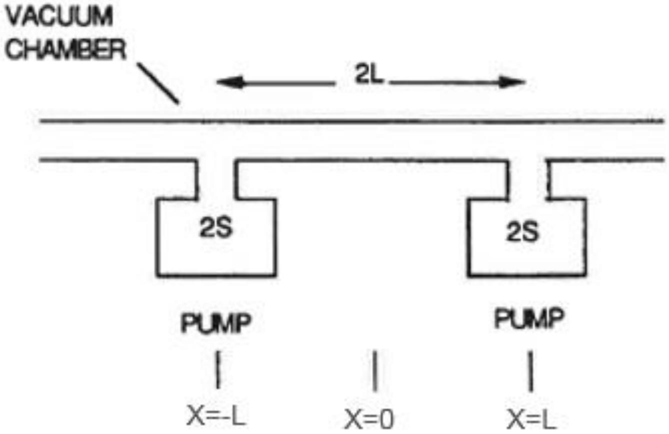
- So the vacuum system is stable if s-b>0 *i.e.* s>b

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:



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

FLUX IN FLUX OUT

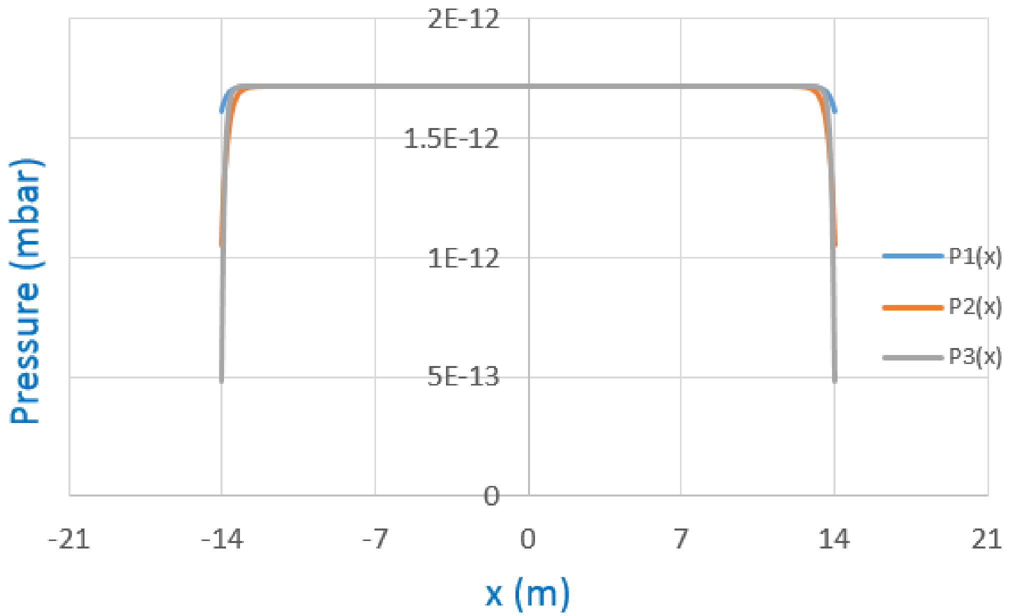
- It gives:

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

Simple machine with distributed pumping: application

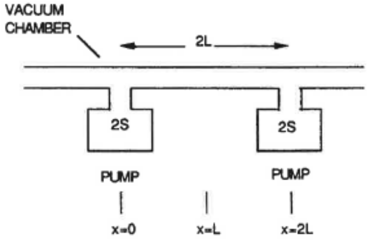
- P is the gas pressure (mbar)
- V is the volume per unit of length (l m^{-1})
- c is the specific conductance of the tube (l s^{-1} m)
- b is set to zero
- a is the gas desorption per unit length of tube (mbar l s^{-1} m^{-1})
- 2L is the distance between the pumps (m)
- 2S is the pumping speed (l s^{-1})

	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}**

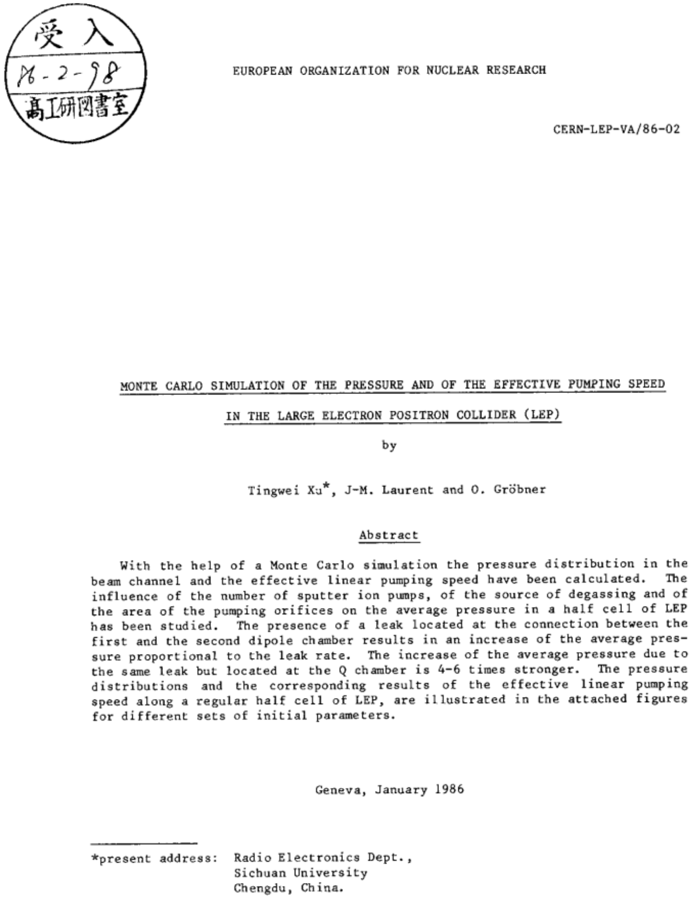


- 50 cm away from the pump, the pressure is independent of its pumping speed

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



Simple machine with distributed pumping: application
Test-Particle Montecarlo (TPMC*) simulation of LEP



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-LEP-VA/86-02

MONTE CARLO SIMULATION OF THE PRESSURE AND OF THE EFFECTIVE PUMPING SPEED
IN THE LARGE ELECTRON POSITRON COLLIDER (LEP)

by

Tingwei Xu*, J-M. Laurent and O. Gröbner

Abstract

With the help of a Monte Carlo simulation the pressure distribution in the beam channel and the effective linear pumping speed have been calculated. The influence of the number of sputter ion pumps, of the source of degassing and of the area of the pumping orifices on the average pressure in a half cell of LEP has been studied. The presence of a leak located at the connection between the first and the second dipole chamber results in an increase of the average pressure proportional to the leak rate. The increase of the average pressure due to the same leak but located at the Q chamber is 4-6 times stronger. The pressure distributions and the corresponding results of the effective linear pumping speed along a regular half cell of LEP, are illustrated in the attached figures for different sets of initial parameters.

Geneva, January 1986

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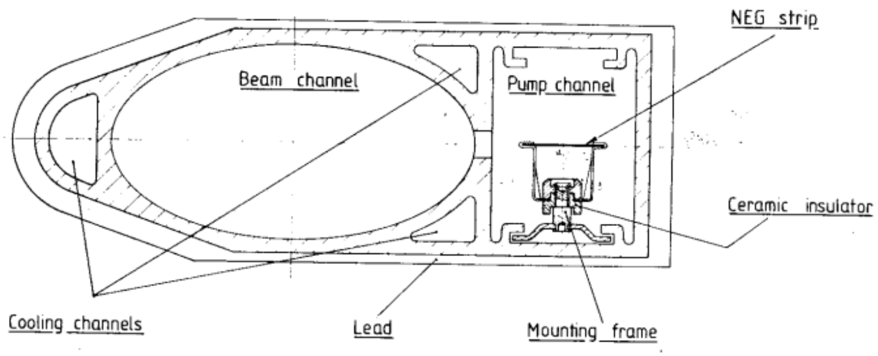
*present address: Radio Electronics Dept.,
Sichuan University
Chengdu, China.

T. Xu, J-M. Laurent, O. Gröbner
cds.cern.ch/record/165167/files/198602098.pdf

Fig 1 - CROSS-SECTION OF THE DIPOLE VACUUM CHAMBER



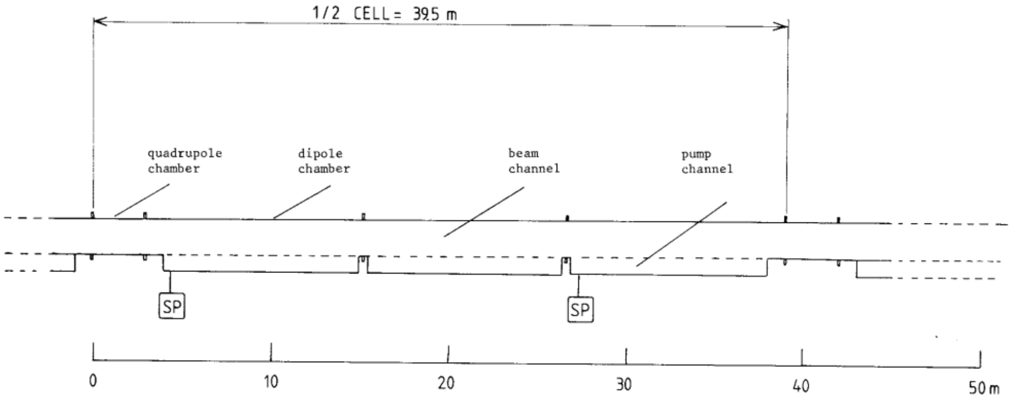
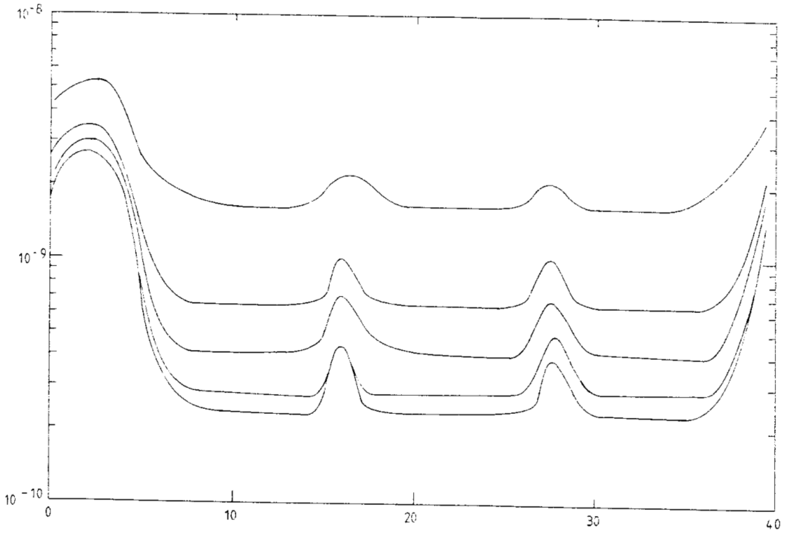
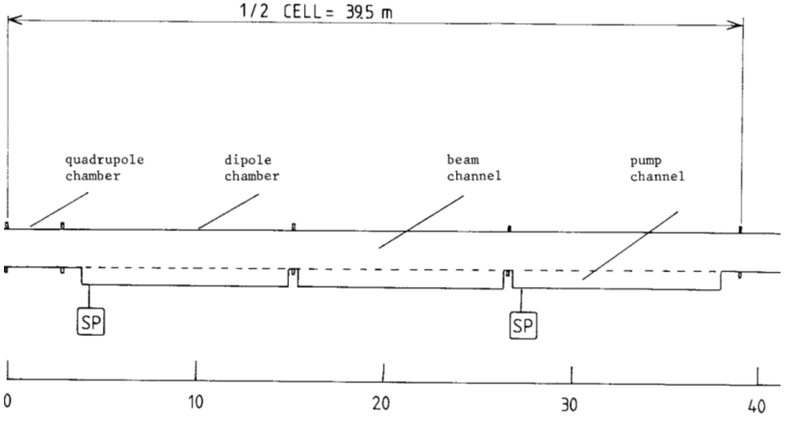


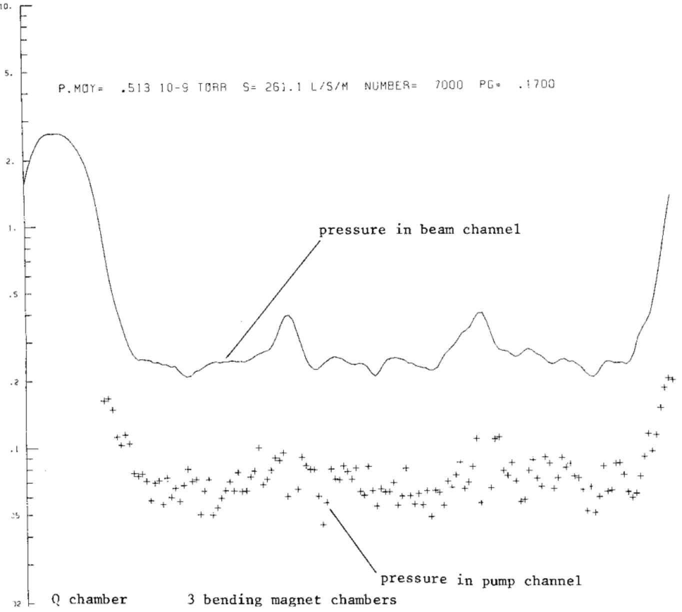
Fig. 2 Schematic layout of a half cell

(*) See practical days Molflow+ training session





Pressure profiles for different pumping probability s for the NEG strip (0.0085<s<0.17)



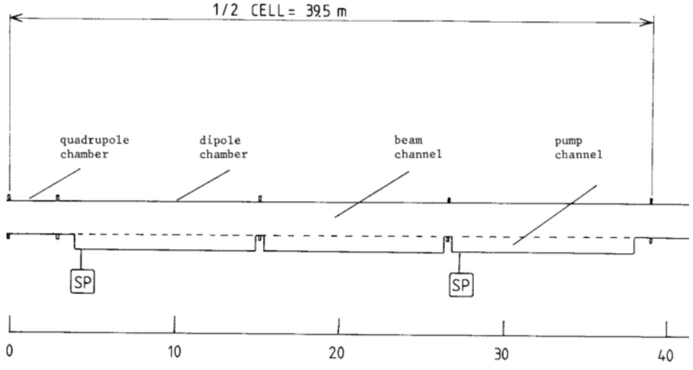
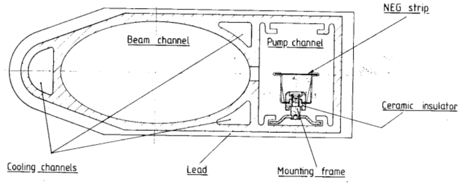
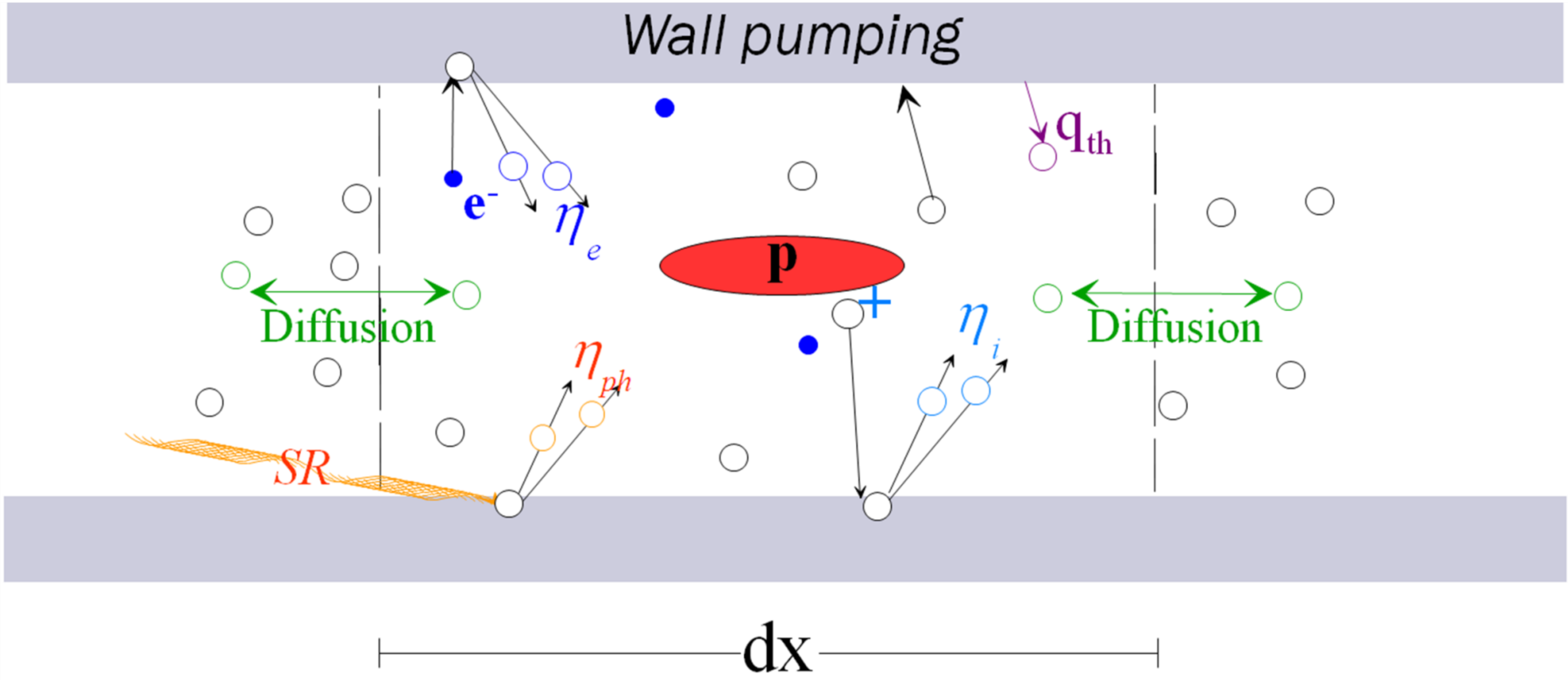


Fig 1 - CROSS-SECTION OF THE DIPOLE VACUUM CHAMBER



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

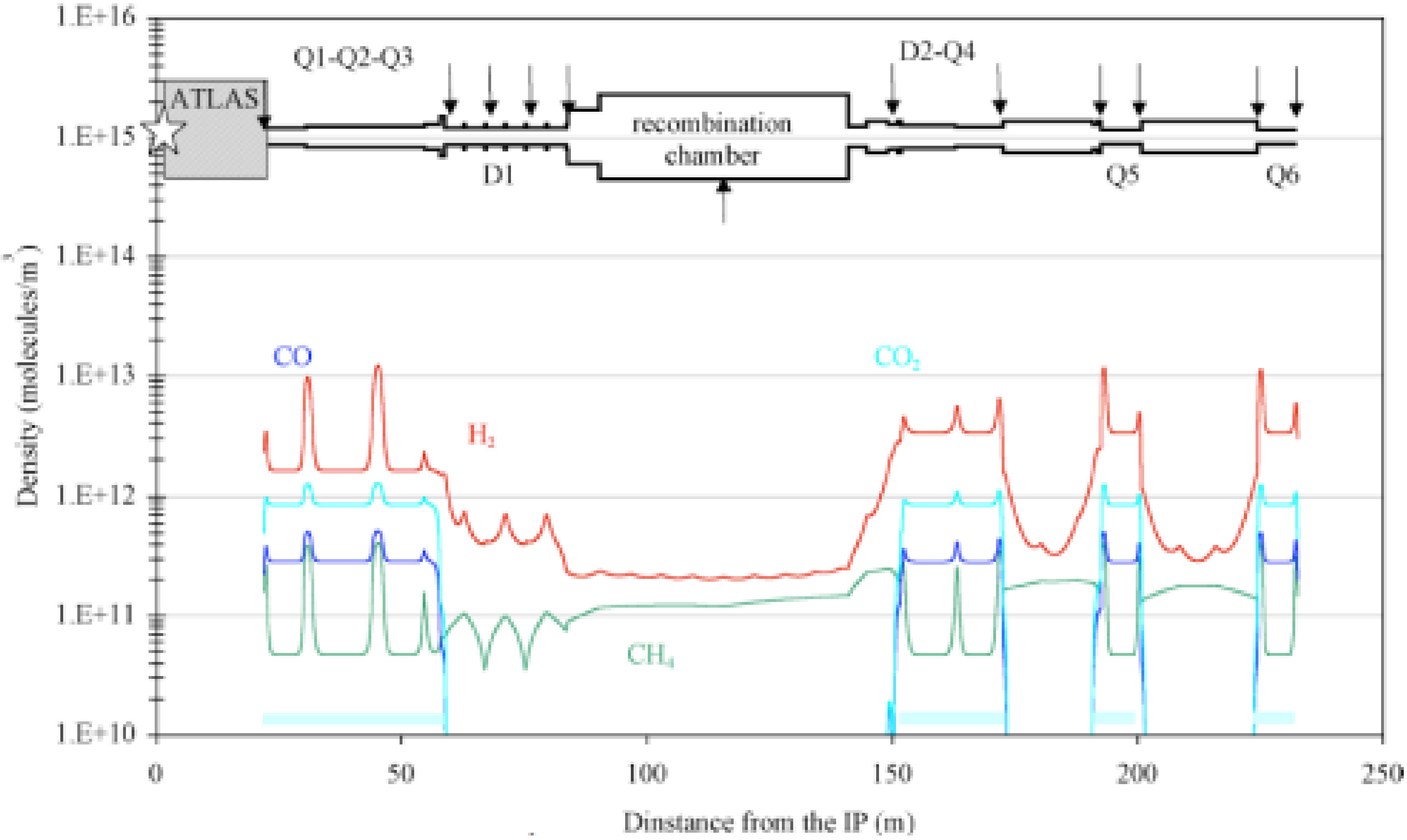
$$\underbrace{V\frac{\partial n_g}{\partial t}}_{\text{Time variation of particles in volume V}} = \underbrace{a\cdot D_g\cdot\frac{\partial^2 n_g}{\partial x^2}}_{\text{Diffusion through surface a}} + \boxed{\underbrace{\frac{I}{e}\sum_j\left\{\eta_{i,j^+\rightarrow g}\,\sigma_j^b\cdot n_j\right\}}_{\text{Ionization by beam and desorption by the ions}}} - \underbrace{\left(\frac{A\cdot v_g}{4}\cdot\alpha_g + C_g\right)\cdot n_g}_{\text{Distributed pumping of NEG or Cryo}} + \underbrace{\eta_{ph,g}\cdot\dot{\Gamma}_{ph}}_{\text{Desorption by photons}} + \underbrace{\eta_{e,g}\cdot\dot{\Gamma}_e}_{\text{Desorption by electron}} + \underbrace{A\cdot q_g}_{\text{Thermal desorption}}$$

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

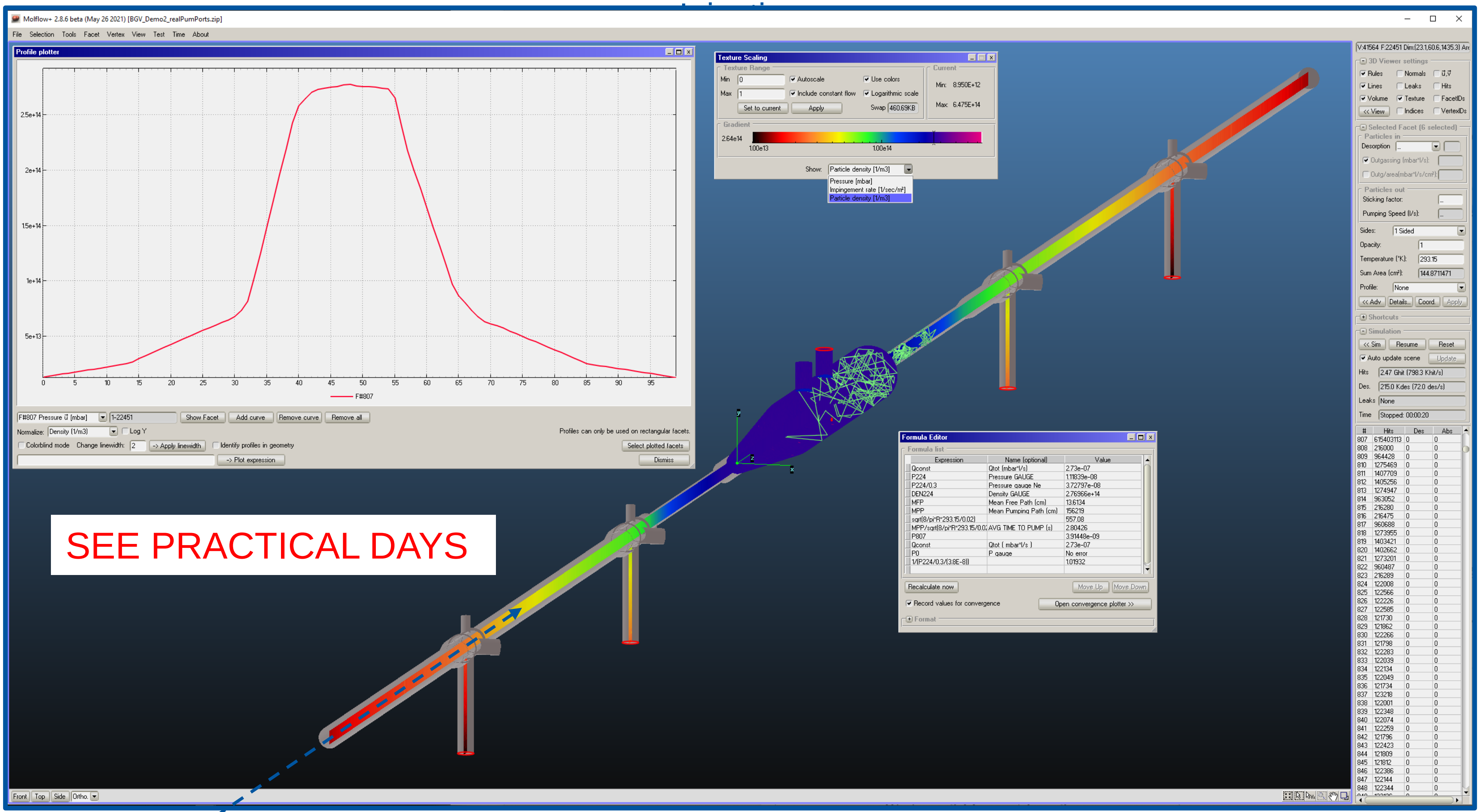
Gas density profile around ATLAS



A. Rossi, CERN LHC PR 783, 2004.

Gas density profile simulation: Molflow+

A **Test-Particle Monte-Carlo Simulator** for molecular flow: example of LHC's BGV, Neon



F#807 Pressure ū [mbar] | 1-22451

Normalize: Density (1/m3) ☐ Log Y

Profiles can only be used on rectangular facets.

☐ Colorblind mode Change linewidth: 2 ☐ Identify profiles in geometry

Min 0 ☑ Autoscale ☑ Use colors

Max 1 ☑ Include constant flow ☑ Logarithmic scale

Swap 460.69KB

Min: 8.950E+12

Max: 6.475E+14

Show: Particle density [1/m3]

- Pressure [mbar]
- Impingement rate [1/sec/m²]
- Particle density [1/m3]

Expression	Name (optional)	Value
Qconst	Qtot (mbar*l/s)	2.73e-07
P224	Pressure GAUGE	1.11839e-08
P224/0.3	Pressure gauge Ne	3.72797e-08
DEN224	Density GAUGE	2.76966e+14
MFP	Mean Free Path (cm)	13.6134
MPP	Mean Pumping Path (cm)	156219
sqrt(8/pi*R*293.15/0.02)		557.08
MPP/sqrt(8/pi*R*293.15/0.02	AVG TIME TO PUMP (s)	2.80426
P807		3.91448e-09
Qconst	Qtot (mbar*l/s)	2.73e-07
P0	P gauge	No error
1/(P224/0.3/(3.8E-8))		1.01932

☑ Record values for convergence

V:41564 F:22451 Dim:(23.1,60.6,1435.3) Are

☑ Rules ☐ Normals ☐ ū,v̄

☑ Lines ☐ Leaks ☐ Hits

☑ Volume ☑ Texture ☐ FacetIDs

☐ Indices ☐ VertexIDs

Desorption: ...

☑ Outgassing (mbar*l/s):

☐ Outg/area(mbar*l/s/cm²):

Sticking factor: ...

Pumping Speed (l/s): ...

Sides: 1 Sided

Opacity: 1

Temperature (°K): 293.15

Sum Area (cm²): 144.8711471

Profile: None

☑ Auto update scene

Hits: 2.47 Ghit (798.3 Khit/s)

Des.: 215.0 Kdes (72.0 des/s)

Leaks: None

Time: Stopped: 00:00:20

#	Hits	Des	Abs
807	615403113	0	0
808	216000	0	0
809	964428	0	0
810	1275469	0	0
811	1407709	0	0
812	1405256	0	0
813	1274947	0	0
814	963052	0	0
815	216280	0	0
816	216475	0	0
817	960688	0	0
818	1273955	0	0
819	1403421	0	0
820	1402662	0	0
821	1273201	0	0
822	960487	0	0
823	216289	0	0
824	122008	0	0
825	122566	0	0
826	122226	0	0
827	122585	0	0
828	121730	0	0
829	121862	0	0
830	122266	0	0
831	121798	0	0
832	122283	0	0
833	122039	0	0
834	122134	0	0
835	122049	0	0
836	121734	0	0
837	123218	0	0
838	122001	0	0
839	122348	0	0
840	122074	0	0
841	122259	0	0
842	121796	0	0
843	122423	0	0
844	121809	0	0
845	121812	0	0
846	122386	0	0
847	122144	0	0
848	122344	0	0

SEE PRACTICAL DAYS

For info: https://molflow.web.cern.ch

3. The LHC case

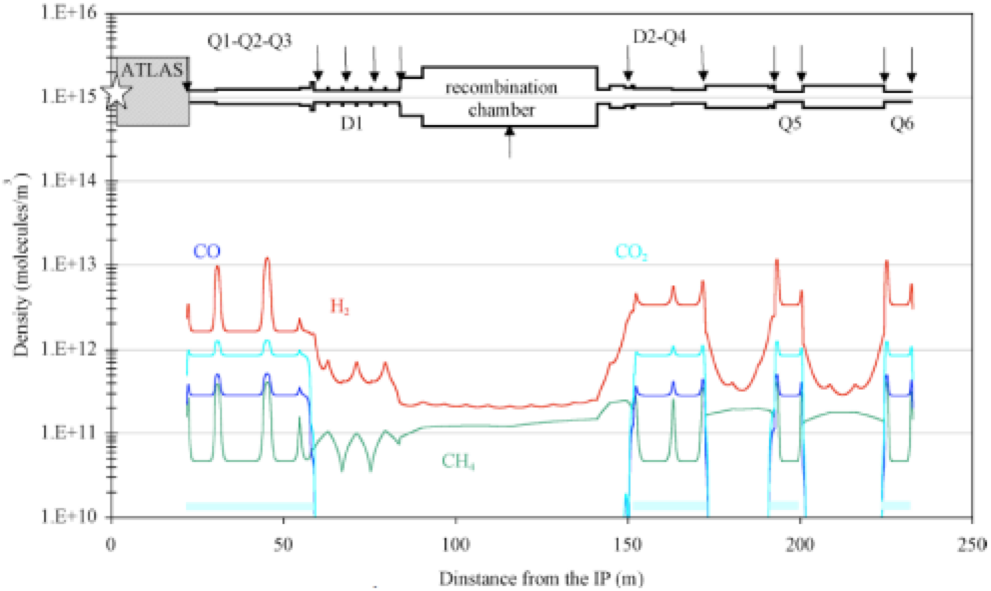
3.1 Design

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



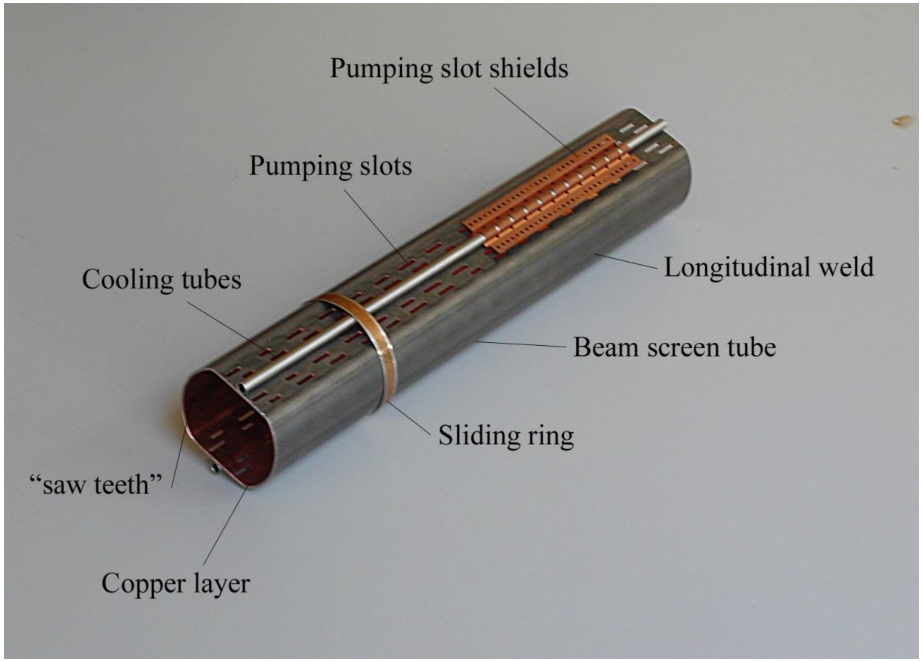
	H_{2_eq} / m^3	mbar
$<LSS_{1\ or\ 5}>$	~ 5 10^{12}	10^{-10}
<ATLAS>	~ 10^{11}	10^{-11}
<CMS>	~ 5 10^{12}	10^{-10}

A. Rossi, CERN LHC PR 783, 2004.

New System: LHC Beam Screens Functionalities

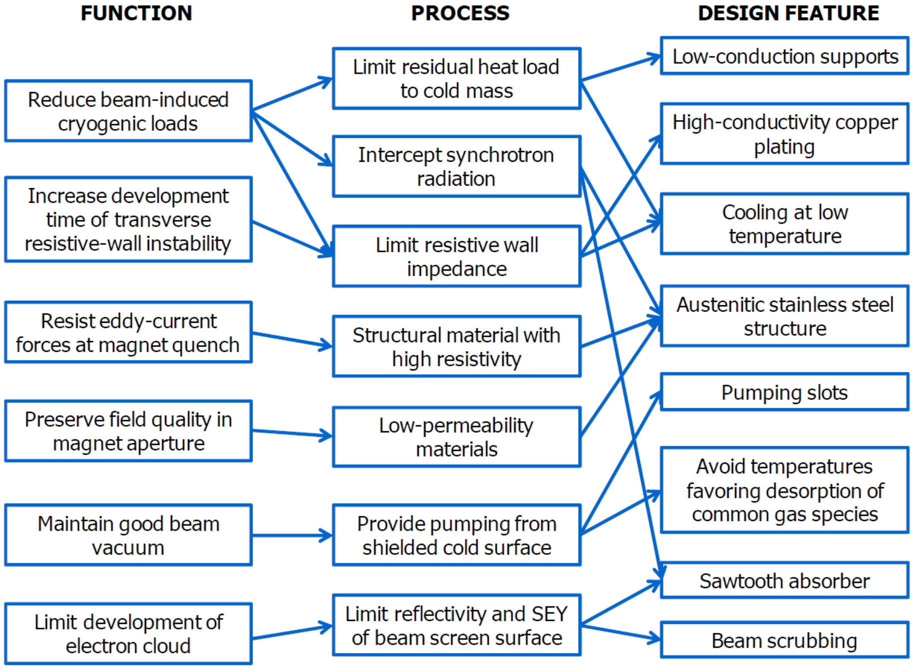
- An innovative and complex system, produced at several 10 km scale !

- 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



FUNCTION

- Reduce beam-induced cryogenic loads
- Increase development time of transverse resistive-wall instability
- Resist eddy-current forces at magnet quench
- Preserve field quality in magnet aperture
- Maintain good beam vacuum
- Limit development of electron cloud

PROCESS

- Limit residual heat load to cold mass
- Intercept synchrotron radiation
- Limit resistive wall impedance
- Structural material with high resistivity
- Low-permeability materials
- Provide pumping from shielded cold surface
- Limit reflectivity and SEY of beam screen surface

DESIGN FEATURE

- Low-conduction supports
- High-conductivity copper plating
- Cooling at low temperature
- Austenitic stainless steel structure
- Pumping slots
- Avoid temperatures favoring desorption of common gas species
- Sawtooth absorber
- Beam scrubbing

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 1994

No perforations

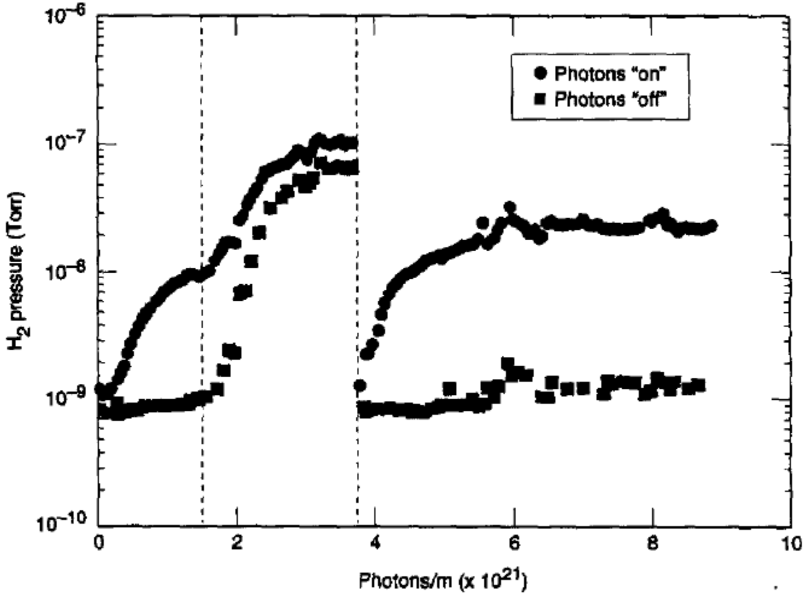


FIG. 1. Room-temperature RGA H_2 pressure measured at the center of the 4.2-K beam tube vs integrated photon flux with photons on and photons off. The raw pressure difference "on" minus "off" has been normalized to 1×10^{16} photons/m/s. The vertical dashed lines correspond to features discussed in the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

With perforations

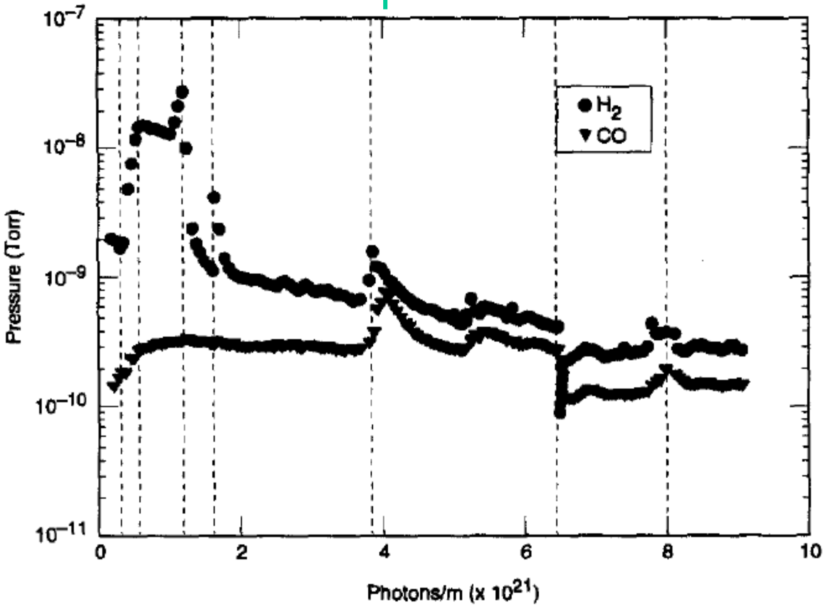
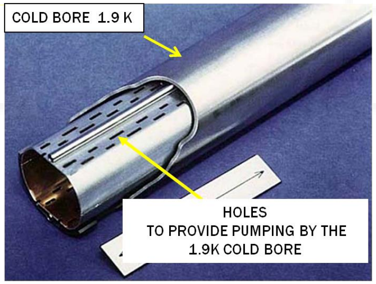


FIG. 2. Room-temperature RGA H_2 and CO dynamic pressures measured at the center of the liner configuration. Dynamic pressure is normalized to 1×10^{16} photons/m/s.



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

SSC proton-proton collider project, Dallas, TX USA; 20+20 TeV beam energy; Cancelled by US Congress in 1994

Gas density & surface coverage equations

V.V. Anashin *et al.* J. Vac. Sci.Technol. A. 12(5) , Sep/Oct 1994

$$\mathrm{V}\,\frac{\partial n}{\partial t} = \underbrace{\eta\dot{\Gamma}}_{\text{Photodesorption}} + \underbrace{\eta'\dot{\Gamma}}_{\text{Recycling}} + \underbrace{\frac{A\Theta}{\tau}}_{\text{Vapour pressure}} - \underbrace{\sigma S n}_{\text{Wall pumping}} - \underbrace{Cn}_{\text{Holes pumping}} + \underbrace{A_c D\,\frac{\partial^2 n}{\partial z^2}}_{\text{Axial diffusion}}$$

$$\mathrm{A}\,\frac{\partial \Theta}{\partial t} = \sigma S n - \eta'\dot{\Gamma} - \frac{A\,\Theta}{\tau}$$

- with:

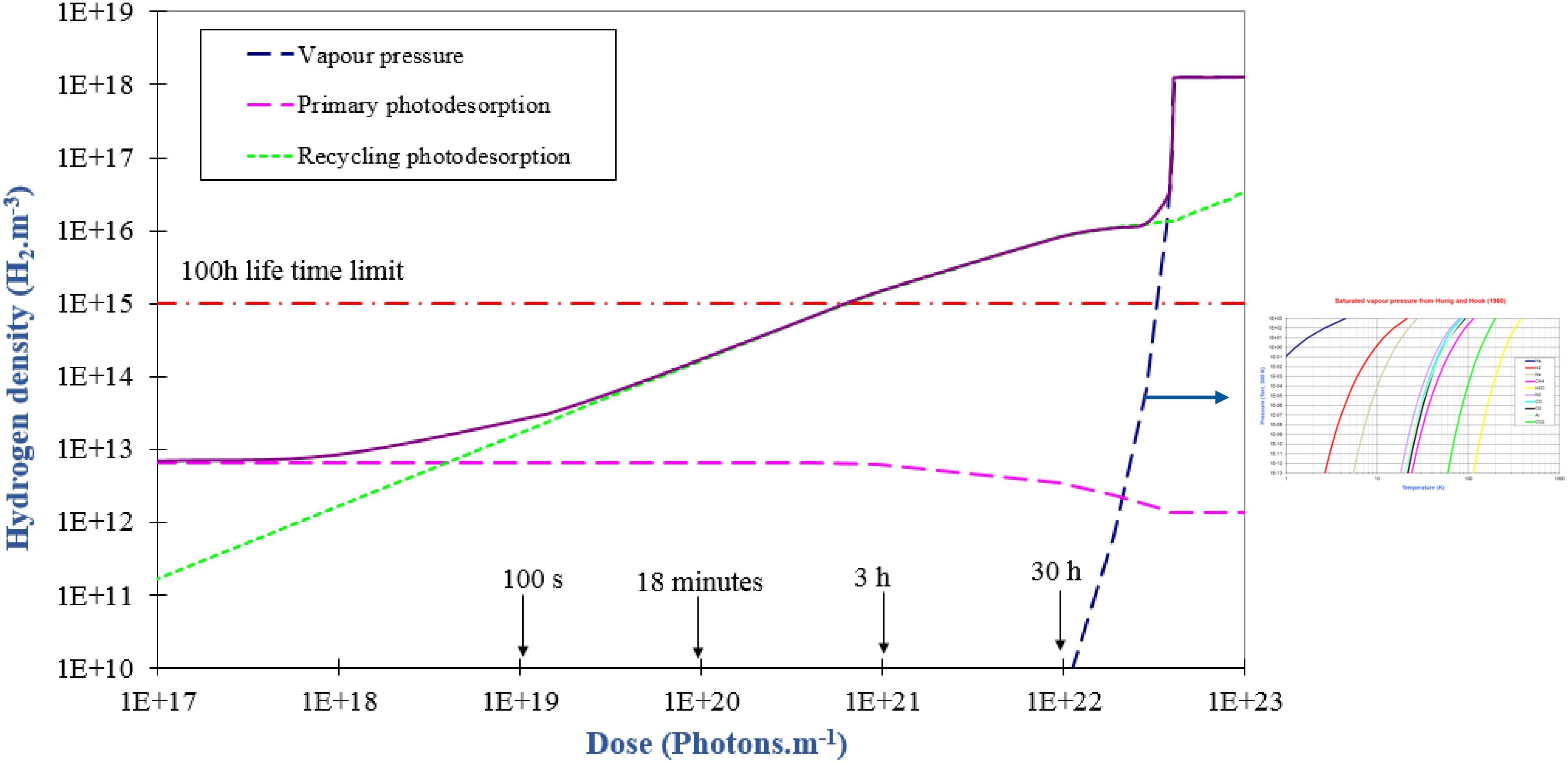
n gas density, s surface coverage, V volume per unit length, A surface per unit length, A_cD axial diffusion term of molecules, σ sticking probability, S ideal speed per unit length, C beam screen holes pumping speed per unit length, τ sojourn time of physisorbed molecule, η desorption yield of chemisorbed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

Cryosorbing tube without holes

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

➔Three terms adds: primary, recycling desorption and vapour pressure

$$n = \frac{\eta\dot{\Gamma}}{\sigma S} + \frac{\eta'\dot{\Gamma}}{\sigma S} + \frac{1}{\sigma S}\frac{A\Theta}{\tau}$$

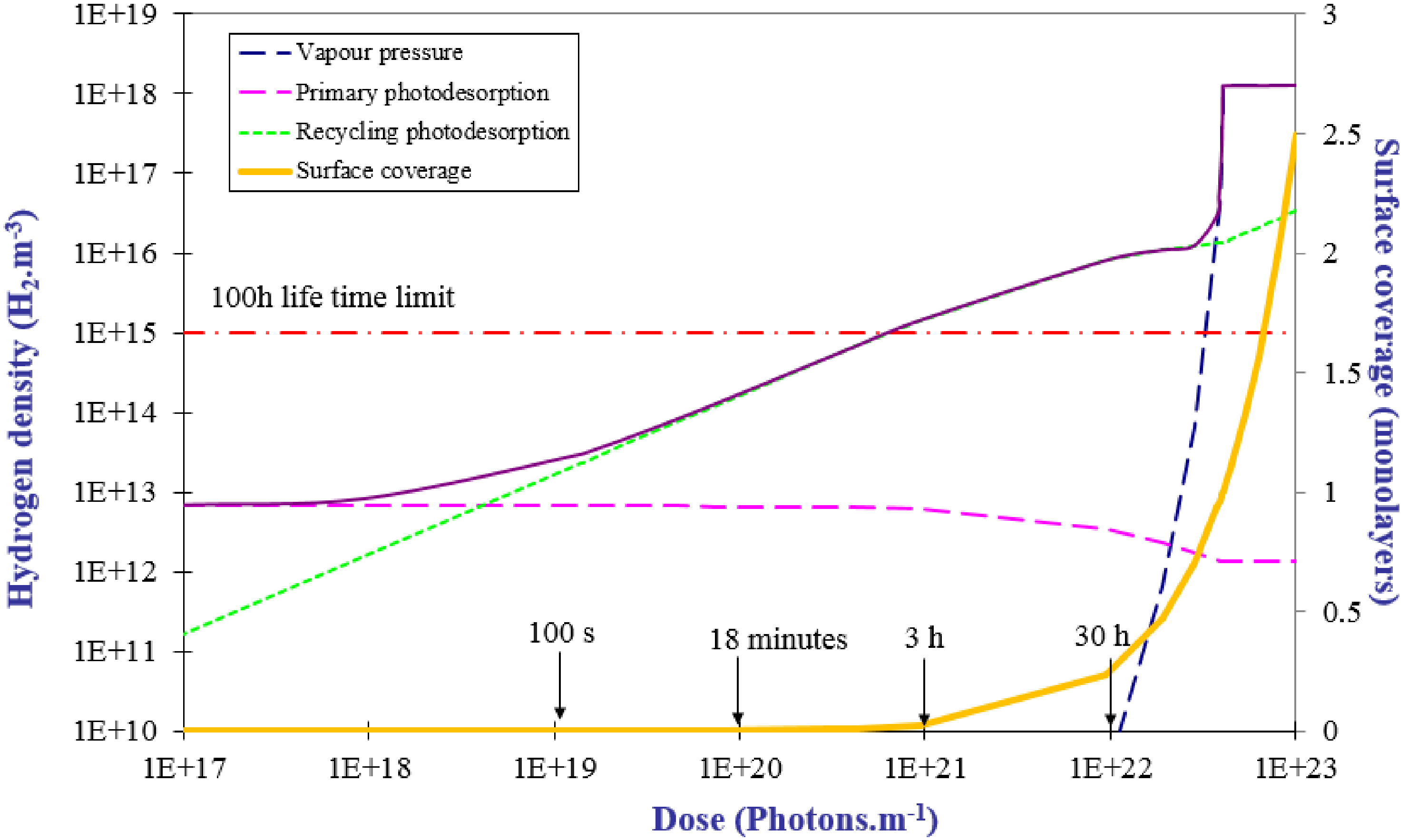


Cryosorbing tube without holes

$$n = \frac{\eta\dot{\Gamma}}{\sigma S} + \frac{\eta'(\Theta)\dot{\Gamma}}{\sigma S} + \frac{1}{\sigma S}\frac{A\Theta}{\tau}$$

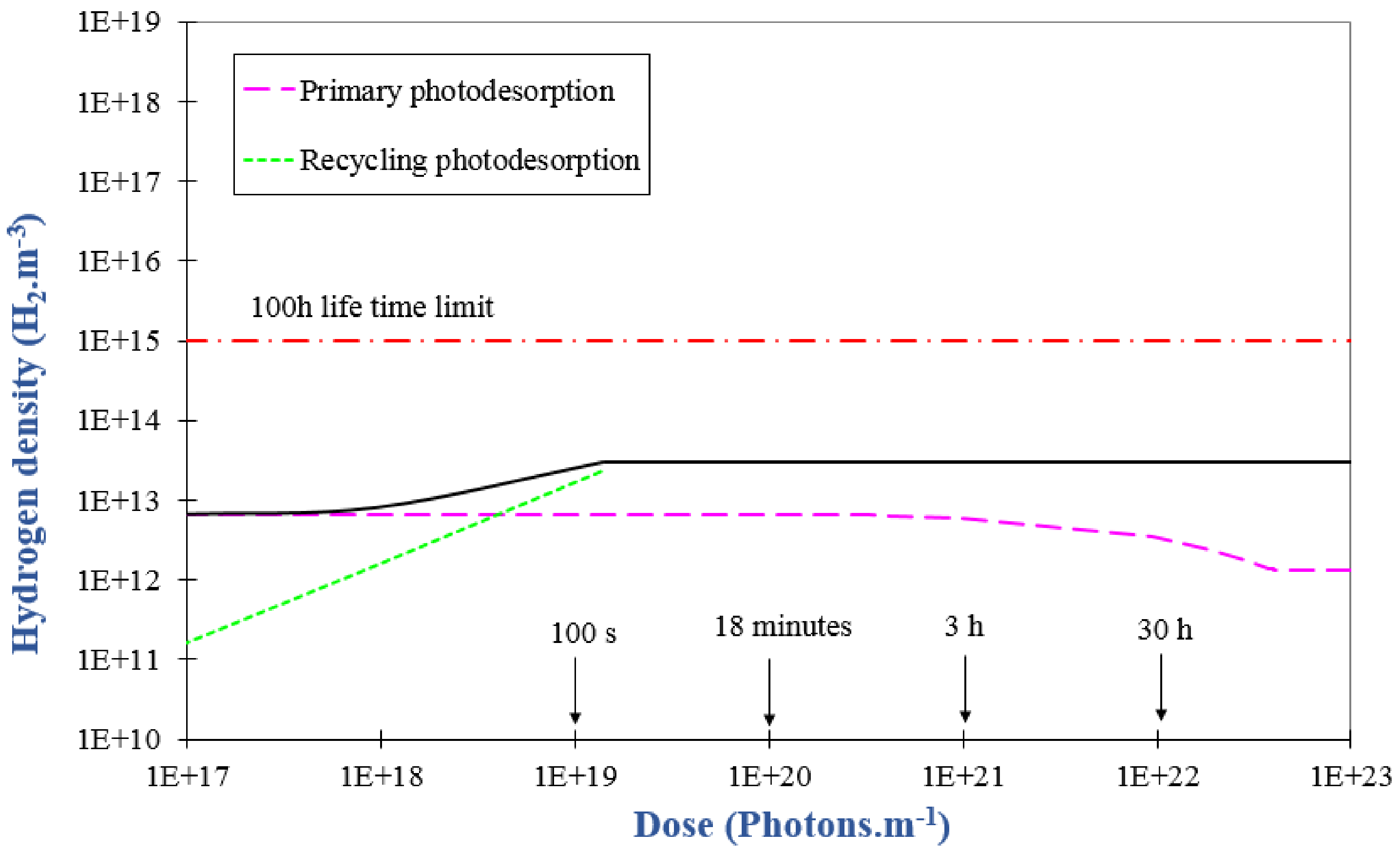
Increase with the surface coverage, Θ

$$\Theta = \frac{1}{A}\int_0^{\Gamma} \eta \, d\Gamma$$



Perforated beam screen

- Infinitely long tube ($A_cD=0$), with a beam screen ($C \neq 0$) and quasi static conditions:
  - The equilibrium pressure n_{eq} is defined by the perforation conductance

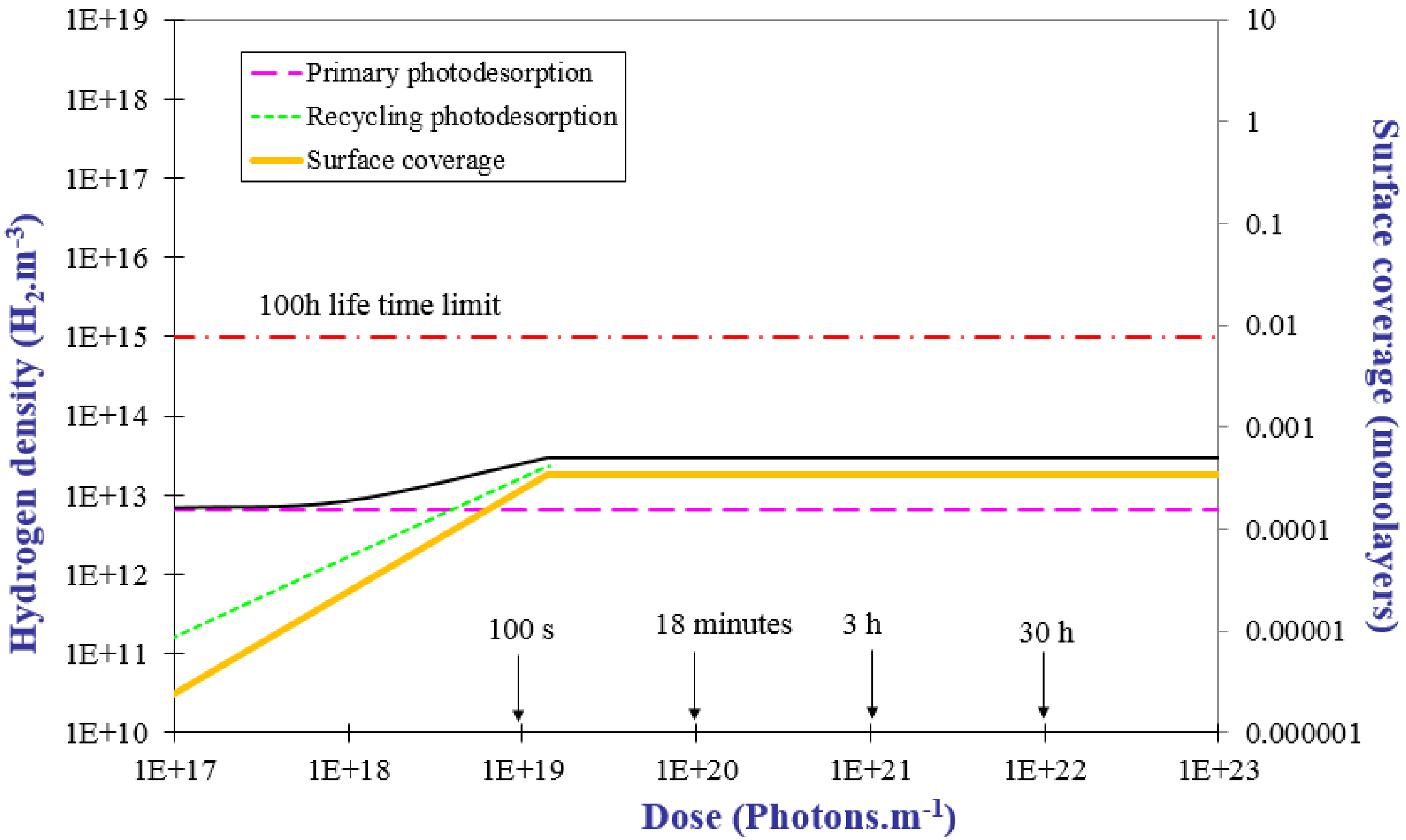


$$n_{eq} = \frac{\eta\dot{\Gamma}}{C}$$

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

Perforated beam screen

- Infinitely long tube ($A_cD=0$), with a beam screen (C=0) and quasi static conditions:
  - The equilibrium coverage is a fraction of a monolayer

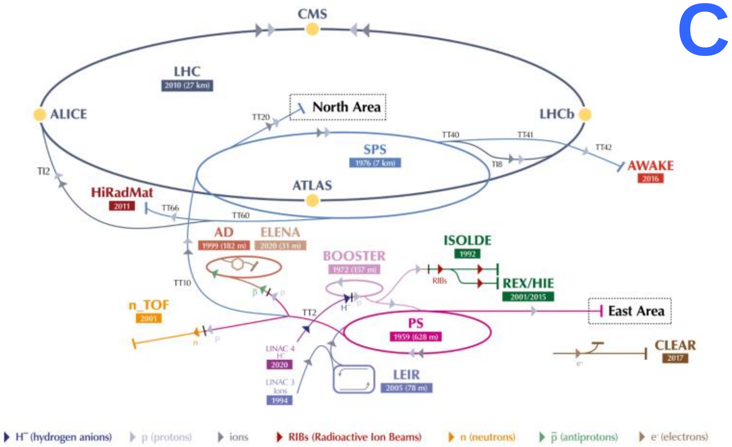


$$\theta_{eq} = \left(\frac{\sigma S}{C} \frac{\eta}{\eta_0'} \right) \theta_m$$

A **perforated** beam screen allows to control the surface coverage

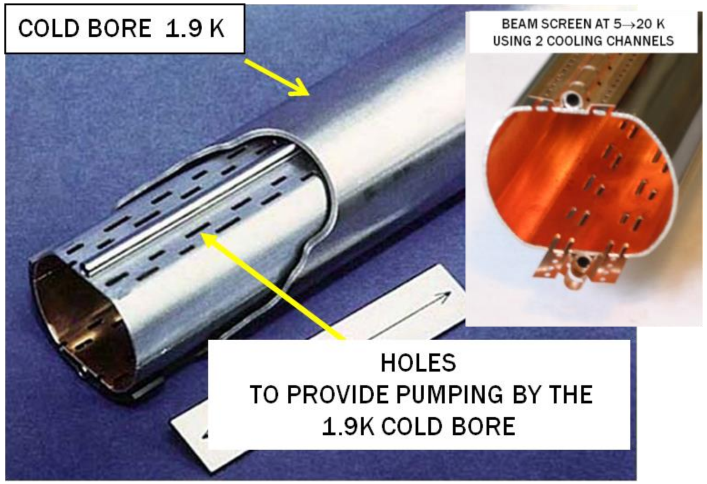
3.2 Arc Vacuum System

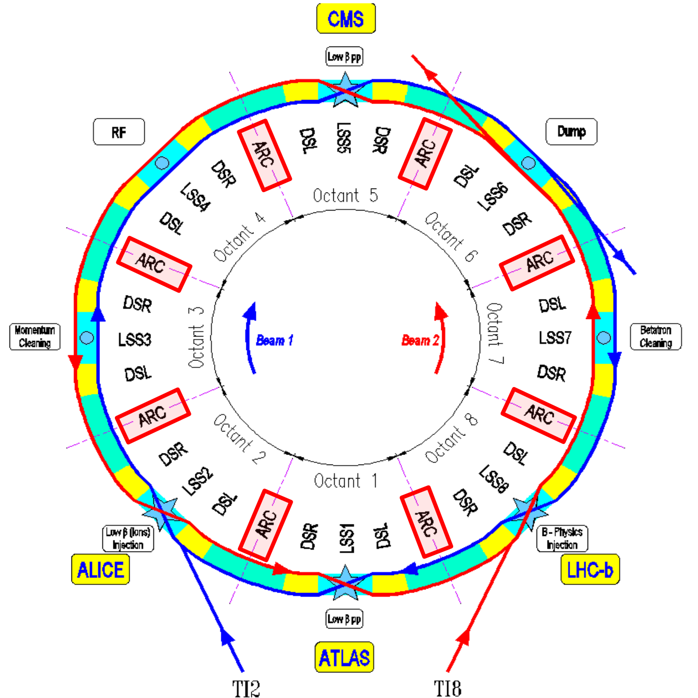
Cryogenic Beam Vacuum

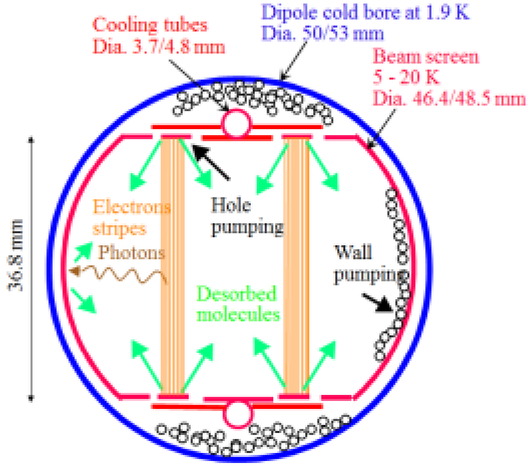


LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

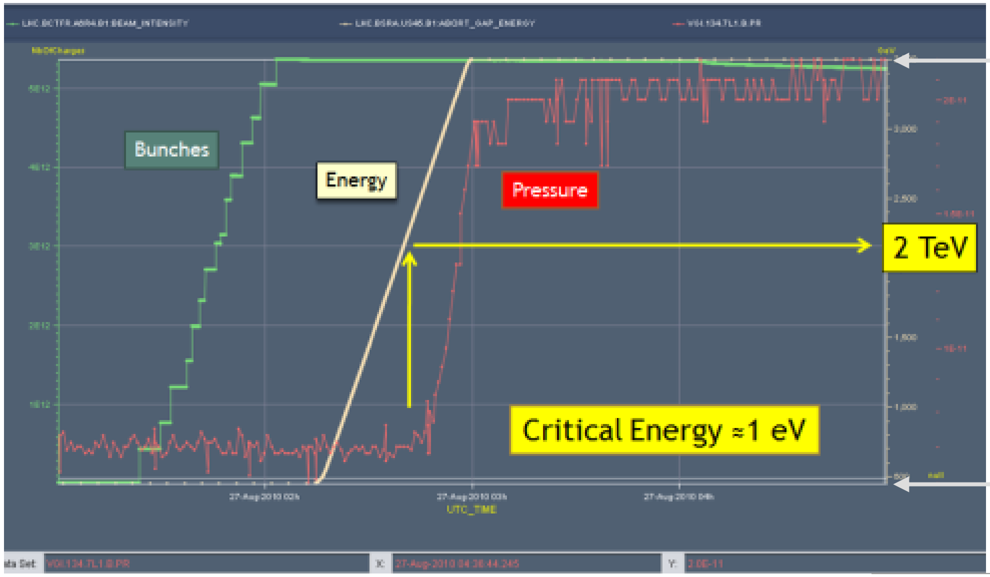
2 independent beam pipes per arc:
8 arcs of 2.8 km each
22.4 km in total







First Observation of Synchrotron Radiation: Aug-2010

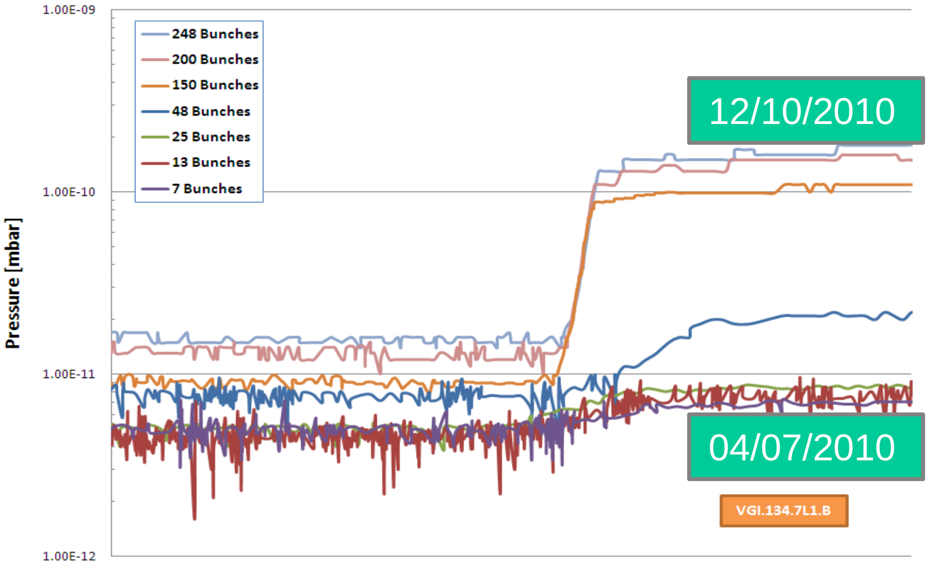


3500 GeV (now 6500 GeV)

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

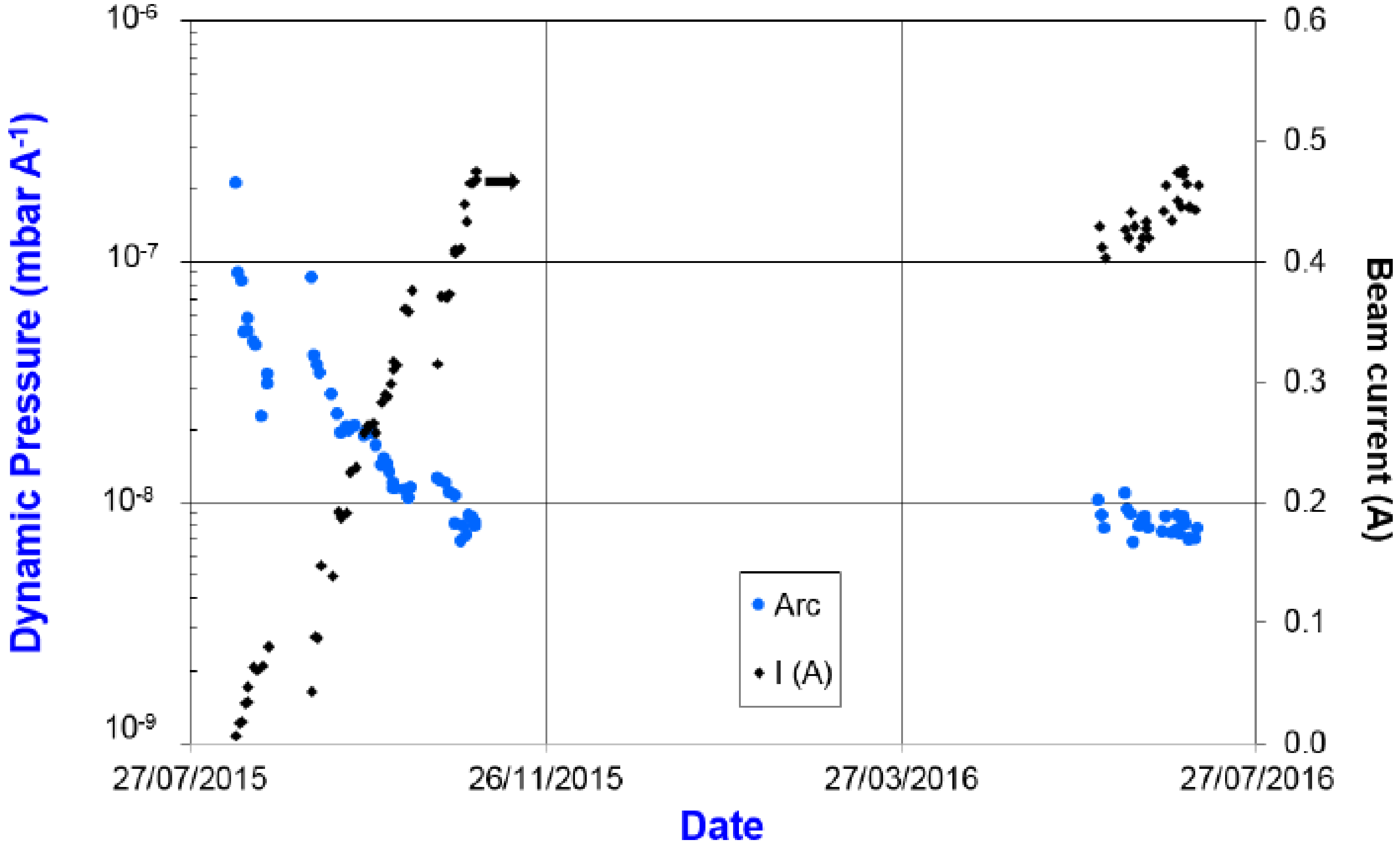
450 GeV (injection from SPS)

- Dynamic pressure increases with beam current
- $\Delta P = 2\ 10^{-10}$ mbar



Beam conditioning in the LHC arcs

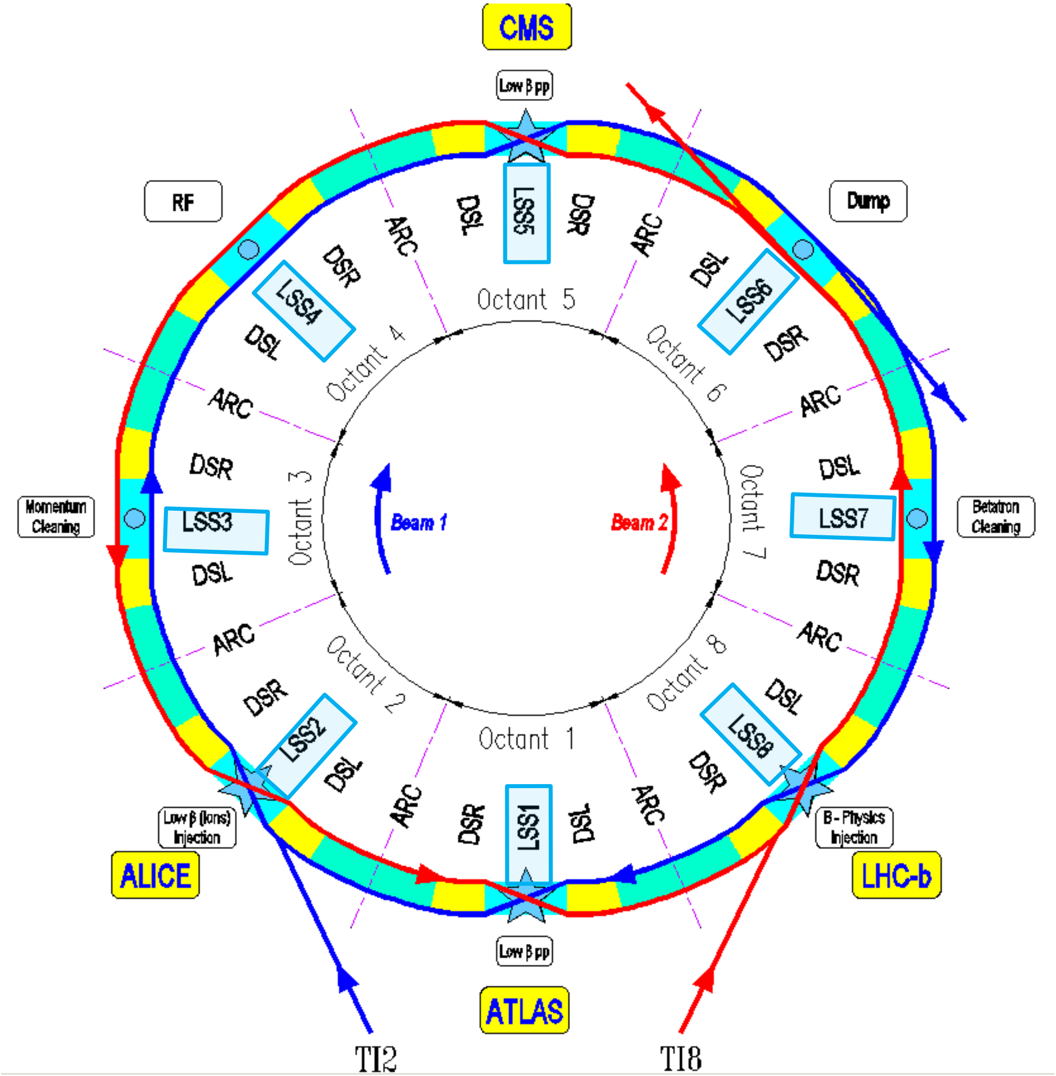
- Dynamic pressure reduction during LHC commissioning.



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

3.3 Room Temp. Vacuum System

Room Temperature Beam Vacuum



6 km of RT beam vacuum in the long straight sections

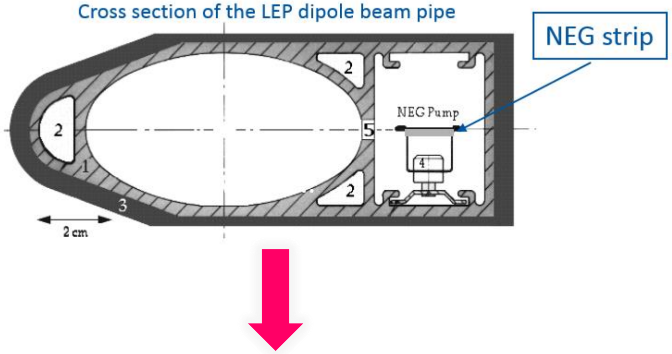
Extensive use of NEG coatings

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

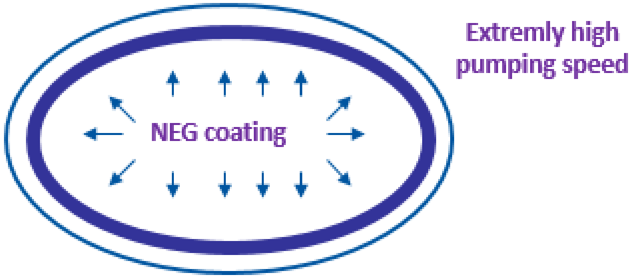
New System: NEG film coating

- 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 (typically 8m-long, 80 mm diameter, 2 mm copper, brazed flanges)

Cross section of the LEP dipole beam pipe



Cross section of an LHC warm dipole beam pipe

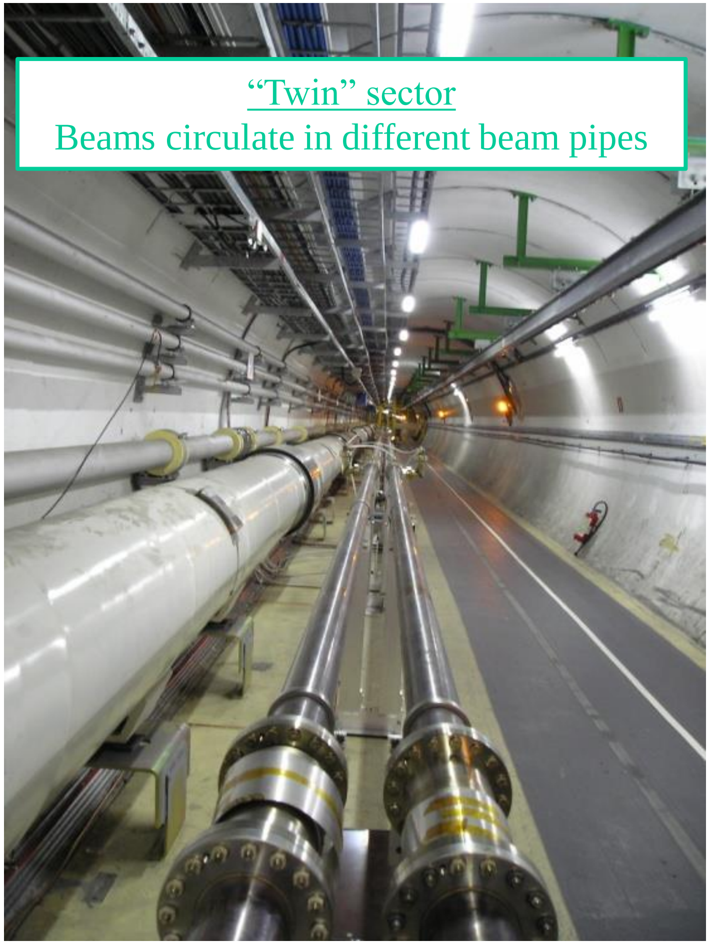


C. Benvenuti *et al.*

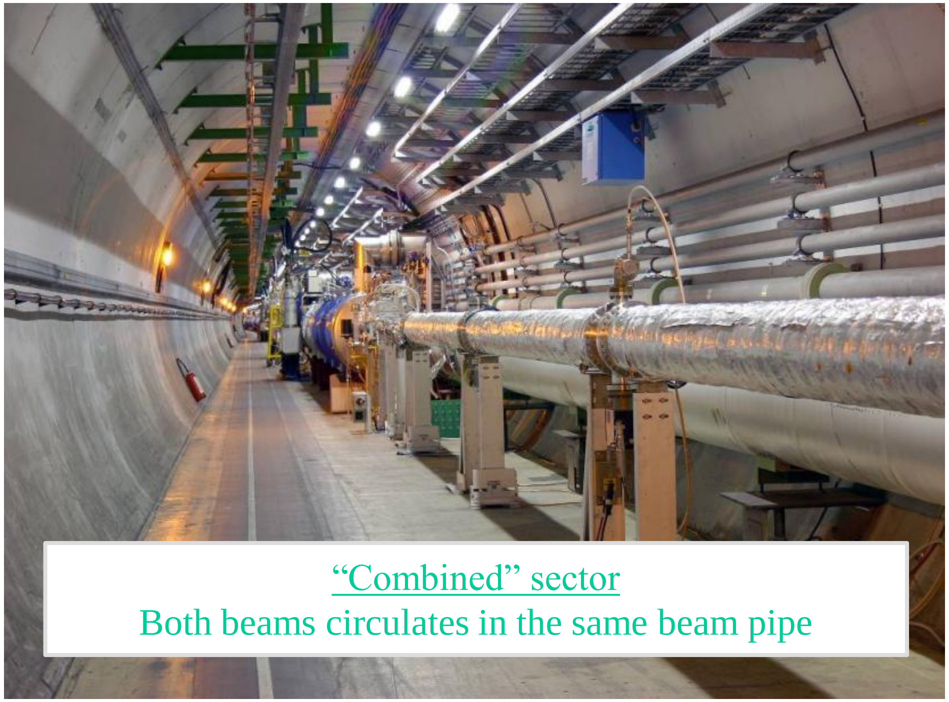
Courtesy R.Veness and P. Chiggiato

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

Room Temperature Vacuum Sectors

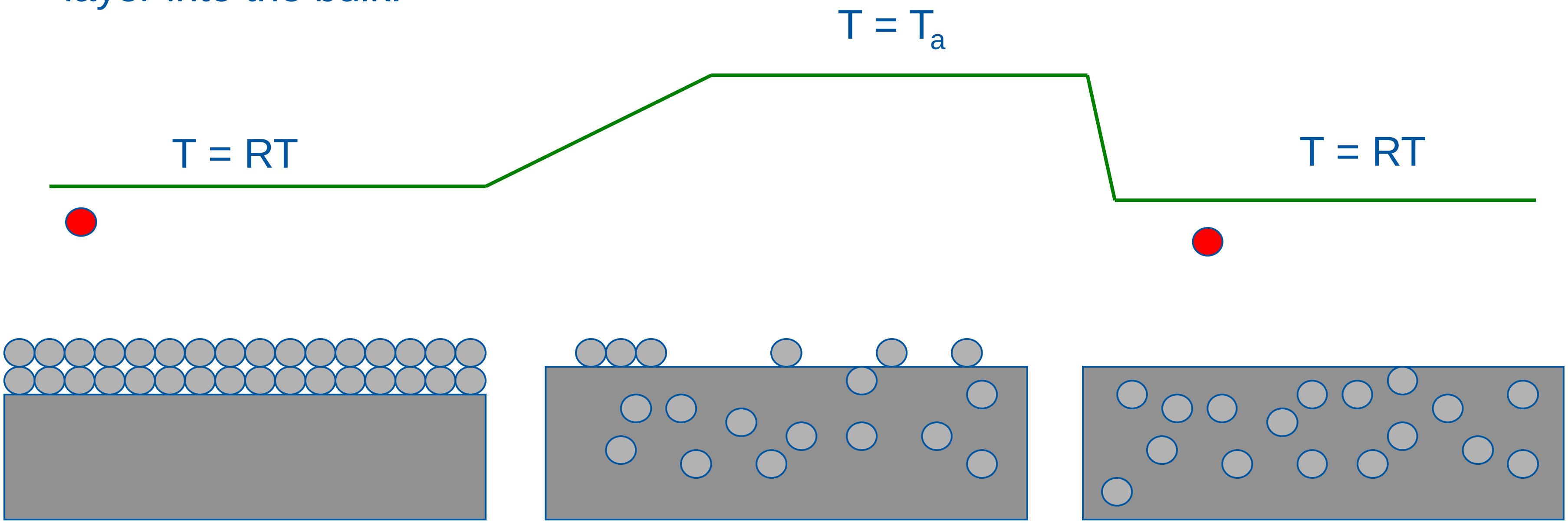
- 185 vacuum sectors at RT
- From 1 m till 150 m long
- Contains : kickers, septum, collimators, masks, beam instrumentation …
- Separation of baked from cryogenic unbaked vacuum sectors

From 28 m up to 115 m NEG beam pipes

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

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

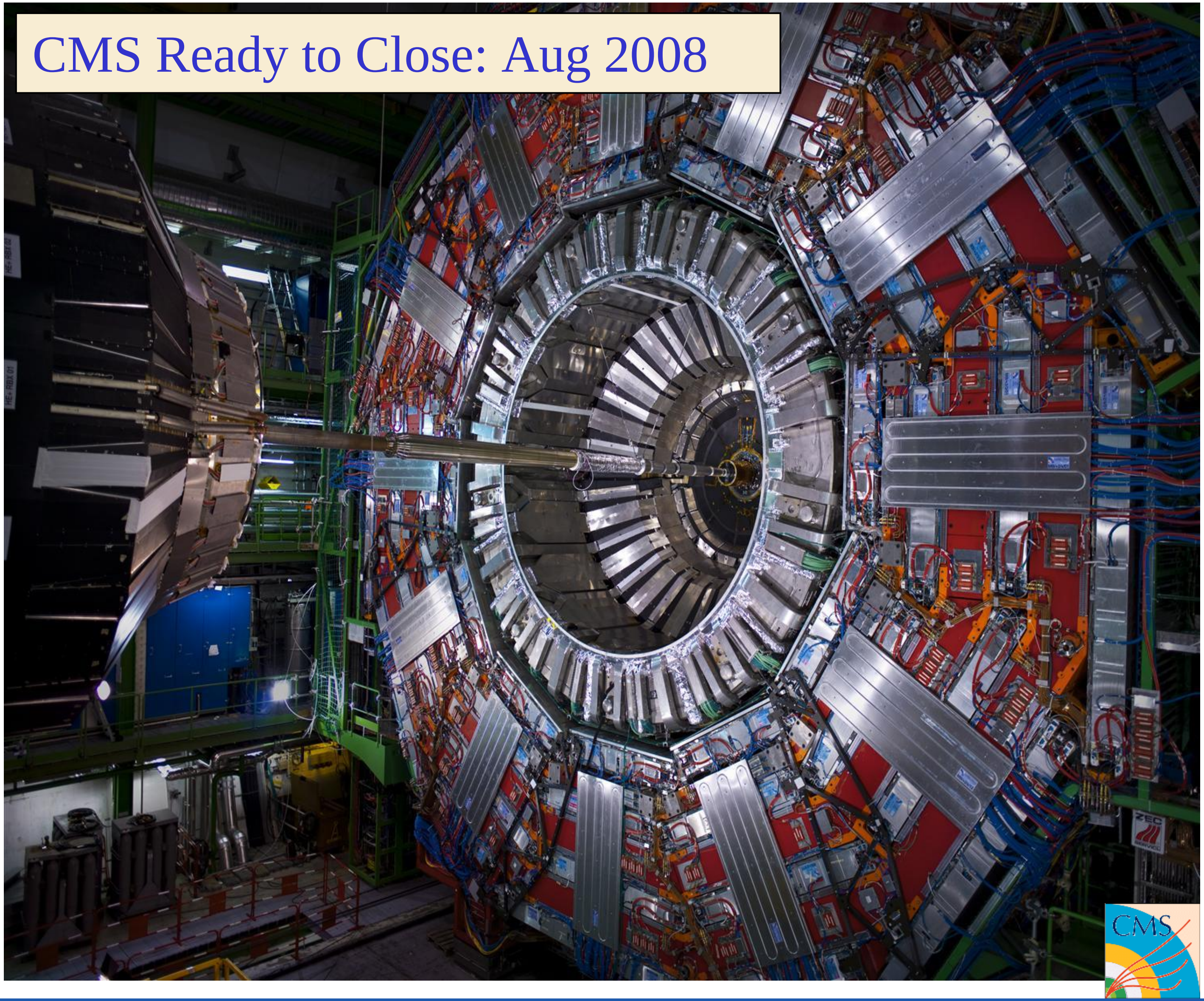
Heating in vacuum
Oxide dissolution -> activation

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

And of Course … Through the LHC Experiments



CMS Ready to Close: Aug 2008

Beam Pipe Installation in ATLAS Before Closure

LHC Experimental Areas

- NEG coated vacuum system

  => Large pumping speeds, low SEY and desorption yields

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

  => No background issues: within specifications

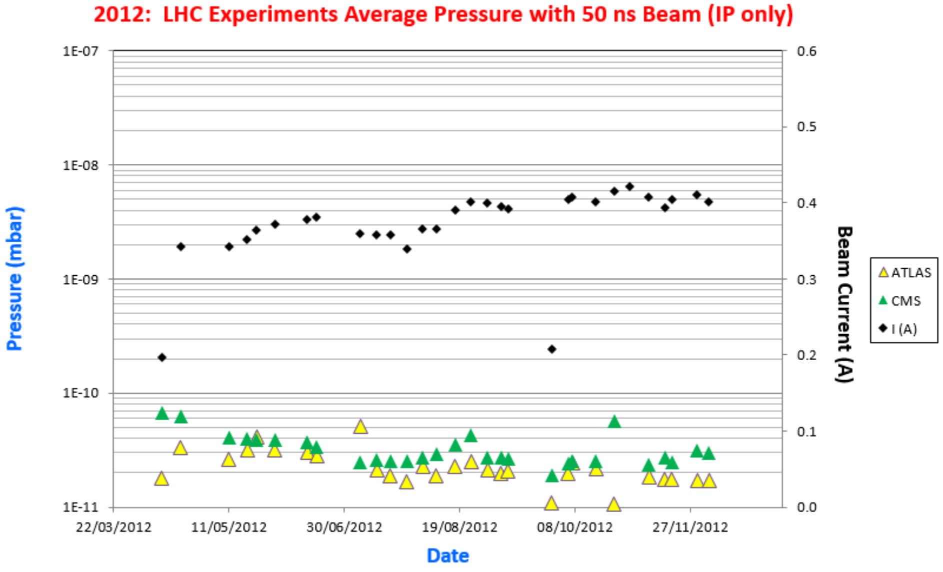
- $<P_{\text{LHC Experiments}}>$ with 50 ns beams

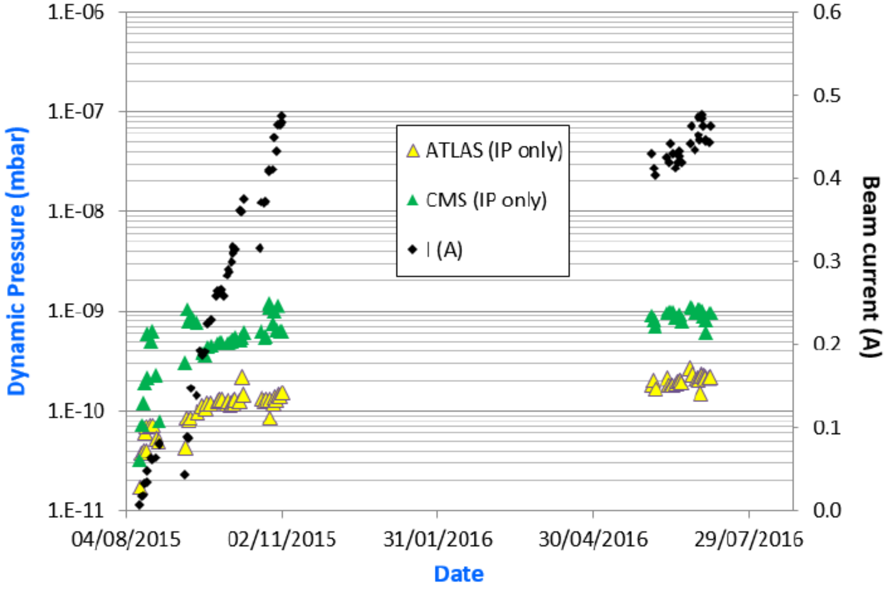
  $\sim 5\ 10^{-10}$ mbar in 2011 at 375 mA

  $\sim 3\ 10^{-11}$ mbar in 2012 at 400 mA

- $<P_{\text{LHC Experiments}}>$ with 25 ns beams

  $\sim 5\ 10^{-10}$ mbar in at 450 mA and 25 ns bunch spacing



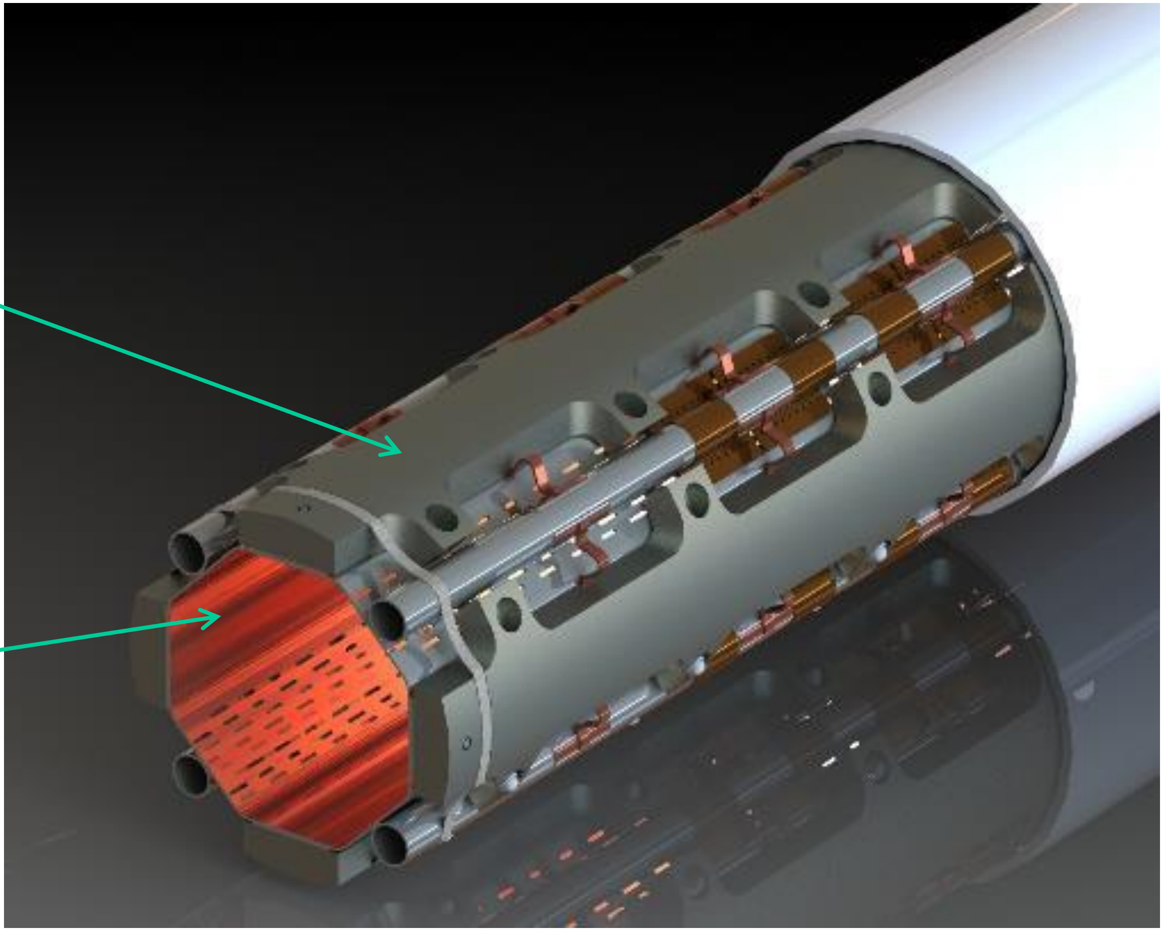


V. Baglin., Vacuum 138 (2017) 112-119

High Luminosity LHC Beam Screens

- Provide vacuum stability, control gas density
- Protect the Triplet cold mass against particle collision debris, $L = 5\ 10^{34}$ Hz/cm^2

Cold bore (CB) at 1.9 K:
4 mm thick tube in 316LN



Tungsten alloy blocks:
- Heat load: 15-25 W/m
- 40 cm long

Beam screen tube (BS) at 60-75 K:
- Perforated tube (~2%, 1600 l/s/m for H_2 at 300K)
- Internal copper layer (75 μm) for impedance
- a-C coating for e- cloud mitigation

Summary

- The vacuum lifetime in an accelerator is driven by elastic & inelastic interactions
- Accelerator vacuum systems can be modelled as a preliminary approach by simple sets of equations.
- Improved pressure (density) profiles can be computed using for instance montecarlo simulations (see practical days training for Molflow+ code)
- The LHC vacuum environment is affected by all possible (known) vacuum effects: photon-stimulated desorption, electron-stimulated desorpion, electron-cloud, ion-instabilities, cryogenic instabilities, conductance limitations, material outgassing, beam induced heating…
- Accelerators operate as designed… but there is always room for mistakes!
- Smart solutions must be developed for specific issues
- Laboratory studies are needed to properly design a machine: large part of the studies are carried out by young students or scientists in their first phase of their career.

WE NEED YOU!

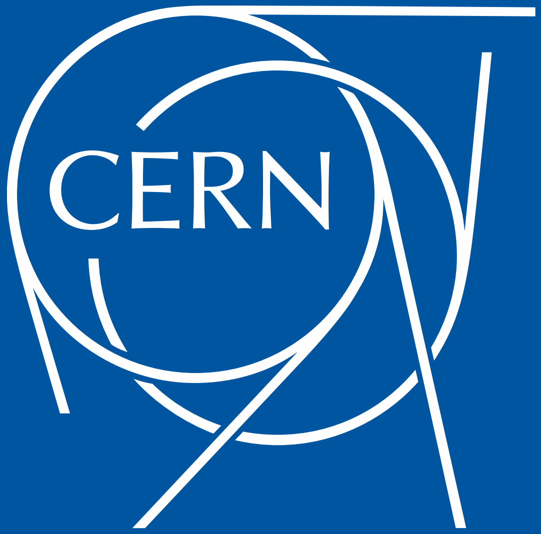
Some References

- 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
- Accelerators and Colliders, Springer, 2013
- Design and modelling of UHV systems of particle accelerators, Wiley, 2019

Some Journals Related to Vacuum Technology and Accelerators

- Journal of Vacuum Science and Technology
- Vacuum
- Applied Surface Science
- Nuclear Instruments and Methods in Physics Research
- Physical Review Accelerators and Beams

Thank you for your attention !!!


CERN