Introduction to High Vacuum in Accelerators

Jonathan YEMANE

Le 18/06/2026

Introduction to High Vacuum in accelerators.

Part1: vacuum basis

1-1 Kinetic behavior of gas molecules

1-2 Mean free path / residence time

1-3 outgassing/desorption

Part2: vacuum in accelerators

2-1 interaction residual gas - beam

- 2-1-a Coulomb scattering
- 2-1-b Bremsstrahlung
- 2-1-c Ionization energy loss
- 2-1-d ion accumulation

2-2 Interaction particles surface

- 2-2-a Synchrotron radiation an Photon stimulated desorption
- 2-2-b Ion stimulated Desorption
- 2-2-c Electron stimulated Desorption an electron-cloud

Part3: Technology evolution

3-1 Pressure distribution in accelerators

3-2 Distributed pumping

- 3-2-a getter pump
- 3-2-b NEG coating

What does vacuum mean?

Vacuum: an absence of matter ?

- Space where the molecules are strongly rarefied compared to atmospheric pressure

10^{-9} mbar ~ 25 millions/cm^3 at 20°C

Pollution source, background noise, parasitic interactions ....

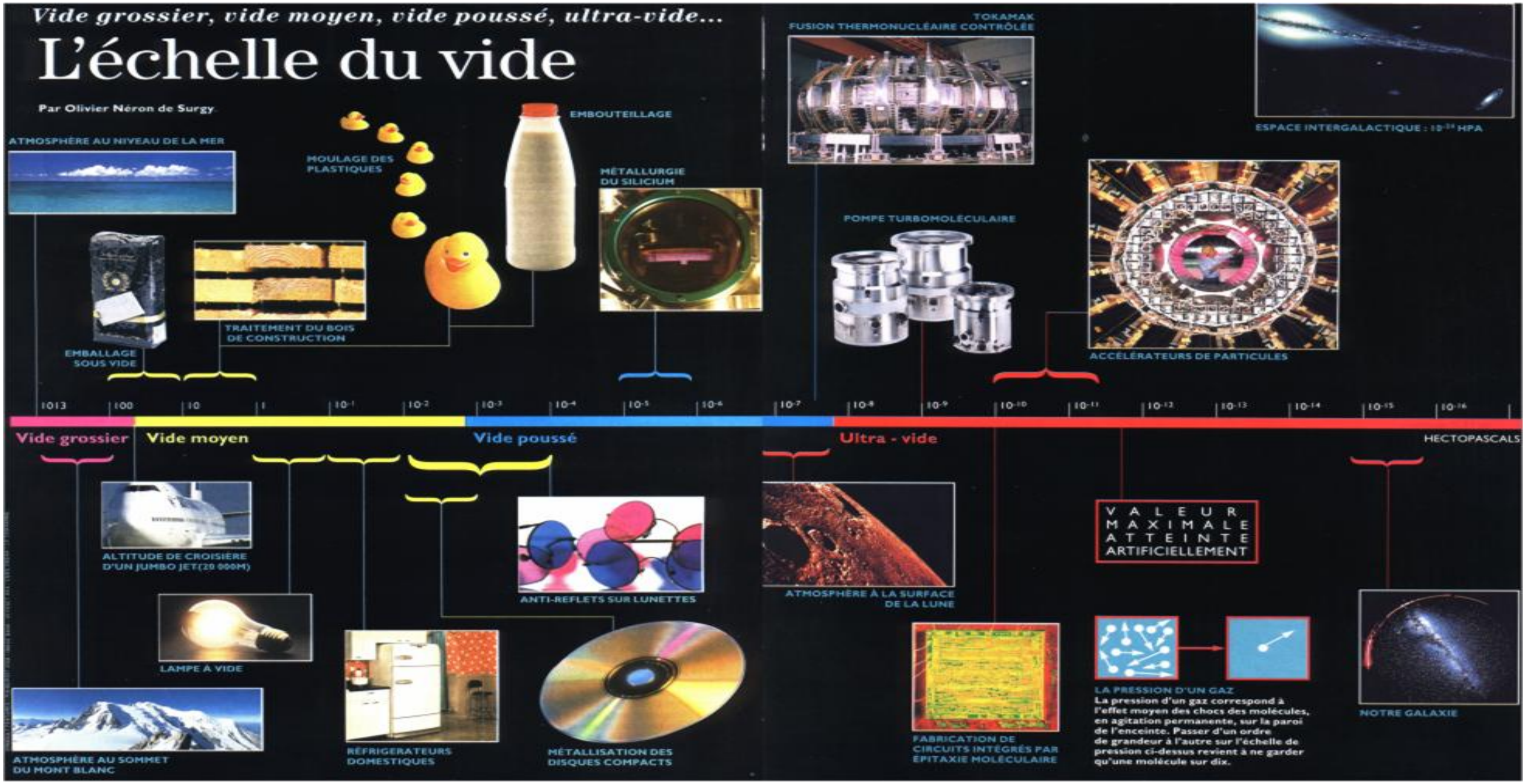
- quantum vacuum:

State minimum energy, vacuum fluctuation, ...

a vacuum: full of matter !!

The scale

Pressure 100 Pa(N/m²) = 1 mbar = 0,75 Torr



Maxwell-Boltzmann velocity distribution

$$\bar{V} = V_m = \sqrt{\frac{8R.T}{\pi.M}} \qquad V_{rms} = c = \sqrt{\frac{3R.T}{M}}$$

$$P(v)dv = \frac{dn}{n} = 4\pi\left(\frac{m}{2\pi kT}\right)^{3/2} v^2\, e^{-\frac{mv^2}{2kT}}\, dv$$

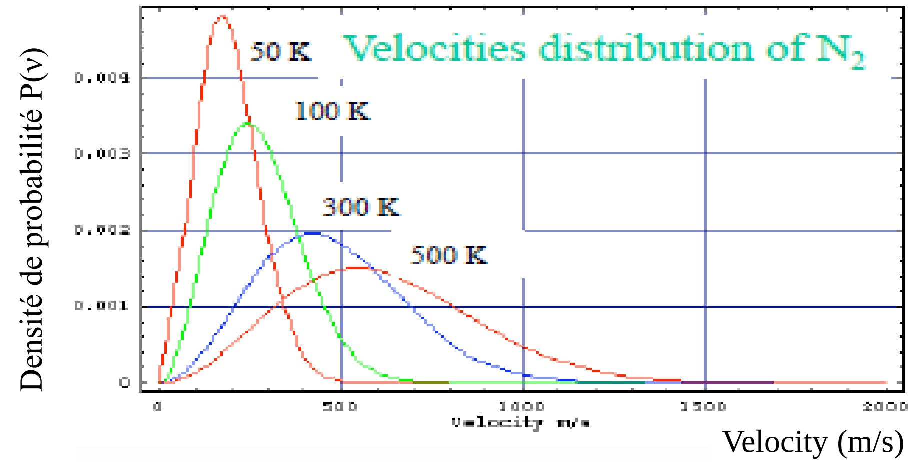
At 20°C

Ar ~ 394 m/s

N_2 ~ 471 m/s

He ~ 1246 m/s

Dependent upon composition of gas and temperature



residence time on the surface

Frenkel formula

$\tau_0 \sim 10^{-13}$ s

$$\tau = \tau_0 \cdot e^{\frac{E}{RT}}$$

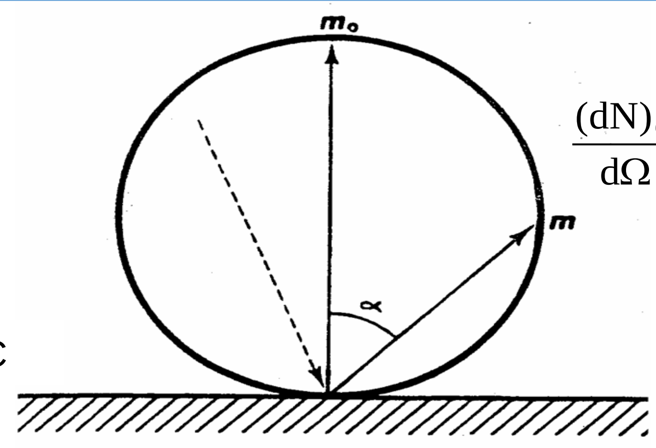
E desorption energy

20 < E < 25 kcal/mol

0,65 < E < 1,08 eV/molecule

→ 80 s < τ < 5 days at 20 °C

Increase pumping time



$$\frac{(dN)_\theta}{d\Omega} = \frac{N}{\pi}\cos(\theta)$$

Emission under cosine law

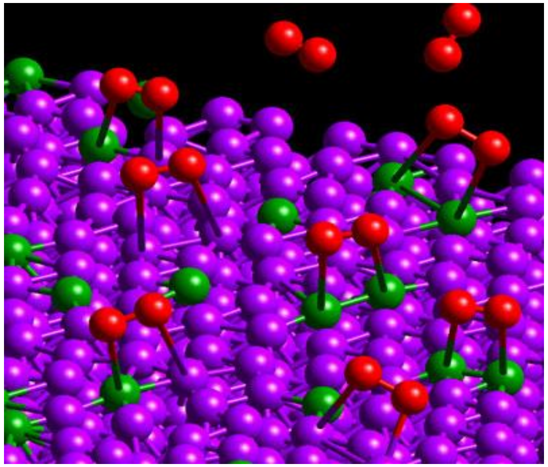
Monolayer formation time

And considering the molecule as spherical, for perfect atomic arrangement:

$$\tau = \frac{4}{d^2.n.v_m}$$

(very approximative)

n molecular density
d molecular diameter
V_m mean velocity



Order of magnitude one monolayer ~ 10^{15} molécules/cm^2

τ ~ 40 min at $P=10^{-9}$ mbar (N_2)
τ ~ 3 sec at $P=10^{-6}$ mbar (N_2)

The concept of monolayer can appreciate the cleanliness of the surface

Mean Free Path

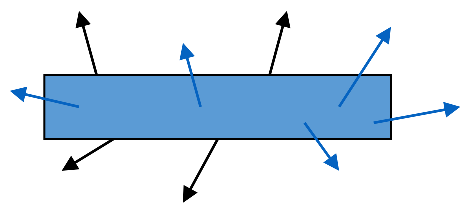
It is the path length that a molecules traverse between two succesives impacts with other molecules.

$$l_m = \frac{1}{\sqrt{2}\pi.d^2.n}$$

l_m ~ 64 km at $P=10^{-9}$ mbar (N_2)
l_m ~ 65 m at $P=10^{-6}$ mbar (N_2)
l_m ~ 0,65 mm at $P=10^{-1}$ mbar (N_2)

outgassing

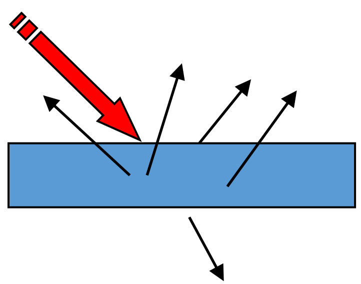
<u>Outgassing</u> is the spontaneous evolution of gas from solid or liquid.



desorption /degassing

<u>Desorption</u> is the release of adsorbed chemical species from the surface of a solid or liquid.

Particles (ions, photons, electrons,….)



Vacuum basis :

Desorption: gas flow

At the thermodynamic equilibrium

Gas flow $$Q = P.\frac{dV}{dt} = \mathbf{P.S} = \frac{dN}{dt}.K.T$$

S effectif pumping speed
N molecule number

$Pa.m^3/s$ (=10 mbar.l/s)

The outgassing rate τ : a gas flow per unit of surface

$$\tau = Q / A$$

A desorption area

$Pa.m^3.s^{-1}.m^{-2} = Pa.m.s^{-1}$ ($=10^{-3}$ $mbar.l.s^{-1}.cm^{-2}$)

Vacuum basis :

Importance of the gas flow

At the thermodynamic equilibrium, the pressure in the system is expressed by:

$$P = \frac{\sum Q}{S} + P_0$$

P_0 limit pressure of pumping system

S effectif pumping speed

Decrease of the work presssure P

⇨ **Increase the pumping speed** — Approximately 2 to 3 orders of magnitude with a high cost and limited effectiveness conductances

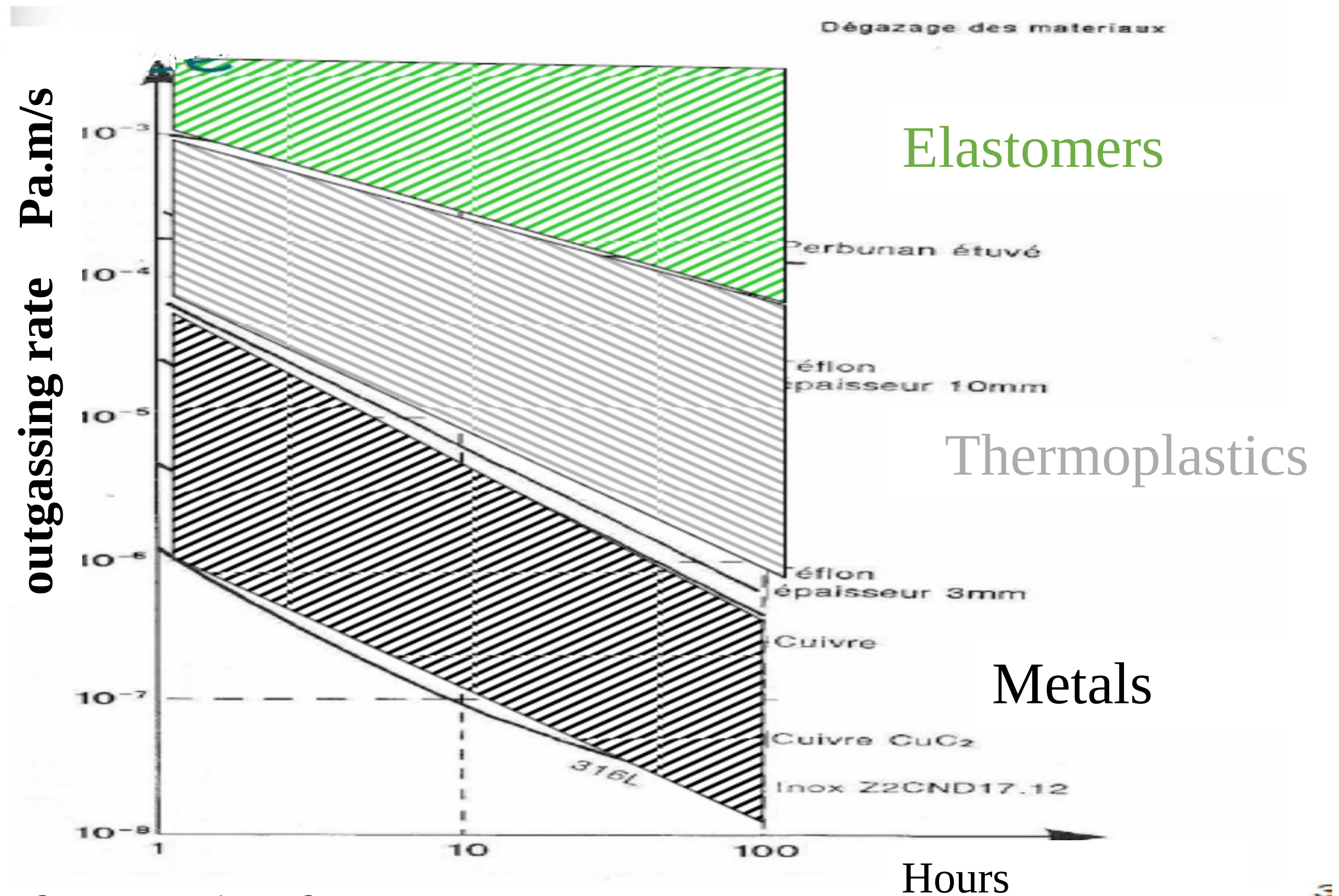
⇨ **Decrease the flow** — About 10 orders of magnitude depending on the choice of materials and treatments

Attention to minority surfaces

First of all decrease the outgassing rates

Vacuum basis :

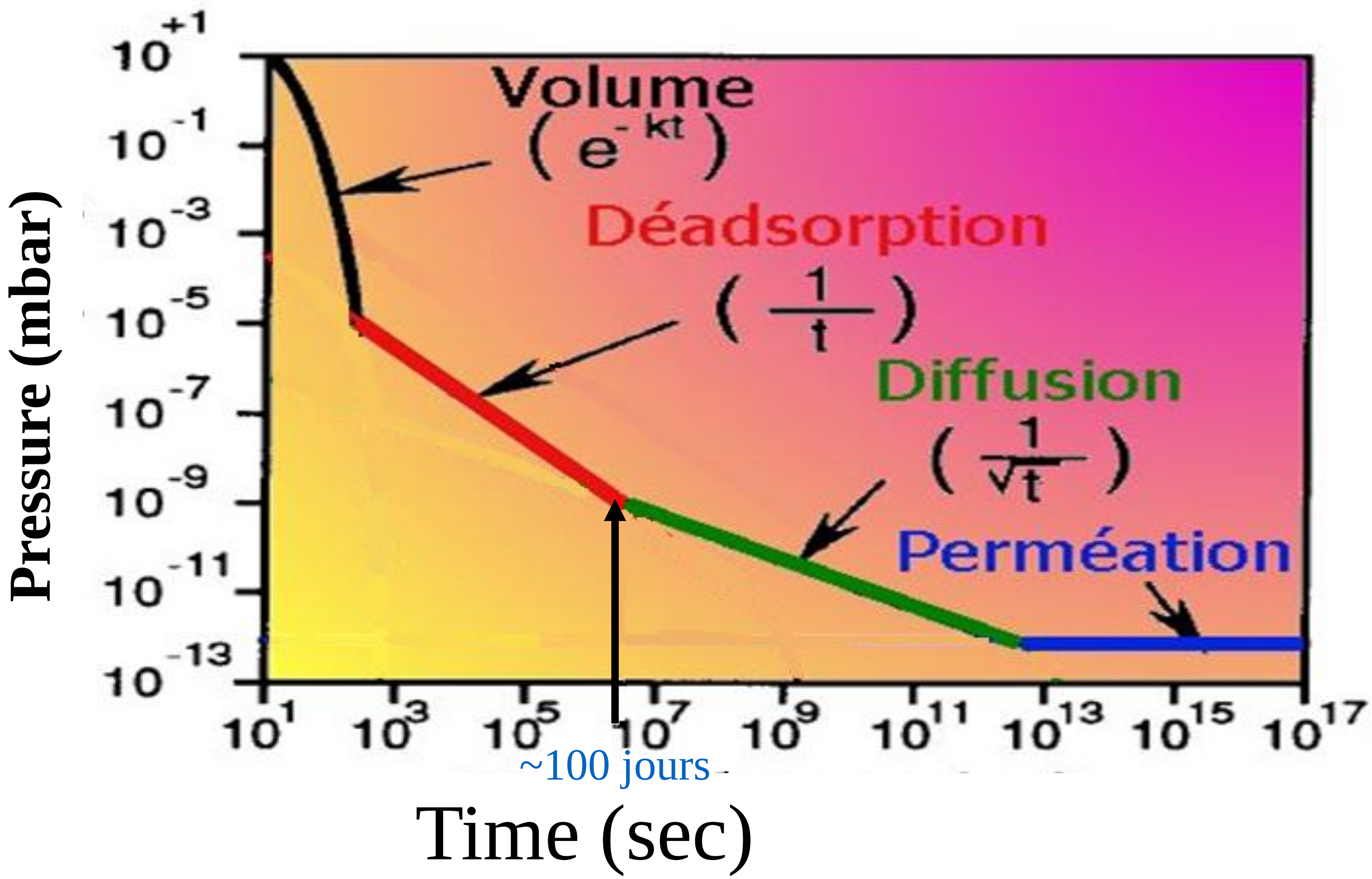
Time dependance of the outgassing flow rate for différent materials



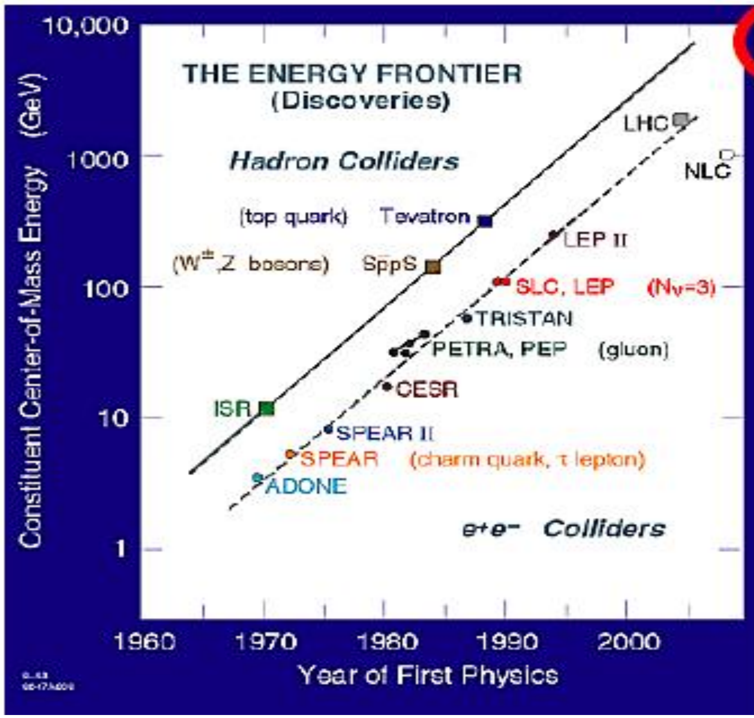
1 Pa.m/s = 10^{-3} mbar.l.s^{-1}.cm^{-2}

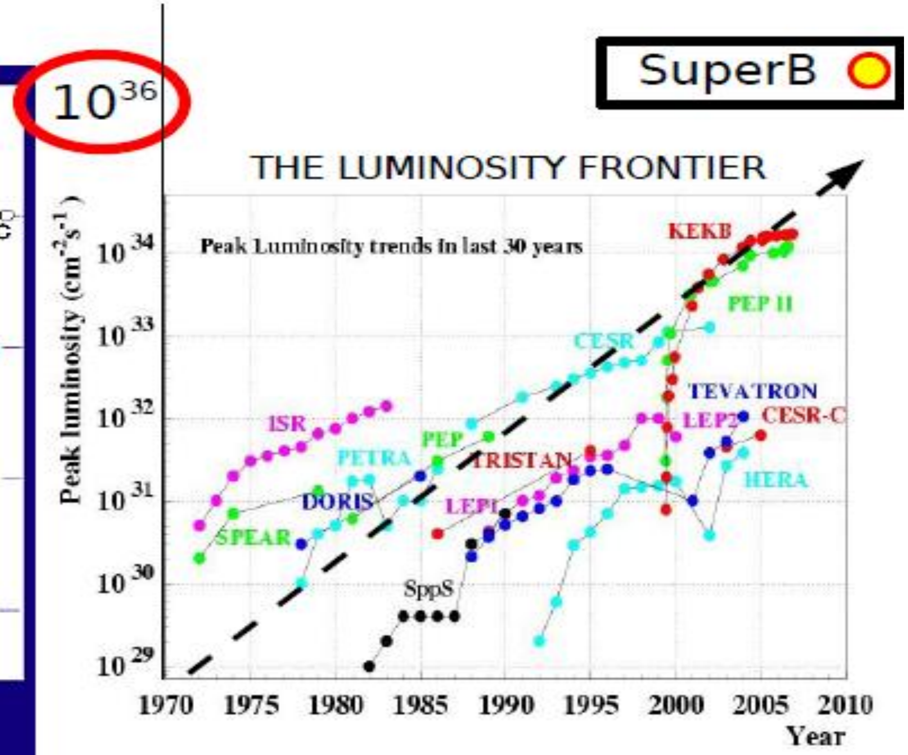
Vacuum basis :

The pressure vs. Time behavior of a typical vacuum system (metal chamber)



Vacuum in accelerators :





$$\mathcal{L} \sim f_{\rm coll} \frac{N^+ N^-}{4\pi \sigma_x \sigma_y} = 10^{36}\,{\rm cm}^{-2}\,{\rm s}^{-1}$$

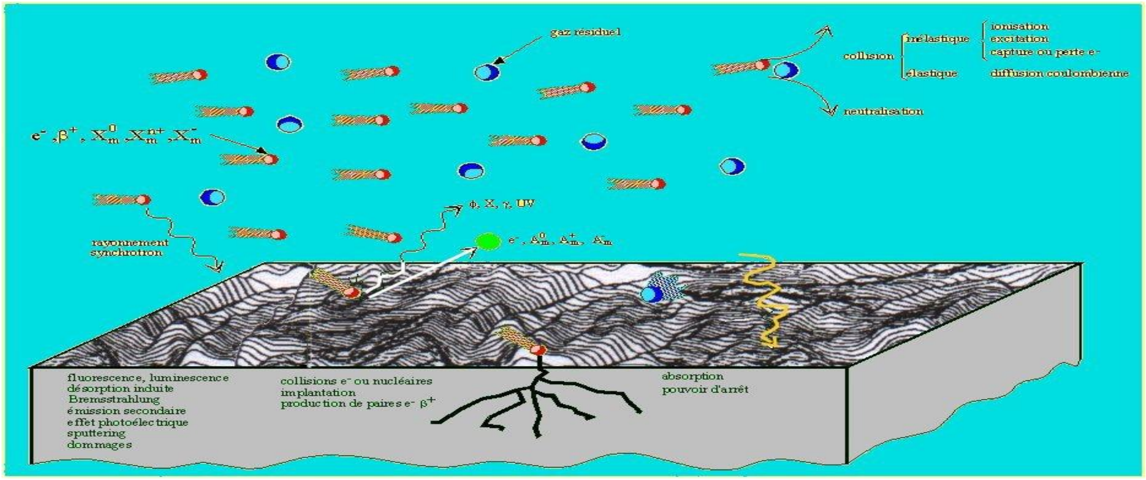
High luminosity

small beam, high intensity and high frequency

⇕

Level and quality of the residual gas (dynamic pressure ~ 10^{-9} mbar)

Vacuum in accelerators :



Beam & Vacuum & Surface: a difficult coexistence!

Interaction: Beam - résidual gas

- Changing the shape and the beam energy
- Secondary particule emission (ion,e-, photons)
- Loss of beam particules

Interaction: Particules (secondary, primary) - surface

- Desorption by electron, photon, ion impact
- Secondary emission

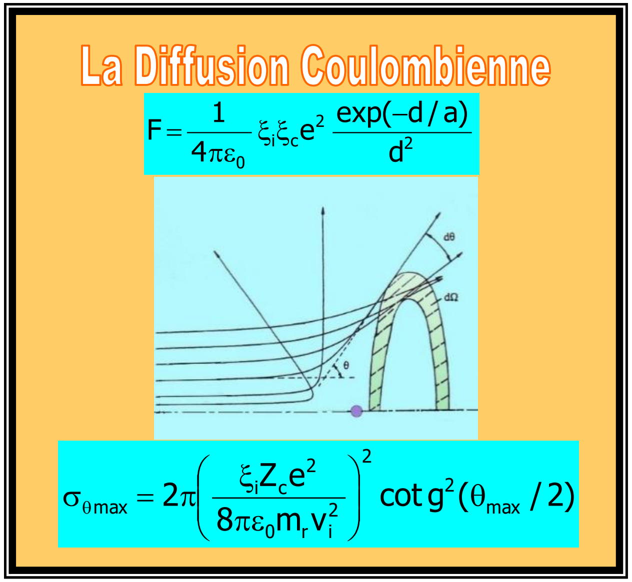
Interaction: Beam- residual gas

INTERACTION

- Elastic
  - **Single Coulomb scattering**
- Inelastic
  - **Bremsstrahlung**
  - **Ionization energy loss**
  - Nuclear reactions

Interaction: Beam- residual gas

Elastic interaction — Single Coulomb scattering



$$\frac{d\varepsilon}{dt} \propto Z^2 \cdot P$$

ε Emittance is proportional to residual gas pressure and depends square residual gas atomic number (Z)

Nuclear scattering LHC — Life time limit ~100h P~10-8 mbar H_2 equivalent

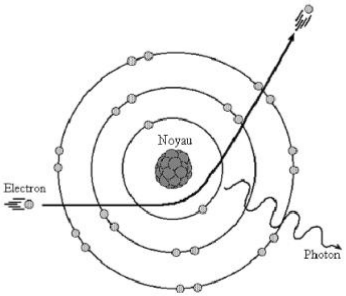
Synchrotron Soleil — Life time limit ~60h P~10-9 mbar N_2 equivalent E=2,15 Gev

Interaction: Beam- residual gas

→ Inelastic interaction
- **Bremsstrahlung**
- Ionization energy loss
- Electron capture
- Electron loss
- Nuclear reactions

Bremsstrahlung

Material	Z	A	Radiation length X_0 [g/cm^2] () is for gas	[cm]	Density [g/cm^3] () is for gas [g/ℓ]
H_2	1	1.01	61.28	865	0.0708(0.090)
D_2	1	2.01	122.6	757	0.162(0.177)
He	2	4.00	94.32	755	0.125(0.178)
Li	3	6.94	82.76	155	0.534
Be	4	9.01	65.19	35.3	1.848



$$\frac{dE}{E} = -\frac{dx}{\chi_0}$$

Valid for light particules (e+,e-)

$$\chi_{0[g/cm^2]} = \frac{714.6 A_c}{Z_c(Z_c+1)Ln(287/\sqrt{Z_c})}$$

Loss beam enregy

the radiation interacts with the surface → Desorption

A very strong dependence on the target atomic number is observed, which means that even a small amount of a heavy gas may have a higher influence on the lifetime than the usually dominating hydrogen content.

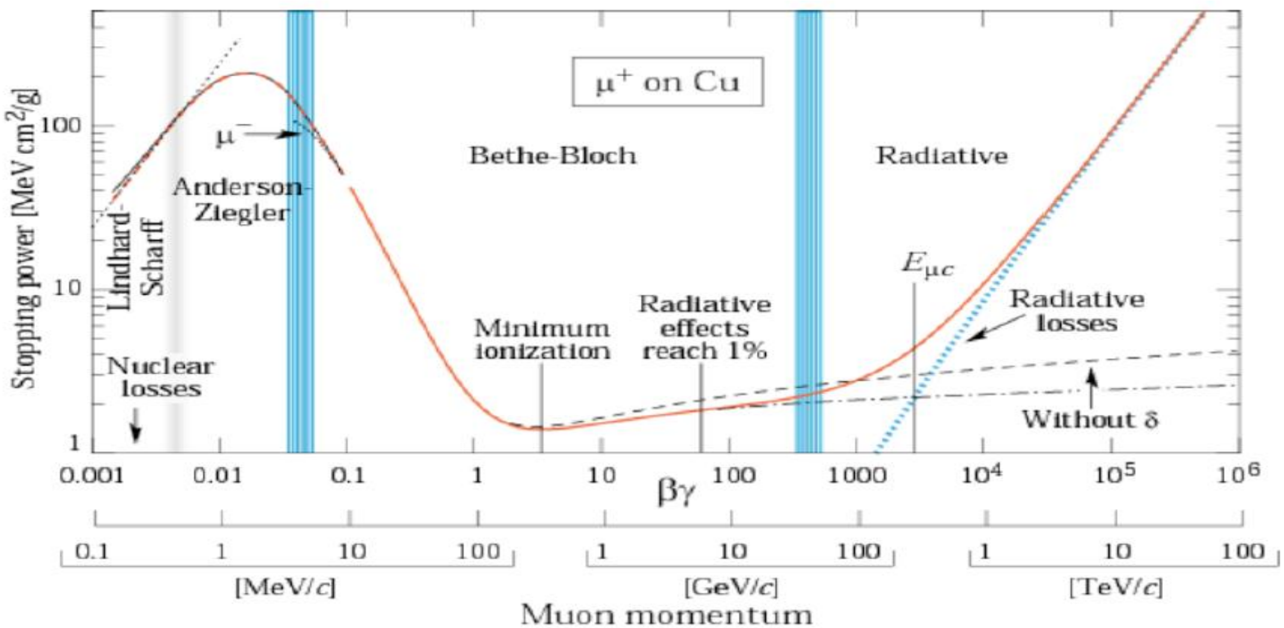
about 4.10^6 times lower for proton

Vacuum in accelerators :

Interaction: Beam – residual gas

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

Ionization energy loss



Loss beam energy **LHC** **ΔE ~ 1350 ev** per LHC revolution sur 7 Tev with 10-8 mbar (H2)

« SOLEIL » synchrotron

Life time limit ~ 60h With P~10-9 mbar N_2eq. E=2,15 Gev RF acceptance ε_{RF} =1,8 %

Secondary particule emission: **electrons, ions** → Interaction on the surface and desorption

Ion accumulation

negative charge beam

An important phenomenon for negative charges beam, for high current and for short bunch spacing

Pressure due to the ion containment

mechanism:

ionisation of residual gas by beam

↓

Electric field (e- beam) focuces ions in chamber center

↓

Defocusing of ions between two bunch

↓

Oscillations and ions trapping and accumulation

consequence:

The pressure (seen by beam) increases

↓

Influence on beam dynamics

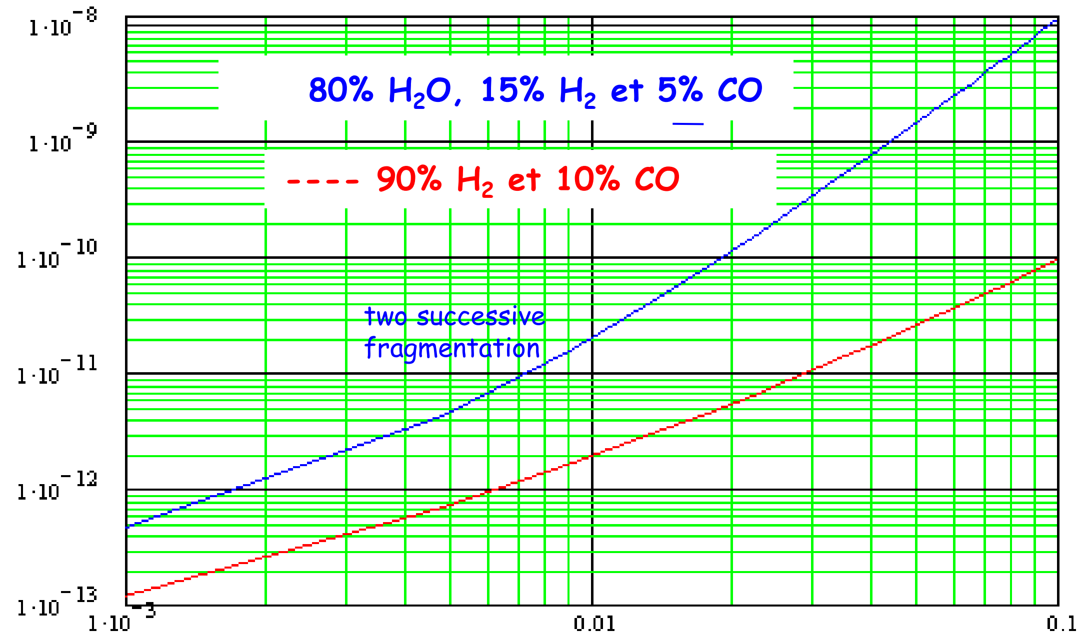
Ion accumulation

Ionic pressure seen by beam

Increased pressure due to the ion density.

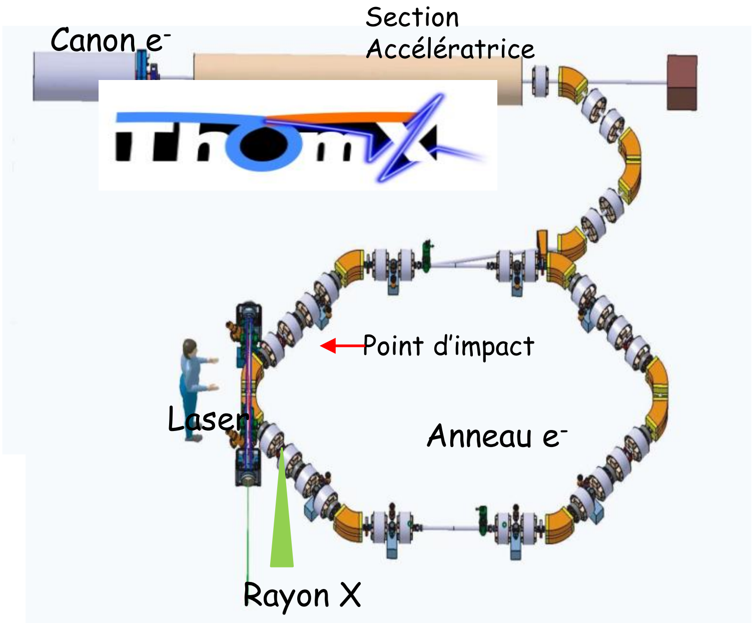
$$P_{ion} = \frac{I}{e} \cdot \frac{\eta^* \cdot k \cdot T}{\beta \cdot C \cdot \pi \cdot 2 \cdot \sigma_x \cdot \sigma_y}$$

Ionic pressure (mbar)



Time (sec)

At l' IP $\sigma_x=\sigma_y=0.07$ mm $P \approx 2{*}10^{-9}$ mbar



Solutions:

Electrodes + gap between two injections (5μs)

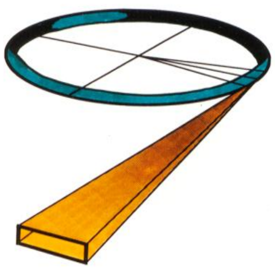
C. Bruni, J. Haissinski, T. Demma

Synchrotron radiation

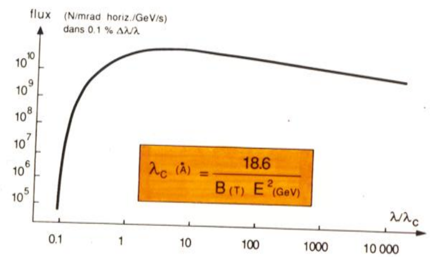
Any charged particle undergoing acceleration, centripetal or longitudinal, produces radiation.

Main source on circular colliders

RAYONNEMENT SYNCHROTRON : DIPOLES



Emission vers l'avant dans un angle très faible $\alpha \frac{1}{E}$



Spectre blanc

Power loss

electron $$P_0\,[W/m] = 88.57\,\frac{E[GeV]^4}{2\pi\,\rho[m]^2}\,I[mA]$$

proton $$P_0\,[W/m] = 7.79\,10^{-12}\,\frac{E[GeV]^4}{2\pi\,\rho[m]^2}\,I[mA]$$

Critical energy

$$\text{Electrons}: \varepsilon_c[eV] = 2.218\,10^{3}\,\frac{E[GeV]^3}{\rho[m]}$$

$$\text{Protons}: \varepsilon_c[eV] = 3.5835\,10^{-7}\,\frac{E[GeV]^3}{\rho[m]}$$

Flux

$$\dot{\Gamma}[photons.m^{-1}.s^{-1}] = 1.288\,10^{17}\,\frac{E[GeV]}{\rho[m]}\,I[mA]$$

$$\dot{\Gamma}[photons.m^{-1}.s^{-1}] = 7.017\,10^{13}\,\frac{E[GeV]}{\rho[m]}\,I[mA]$$

synchrotron radiation

some examples

		Soleil	KEK-B		LEP			LHC	
			LER	HER	Inj.	1	2	Inj.	Col.
Particule		e^-	e^+	e^-	e^-	e^-	e^-	p	p
Courant	mA	500	2600	1100	3	3	7	584	584
Energie	GeV	2.75	3.5	8	20	50	96	450	7000
R. courbure	m	5.36	16.31	104.46	2962.96			2784.302	
Puissance	**W/m**	**14 030**	**20 675**	**5 820**	**0.8**	**30**	**955**	**0**	**0.2**
En. critique	**eV**	**8 600**	**5 800**	**11 000**	**6 000**	**94 000**	**660 000**	**0**	**44**
Flux	**photons/m/s**	**$3\ 10^{19}$**	**$7\ 10^{19}$**	**$1\ 10^{19}$**	**$3\ 10^{15}$**	**$7\ 10^{15}$**	**$3\ 10^{16}$**	**$7\ 10^{15}$**	**$1\ 10^{17}$**
Dose a 3000 h	photons/m	$4\ 10^{26}$	$8\ 10^{26}$	$1\ 10^{26}$	$3\ 10^{22}$	$7\ 10^{22}$	$3\ 10^{23}$	$7\ 10^{22}$	$1\ 10^{24}$

Vacuum in accelerators :

Photon stimulated desorption

photodesorption Yield η

$$\eta = \frac{\text{desorbed molecule}}{\text{Incident photons}}$$

→ material type, surface finish, energy and particle type, incidence angle, particule dose

Experimental determination

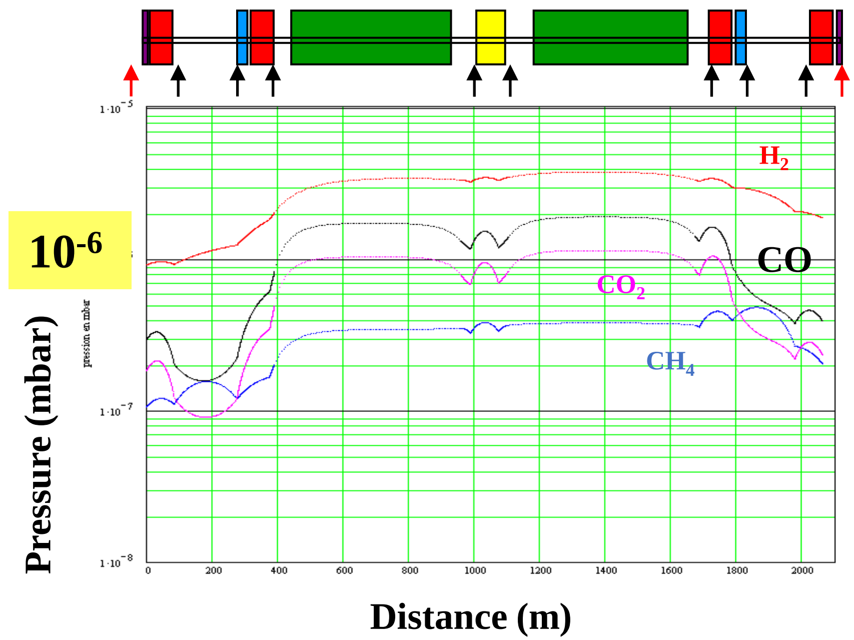
photodesorption Yield η at machine start-up

gas	η (mol/ph)
H_2	~ 1.10^{-3}
CH_4	~ 1.10^{-4}
Co	~ 5.10^{-4}
Co_2	~ 3.10^{-4}

For baked Cu 150°C and Ec = 4,5 Kev

Gröbner and all, JVSTA 12(3) 1994

the pressure distribution in Cell HER (SUPERB) with synchrotron radiation at machine start-up



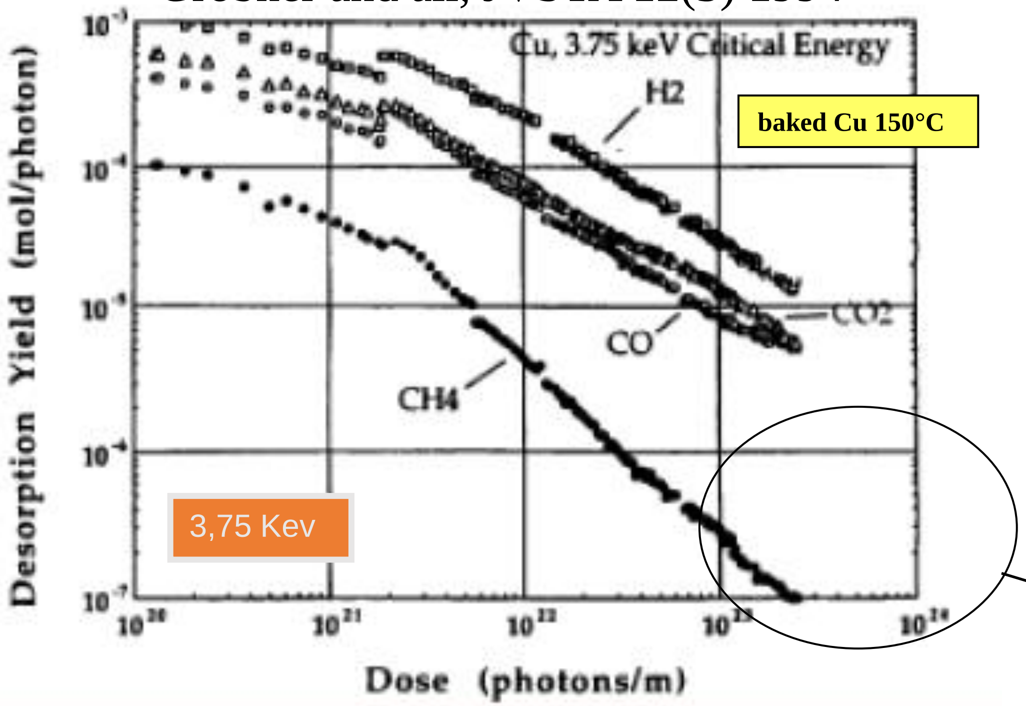
The static pressure increases by several orders of magnitude due to dynamic effects

photodesorption

Conditioning - Scrubbing

Surface conditioning according to the received dose

Gröbner and all, JVSTA 12(3) 1994



After conditionning

D = photon dose 10^{25} photons/m ~360 A.h

gas	η (mol/ph)
H_2	~ 6.10^{-7}
CH_4	~ $2.5.10^{-8}$
Co	~ $2.5.10^{-7}$
Co_2	~ $2.5.10^{-7}$

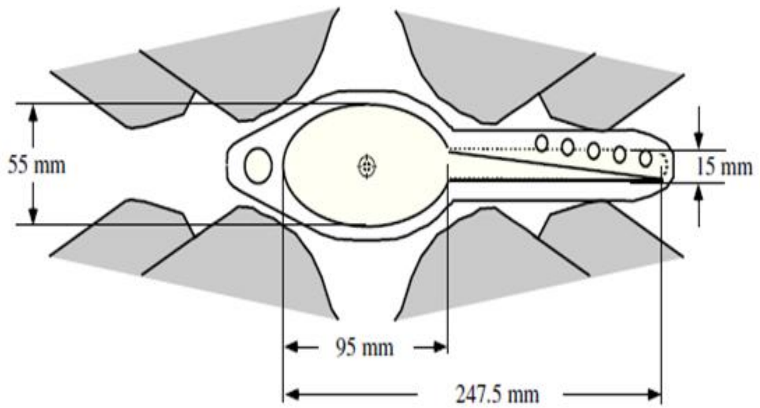
$$\eta = \eta_0 \cdot \left(\frac{D}{D_0}\right)^{-\alpha}$$

$\alpha = 0.84$

Scrubbing but needed time

Photon stimulated desorption

Important implications for the design



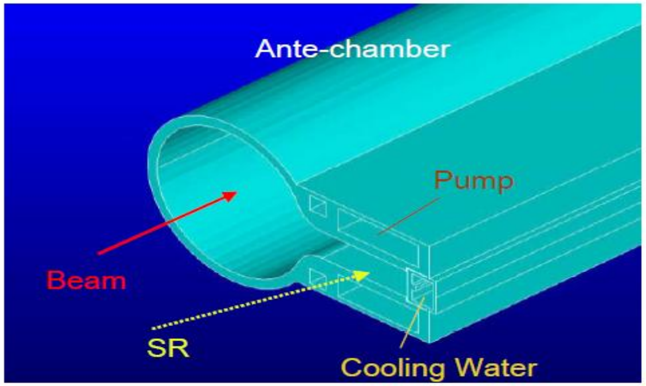
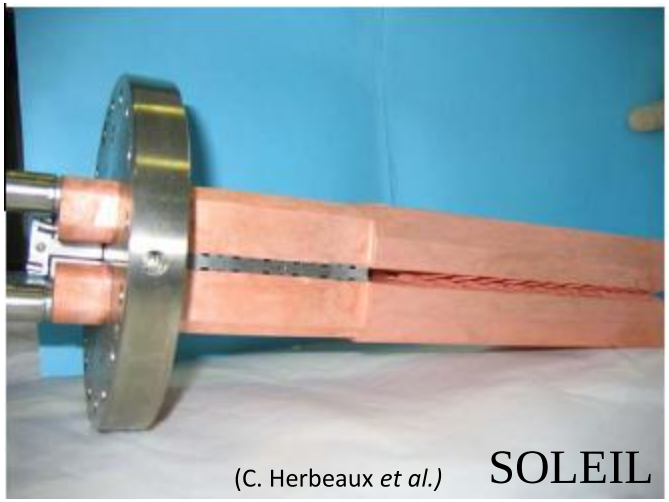


Figure 1: Typical structure of ante-chamber for the LER of Super-KEKB.



SOLEIL

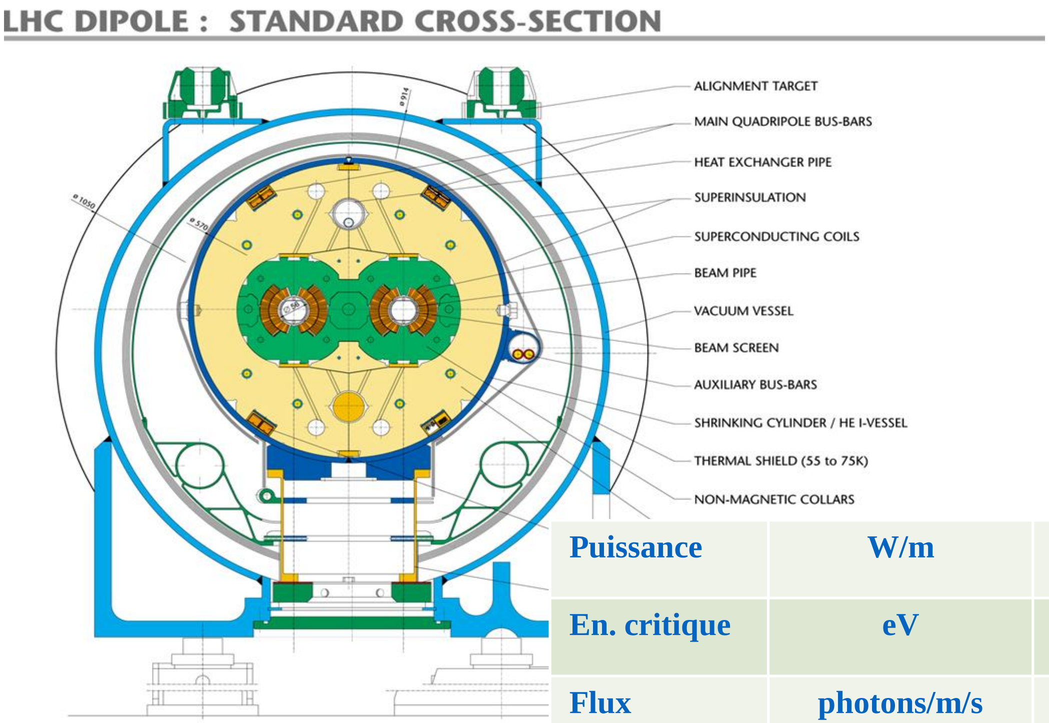
Puissance	**W/m**	**14 030**
En. critique	**eV**	**8 600**
Flux	**photons/m/s**	**$3\ 10^{19}$**

Absorbing power "crotch" : GLIDCOP copper cooled by water(256 W / mm2)

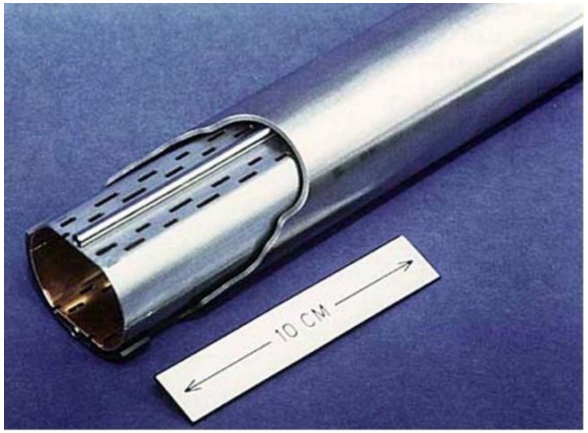
Photon stimulated desorption

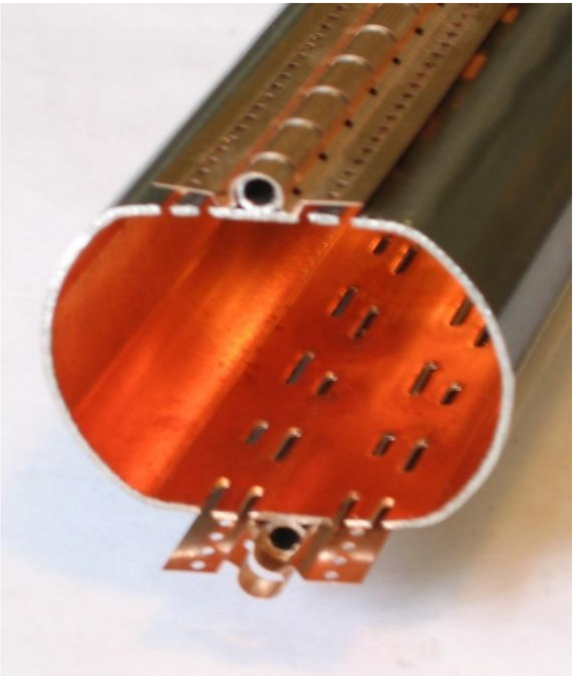
LHC Dipole Vacuum System

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



Puissance	W/m	0.2
En. critique	eV	44
Flux	photons/m/s	$1\ 10^{17}$





Courtesy N. Kos CERN AT/VAC

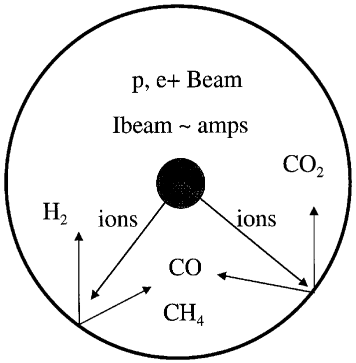
V. BAGLIN

Ion stimulated desorption

Positive charge beam

The mechanism:

ionization of the residual gas by the beam
↓
Acceleration of these ions by the beam electric field (e +, p)
↓
The ions/surface impact creates a molecular desorption

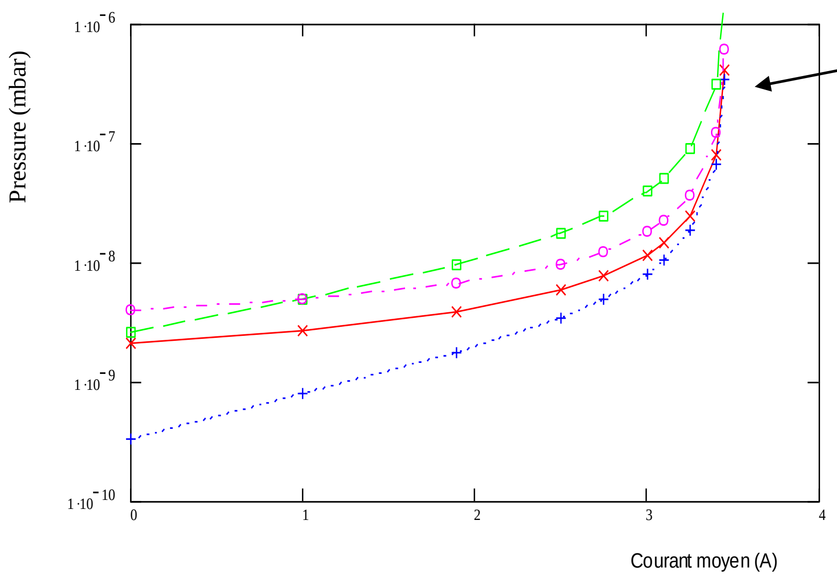


The important parameter

Rendement η = $\frac{\text{desorption molecular}}{\text{Incident ions}}$

$$\textbf{flux:}\quad \Gamma_{ion} \approx \sigma \frac{I}{e} \cdot \frac{\beta \cdot P}{k \cdot T}$$

HER (SuperB) simulation



pressure divergence

$$I_{crit} \approx \frac{1}{\eta} \frac{eS}{\sigma}$$

← Effective Pumping speed (S)

← Cross section (σ)

(Avoid heavy gas)

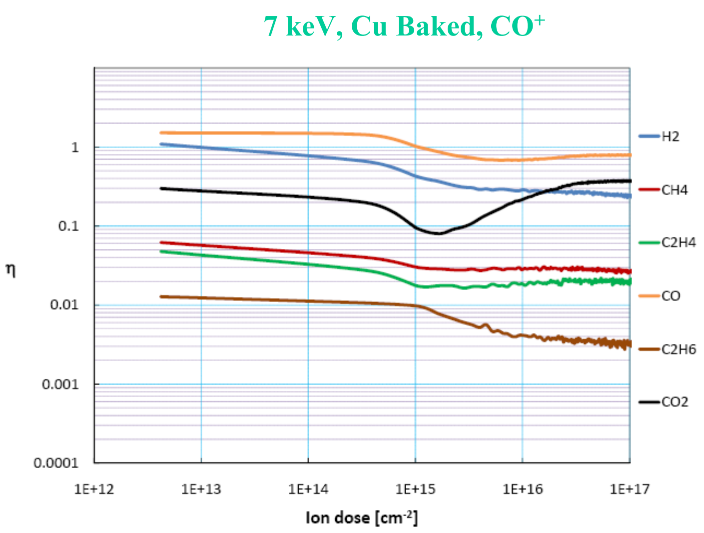
- High current accelerators : ISR, SNS, LHC…

Ion stimulated desorption

Ionodesorption Yield η → material type, surface finish, energy and particle type, incidence angle, particle dose

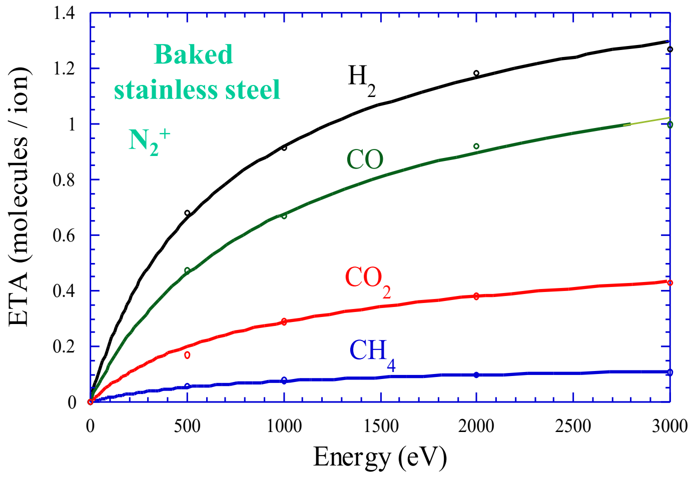
Experimental determination

η versus ion dose



G. Hulla, PhD Thesis, Vienna Tech. U, 2009

η versus energy



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

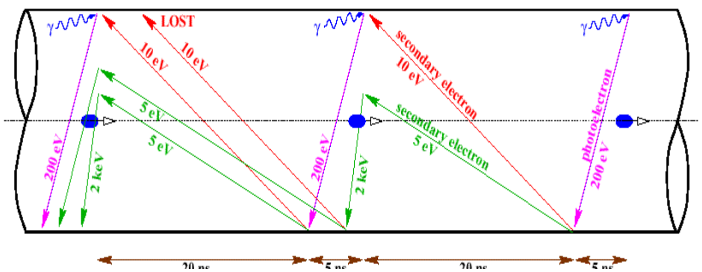
LHC : ion dose ~ 3 10^{15} ions/(cm2.an)

Inefficient scrubbing !!

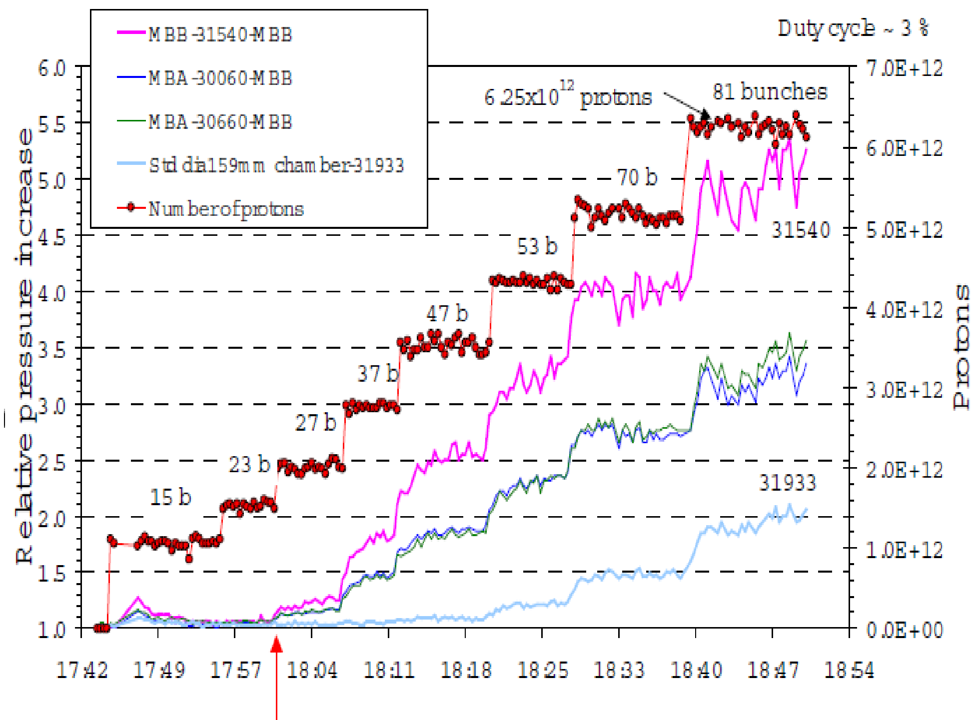
Electron-Cloud / Electron Stimulated Desorption

KEKB, PEP II, SPS ~ année 2000
RHIC, LHC

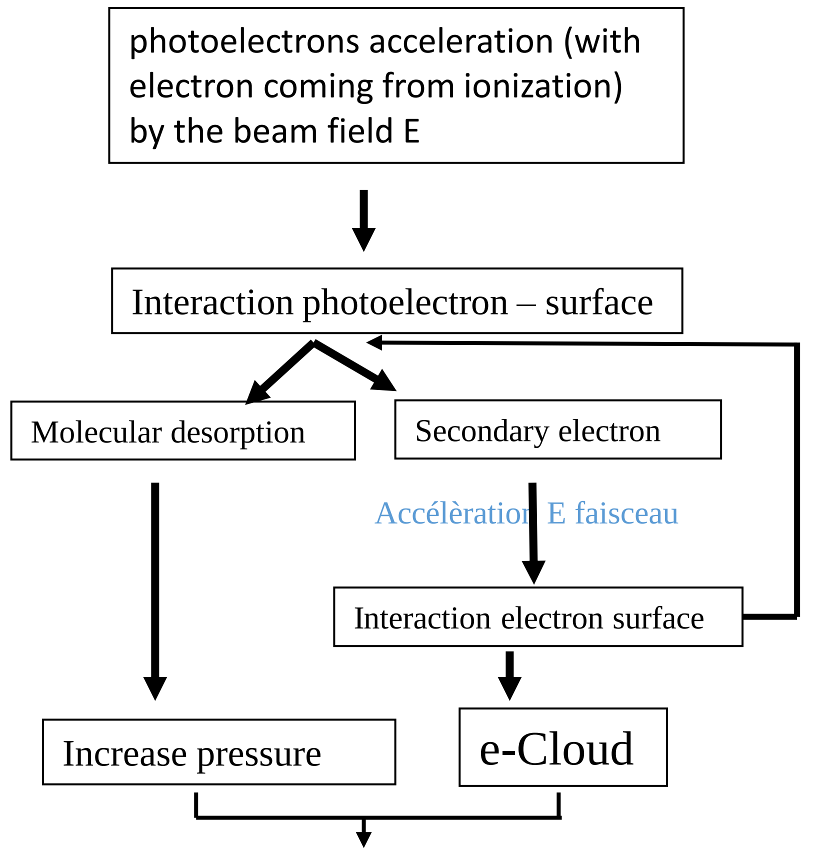
The mechanism:



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



J.M. Jimenez *et al.*, EPAC 2000, Vienna, Austria



Increase emittance and beam loss, heat load, decrease luminosity

Electron-Cloud / Electron Stimulated Desorption

An important phenomenon for positive charges beam, for high current and for short bunch spacing

Main parameters:

- Beam structure(size,time between bunch)
- bunch/charge
- chamber size and geometry
- secondary electron yeld (SEY)
- photo-electrons rate
- photons /electrons reflected
- electron stimulated desorption (ESD)

↓ reduction

Some Solutions

material (coating), surface finish, scrubbing,

Cleaning electrodes, solenoidal field,

Geometry chamber (antichamber)

Electron-Cloud / Electron Stimulated Desorption

Surface conditionning by electron impingement

(Scrubbing)

Reduction ESD and SEY

Secondary electron yeld (SEY)

$$\text{SEY} = \frac{\text{number of emitted electrons (secondary)}}{\text{number of impinging electrons (primary)}}$$

Electron Stimulated Desorption (ESD)

ESD versus e- dose

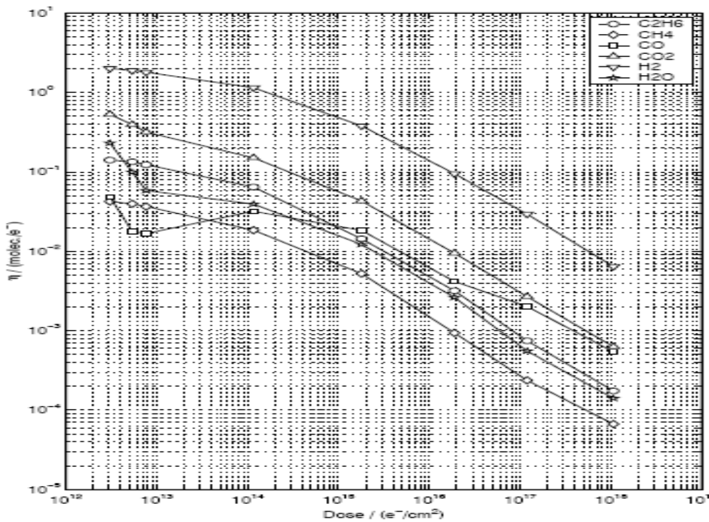
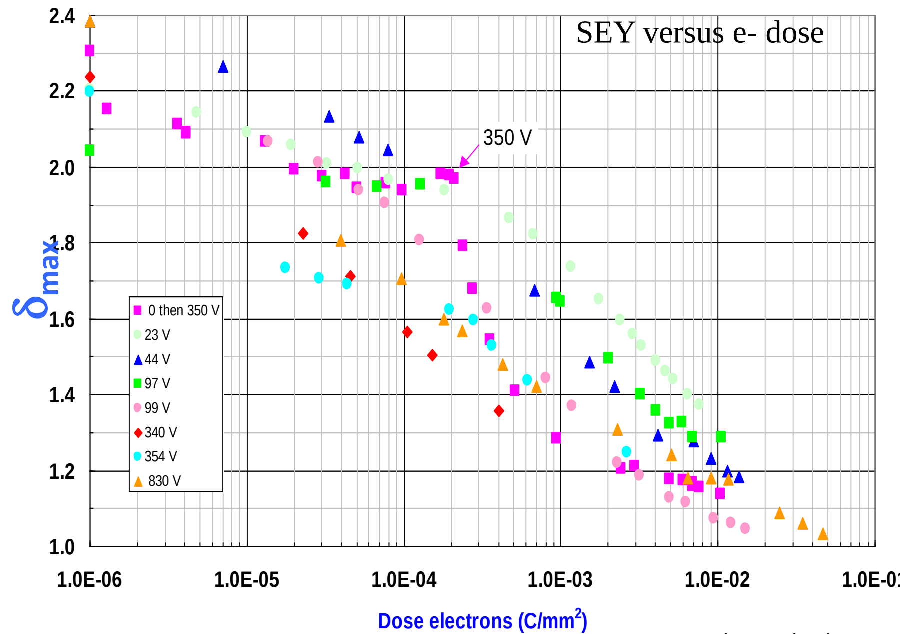


Figure 3: Effect of the electron dose on the electron induced desorption yield of an unbaked copper sample. The electron energy during bombardment and measurement was 300 eV.

G. Vorlaufer *et al.,* CERN VTN, 2000



V. Baglin *et al.,* Chamonix, 2001

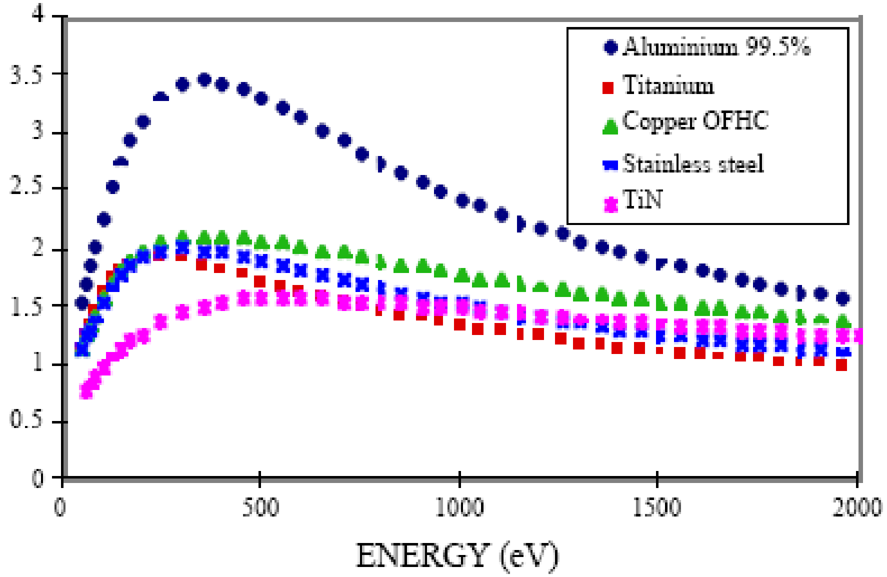
Carbone layer on surface (AES, XPS,..)

Scrubbing but needed time

Electron-Cloud / Electron Stimulated Desorption

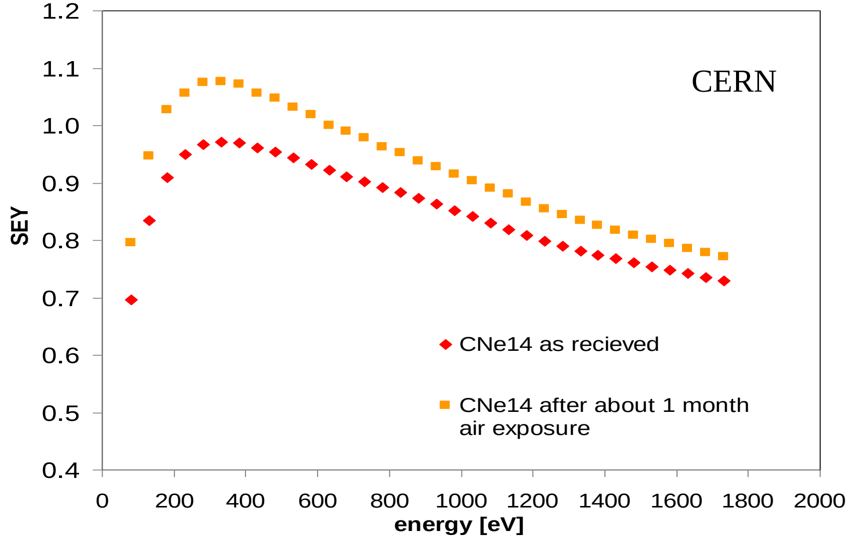
SEY Reduction

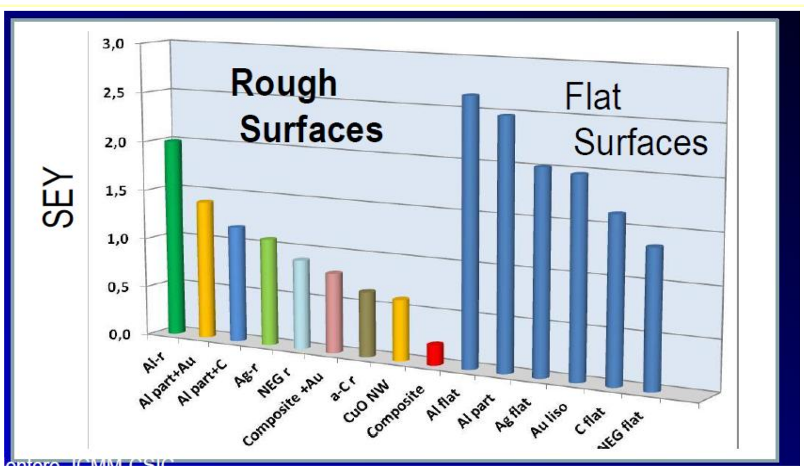
Material and relief surface



New

Amorphe carbone coating





Coating TiN, TiZrV, amorphe C coating on vacuum chamber

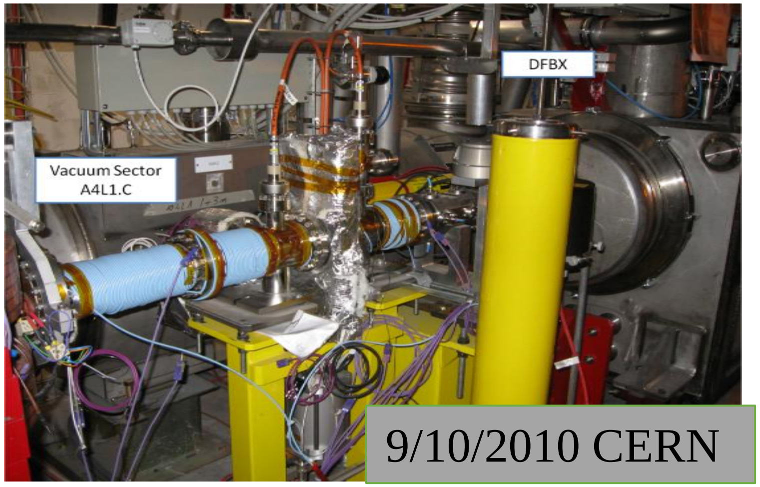
Isabel Montero, ICMM-CSIC (AEC 2012)

Vacuum in accelerators :

interaction particules- surface

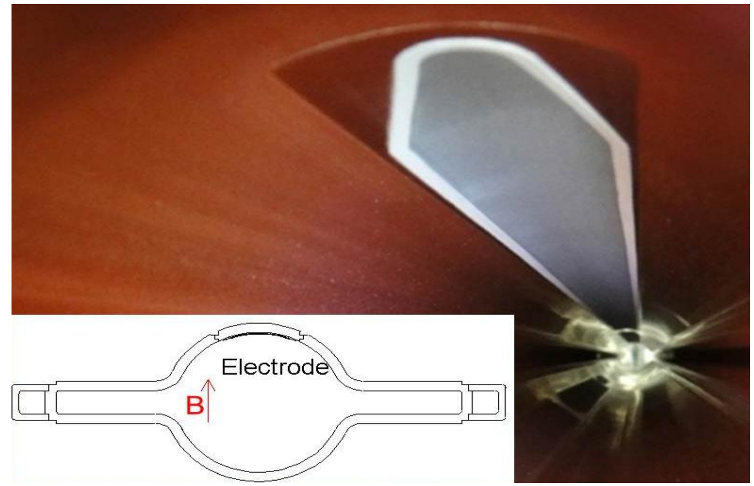
Electron-Cloud / Electron Stimulated Desorption

External solenoid on chamber



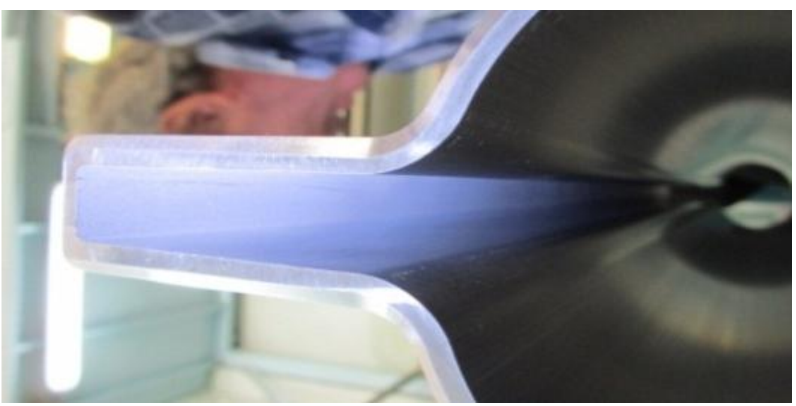
Other solution for e-Cloud decrease

Clearing electrodes



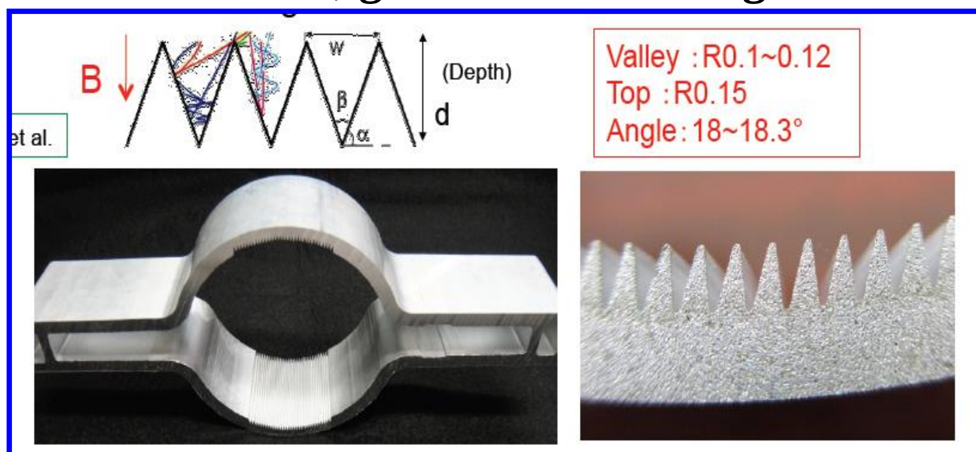
Y. Suetsugu SuperKEKB

Antichamber and Rough surface at the side wall (Ra ~20) reduces the photon reflection.



Y. Suetsugu SuperKEKB

antichamber, grooves and coating TiN



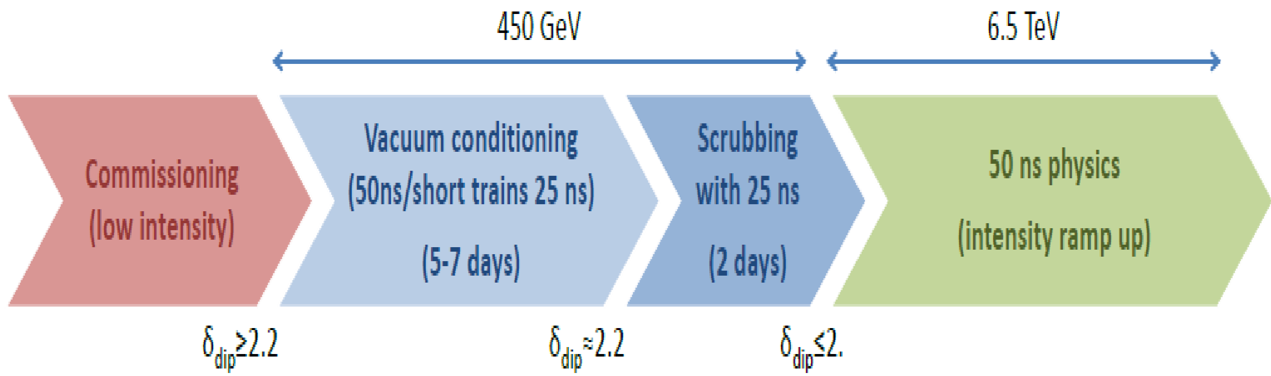
SuperKEKB Dipole Chamber Extrusion

Electron-Cloud / Electron Stimulated Desorption

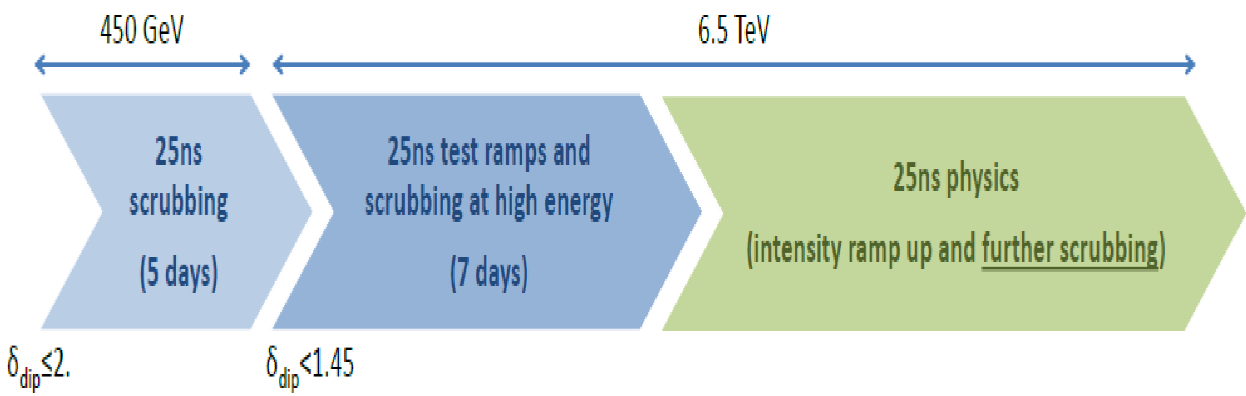
Scrubbing strategy for operation restart in 2015

Requirements for operation with 50 ns beams:

After the 2013-14 Long Shutdown, the Secondary Electron Yield of the beam screen in the arcs will likely be reset to values higher than 2.3, as it was before the 2011-2012 machine scrubbing.



Further requirements for operation with 25 ns beams:



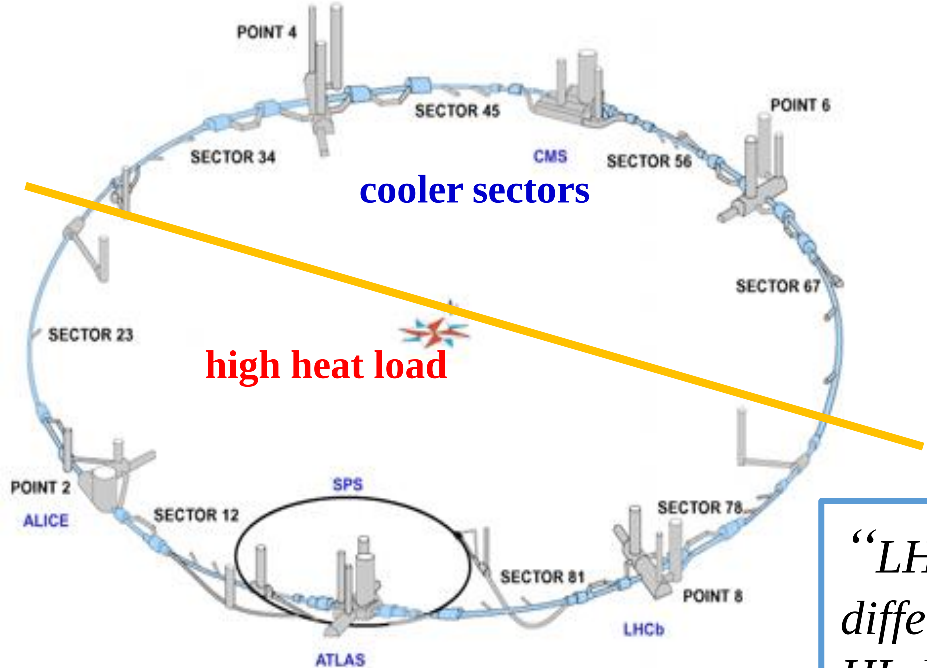
According to the 2012 experience, the proposed scrubbing run(s) will not completely suppress the EC in the LHC. Further scrubbing will have to be achieved during the physics run implying a slow down of the intensity ramp-up process due to heat load, emittance blow up and poor lifetime.

Electron-Cloud / Electron Stimulated Desorption

Frank Zimmermann ECLOUD'18

G. Iadarola, L. Tavian, et al, 2018

what is different in the high-load sectors?
lowest heat in sectors around CMS



highest heat in sectors around ATLAS

arc heat loads already **challenge for LHC Run 2 with 25 ns**

- **close to cryogenics limits** in some of the arcs
- heat load much **larger** than expected from **impedance and synchrotron radiation**
- large **differences observed between sectors**
- **e-cloud** most plausible explanation

extrapolated HL-LHC heat loads for high-load sectors **not acceptable!**

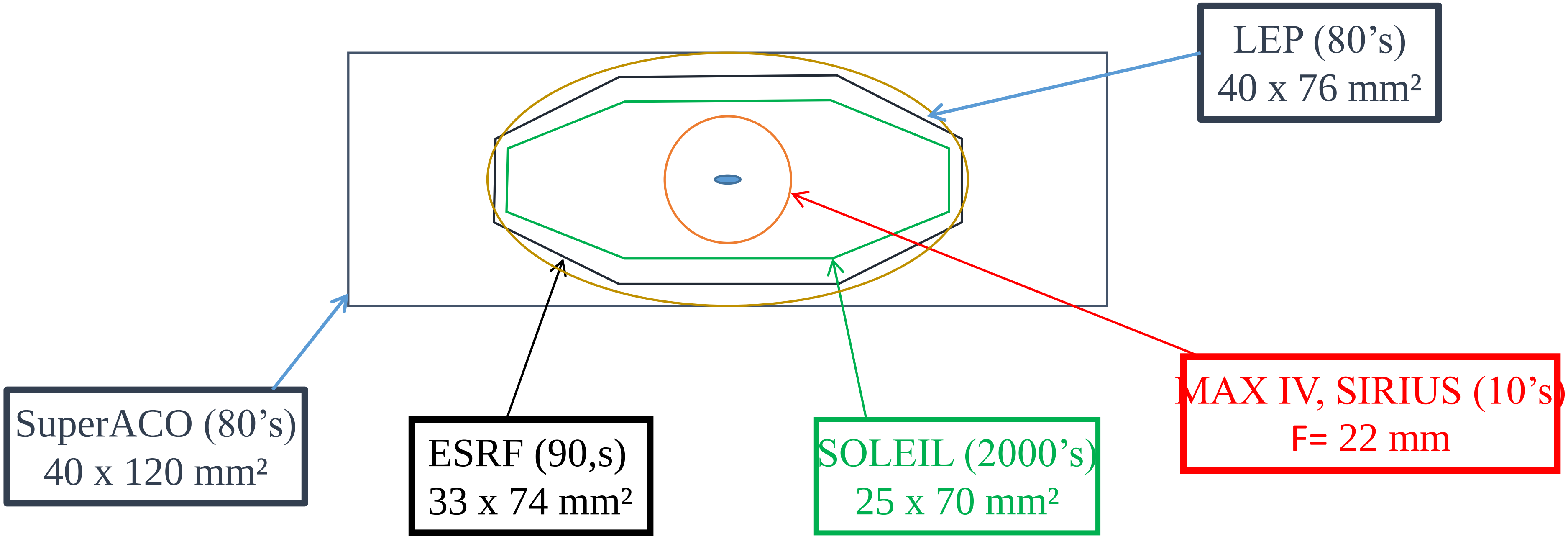
"LHC electron cloud is top priority. If e-cloud heat differences between sectors are not understood and HL-LHC not mastered, CERN may be shut down!"
Norbert Holtkamp, Chair CERN MAC, 28 January 2018

Evolution vacuum technology

size evolution of vacuum chambers on Accelerators

Size vacuum chambers are constrained by the beam performance expected by the magnetic system including:

- Strong focus therefore reduces throat circle
- Low distance between the magnets.

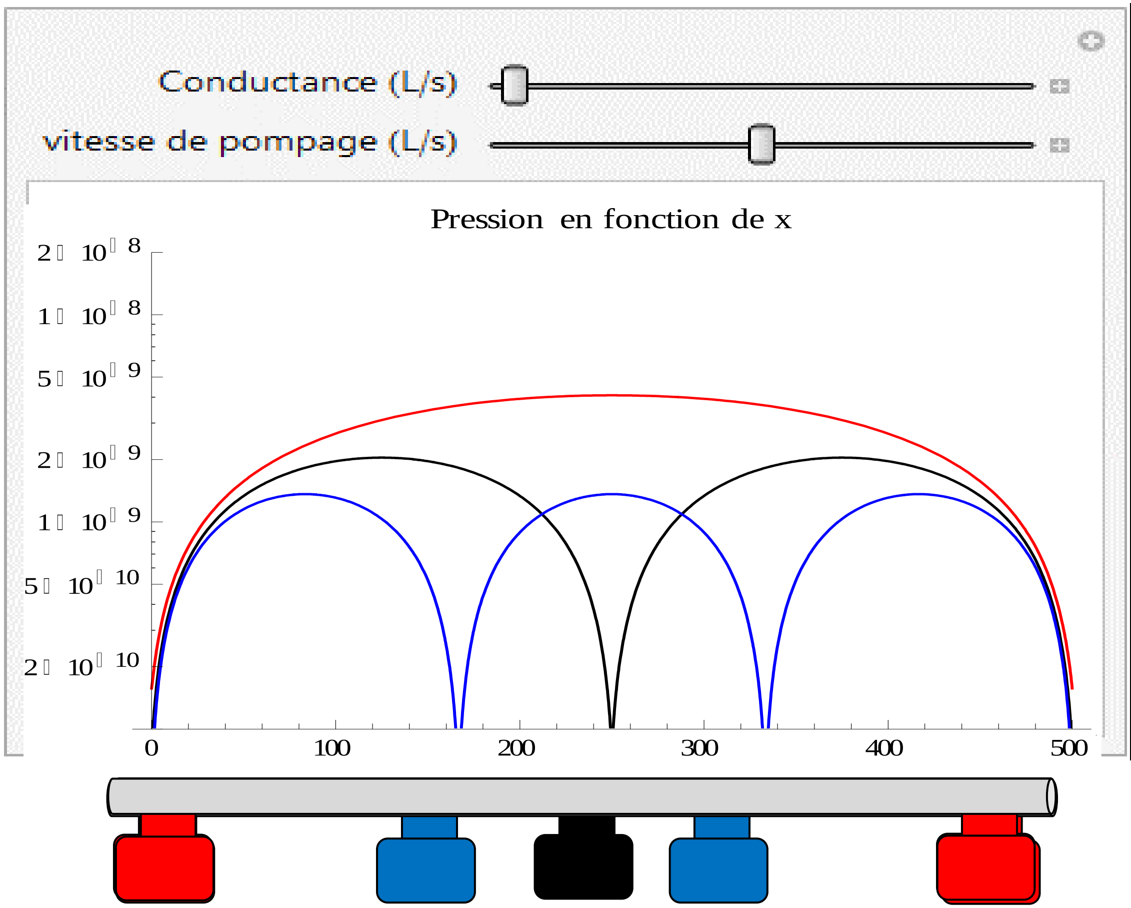


C. Herbeaux SFP – Journées des accélérateurs, Roscoff, SFP 2013

Evolution vacuum technology

Consequences : size room more and more small

Significant decrease in conductance and increasing the maximum pressure



$$P_{mean} = A \cdot \tau \cdot L\left(\frac{1}{12C} + \frac{1}{S}\right)$$

$$P_{\max} = A \cdot \tau \cdot L\left(\frac{1}{8C} + \frac{1}{S}\right)$$

τ outgassing rate C conductance

A circonference of chamber

if S>> 8C then $P_{max} \sim A\tau L/(8C)$

Decrease of Pmean and Pmax is limited by the conductance C :

- Reduce outgassing rate (τ) and the stimulated desorption

- Reduce length L

distributed pumping

Evolution vacuum technology

distributed pumping

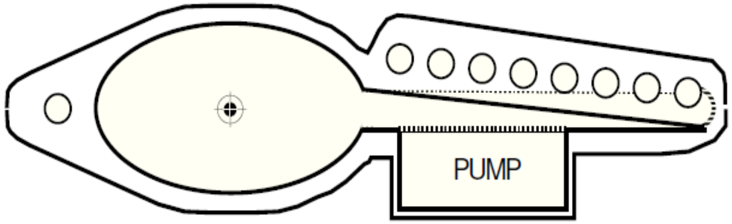
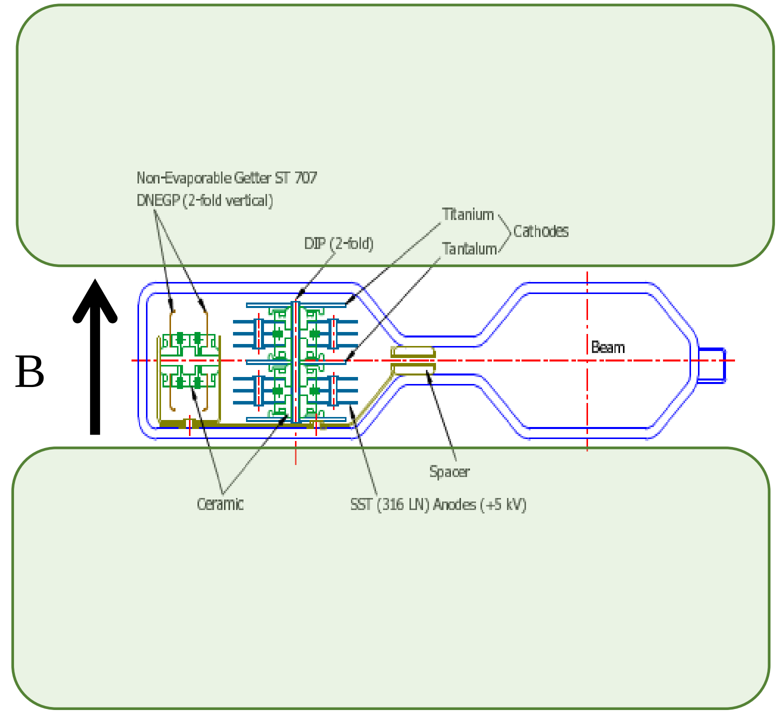
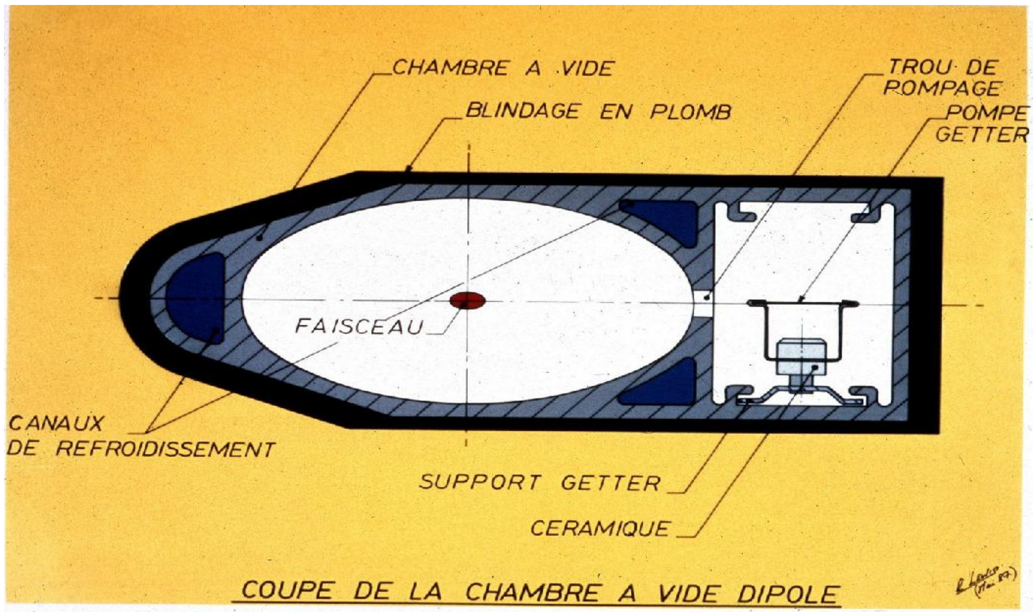
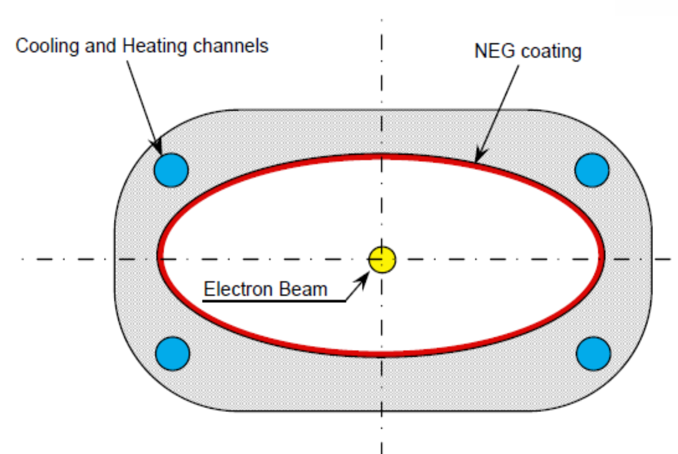


Figure 3-108. *LER dipole vacuum chamber concept. Inside dimensions match those of Fig. 3-107.*







LHC

LEP Design (CERN LEP Vacuum group)

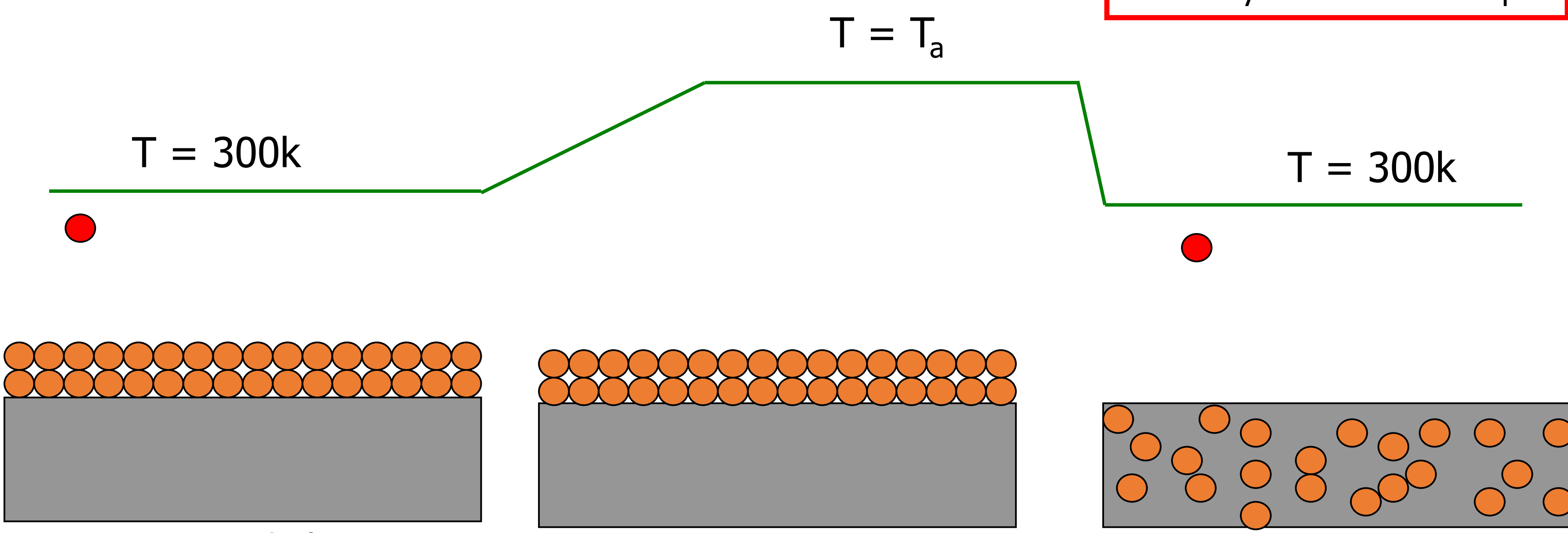
Non evaporable Getter (NEG)

Principle

coating of metal alloy (NEG) on the walls of vacuum chambers or on a strip

- **coating Zr-Al, Zr-V-Fe, Ti-Zr-V, ….**
- **Ta activation temperature**

The alloy becomes a Pump!



Native oxide layer

No pumping

Heating in vacuum
Oxide dissolution -> activation

Paolo Chiggiato

Reactive metallic surface
Pumping

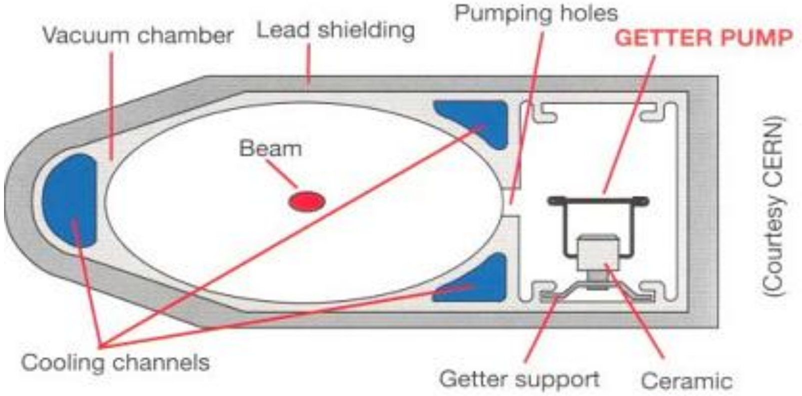
CERN European Organization for Nuclear Research

NEG strips

St101 NON-EVAPORABLE GETTER (Zr Al)
activation temperature at 700°c

St707 NON-EVAPORABLE GETTER (Zr 70-V 24.6-Fe 5.4 wt%)
activation temperature at 450°c

NEG materials are embedded in a constantan ribbon that is heated by the Joule effect



LEP – (CERN) 24 km de ruban installés
P< 10^{-11} mbar

The high temperature activation NEG can generate mechanical stresses in the vacuum chamber.

Need to have an antechamber

C. Herbeaux SFP – Journées des accélérateurs, Roscoff, SFP 2013

NEG strips

Design and construction of the SuperKEKB vacuum system

Yusuke Suetsugu,[a] Ken-ichi Kanazawa, Kyo Shibata, Takuya Ishibashi, Hiromi Hisamatsu, Mitsuru Shirai, and Shinji Terui
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

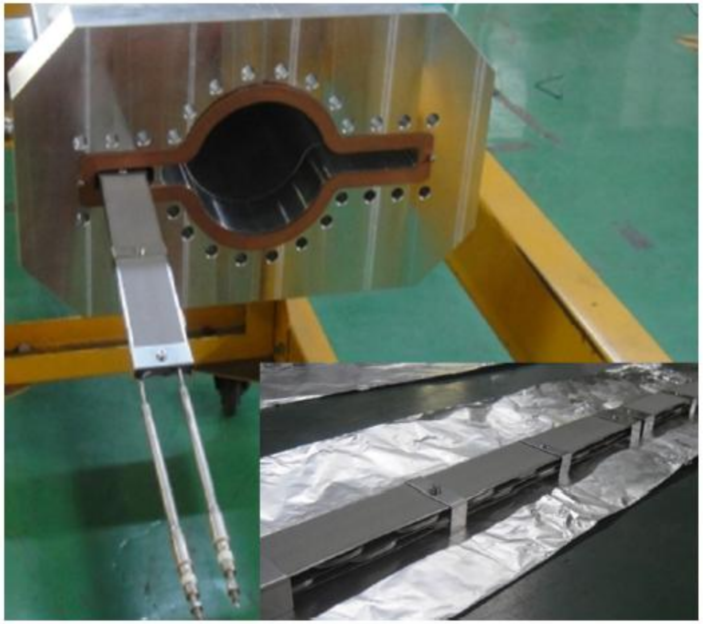


FIG. 4. (Color online) Multilayered NEG strips for the antechamber.

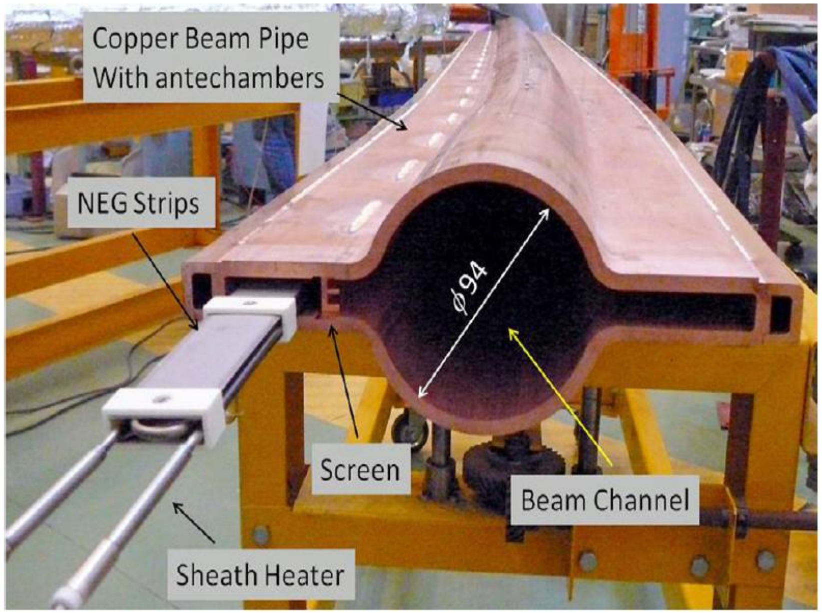


Fig. 1. Example of a beam pipe with antechambers and distributed pumps.

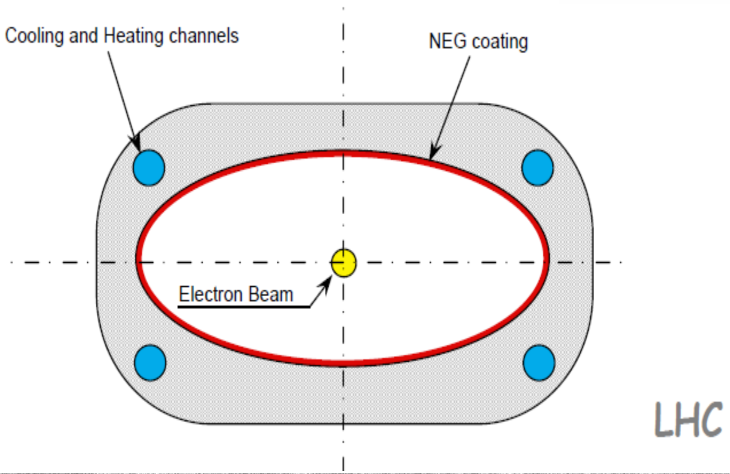
St707 NON-EVAPORABLE GETTER

J. Vac. Sci. Technol. A, Vol. 30, No. 3, May/Jun 2012

NEG coating in vacuum chamber

- Titane Zirconium Vanadium coating
- Low activation temperature Ta=180°C

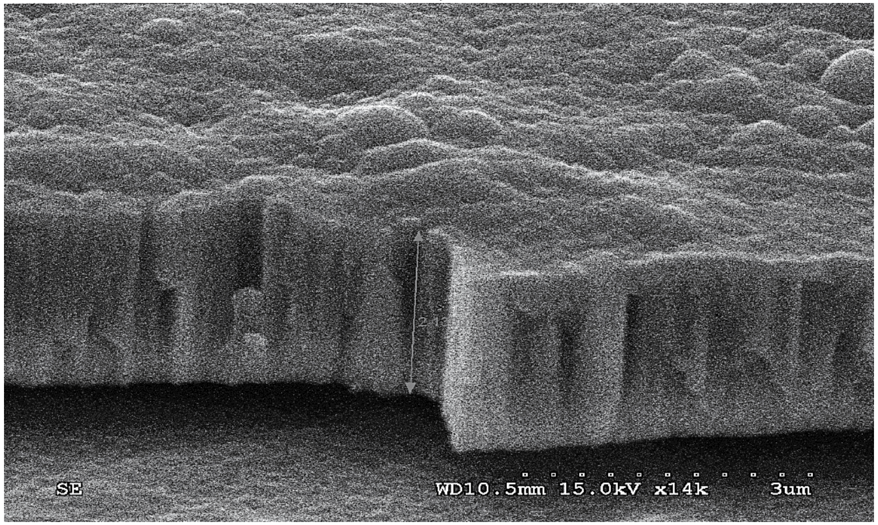
surface of vacuum chamber becomes a pump!!!



SOLEIL: NEG 60 % of the circumference
Upgrade : 100% of the ring!

LHC : 6 km in warm part

MAX IV: 95% of the circumference

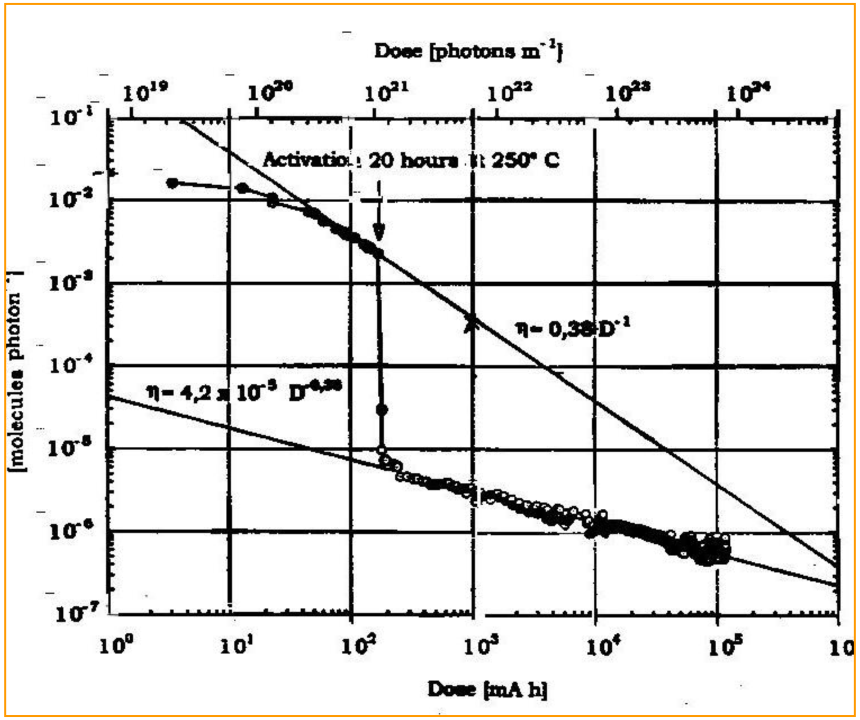


Coating at LAL (~2 μm)

NEG coating-vacuum performances

Titane ZirconiumVanadium coating

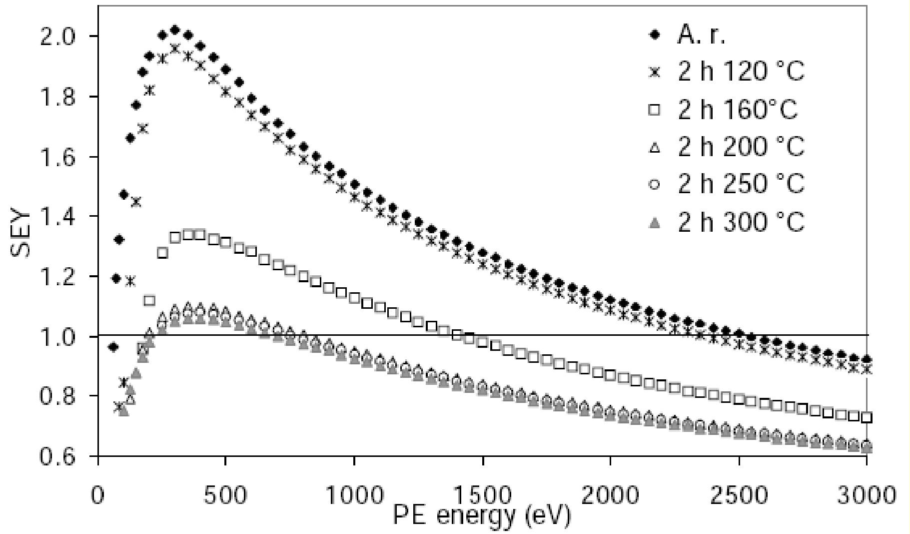
Electron and photon stimulated desorption photons (ESD and PSD) are reduced



P. Chiggiato, R. Kersevan / Vacuum 60 (2001) 67-72

A low secondary electron yield (SEY)

NEG SEY



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

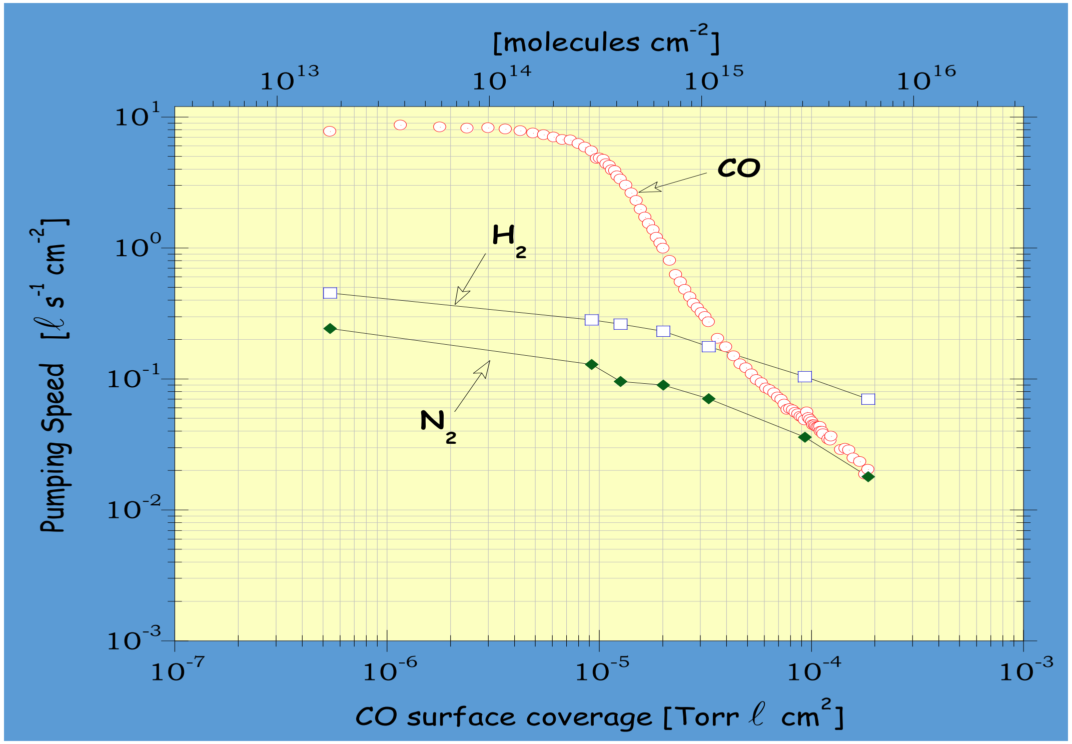
NEG coating-vacuum disadvantage

Titane ZirconiumVanadium coating

Selective pumping speed

(No pumping of rare gas, CH_4)

saturation effect



P. Chiggiato, R. Kersevan / Vacuum 60 (2001) 67-72

Conclusion

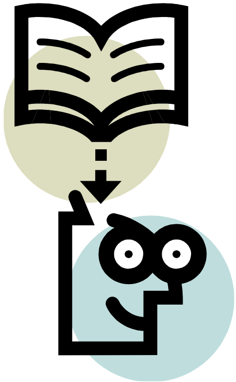
Trend: High luminosity accelerators (involves small-sized beams, high current and a high repetition frequency).

Many beams interactions, residual gas and surface will generate induced outgassing sources and impact the shape and the beam energy

Reduction of induced outgassing sources — Geometry, coating, surface condition, scrubbing,…..

Increase the effective pumping speed — Distributed pumping

NEG strips — Neg coating (TiZrV)



Some references

- Cern Accelerator School, Vacuum technology, CERN 99-05
- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03
- Scientific foundations of vacuum technique, S. Dushman, J.M Lafferty.

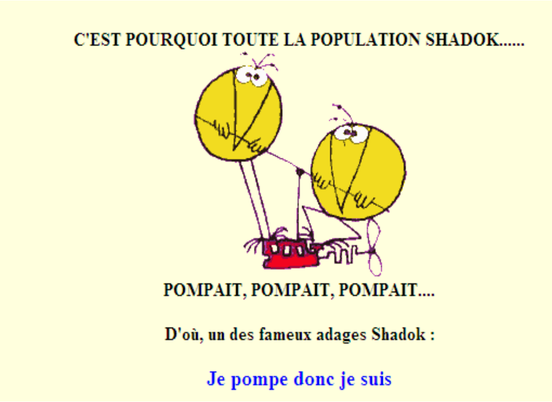
J. Wiley & sons. Elsevier Science.

- Vacuum Technology, A. Roth. Elsevier Science.
- Jacow

•L'ultra vide des grands instruments – V. Baglin Gif-sur-Yvette - 22 septembre2009

Journals

- Journal of vacuum science and technology
- Vacuum
- Physical review special topics Accelerators and Beam



Interaction: Beam- residual gas

Elastic interaction — Single Coulomb scattering

$$\frac{d\varepsilon}{dt} \propto Z^2 \cdot P$$

ε Emittance is proportional to residual gas pressure and depends sqare residual gas atomic number (Z)

Diffusion sur les noyaux du gaz résiduel

$$\frac{1}{\tau_{DN}} := \frac{2\pi r_0^2}{\gamma^2} z^2 \rho c \left[\frac{\langle\beta_z\rangle\beta_{zmax}}{a^2} + \frac{\langle\beta_x\rangle\beta_{xmax}}{b^2}\right]$$

βz(m) oscillation betatron verticale
βz max(m) oscillation betatron verticale
βx(m) oscillation betatron horizontale
βx max(m) oscillation betatron horizontale
ρ densité des noyaux du gaz
γ Facteur gamma

a (m) demi ouverture verticale
b (m) demi ouverture horizontale
Z n° atomique moyen du gaz

Nuclear scattering LHC — Life time limit ~100h P~10-8 mbar H_2 equivalent E=7 Tev

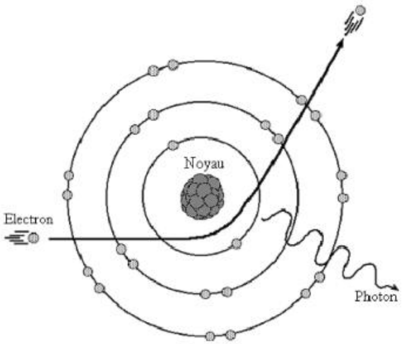
Synchrotron Soleil — Life time limit ~60h P~10-9 mbar N_2 equivalent E=2,15 Gev

Interaction: Beam- residual gas

→ Inelastic interaction
- **Bremsstrahlung**
- Ionization energy loss
- Electron capture
- Electron loss
- Nuclear reactions

Bremsstrahlung

Material	Z	A	Radiation length X_0 [g/cm²] () is for gas	[cm]	Density [g/cm³] () is for gas [g/ℓ]
H_2	1	1.01	61.28	865	0.0708(0.090)
D_2	1	2.01	122.6	757	0.162(0.177)
He	2	4.00	94.32	755	0.125(0.178)
Li	3	6.94	82.76	155	0.534
Be	4	9.01	65.19	35.3	1.848



$$\frac{dE}{E} = -\frac{dx}{\chi_0}$$

Valid for light particules (e+,e-)

$$\chi_{0[g/cm^2]} = \frac{714.6 A_c}{Z_c(Z_c+1)Ln(287/\sqrt{Z_c})}$$

- Loss beam enregy

Synchrotron Soleil

$$\frac{1}{\tau_{BN}} := \frac{16}{411} r_0^2 z^2 \rho c \left[\ln\left(\frac{183}{z^{1/3}}\right)\left(-\ln(\varepsilon_{RF}) - \frac{5}{8}\right) + \frac{1}{12}\lfloor -\ln(\varepsilon_{RF}) - 1 \rfloor \right]$$

Life time limit ~60h   P~10-9 mbar N_2eq. E=2,15 Gev   RF aceptance ε_{RF} =1,8 %

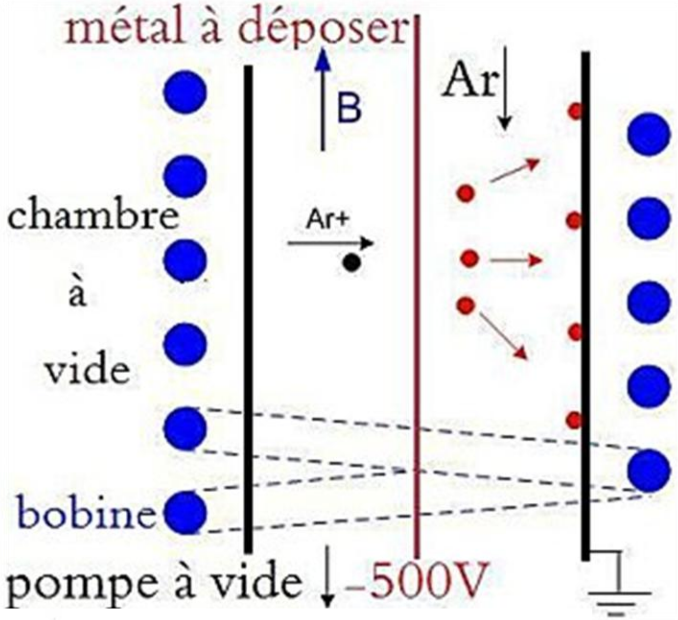
- the radiation interacts with the surface ⟶ Desorption

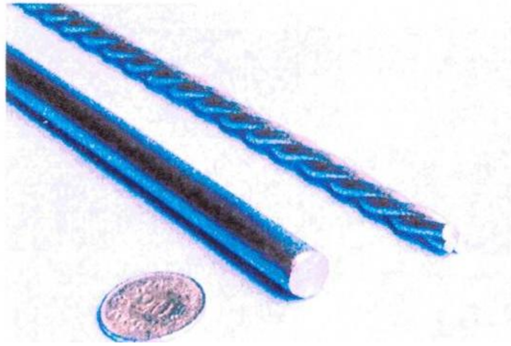
A very strong dependence on the target atomic number is observed, which means that even a small amount of a heavy gas may have a higher influence on the lifetime than the usually dominating hydrogen content.

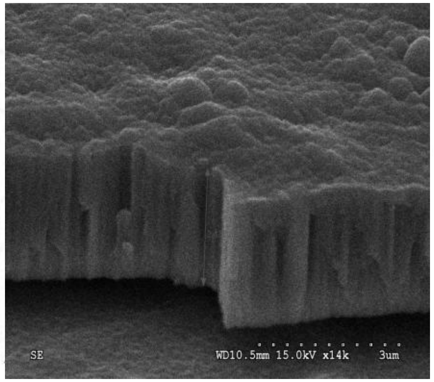
about 4.10^6 times lower for proton

Le dépôt NEG

La pulvérisation cathodique magnétron







Paramètres de dépôt

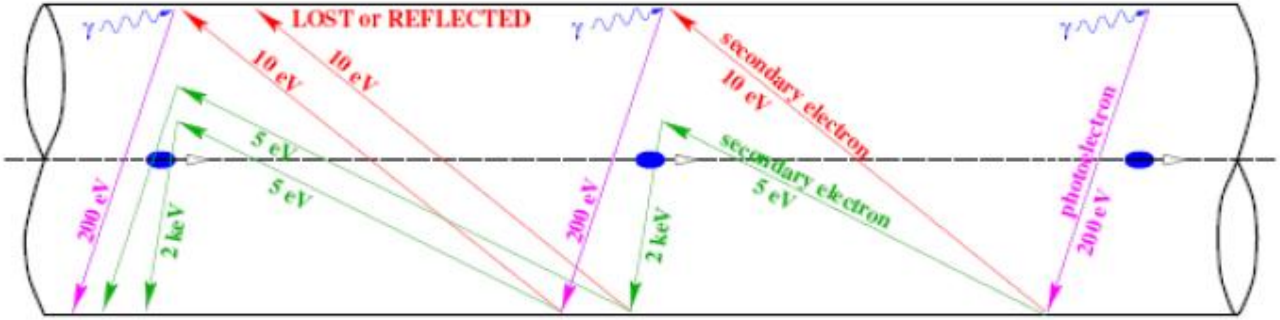
B = 100 G

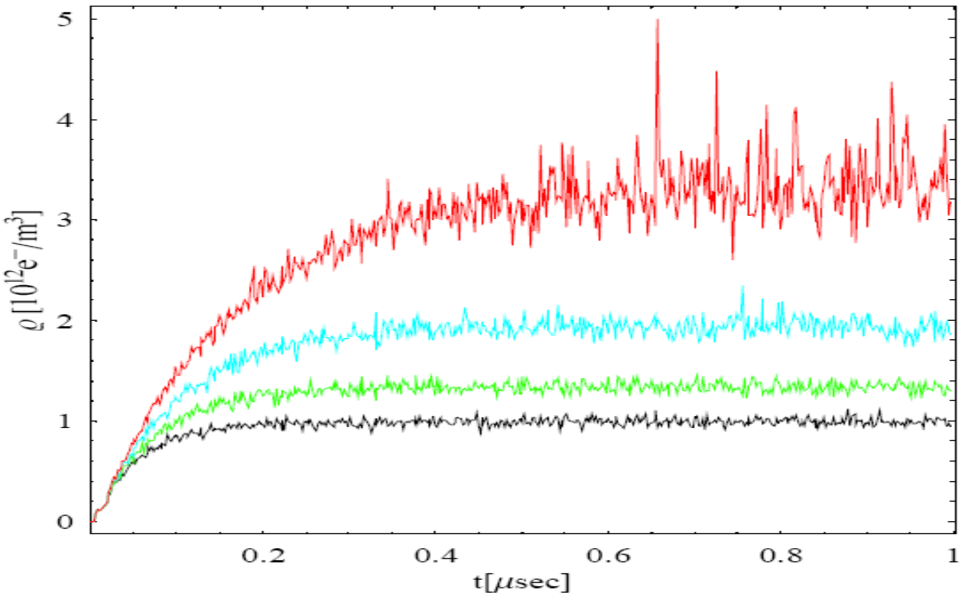
V = - 500 V

Pression Krypton : 2 10^{-2} mbar

Vitesse de dépôt : 1 Å/s

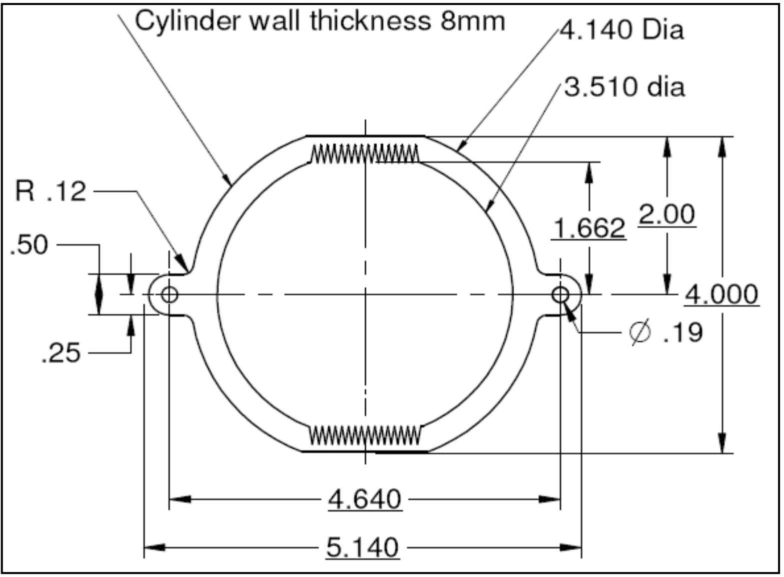
Electron Cloud Effects



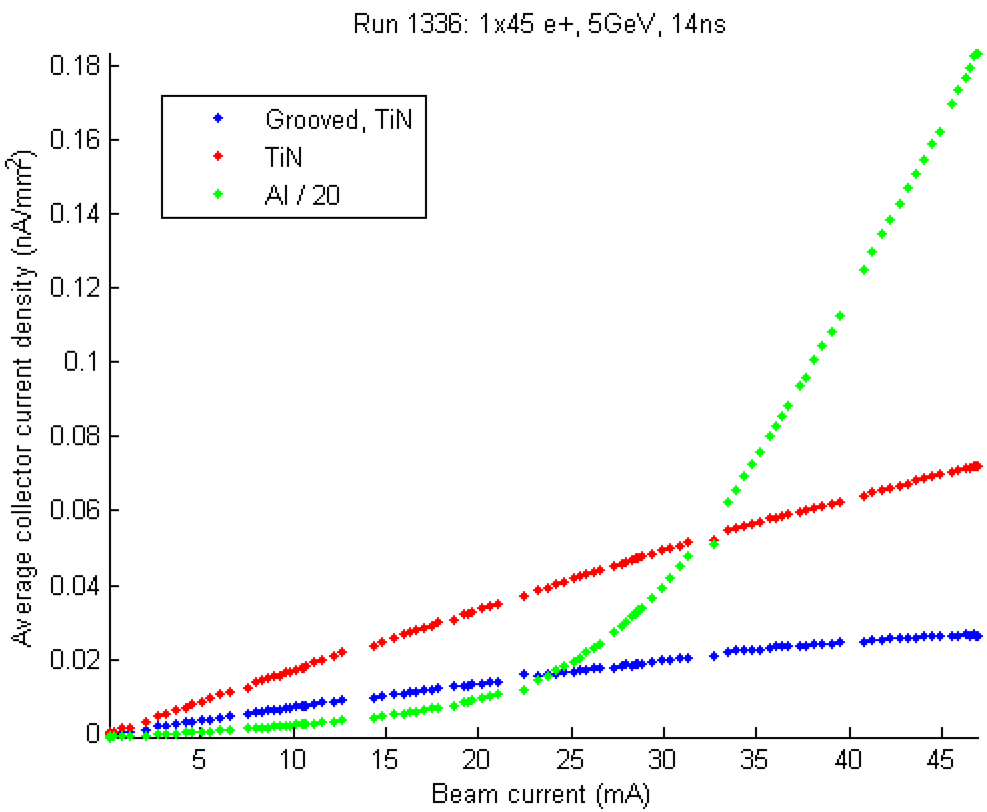


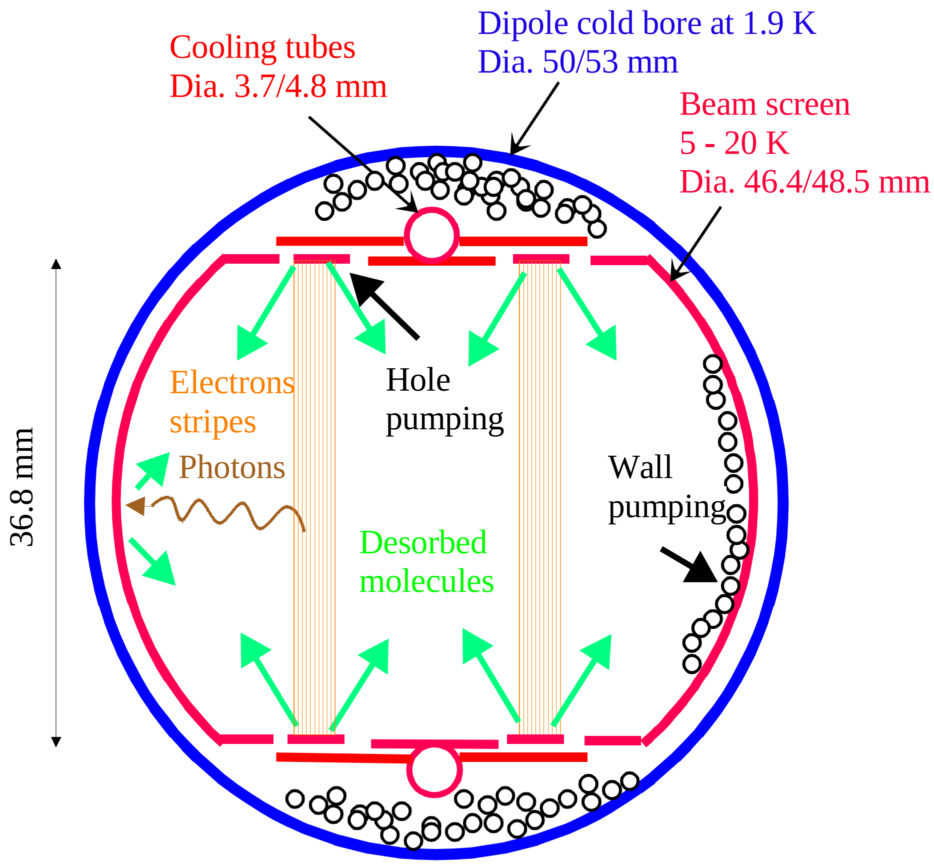
95% prot.

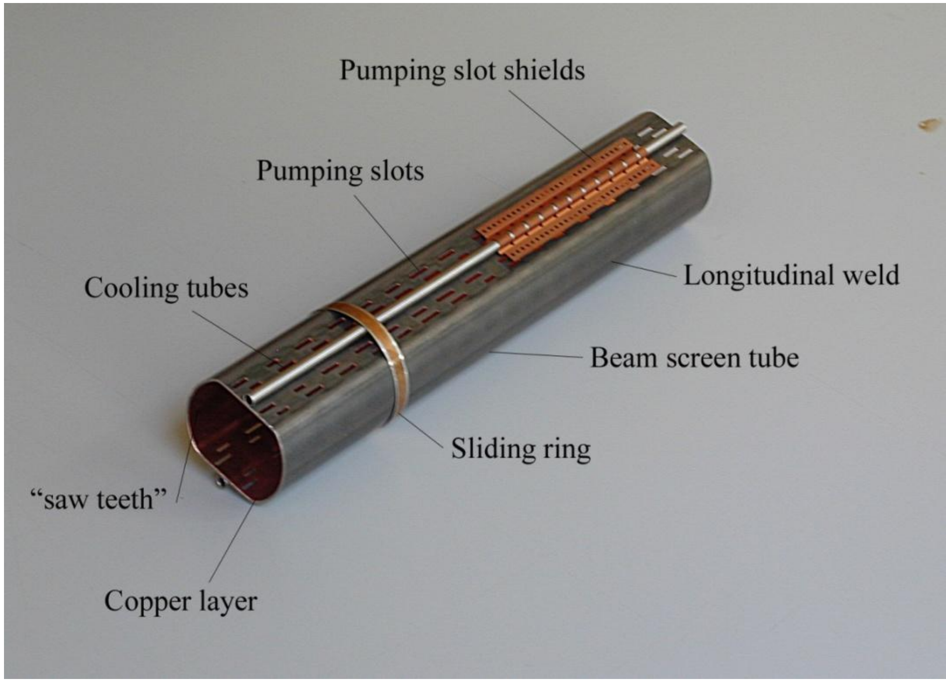
δmax=1
δmax=1.1
δmax=1.2
δmax=1.3



M. Pivi and L. Wang design, SLAC




Cooling tubes
Dia. 3.7/4.8 mm
Dipole cold bore at 1.9 K
Dia. 50/53 mm
Beam screen
5 - 20 K
Dia. 46.4/48.5 mm
36.8 mm
Electrons stripes
Photons
Hole pumping
Wall pumping
Desorbed molecules


Pumping slot shields
Pumping slots
Cooling tubes
Longitudinal weld
Beam screen tube
Sliding ring
"saw teeth"
Copper layer

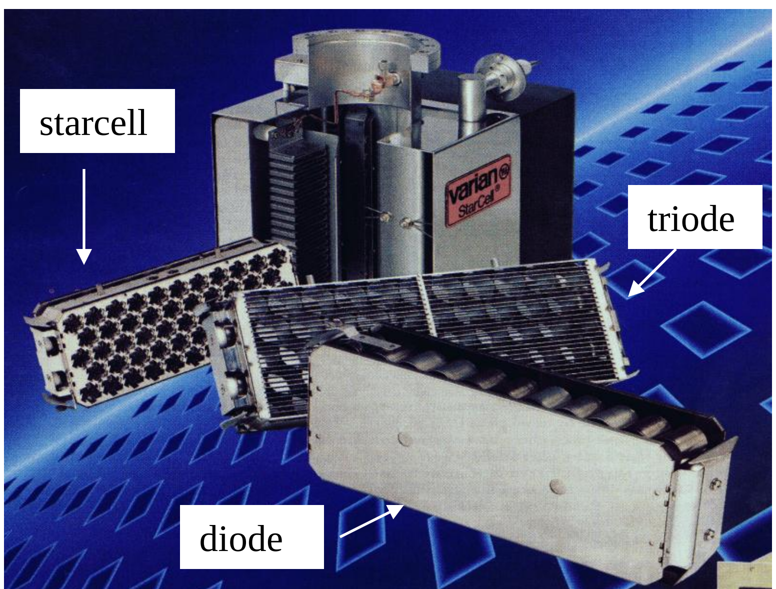
POMPES IONIQUES

Trois phénomènes de pompage :

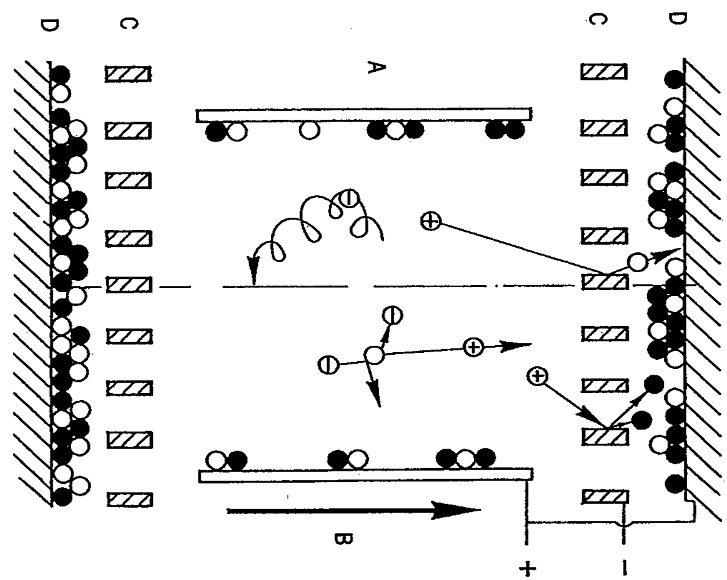
- par chimisorption → effet Getter (gaz actifs, CO, CO2, H2, N2, O2,..)
- par diffusion (principalement H2)
- par physisorption → enterrement (unique pompage pour les gaz rares)

Principalement deux configurations:

- Pompes ioniques Diodes (et noble diode)
- Pompes ioniques triodes (et starcell)



● Atomes de titane
○ Particules gazeuses
⊕ ions
⦶ électrons



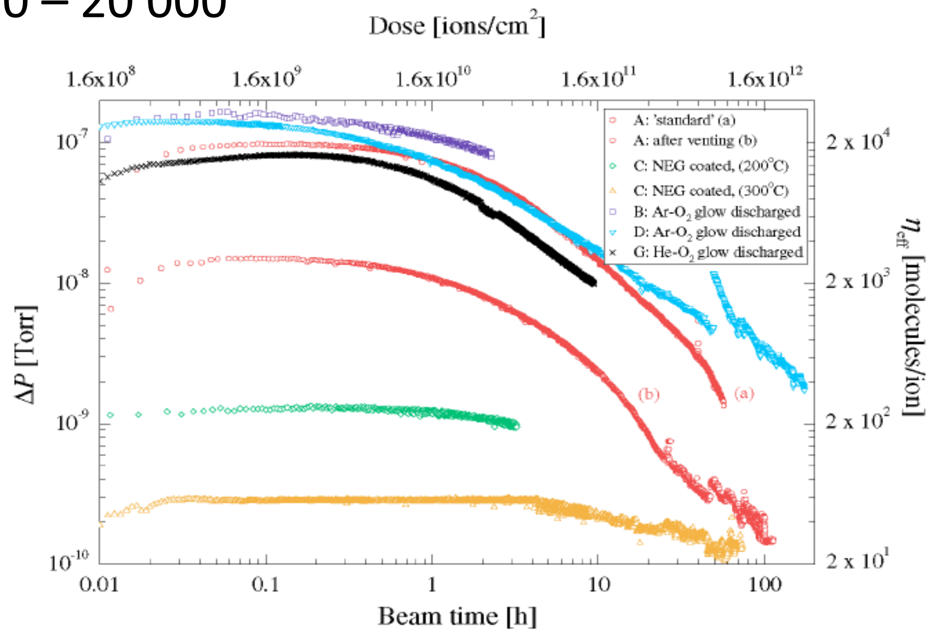
Pompe ionique triode

Ions à très haute énergie

- Des taux de desorption de 20 – 20 000

Pb^{53+}, 4. 2 MeV/u, 14 mrad

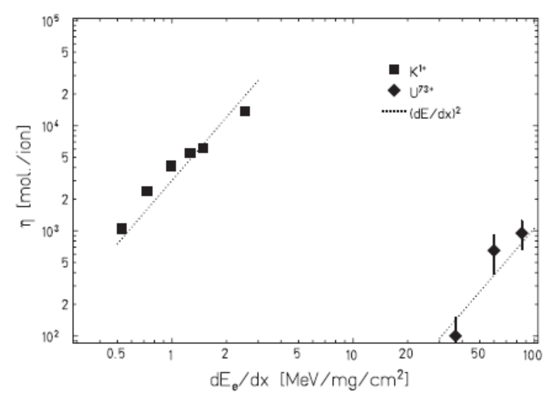
E. Mahner *et al.* , Phys. Rev. ST Accel. Beams 6, 013201 (2003)



- La désorption est déterminée par l' énergie donnée aux électrons (pouvoir d'arrêt électronique)

$$\eta_{ion} \propto \left(\frac{dE_e}{dx}\right)^2$$

L. Prost *et al.* , PRL 98, 064801 (2007)



- La désorption induite par les électrons est le mécanisme responsable

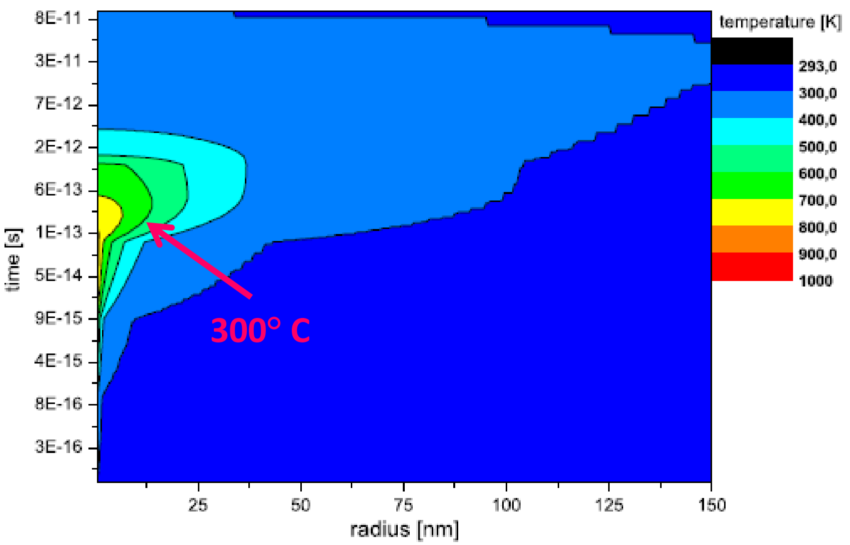
Mécanisme

- Effet de surface (sauf diffusion H_2) dû à une activation thermique
- « Inelastic thermal spike model » : carte de température couplée au modèle de désorption thermique

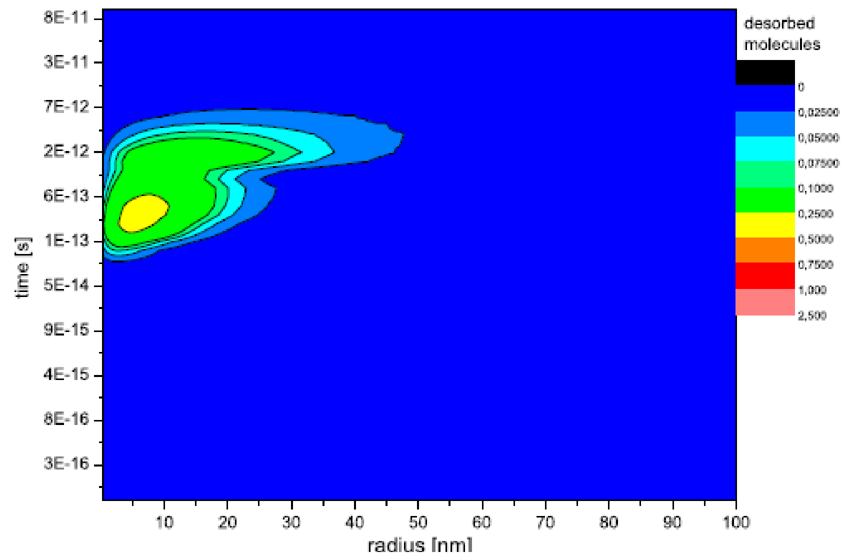
$$\eta = \int_0^{t_{max}} \int_0^{r_{max}} v_0(T(r,t)) \cdot \tilde{n}(r,t) \cdot \exp\left(-\frac{E_{des}}{k_B \cdot T(r,t)}\right) \cdot 2\pi \cdot r dr dt,$$

M. Bender *et al.* , NIM B 267 (2007) 885-890

Xe^{29+}, 1.4 MeV/u, Perpendiculaire



Temperature of atomic Cu subsystem after Xe impact



Desorbed particles per Xe per dt

$$\eta_{calculated} = 185$$

Remèdes

- Utilisation de revêtements NEG (LEIR, RHIC, GSI)

- Intercepter les ions « perdus » sur des collimateurs dédies :
  - LEIR : plaquage d'or de 30 µm sur de l'acier 316 LN, incidence perpendiculaire
  - GSI : plaquage d'or de 0.1 µm, incidence perpendiculaire. Absorbeur introduit dans une chambre secondaire. Revêtement NEG

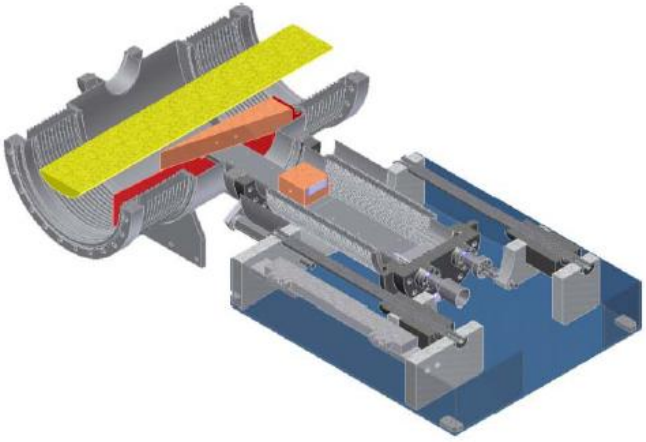
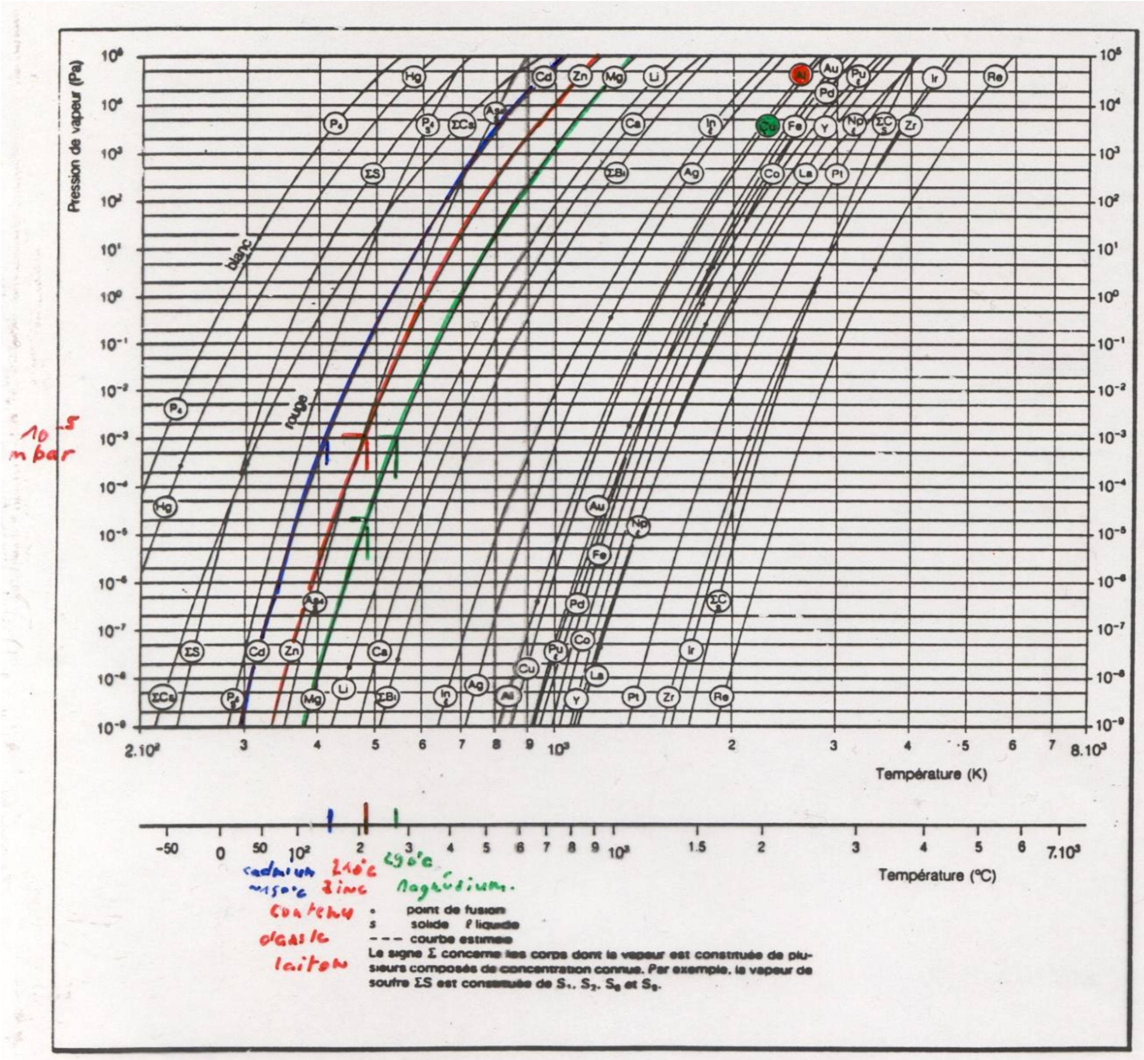


Figure 2: Horizontal cut through the installed SIS18 ion catcher prototype. Yellow: beam, red: secondary chamber, brown: beam absorbers.

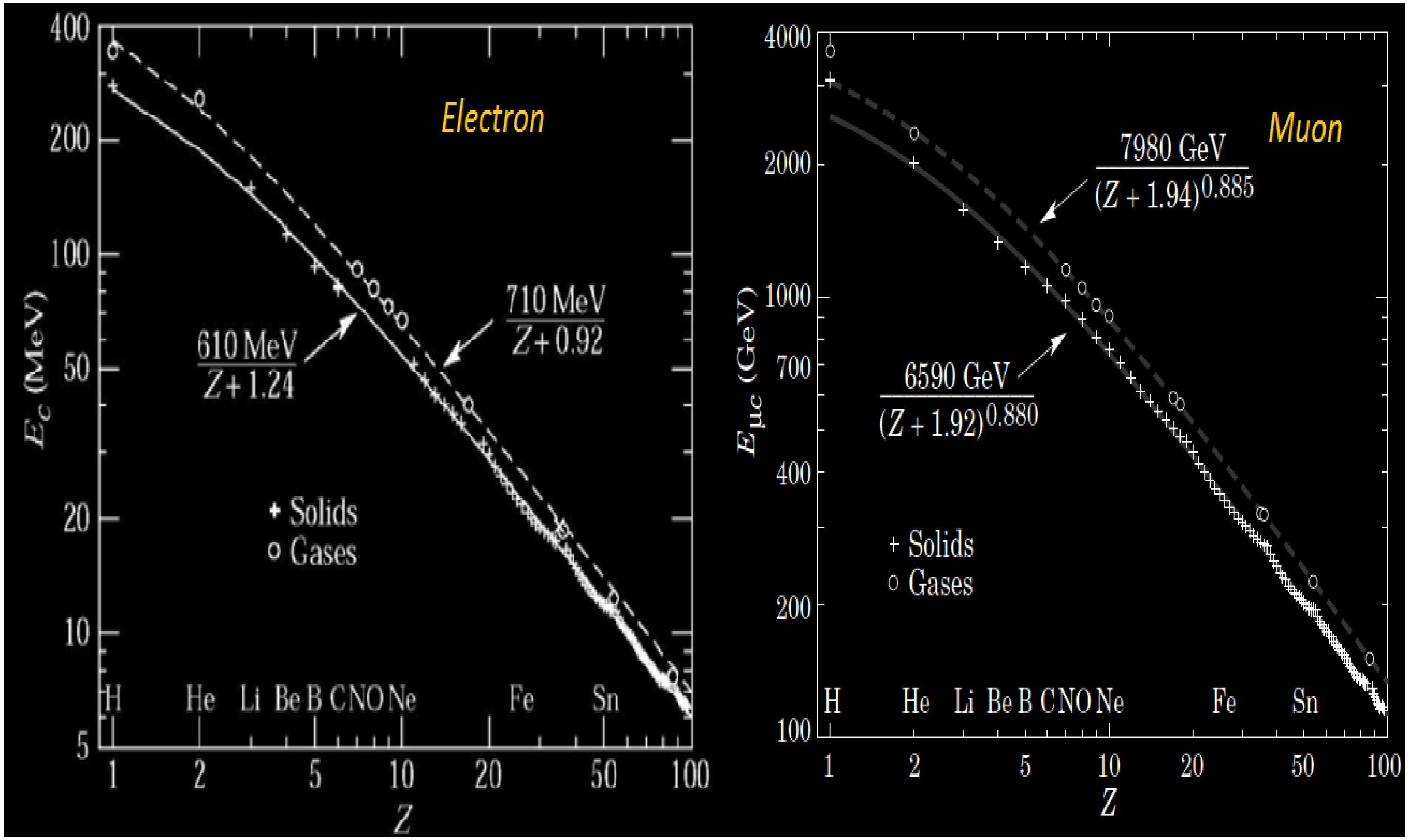
C. Omet *et. al.* EPAC 2008, Genoa, Italy

- Utiliser le conditionnement par le faisceau

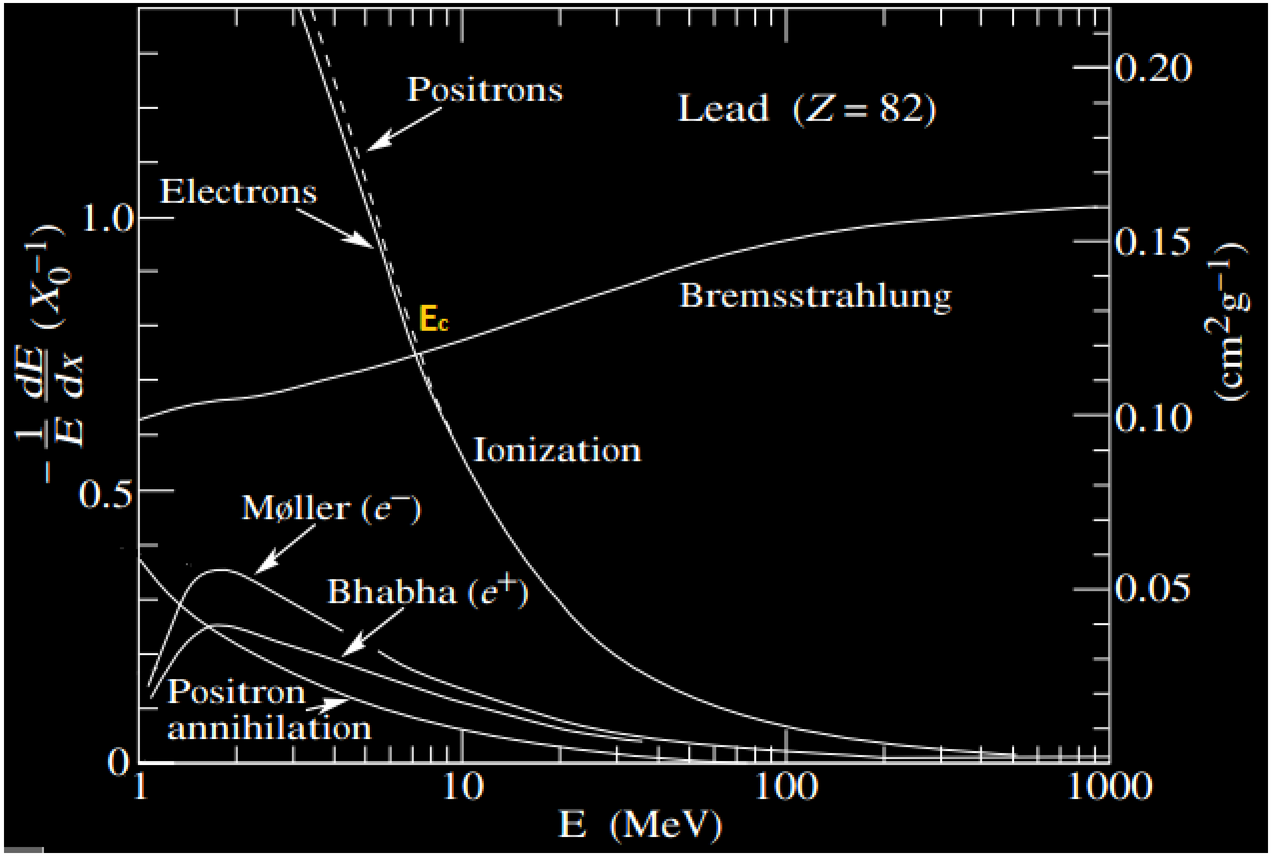
Vapor pressure



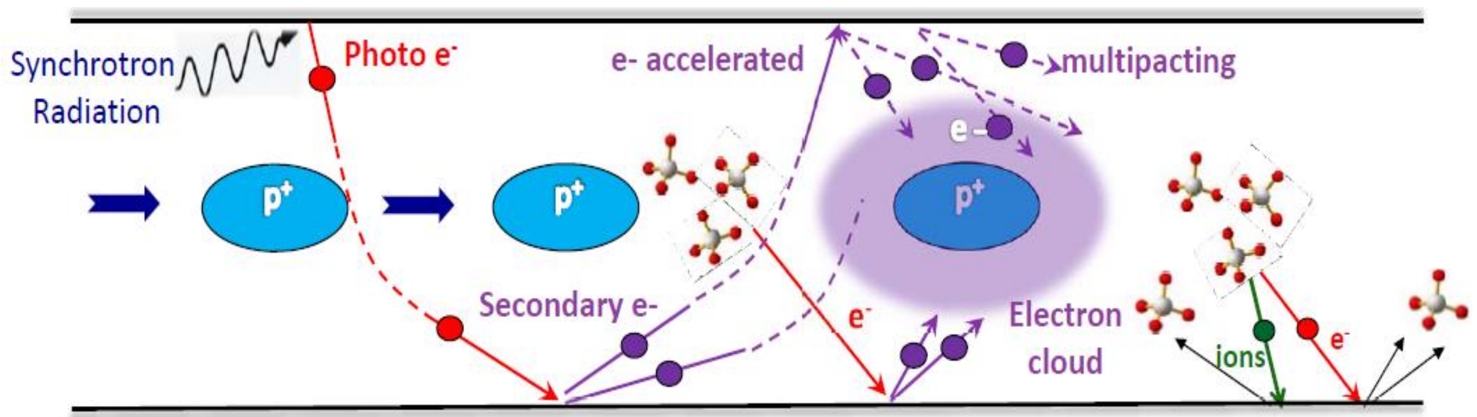
Energie critique ‘collision élastique/ émission radiative) en fonction de Z



Perte d'énergie des électrons dans du plomb par unité de radiation X0.
L'énergie critique est de 7,43 MeV.



Plomb 11,35 g/cm3 (20°C)



2018 LHC
26.7 km, 7.74 T
13 TeV, 2556 b, 1.1x10^{11} ppb
RUN 2

LHC
27 km, 8.33 T
14 TeV, 2808 b, 1.2x10^{11} ppb
NOMINAL PARAMETERS

To stay operational during 2018, the LHC was limited to fewer than the nominal number of bunches due to dynamic pressure phenomena

HL-LHC (2026)
26,7 km, 8.33 T
14 TeV, 2808 b, 2.2x10^{11} ppb

FCC-hh
100 km, 16 T
100 TeV, 10600 b

FCC-ee
100 km
45 GeV, 16640 b

Can these nominal parameters be reached for future colliders ?

Ion accumulation

Ions stability criterion :

[1] Neutralisation of accelerator beams by ionisation of the residual gas Y. Baconnier, A. Poncet and P.F. Tavares CERN

Calculation of critical mass [1] :

All ions of mass greater than the critical mass will be accumulated.

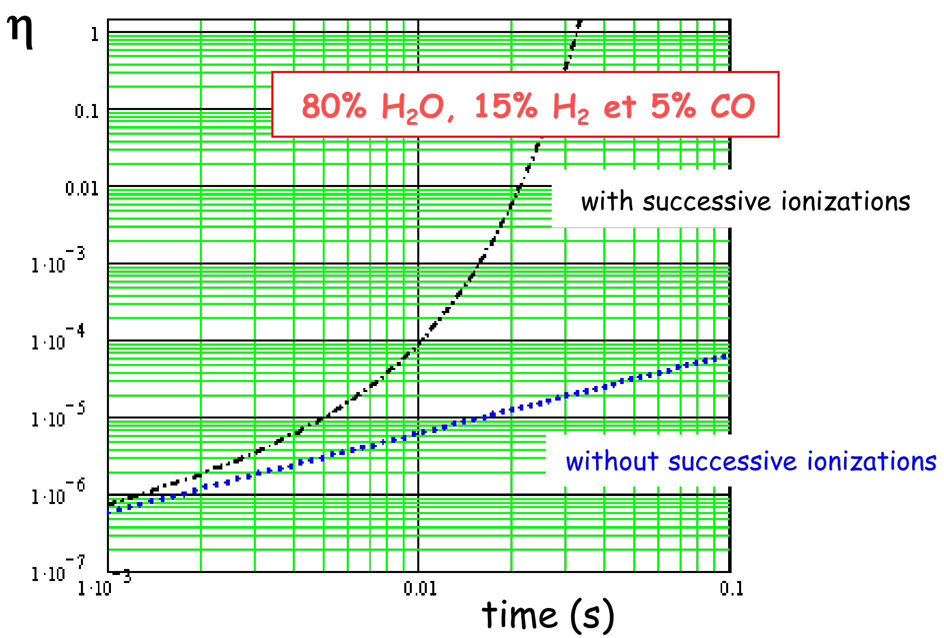
$$A_c = \frac{N_e}{N_b^2} \cdot r_p \cdot \frac{2 \cdot \pi \cdot R}{\beta \cdot b^2 \cdot (1 + a/b)}$$

avec Ne e- number, N_b bunch number, r_p proton radius, 2.π.R ring circumference, β ratio of *v* to the speed of light *c*, a and b beam size .

Neutralizing Factor

$$\eta = \frac{\text{number of positive charge (ions)}}{\text{Number of negative charge (beam electron)}}$$

Neutralizing factor Versus time



Vacuum basis :

summary Tables

Pour N_2 at 20°C

Pressure (hPa)	Strength per unit area	density molecular (molecule/cm^3)	Mean free path	Impingement rate (per cm^2 and per sec)	Monolayer formation time
1013	1 kg/cm^2	2,50x10^{19}	0,1 µm	2,9x10^{23}	3,4x10^{-9} s
1	1 g/cm^2	2,47x10^{16}	0,1 mm	2,9x10^{20}	3,4x10^{-6} s
10^{-3}	1 mg/cm^2	2,47x10^{13}	10 cm	2,9x10^{17}	3,4x10^{-3} s
10^{-6}	1 µg/cm^2	2,47x10^{1}	100 m	2,9x10^{14}	3,4 s
10^{-9}	10 µg/m^2	2,47x10^{7}	100 km	2,9x10^{11}	1 heure
10^{-12}	0,01 µg/m^2	2,47x10^{4}	10^{5} km	2,9x10^{8}	40 jours
10^{-16}	1 µg/km^2	2,47	10^{9} km	2,9x10^{4}	1000 ans
10^{-23}	10^{-7}µg/km^2	2,47x10^{-7}	10^{16} km	2,9x10^{-3}	10^{10} ans