CERN

Cryogenic Beam Vacuum Specificities Applicable to FCC hh

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Outline

1. Adsorption Isotherms

2. Beam Screens

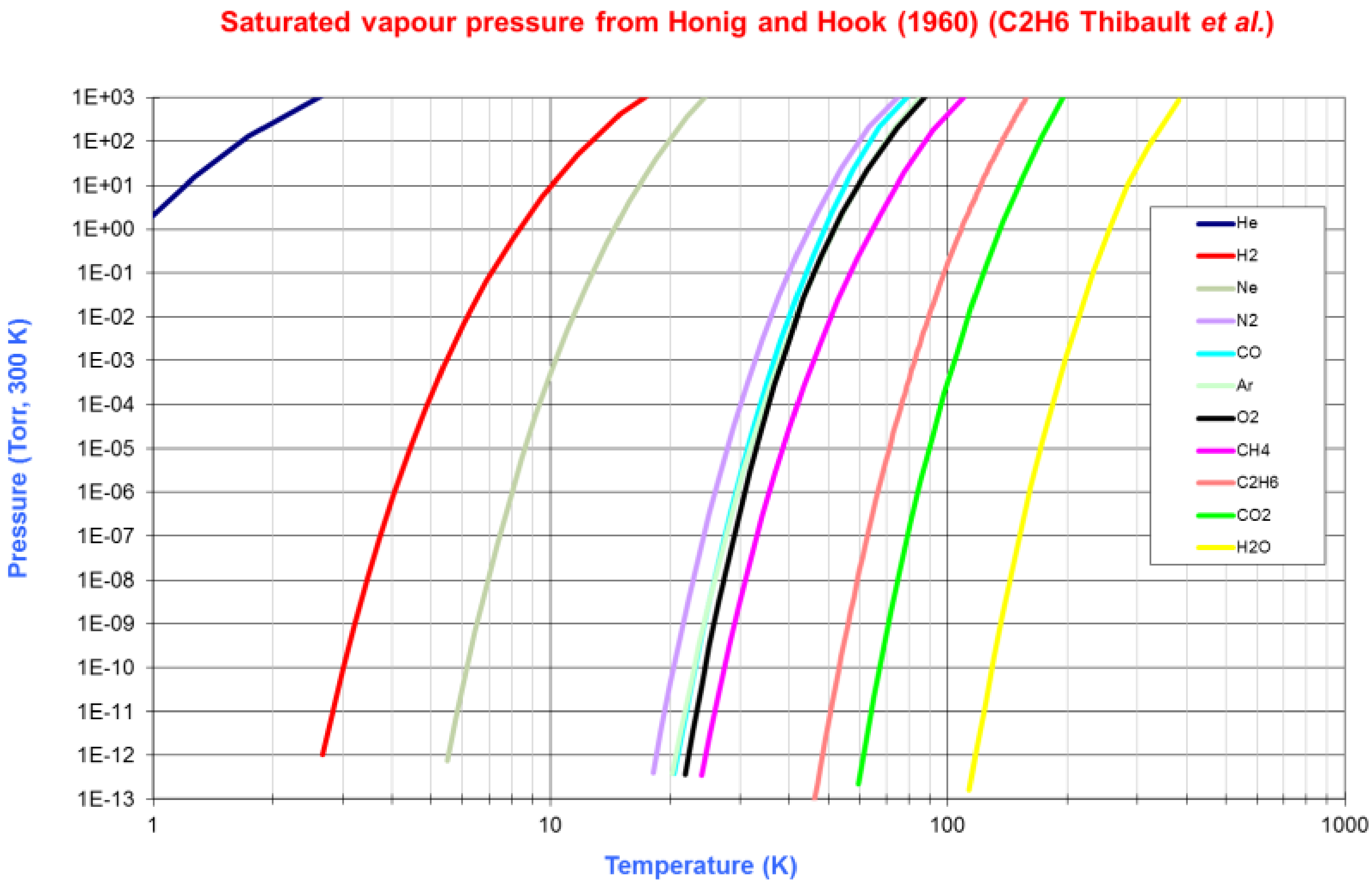
3. Vacuum Dynamics
under Ions, Photons and Electrons Irradiation

4. Summary

1. Adsorption Isotherms

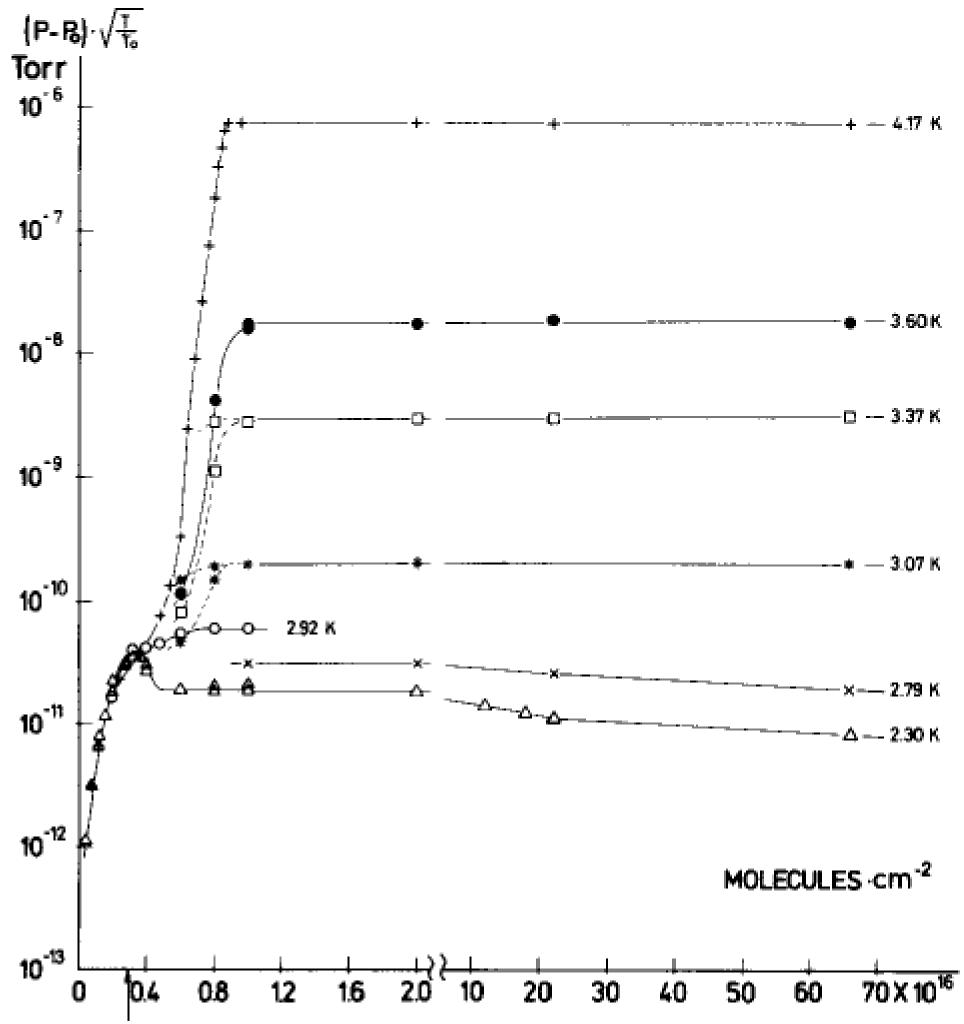
Saturated Vapor Pressure

- Pressure over liquid or gas phase (many monolayers condensed)
- Follows the Clausius-Clapeyron equation: Log $P_{sat} = A – B/T$



H_2 Adsorption Isotherm on Stainless Steel

- The vapor pressure increases when increasing the adsorption of gas up to a few monolayers (~ 10^{15} molecules/cm^2)
- The vapor pressure saturates when several monolayers of gas are adsorbed
- The pressure level of the saturation is a function of the temperature



A monolayer

C. Benvenuti, R. Calder, G. Passardi
J.Vac.Sci. 13(6), Nov/Dec 1976, 1172-1182

"Anomalous" Saturated Vapor Pressure in a Machine

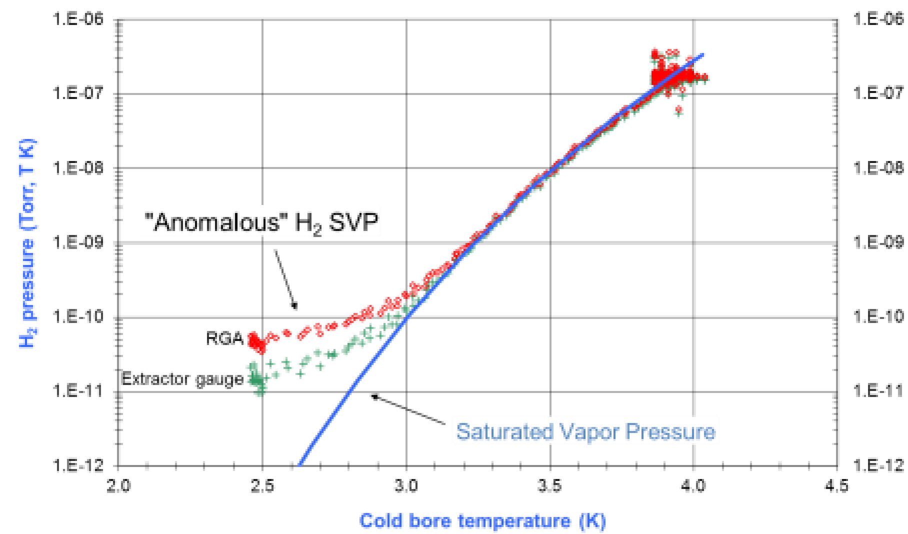
- Thermal radiation induced desorption:
  - Case of the H_2 condensed on the FCC cold bore when exposed to high temperature

- In a "LHC type" mock-up (COLDEX):

- After condensation of 10 monolayers of H_2, the pressure follows the Clausius-Clapeyron equation while the cold bore temperature is decreased from 4 to 3 K

- Below 3 K, a deviation is observed due to the thermal radiation coming from the room temperature parts located at the extremities of the 2 m long system.

- Increasing the beam screen temperature from 20 K to 100 K has no impact on the observed deviation while the cold bore is held at 2.7 K



V. Baglin, B. Jenninger, COLDEX Run 24, September 1999

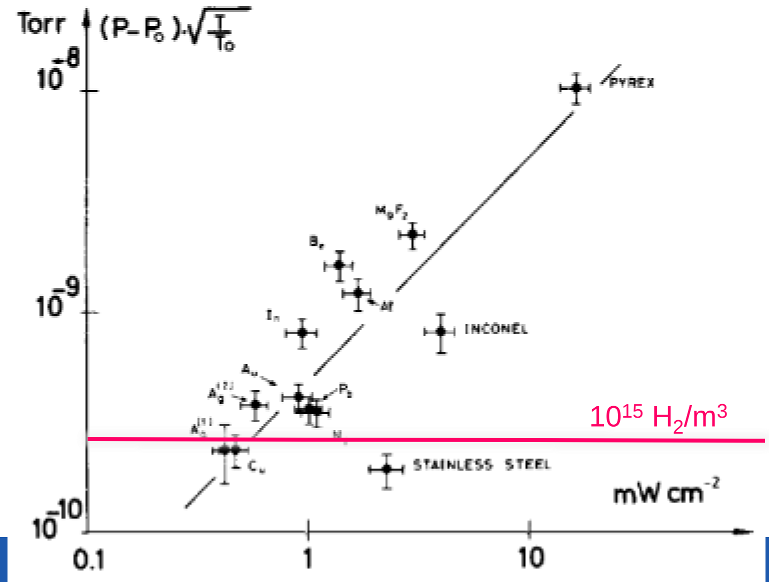
- Cryopump optimisation:

- 10 monolayers of H_2 is condensed at 2.3 K

- The different cryosurface types are fully exposed to 300 K radiation

- Linear dependence with the absorbed power (incident radiation x substrate emissivity)

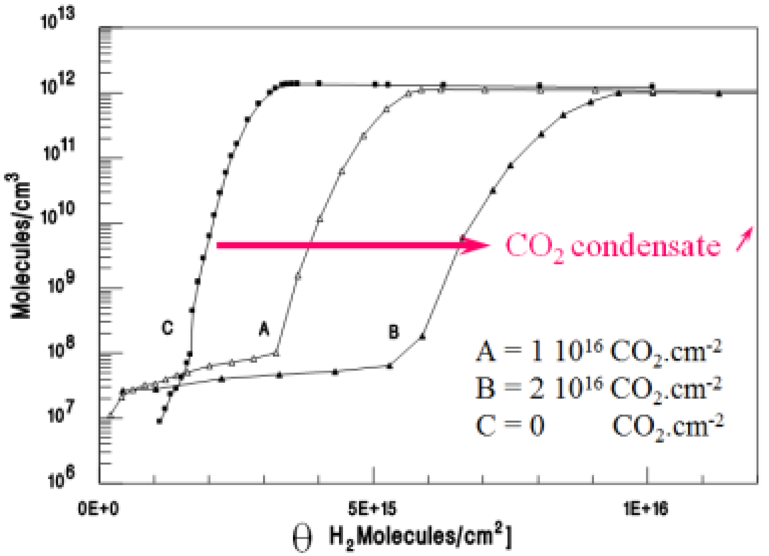
- The pressure, measured at 2.3 K, varies from 10^{-10} to 10^{-8} Torr
  => gas density 5 10^{14} to 5 10^{16} H_2/m^3

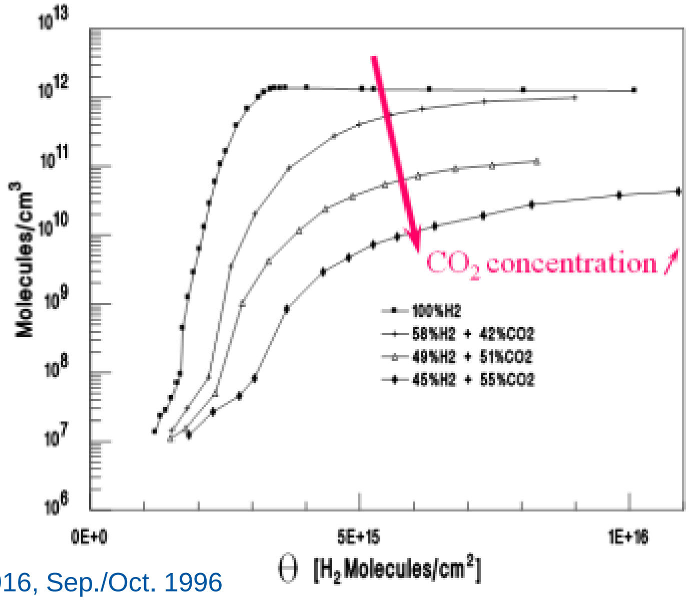


C. Benvenuti, R. Calder, G. Passardi J.Vac.Sci. 13(6), Nov/Dec 1976, 1172-1182

Vapor Pressure in a Machine

- Several types of molecules are present in machine vacuum systems
- The adsorption isotherm is affected by the presence of these molecules
- Condensed CO_2 forms a porous layer increasing the hydrogen capacity
- Co-adsorption of CH_4, CO and CO_2 reduce the vapor pressure of H_2 by cryotrapping





E. Wallén, JVSTA 14(5), 2916, Sep./Oct. 1996

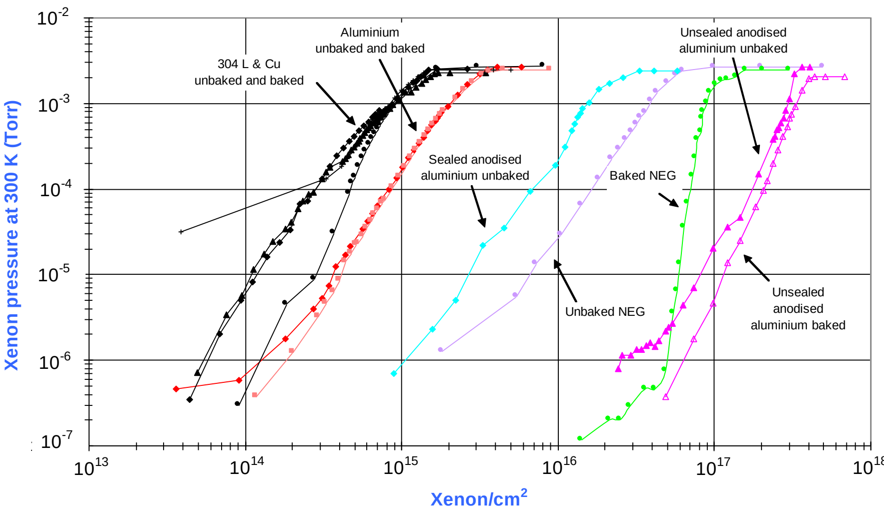
➔ Studies with real machine environments are mandatory

BET surface area – Roughness factor - Cryosorbers

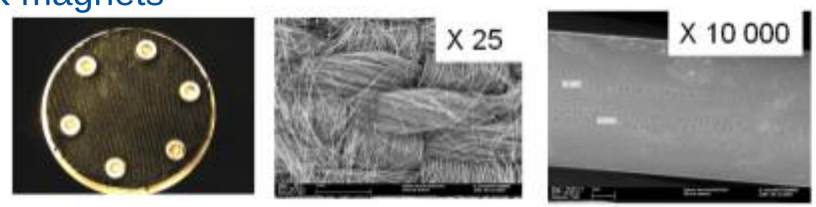
- Xe adsorption isotherms are used to derive the roughness factor of surface using the BET multi-monolayer theory

Technical surface	Unbaked	Baked at 150 °C
Copper Cu-DHP acid etched	1,4	1,9
Stainless steel 304 L vacuum fired	1,3	1,5 (at 300 °C)
Aluminium degreased	3,5	3,5
Sealed anodised aluminium 12 V	24,9	not measured
Unsealed anodised aluminium 12 V	537,5	556,0
NEG St 707	70,3	156,3

V. Baglin. CERN Vacuum Technical Note 1997



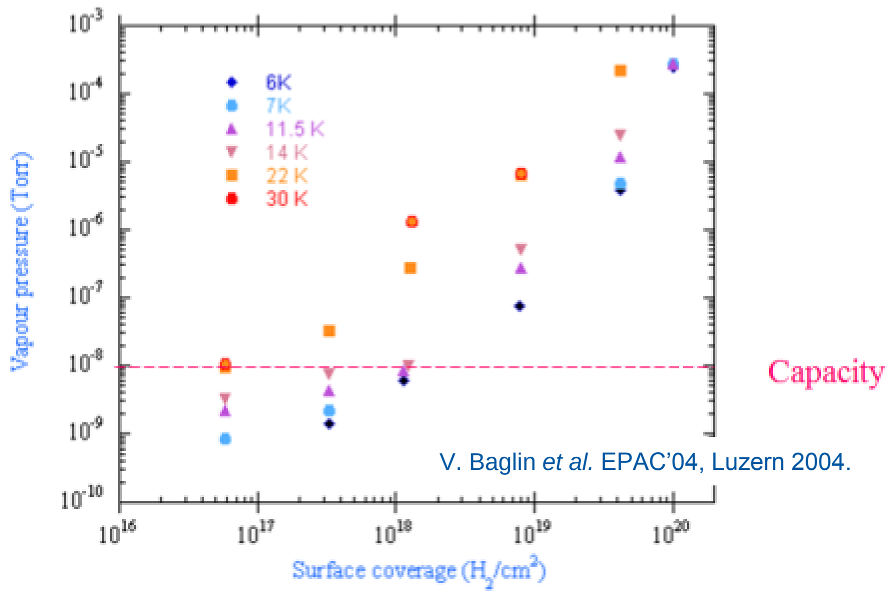
- Woven carbon fibers are used in LHC as cryosorbers in 4.5 K magnets



V. Anashin *et al.* Vacuum 75 (2004) 293-299

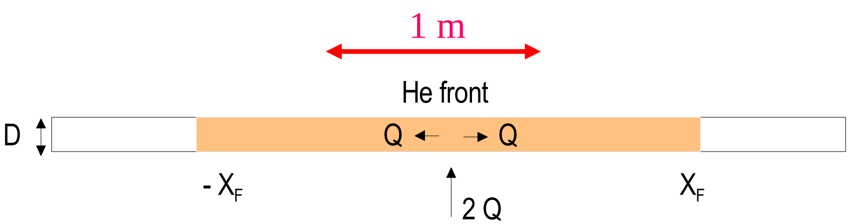
- Capacity: 10^{18} H_2/cm^2 at 6K, 10^{17} H_2/cm^2 at 30 K

$$R \sim 10^3 R_{Cu}$$

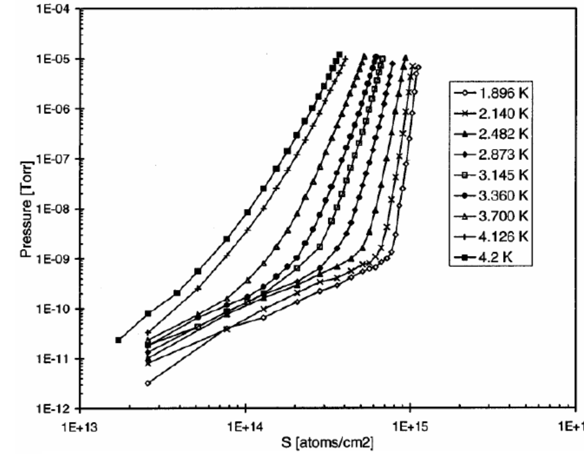


V. Baglin *et al.* EPAC'04, Luzern 2004.

He leaks at 1.9 K



P. Hobson *et al*. J.Vac.Sci. A. 11(4), Jul/Aug 1993, 1566-1573

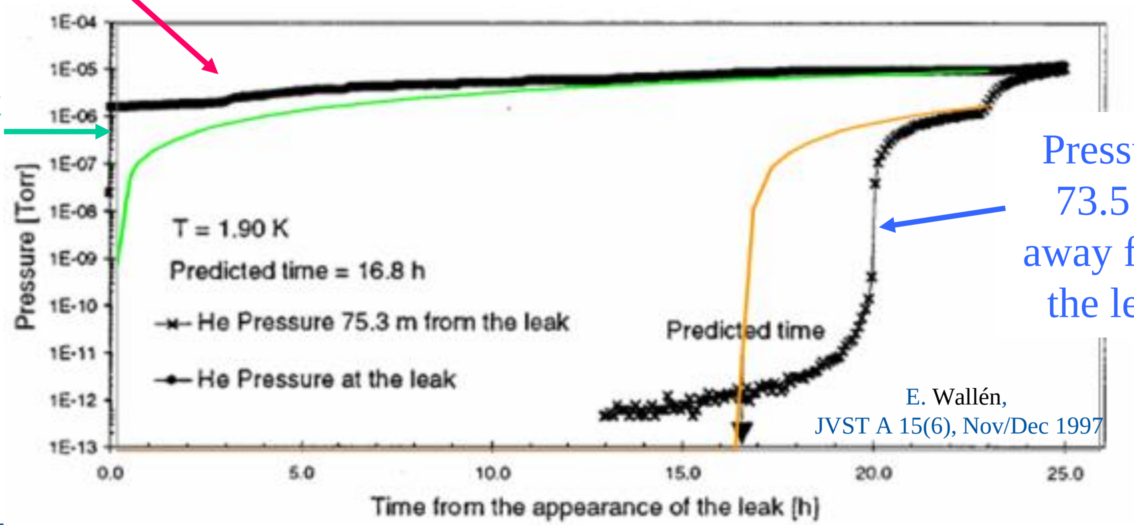


E. Wallén. J.Vac.Sci.A 15(2), Mar/Apr 1997, 265-274.

- A He pressure wave is developed with time along the beam vacuum chamber
- The He wave can span over several tens of meter without being detected
- The local pressure bump gives a local proton loss (risk of magnet quench)

Pressure at the level of the leak

Quench limit
$4\ 10^{-7}$ Torr



E. Wallén,
JVST A 15(6), Nov/Dec 1997

Pressure
73.5 m
away from
the leak

Example : LHC Test string
Leak rate 6 10^{-5} Torr.l/s
Distance 75.3 m

2. Beam Screens

LHC design : 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

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

$$P_{cold\ mass} = \frac{I E}{c \tau}$$

Table 5.5: Nuclear scattering cross sections, the implied maximum allowed densities, and the accompanying emittance growth at injection for various gas species.

molecule	σ [barn] at 7 TeV	n [m^{-3}] at 7 TeV for τ_{nucl} = 100 h	equiv. gas pressure at 300 K [ntorr]	τ_ϵ [h] at 450 GeV for τ_{nucl} = 100 h
H_2	0.078	1.2×10^{15}	37.8	17.0
He	0.133	6.9×10^{14}	21.7	12.5
CH_4	0.511	1.8×10^{14}	5.6	7.6
H_2O	0.510	1.8×10^{14}	5.7	9.5
CO	0.751	1.2×10^{14}	3.8	7.5
CO_2	1.171	7.9×10^{13}	2.5	5.0

LHC Design Report, CERN-2004-003

- FCC-hh, heat load in cold mass (mW/m):
  - Neglecting the elastically scattered protons catched by the collimation system

Life time (h)	LHC	HL-LHC	16 T	20 T
100	80	140	620*	755
500	15	30	125	145
1000	8	14	65	75

* 9 W/m/dipole assuming 15 m long dipole cold mass

A FCC with life time of ~ 500 h would maintain < 2 W/m/dipole cold mass:
➔ pressure levels divided by ~ 7 wrt LHC !

LHC Vacuum System Principle

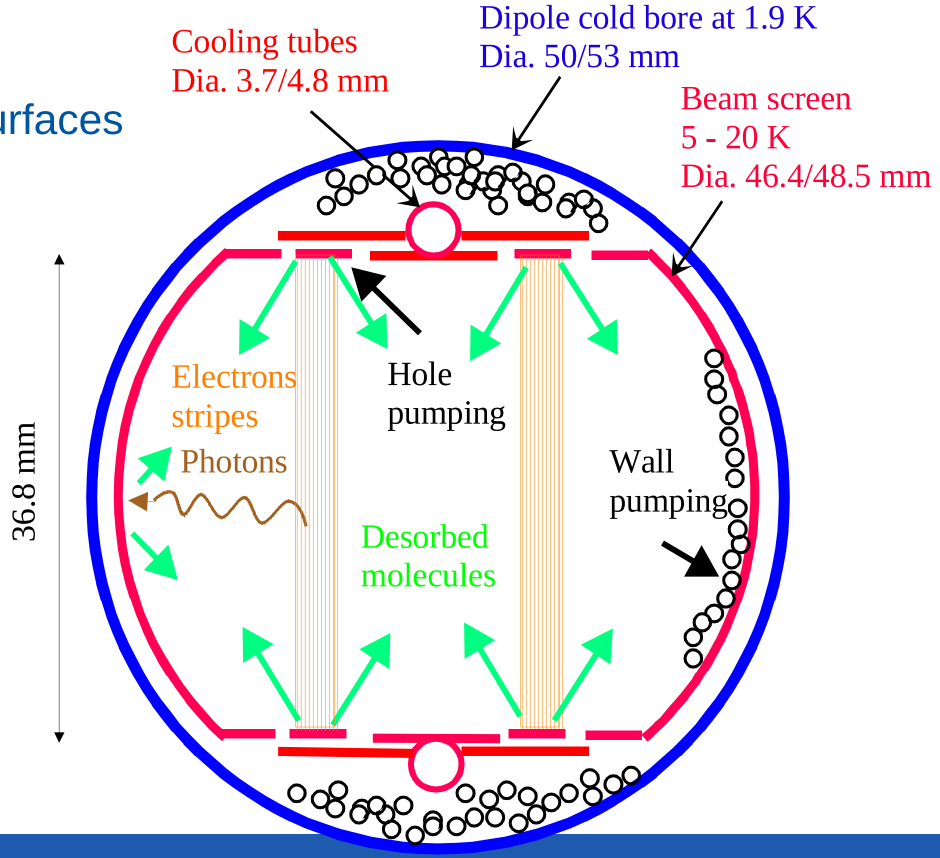
- Molecular desorption stimulated by photon, electron and ion bombardment
- Desorbed molecules are pumped on the beam vacuum chamber
- 100 h beam life time (nuclear scattering) equivalent to ~ 10^{15} H_2/m^3 (10^{-8} Torr H_2 at 300 K)

In cryogenic elements

- Molecular physisorption onto cryogenic surfaces (weak binding energy)

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

- H_2 is physisorbed onto the cold bore



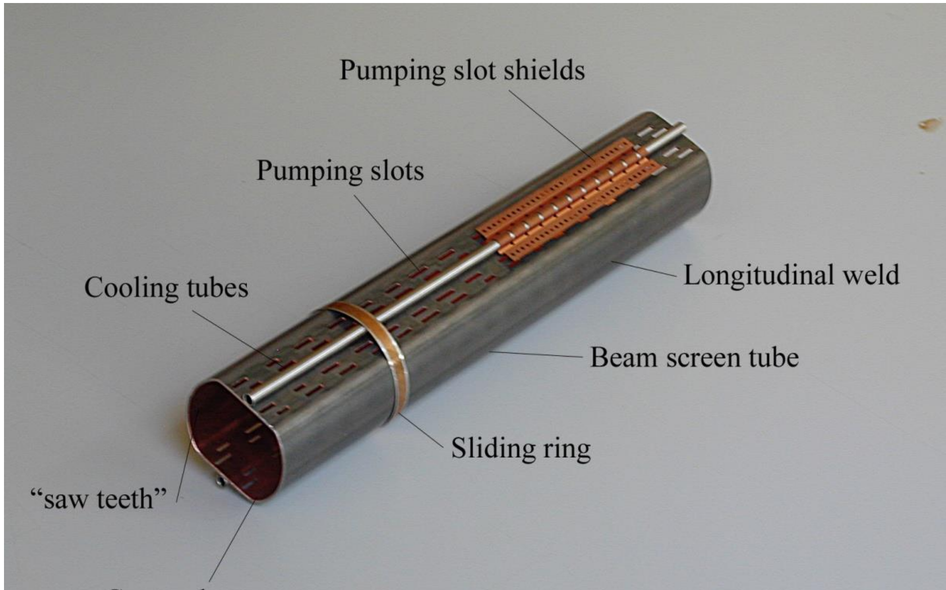
LHC Beam Screens Functionalities

- Intercept the heat load induced by the circulating beam (impedance, synchrotron radiation, electron cloud)

- Operate between 5 and 20 K

- Non-magnetic stainless steel substrate to withstand quench forces (few tons) and to ensure a good field quality

- Copper colamination onto non-magnetic stainless steel to reduce impedance



Courtesy N. Kos CERN AT/VAC

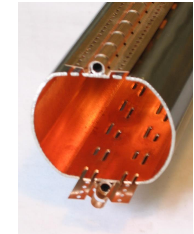
- Pumping holes to control the gas density

- Rounded pumping slots to reduce electromagnetic leakage towards the cold bore held at 1.9 K or 4.5 K

- Electron shield to protect the cold bore from the heat loads induced by the electron cloud

- Saw teeth to reduce photoelectron yield and forward reflectivity of photons to decrease the seed of electrons

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

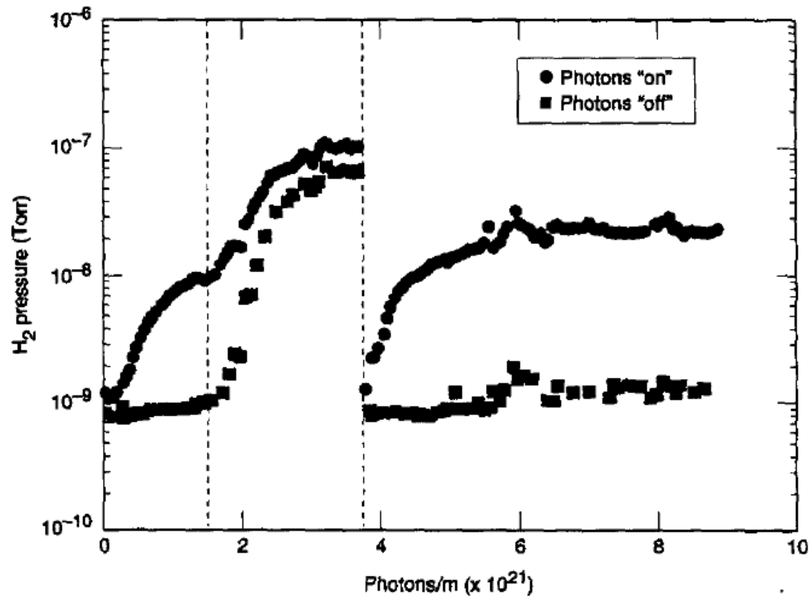


FIG. 1. Room-temperature RGA H_2 pressure measured at the center of the 4.2-K beam tube vs integrated photon flux with photons on and photons off. The raw pressure difference “on” minus “off” has been normalized to 1×10^{16} photons/m/s. The vertical dashed lines correspond to features discussed in the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

With perforations

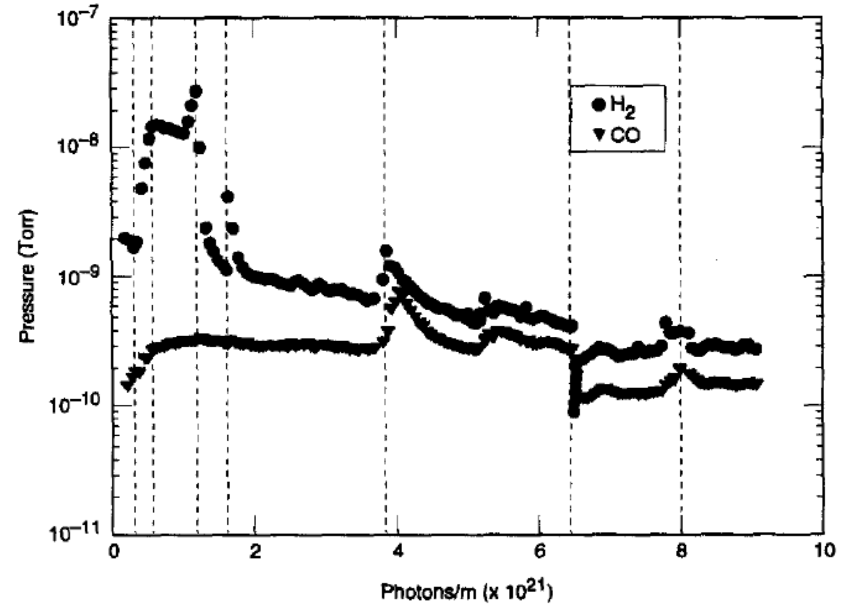


FIG. 2. Room-temperature RGA H_2 and CO dynamic pressures measured at the center of the liner configuration. Dynamic pressure is normalized to 1×10^{16} photons/m/s.

$$n=\frac{\eta_1\dot{\Gamma}}{\sigma_w S_w}+\frac{\eta'\dot{\Gamma}}{\sigma S_w}+n_e;$$

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

- Increase with coverage

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

- Equilibrium pressure

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

- Equilibrium coverage

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

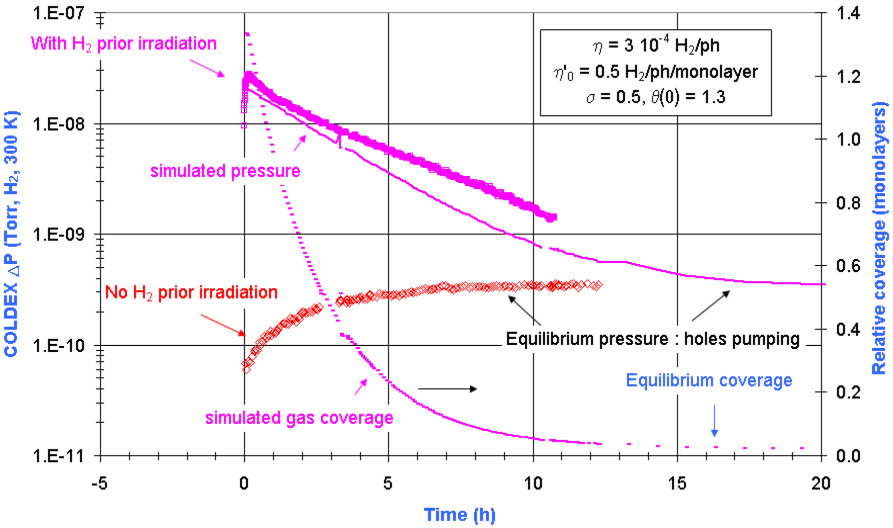
Vacuum Transients

- Transients are due to an excess of physisorbed gas onto the beam screen : beam screen's surface must be bared *i.e.* free of physisorbed molecules.

- Transients level varies with the gas species, the local pumping speed, the temperature, the driving mechanism (temperature excursion, electron cloud, synchrotron radiation, ion bombardment, particle loss …)

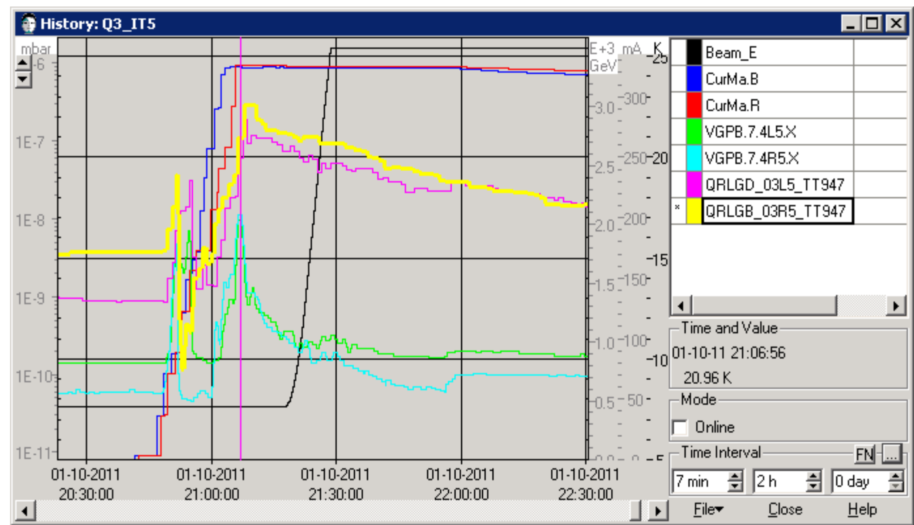
- Appropriate cooling scenario with decoupling between cold bore and beam screen with the possibility of BS warming up to 80 K have been implemented in the LHC base line

In a LHC-type mock –up (SR driven)



V. Baglin, Chamonix 2004

In LHC (T driven)

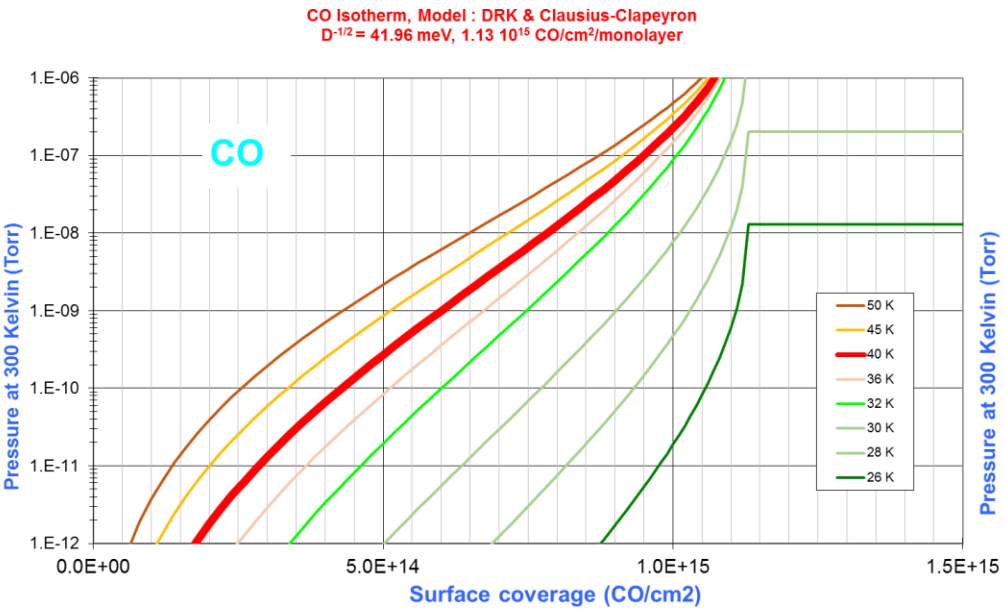


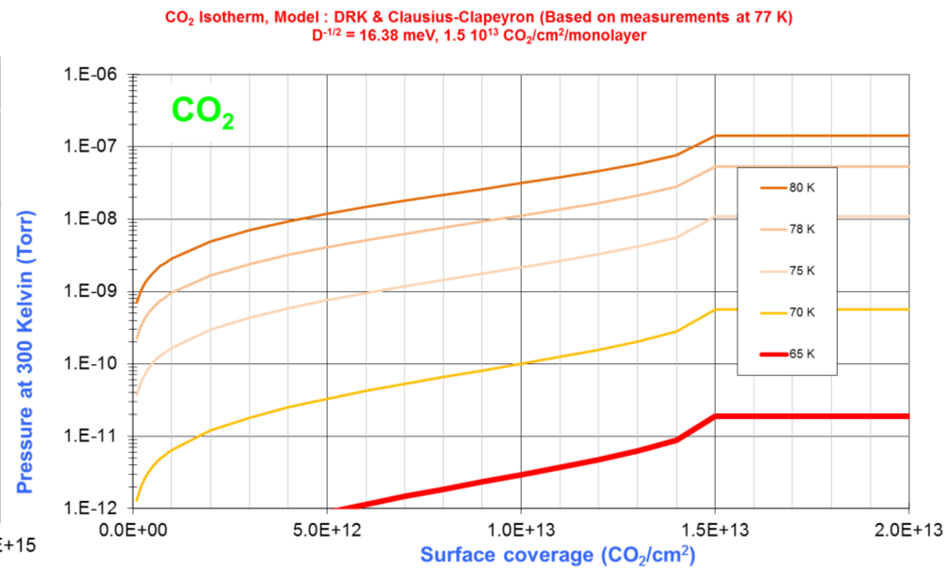
Fill 2177, 1st October 2011

Beam screen heaters in LHC are used to flush the gas towards the cold bore

Temperature Window

- Temperature excursions of the beam screens must not lead to vacuum transients.
- Around ~ 40 K, physisorbed CO with a sub-monolayer capacity, will be thermally desorbed / condensed
- Above ~ 60 K, physisorbed CO_2 with a sub-monolayer capacity, will be thermally desorbed / condensed



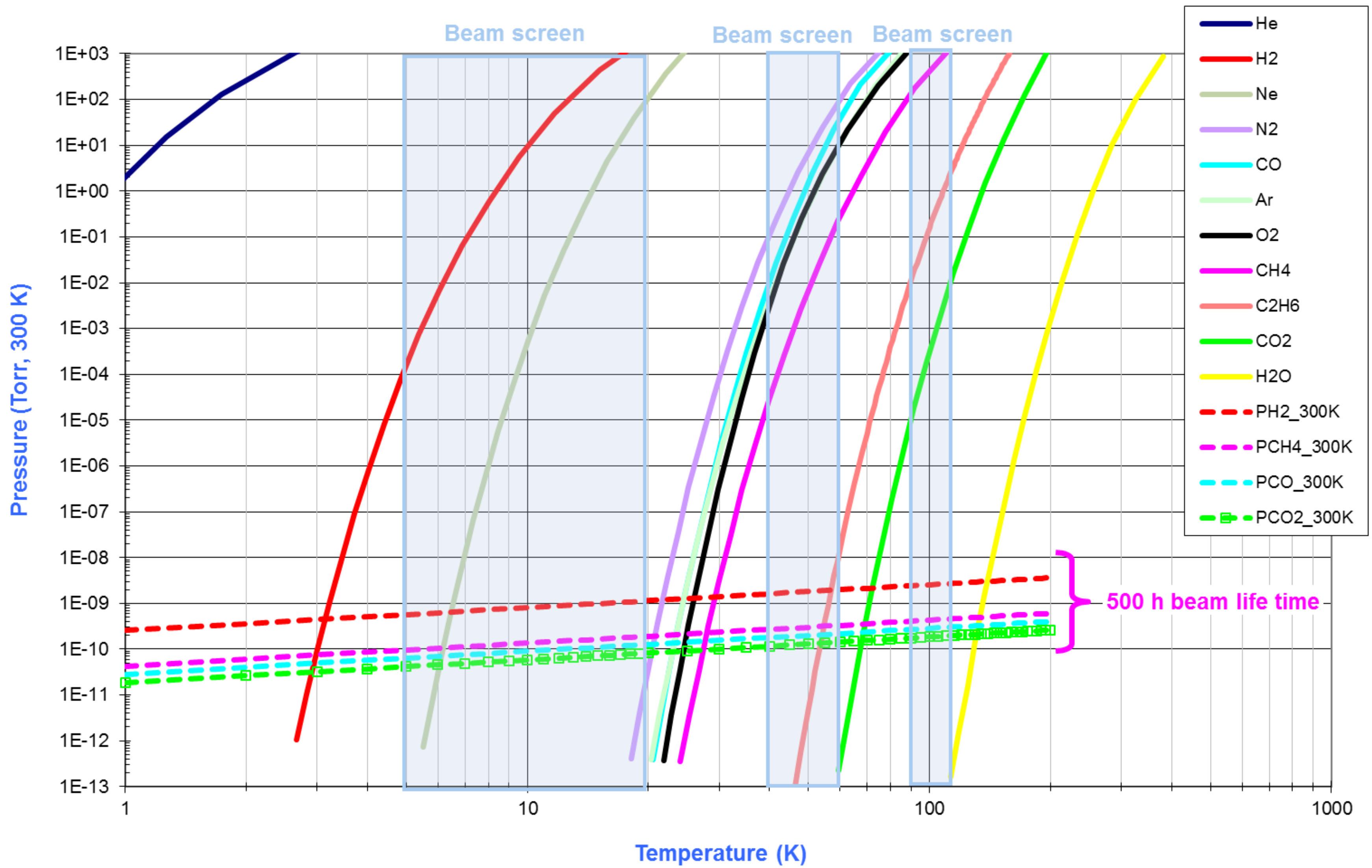


Based on measurements by V.V Anashin *et al.*

Experimental qualification of the proposed FCC temperature window is mandatory

Beam Screens Operating Temperature

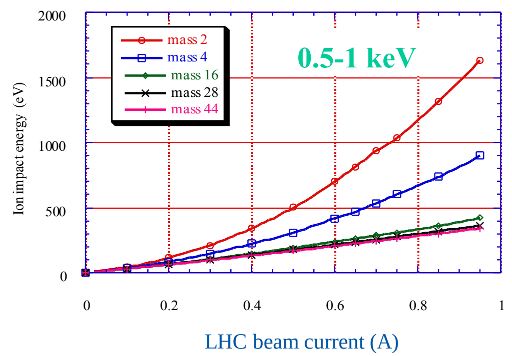
Saturated vapour pressure from Honig and Hook (1960) (C2H6 Thibault *et al.*)



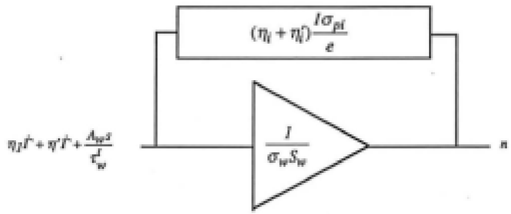
3. Vacuum Dynamics under Ions, Photons and Electrons Irradiation

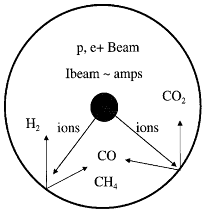
Vacuum Instability

- Origin are ions, produced by beam ionisation, desorbing molecules which are subsequently ionised
- Ion impact energy in the keV range



O. Gröbner, CERN 99-05



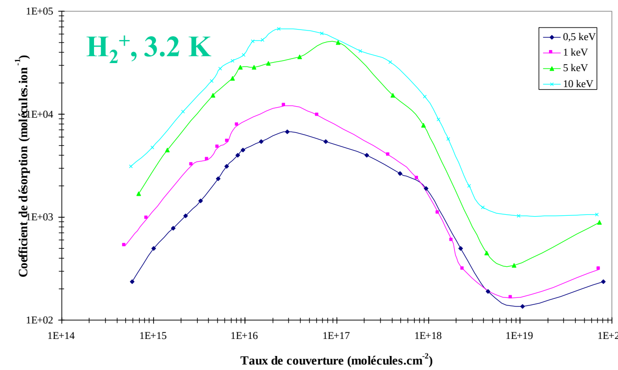


W.C. Turner. J. Vac. Sci.Technol. A. 14(4) , Jul/Aug 1996
O. Grobner, R. Calder, IEE Trans. Nucl. Sci. NS-20, 760 (1976)

- Simple beam tube without beam screen

$$I_{\text{crit, tube}} = \frac{\sigma_w S_W}{\left(\eta_{\text{ion}} + \eta'_{ion}\right)\frac{\sigma}{e}}$$

$\eta'_{H2} \sim 1000$
$\eta'_{CO2} \sim 2$
@ 1 keV and 1 monolayer

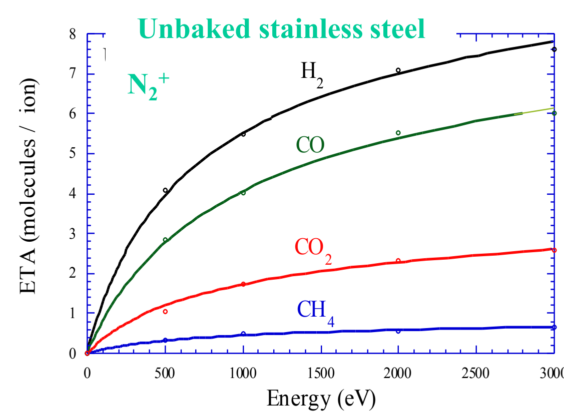


(N. Hilleret, R. Calder, IVC, 1977)

- With a perforated beam screen, C

$$I_{\text{crit, BS}} = \frac{1}{\eta_{\text{ion}}} \frac{C}{\sigma/e}$$

$\eta_{H2} \sim 5$
$\eta_{CO2} \sim 1$
@ 1 keV and 1 monolayer



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

- In both cases, when the beam current approach the **critical current**, the pressure increases to infinity

Vacuum Instability

- Perforated beam screens are preferred to simple beam tube: more margin against instability

$$I_{\text{crit, BS}} = \frac{\left(\eta_{\text{ion}} + \eta'_{ion}\right)}{\eta_{\text{ion}}} \frac{C}{\sigma_w S_w} I_{\text{crit, tube}} \geq \frac{10}{\sigma_w} I_{\text{crit, tube}}$$

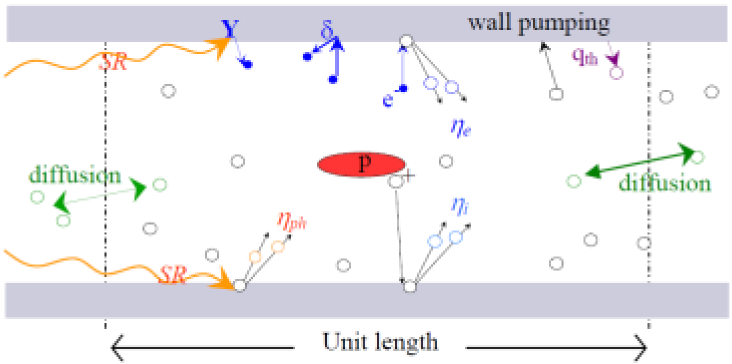
- The desorption of several type of gas species induced by ions, requires the use of dedicated code to study the multigas-system:

O. Gröbner, ISR-VA/76-5

W.C. Turner. J. Vac. Sci.Technol. A. 14(4) , Jul/Aug 1996

O.B. Malyshev, A. Rossi, EPAC 2000, Vienna, Austria

A. Rossi, VASCO code, LHC project note 341



Ion induced desorption yields from the wall bulk material [molecules/ion]

$$\overline{\overline{\eta}}_i = \begin{bmatrix} \eta_{H_2^+-H_2} & \eta_{CH_4^+-H_2} & \eta_{CO^+-H_2} & \eta_{CO_2^+-H_2} \\ \eta_{H_2^+-CH_4} & \eta_{CH_4^+-CH_4} & \eta_{CO^+-CH_4} & \eta_{CO_2^+-CH_4} \\ \eta_{H_2^+-CO} & \eta_{CH_4^+-CO} & \eta_{CO^+-CO} & \eta_{CO_2^+-CO} \\ \eta_{H_2^+-CO_2} & \eta_{CH_4^+-CO_2} & \eta_{CO^+-CO_2} & \eta_{CO_2^+-CO_2} \end{bmatrix}$$

Ion induced desorption yields physisorbed on cold surfaces [molecules/ion]

$$\overline{\overline{\eta'}}_i(\overline{\theta'}) = \begin{bmatrix} \eta'_{H_2^+-H_2}(\theta'_{H_2}) & \eta'_{CH_4^+-H_2}(\theta'_{H_2}) & \eta'_{CO^+-H_2}(\theta'_{H_2}) & \eta'_{CO_2^+-H_2}(\theta'_{H_2}) \\ \eta'_{H_2^+-CH_4}(\theta'_{CH_4}) & \eta'_{CH_4^+-CH_4}(\theta'_{CH_4}) & \eta'_{CO^+-CH_4}(\theta'_{CH_4}) & \eta'_{CO_2^+-CH_4}(\theta'_{CH_4}) \\ \eta'_{H_2^+-CO}(\theta'_{CO}) & \eta'_{CH_4^+-CO}(\theta'_{CO}) & \eta'_{CO^+-CO}(\theta'_{CO}) & \eta'_{CO_2^+-CO}(\theta'_{CO}) \\ \eta'_{H_2^+-CO_2}(\theta'_{CO_2}) & \eta'_{CH_4^+-CO_2}(\theta'_{CO_2}) & \eta'_{CO^+-CO_2}(\theta'_{CO_2}) & \eta'_{CO_2^+-CO_2}(\theta'_{CO_2}) \end{bmatrix}$$

Experimental parameters are needed to complete the inputs for computing tools

LHC, HL-LHC and FCC Parameters

	LHC Design		HL-LHC	FCC	
	Nominal	Ultimate	Nominal	16 T	20 T
Energy [TeV]	7			50	
Luminosity [$x10^{34}$ $cm^{-2}.s^{-1}$]	1.0	2.3	5*	5 to 30	
Current [mA]	584	860	1090	509	609
Proton per bunch [$x10^{11}$]	1.15	1.7	2.2	1.0	
Number of bunches	2808		2736	10600	8900
Bunch spacing [ns]	25			25 (then 5 ?)	
Critical energy [eV]	44.1			4300	5375
Photon flux [ph/m/s]	$1\ 10^{17}$	$1.5\ 10^{17}$	$1.9\ 10^{17}$	$1.7\ 10^{17}$	$2.6\ 10^{17}$
SR power [W/m]	0.22	0.33	0.42	36.3	68.0
Photon dose [ph/m/year]	$1\ 10^{24}$	$1.5\ 10^{24}$	$1.9\ 10^{24}$	$1.7\ 10^{24}$	$2.6\ 10^{24}$

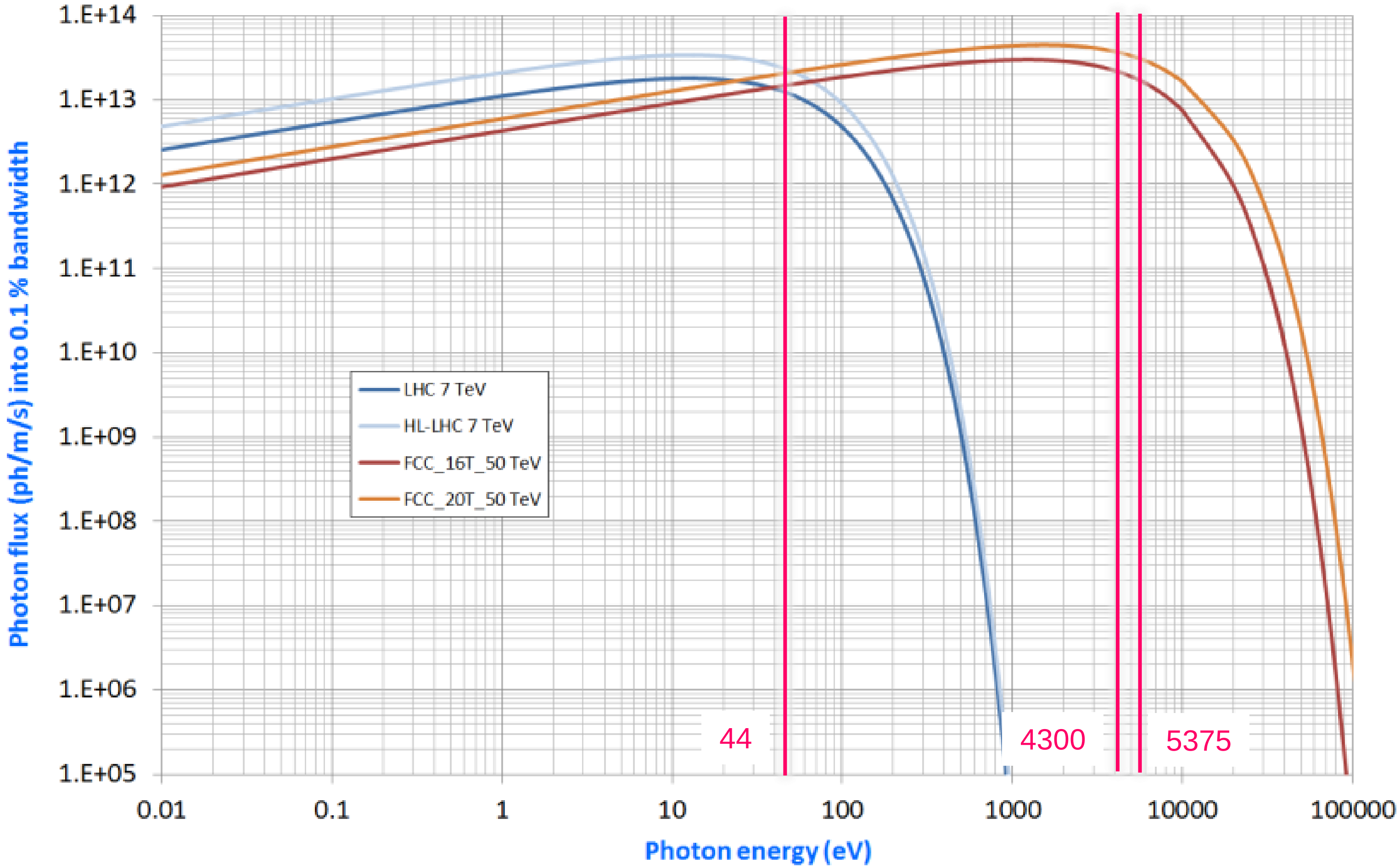
* Levelled luminosity
** to be multiplied by 0.8 to get the average power in the arc taking into account the quadrupoles and interconnects lenghts

* During MD periods

SR Spectrum

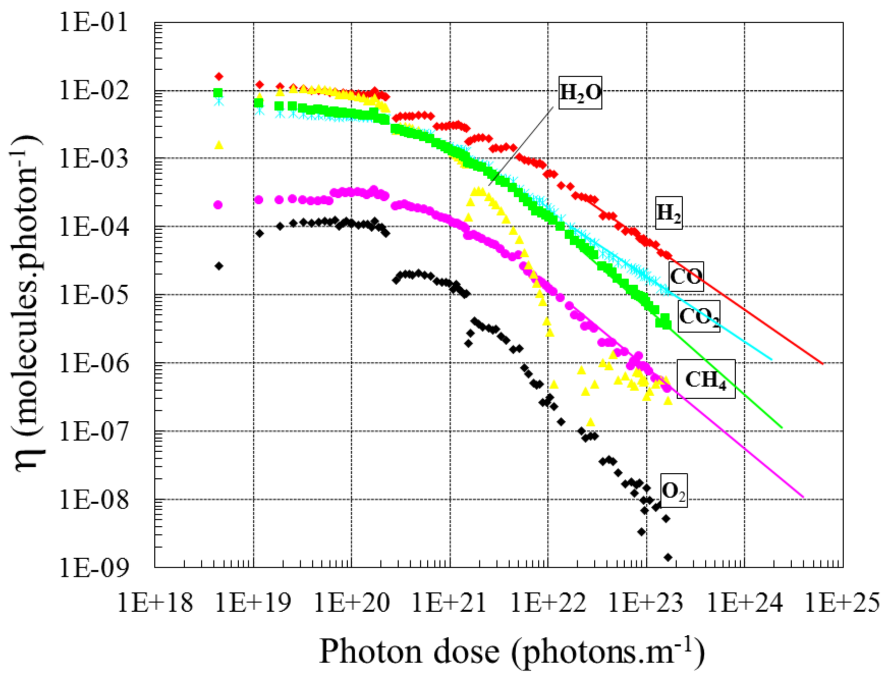
- LHC & HL-LHC: UV range = > 4 to 7 kW per ring
- FCC: X-rays = > 2.4 to 3.6 MW per ring ➔ should it be (all) absorbed at the cryogenic level ?

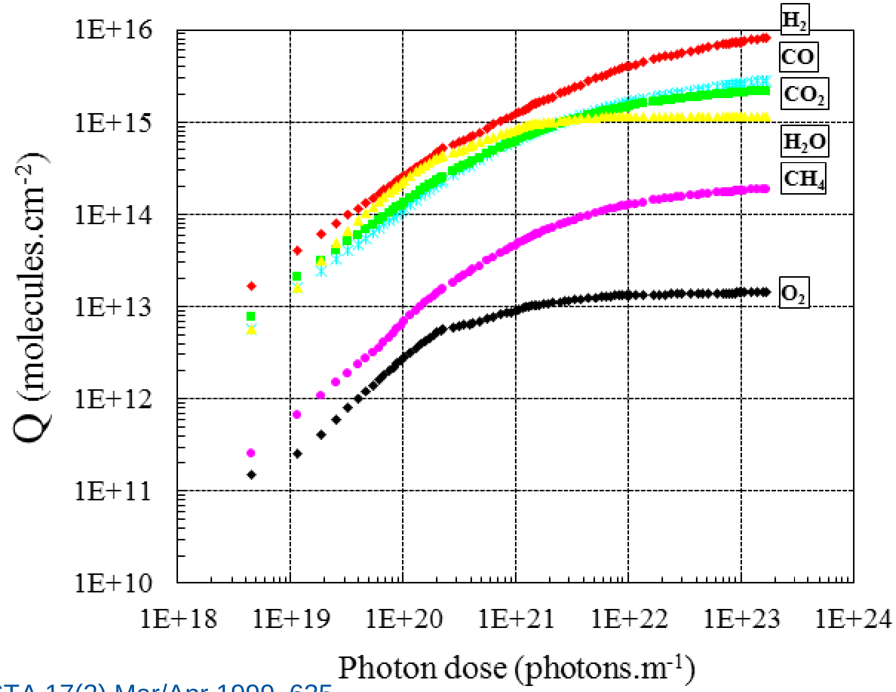
➔ Ideally: the light should be reflected forward and absorbed at room temperature



PSD yields: RT data input

Unbaked stainless-steel at 3.75 keV critical energy





C. Herbeaux *et al.* JVSTA 17(2) Mar/Apr 1999, 635

Gas	H_2	CH_4	H_2O	CO	CO_2	Total
molecules/cm^2 x 10^{15}	5.6	0.2	1.1	2.0	1.7	10.6

1) A couple of years are needed to condition below 10^{-6} molecules/photon

2) Several monolayers of gas can be desorbed

➔ Ex-situ pre-treatment must be considered

Impact of larger critical energy

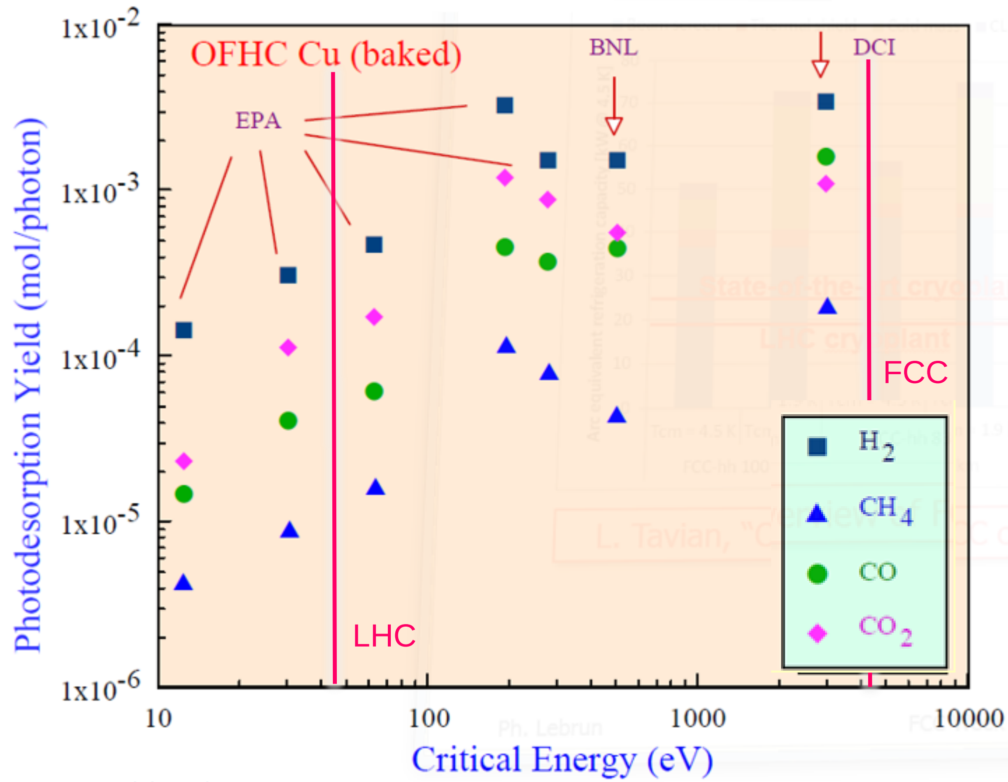
- At room temperature: measured desorption yields of OFHC Cu baked vacuum chambers

E_c	H_2	CH_4	CO	CO_2
44 eV	$5\ 10^{-4}$	$2\ 10^{-5}$	$5\ 10^{-5}$	10^{-4}
4.3 keV	$5\ 10^{-3}$	$2\ 10^{-4}$	$2\ 10^{-3}$	10^{-3}

X 10

- In this low energy range (E_c < 10 keV), the photoelectric effect dominates and the PSD scales like Ec

$$\eta(H_2)\sim E_c^{0.74},\quad \eta(CH_4)\sim E_c^{0.94}$$
$$\eta(CO)\sim E_c^{1.01},\quad \eta(CO_2)\sim E_c^{1.12}$$

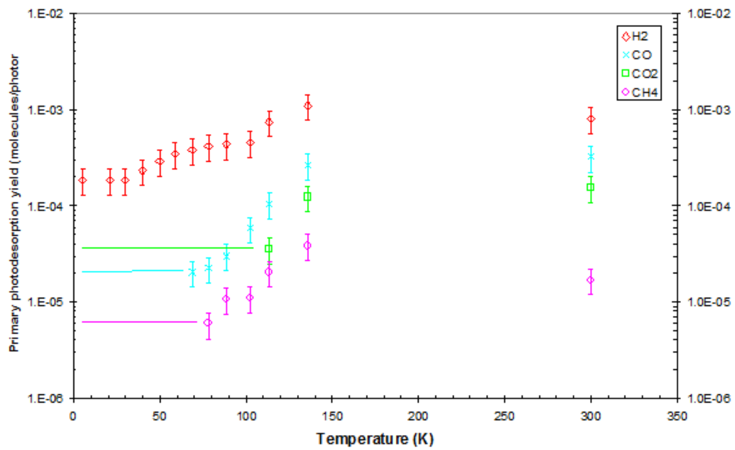


J. Gómez-Goñi *et al.* JVSTA 12(4) Jul/Aug 1994, 1714

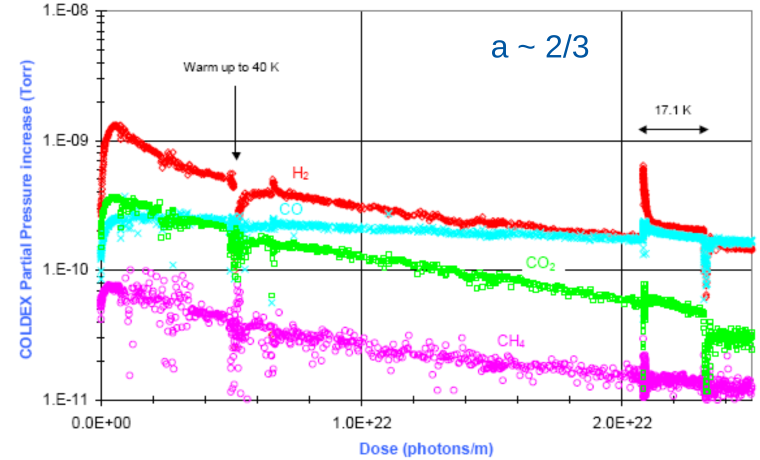
Photodesorption at Cryogenic Temperature

- Initial yield, η_0, and conditioning rate, a, are smaller than at room temperature

V. Baglin *et al.*, Vacuum 67 (2002) 421-428



Cu co-laminated beam screen held at 77K



V. Baglin *et al.* EPAC 2002, Paris, France.

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

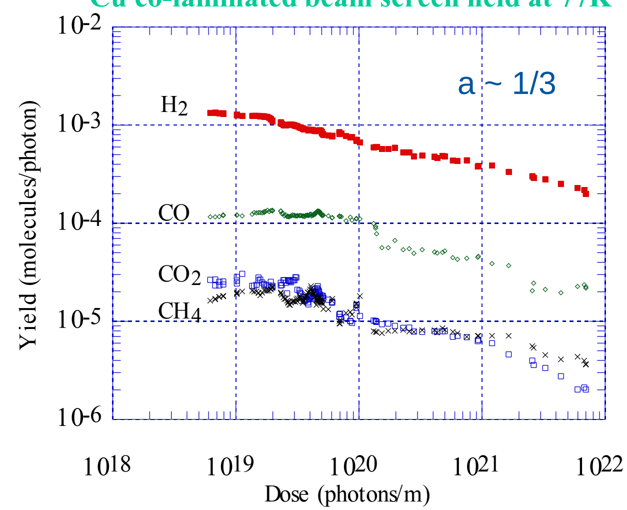
Table 1 : Primary, recycling photodesorption yield measured at 10^{22} photons/m and cleaning rate

	H_2	CH_4	CO	CO_2
η	$2\ 10^{-4}$	$> 6\ 10^{-6}$	$> 3\ 10^{-5}$	$> 2\ 10^{-5}$
(η+η')/ σ	$2\ 10^{-2}$	$6\ 10^{-4}$	$3\ 10^{-3}$	$2\ 10^{-3}$
a	0.6	0.6	0.2	0.8

Cu co-laminated beam screen held at 7K

V. Baglin *et al.* EPAC 2002, Paris, France.

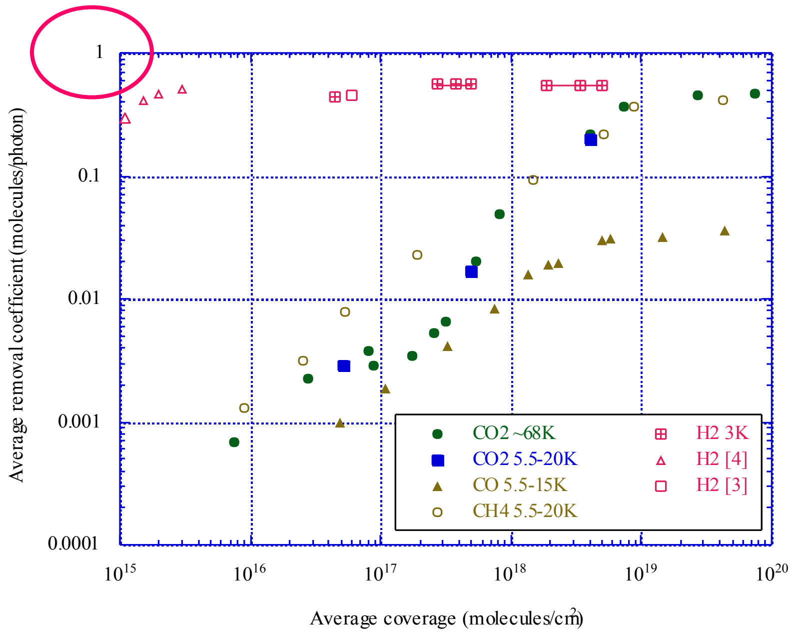
Cu co-laminated beam screen held at 77K



R. Calder *et al.*, J. Vac. Sci. Technol. A 14(4) (1996) 2618

Photodesorption of Physisorbed Gases

- Desorption of physisorbed molecules:
  Large recycling yields η'



V. Anashin *et al.*, Vacuum 53 (1-2), 269, (1999)

Stainless steel, 250-300 eV. Perpendicular incidence

- Photo-craking of molecules:
  CH_4 into H_2
  CO_2 into CO and O_2

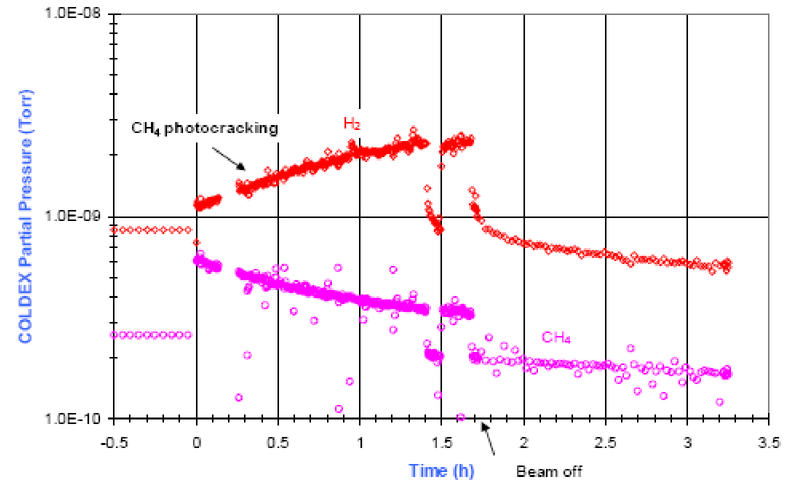


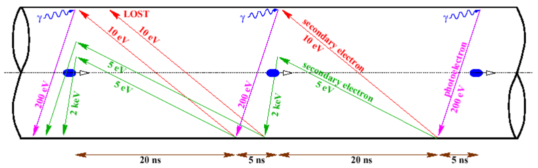
Figure 5 : ~ 10 monolayers of CH_4 condensed onto a BS without hole prior to irradiation at 6 K

V. Baglin *et al.* EPAC 2002, Paris, France.

Recycling and photo-cracking of molecules must be taken into account in models

Electron Cloud

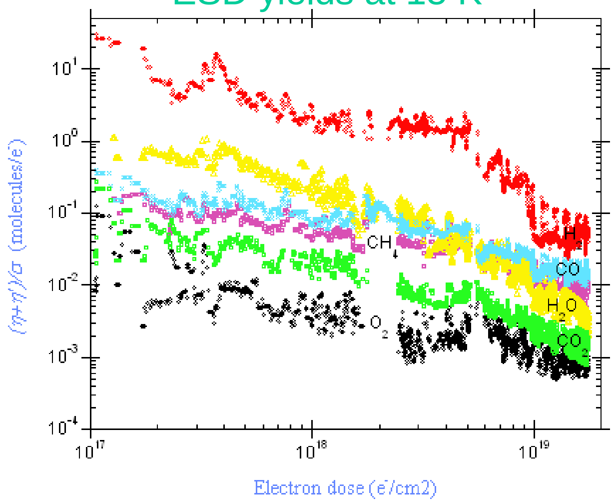
F. Ruggiero *et al.*, LHC Project Report 188 1998, EPAC 98



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

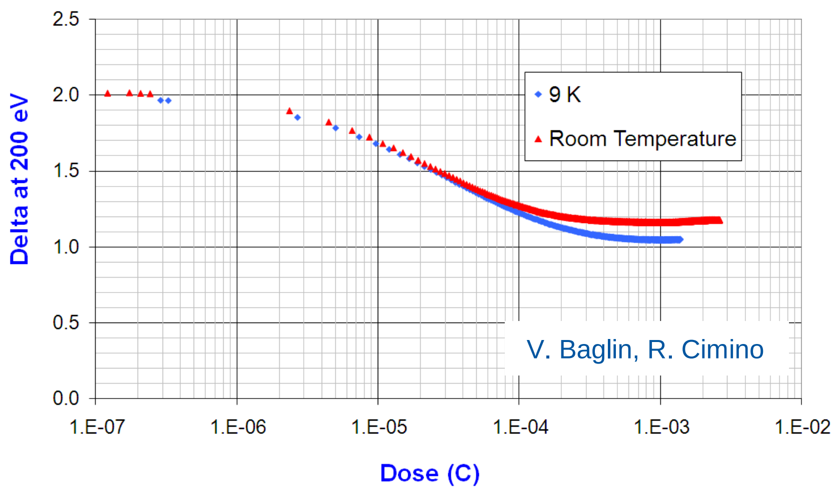
- Generates heat load certainly negligible wrt to synchrotron radiation power
- However, photoelectron production larger than in LHC : 44 eV => 4.5 keV
- Moreover, 3lectron stimulated molecular gas desorption will reduce the vacuum life time
- But, secondary electron yield decreases under electron irradiation

ESD yields at 15 K



V. Baglin *et al.*, CERN LHC PR 721, 2004

Scrubing at 200 eV



Inputs parameters need to be known and optimised against the design

➔ Ex-situ pre-treatment must be considered also

Electron Interaction with Physisorbed Gases

- Electron stimulated molecular gas desorption increase with surface coverage: 0.5 CO_2/e at one monolayer
- Condensed gas have large secondary electron yields (deltamax_CO2 > 1.6)

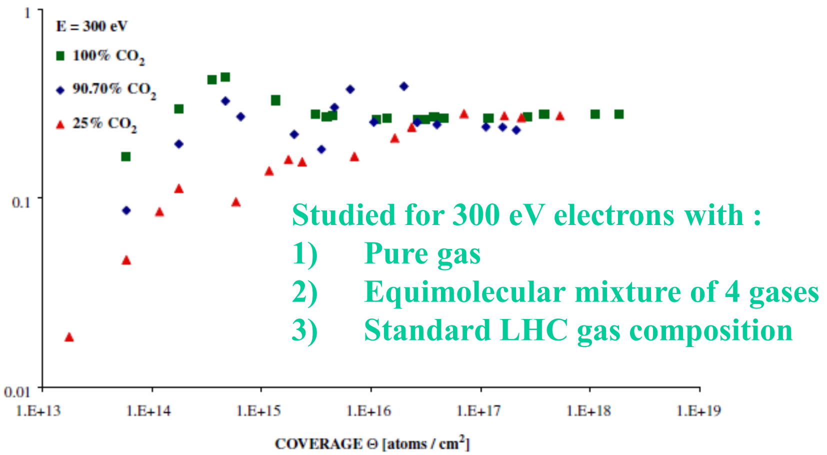
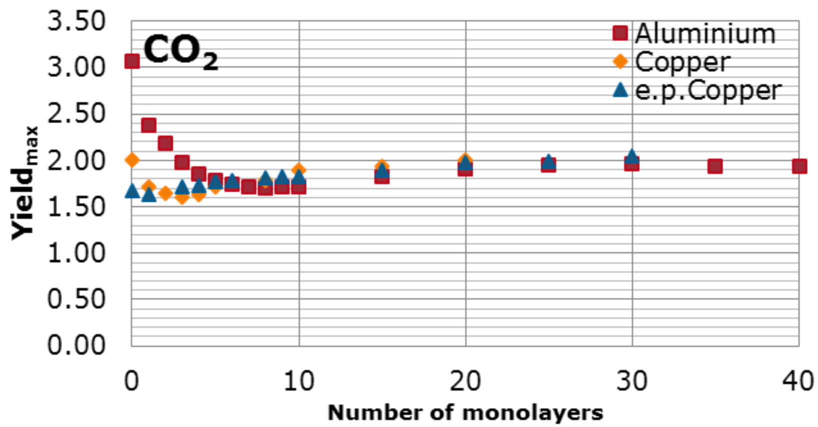


Fig. 8. The CO_2 desorption yield as a function of CO_2 coverage for different condensed gas composition (electron energy 300 eV).

H. Tratnik *et al.*, Vacuum 81, 731,(2007)



A. Kuzucan *et al*. J.Vac.Sci. A. 30, 051401 (2012)

Inputs parameters need to be known and optimised against the design

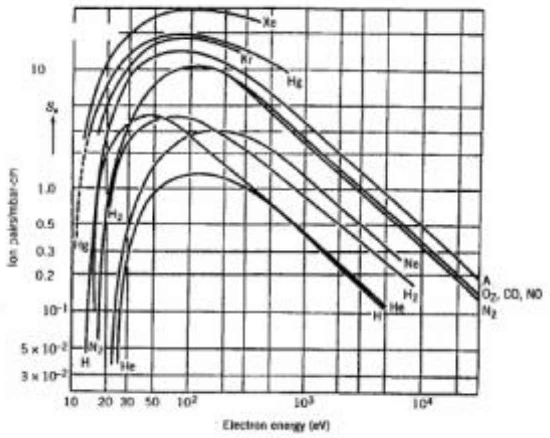
➔ The beam screen surface must remain bare

Electron Cloud and Vacuum Stability

- The electrons along their path length, L_e, ionise also the residual gas (σ_e)
- 2nd source of ion flux to the wall (ion/s/m)

$$V\frac{dP}{dt} = Q_0 + \eta_e kT\frac{I_e}{e} + \eta_{ion}\frac{(\sigma I + \sigma_e I_e L_e)}{e}P + C\frac{d^2P}{dx^2}$$

⟶ Electron cloud can trigger vacuum instability



Handbook of vacuum Technology, ed by K. Jousten, 2008

- Quasi stationary long tube (C=0)

$$P\,S_{eff} = Q_0 + \eta_e kT\frac{I_e}{e} + \eta_{ion}\frac{(\sigma I + \sigma_e I_e L_e)}{e}P$$

$$P = \frac{Q_0 + \eta_e kT\frac{I_e}{e}}{S_{eff}\left(1 - \frac{\eta_{ion}}{S_{eff}}\frac{(\sigma I + \sigma_e I_e L_e)}{e}\right)}$$

- The presence of the electron cloud **reduces** the stability limit and hence the **critical current**

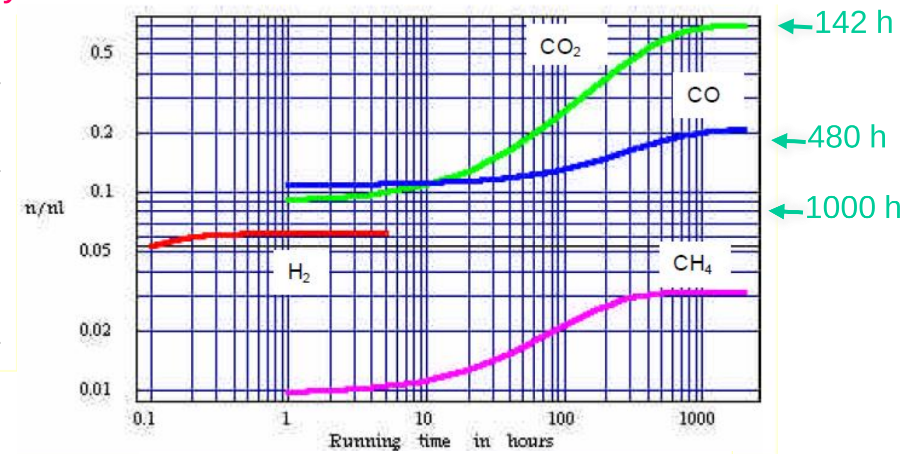
LHC: Beam Life Time

- With photons, the beam life time at equilibrium density is 99 h

Primary photodesorption yield, temperature, recycling yield, relative nuclear scattering cross section at 7 TeV as well as individual and total beam life times.

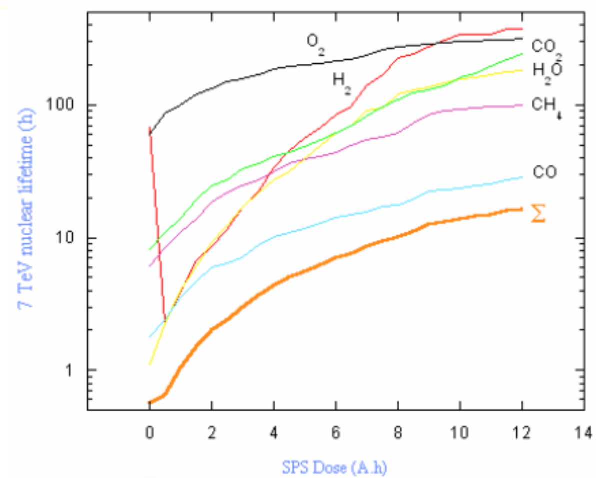
Gas	η (molecules/photon)	T (K)	σ	η' [7] (molecules/photon)	n_{H2}/n_{gas}	τgas (h)	τ (h)
H_2	2.0 10^{-4}	5-20	0.02	0.1	1	1620	
CH_4	6.0 10^{-6}	78	0.05	1 10^{-4}	6.0	3200	99
CO	2.0 10^{-5}	69	0.02	2 10^{-5}	9.0	480	
CO_2	3.5 10^{-5}	114	0.15	1 10^{-4}	13.9	142	

V. Baglin *et al.*, Vacuum 67 (2002) 421-428



- In the presence of electron cloud, the beam life time is well below 100 h

- Electron conditioning is mandatory to reduce SEY and also ESD yields



V. Baglin *et al.*, CERN LHC PR 721, 2004

➔ No photon conditioning is needed

➔ Electron conditioning is needed to reach 100 h

Electron dominates !

4. Summary

Summary

- Adsorption Isotherms are key ingredients to understand the impact of temperature, gas species and surface properties in a cryogenic vacuum system.

- Perforated beam screens have been proven to be effective during LHC RUN 1 to control the gas density and reduce the beam induced heat load onto the cryogenic system.

- Input parameters characterising the surface properties and the machine environment of the proposed beam screen material must be studied in details in order to validate and optimise the proposed FCC vacuum system design(s).

Credits & Acknowledgments

- The slides presented here are the fruit of the work of many CERN and external collaborators who participated to the design and installation of the LHC vacuum system under the successive directions of A.G. Mathewson, O. Gröbner and P. Strubin

- Credits and warm thanks also to J M. Jimenez and P. Chiggiato for the constant support and to the TE-VSC-LBV team for its investment and fantastic commitment during installation of the LHC, RUN1 and the Long Shutdown 1.

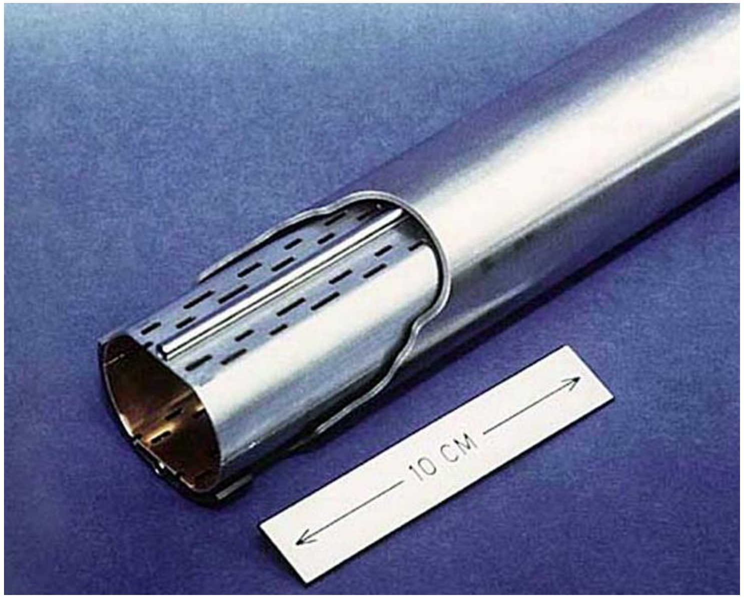
Thank you for your attention !!!

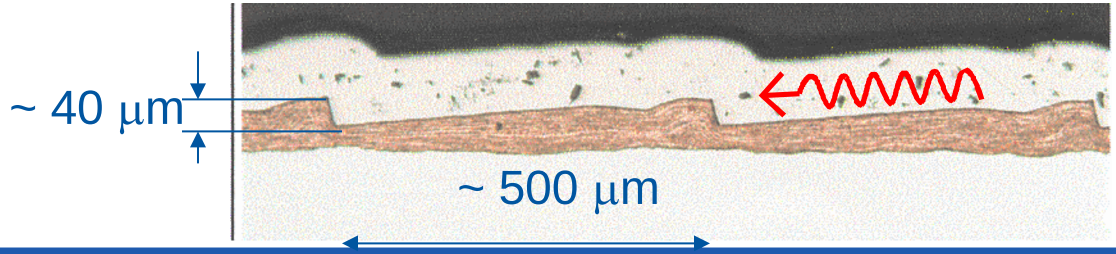
CERN

Beam Screen Design

- Sawteeth are provided in the LHC beam screen to reduce the photoelectron yield and the forward reflectivity (due to the quasi-perpendicular incidence)

- In dipoles, electron shield are clamped to protect the cold bore



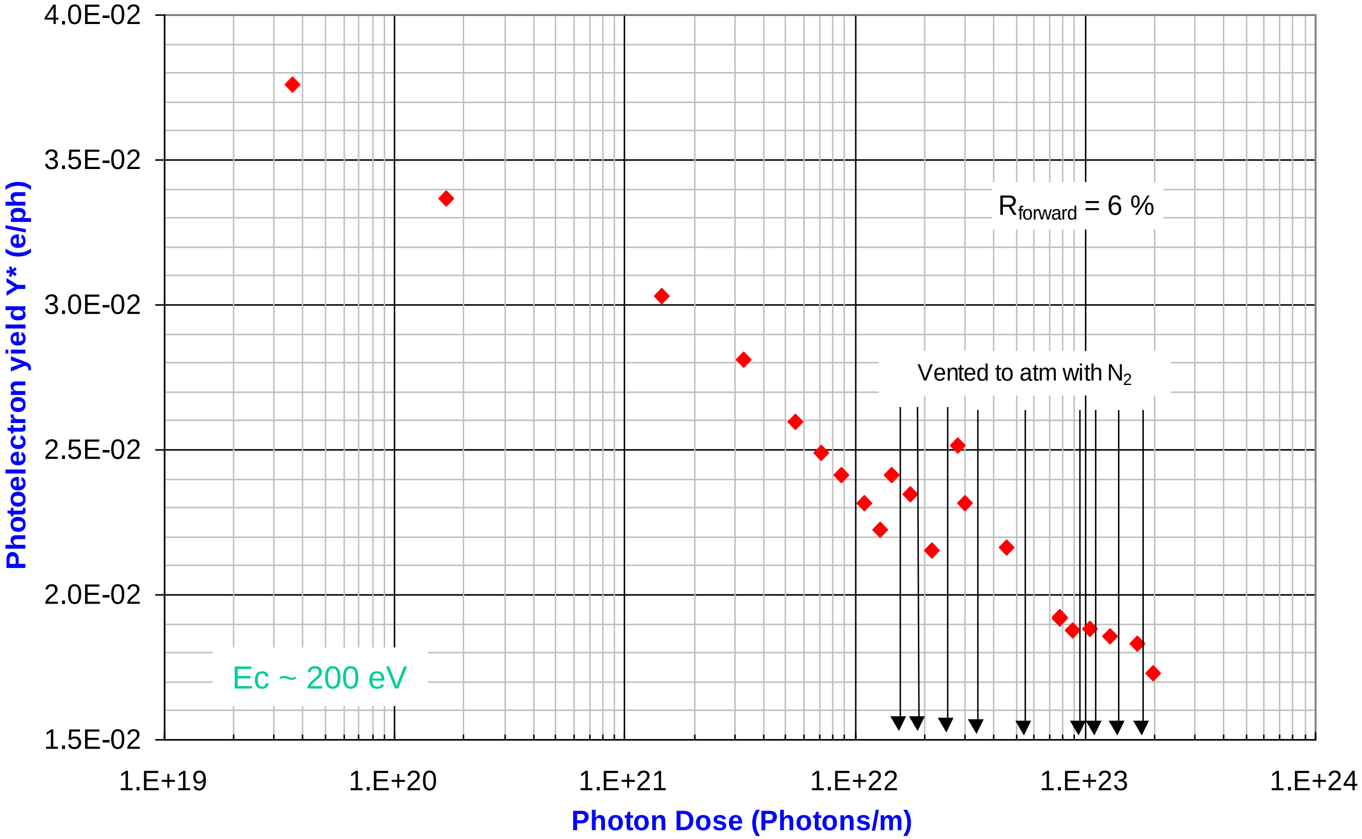


Courtesy N. Kos CERN TE/VSC

LHC Beam Screen: Sawteeth

- Photon electron yield reduces under beam conditioning and reach ~ 0.01 e/ph after ~ 1 month operation with nominal parameters

- Forward reflectivity equals 6 %



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