

# Vacuum Systems

## Lecture 4

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# Outline

1. Synchrotron radiation and photodesorption
2. Vacuum instability and ion stimulated desorption
3. Particle losses and ion stimulated desorption
4. Electron cloud and related surface parameters

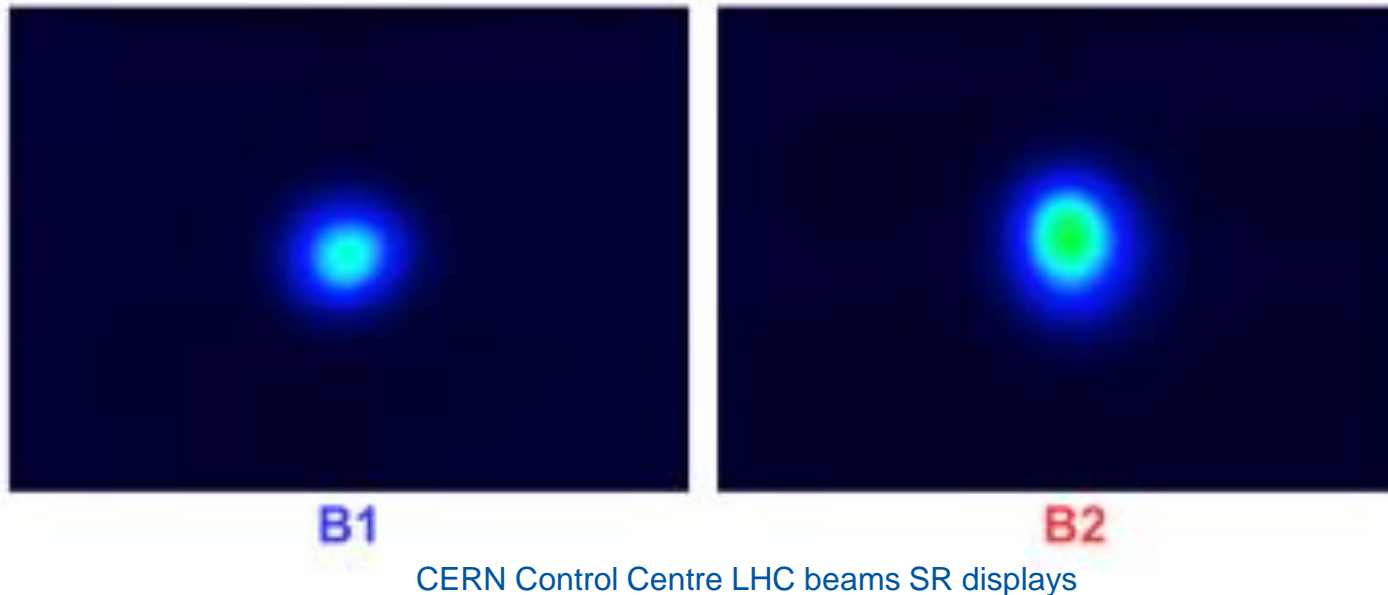
# 1. Synchrotron radiation and photodesorption

# 1.1 Synchrotron radiation

# Synchrotron radiation: visible light

- In synchrotron, particles can radiate light by synchrotron radiation
- Can be used for diagnostics purposes :

## LHC SYNCHROTRON LIGHT MONITORS



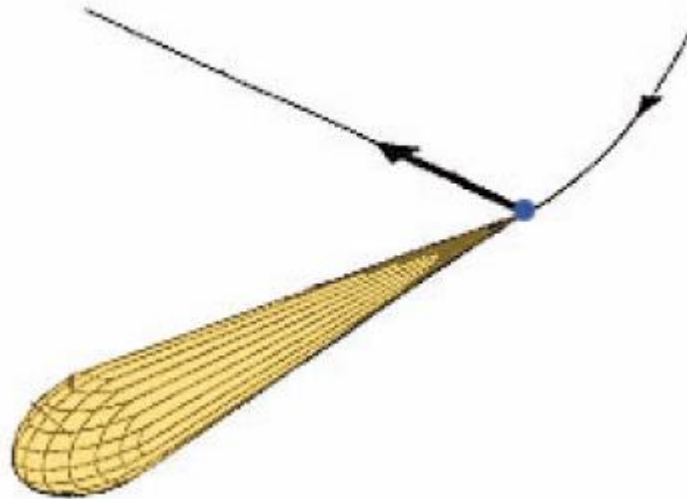
- But particles loose energy by synchrotron radiation → should be compensated by RF system
- Beam emittance shrink by synchrotron radiation
- Power is dissipated on the machine elements
- **Molecules are desorbed** from the vacuum chamber wall due to synchrotron radiation

# Synchrotron Radiation

- A charged particle which is accelerated produce radiation
- The power of the centripetal radiation is larger than the longitudinal radiation (factor  $\gamma^3$ )
- For a relativistic particle, the radiation is highly peaked (opening angle  $\sim 1/\gamma$ )
- The radiation energy range from infra-red to gamma rays: from meV to MeV

## References :

- K. Hübner, CAS 1984, CERN 85-19
- R.P. Walker, CAS 1992, CERN 94-01
- A. Hofmann, CAS 1996, CERN 98-04
- L. Rivkin, CAS 2008



# Critical energy

- The critical energy split the power spectrum in two equals parts

$$\varepsilon_c = \frac{3}{2} \frac{hc}{2\pi} \frac{\gamma^3}{\rho}$$

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

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

- 90 % of the emitted photons have an energy lower than the critical energy
- Magnetic rigidity:

$$B \rho = \frac{p}{e} \approx \frac{E}{e c}$$

$$\frac{1}{\rho} \approx \frac{3}{10} \frac{B[\text{T}]}{E[\text{GeV}]}$$

$$\varepsilon_c \propto \frac{E^3}{\rho} \propto B E^2$$



# Dissipated power

- The energy emitted by the synchrotron radiation per turn and per particle is:

$$\Delta E = \frac{e^2}{3\epsilon_0} \frac{\gamma^4}{\rho} = \frac{4\pi}{3} r m_0 c^2 \frac{\gamma^4}{\rho}$$

with  $r = \frac{1}{4\pi\epsilon_0} \frac{e^2}{m_0 c^2}$  (classical radius)

- The average power emitted per turn by the beam is:

$$P_{\text{tour}} = \Delta E \frac{N}{t} = \frac{e \gamma^4}{3\pi\epsilon_0 \rho} I$$

- So, the average power emitted by the beam per unit of length is:

$$P_0 = \frac{\partial P}{\partial s} = \frac{e \gamma^4}{6\pi\epsilon_0 \rho^2} I$$

$$P_0 \propto \frac{E^4}{\rho^2} I \propto B^2 E^2 I$$

# Dissipated power

- The average power emitted by the beam per unit of length is

$$P_0 \text{ [W/m]} = \frac{e}{3\epsilon_0 (m_0 c^2)^4} \frac{E^4}{2\pi \rho^2} I$$

$$P_0 \propto \frac{E^4}{\rho^2} I \propto B^2 E^2 I$$

- Electrons :

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

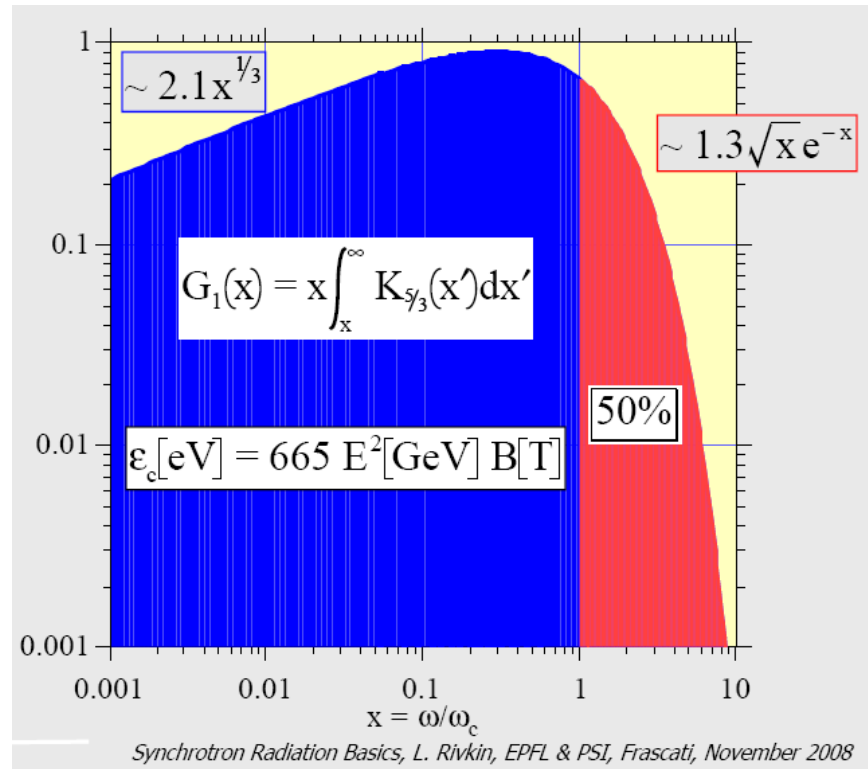
- Protons:

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

# Power spectrum

- The SR power emitted by a particle is a function of the vertical angle and the wavelength.
- Integrating over the vertical angle, one obtains the **spectral power density** per unit of length :

$$\frac{\partial^2 P}{\partial s \partial \varepsilon} = P_0 \frac{1}{\varepsilon_c} S\left(\frac{\varepsilon}{\varepsilon_c}\right) \quad \text{with } S(x) = \frac{9\sqrt{3}}{8\pi} x \int_x^\infty K_{5/3}(z) dz \text{ ("universal function" )}$$



# Photon flux

- Since the photon flux is linked to the power by :  $P = \dot{\Gamma} \varepsilon$
- The photon flux per unit length in a relative energy band is written:

$$\frac{\partial \dot{\Gamma}}{\partial \varepsilon / \varepsilon} = \frac{\partial^2 P}{\partial s \partial \varepsilon} = P_0 \frac{1}{\varepsilon_c} S\left(\frac{\varepsilon}{\varepsilon_c}\right)$$

- So, the total photon flux per unit of length is:

$$\dot{\Gamma} = \int_0^\infty \frac{\partial \dot{\Gamma}}{\partial \varepsilon} d\varepsilon = \frac{P_0}{\varepsilon_c} \times \int_0^\infty \left(\frac{\varepsilon}{\varepsilon_c}\right)^{-1} S\left(\frac{\varepsilon}{\varepsilon_c}\right) d\left(\frac{\varepsilon}{\varepsilon_c}\right) = \frac{15\sqrt{3}}{8} \frac{P_0}{\varepsilon_c} = \frac{5\sqrt{3}e}{12 h \varepsilon_0 c} \frac{\gamma}{\rho} I$$

$$\dot{\Gamma} \propto \frac{E}{\rho} I \propto B I$$

# Linear photon flux

- The photon flux per unit of length is given by :

$$\dot{\Gamma} = \frac{15\sqrt{3}}{8} \frac{P_0}{\varepsilon_c} = \frac{5\sqrt{3}e}{12 h \varepsilon_0 c} \frac{\gamma}{\rho} I$$

$$\dot{\Gamma} \propto \frac{E}{\rho} I \propto B I$$

- Electrons :

$$\dot{\Gamma}[\text{photons.m}^{-1}.\text{s}^{-1}] = 1.28810^{17} \frac{E[\text{GeV}]}{\rho[\text{m}]} I[\text{mA}]$$

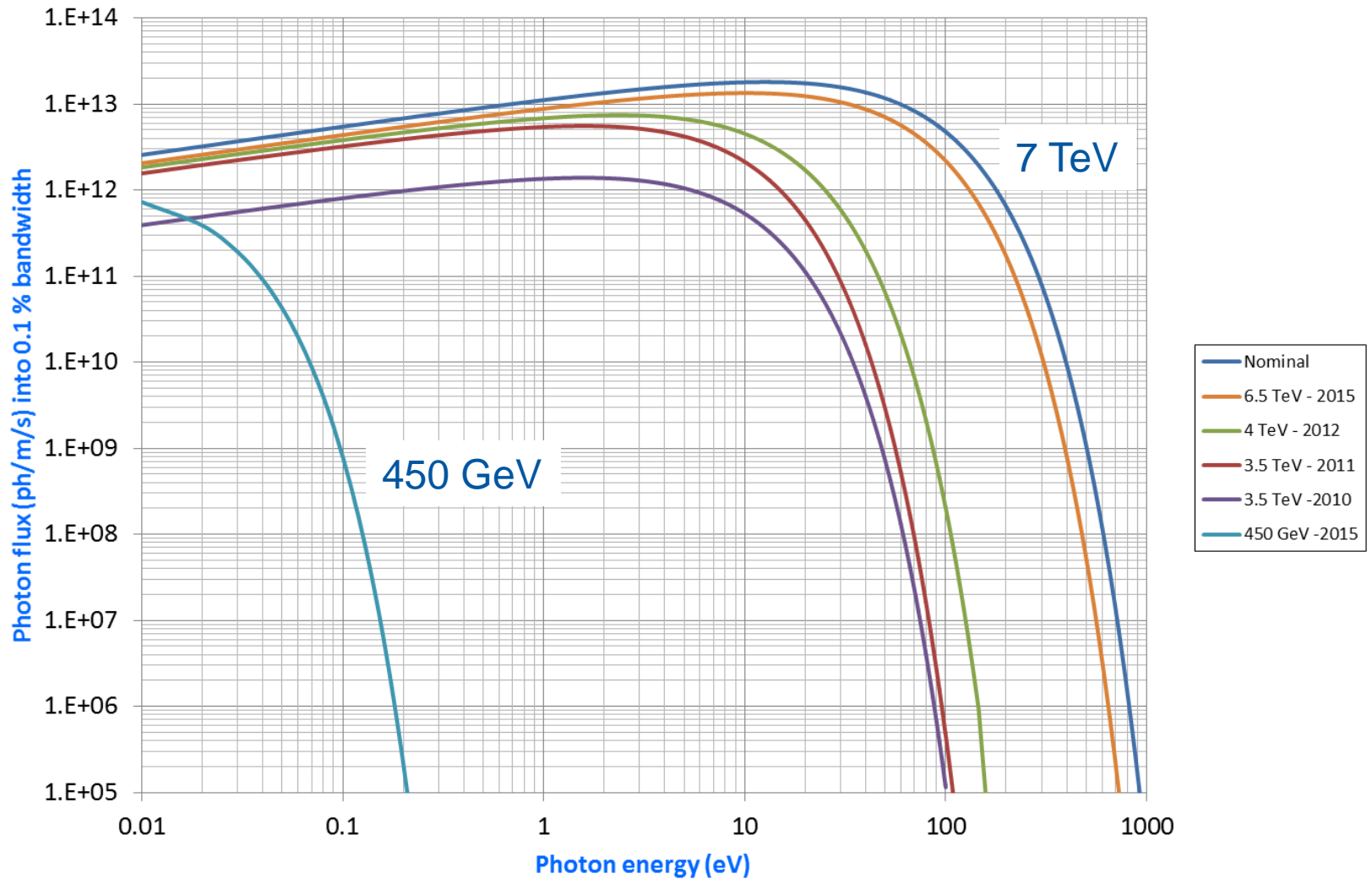
- Protons:

$$\dot{\Gamma}[\text{photons.m}^{-1}.\text{s}^{-1}] = 7.01710^{13} \frac{E[\text{GeV}]}{\rho[\text{m}]} I[\text{mA}]$$

# LHC SR Spectrum : from IR to UV

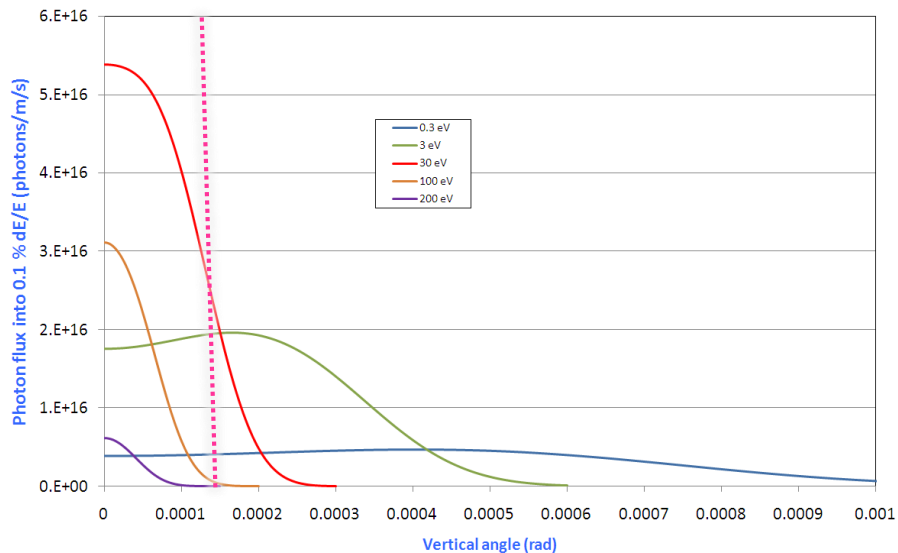
- With nominal parameters : 7 TeV and 585 mA
- 2010, 2011, 2012 and 2015 spectra

Key parameter: **photodesorption yield**

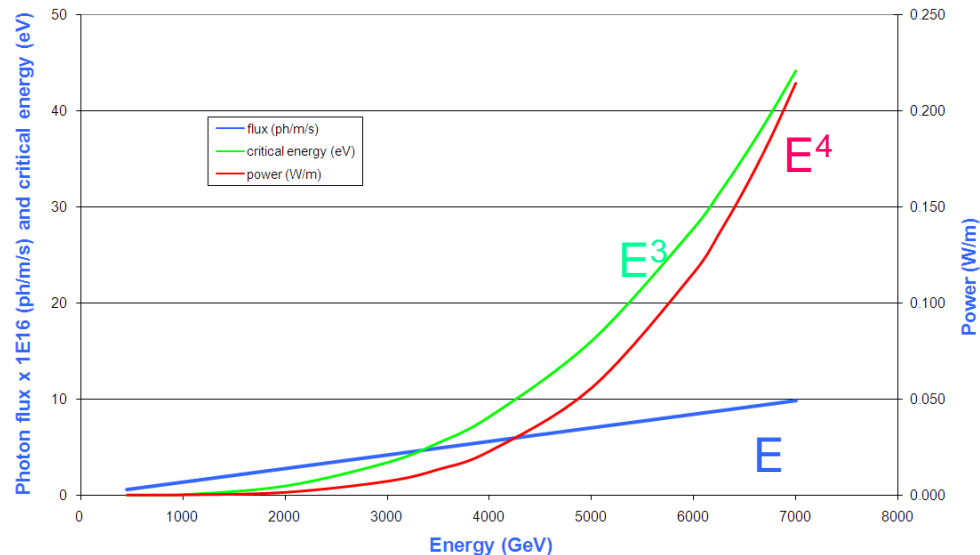


# LHC SR properties

Vertical distribution of LHC photon flux



LHC synchrotron radiation at 560 mA



1/gamma opening angle

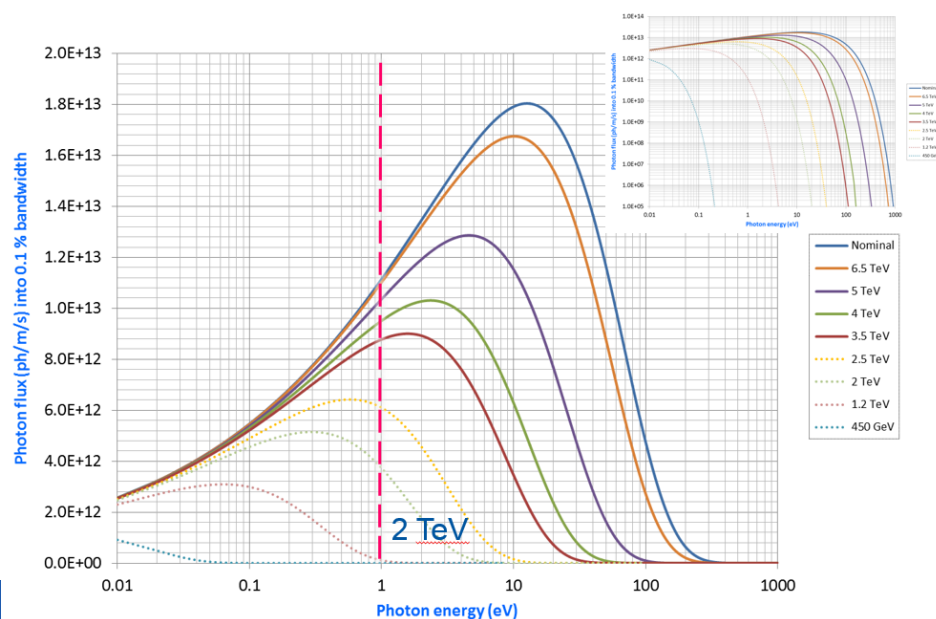
7 TeV

$\epsilon_c = 44$  eV

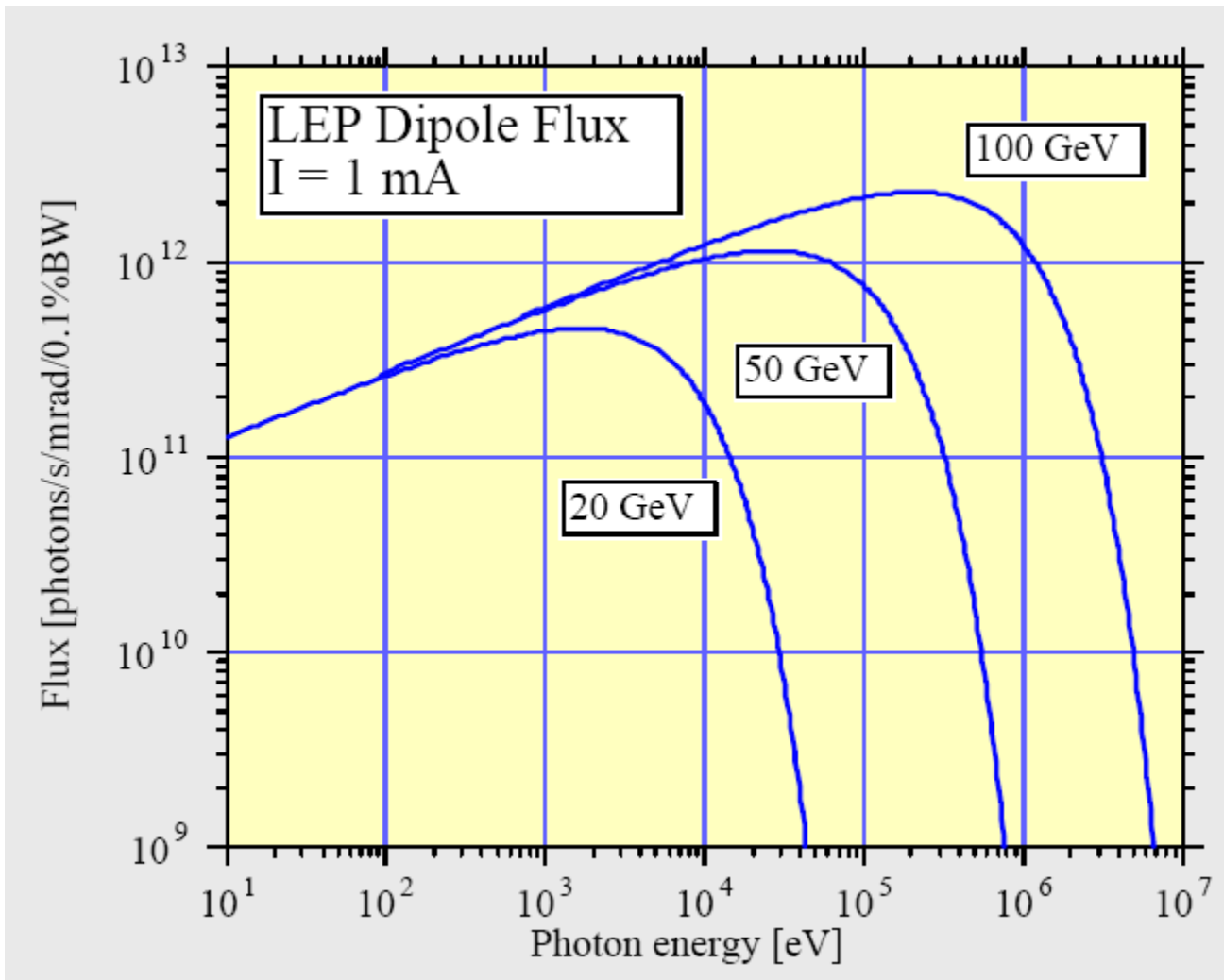
0.2 W/m

$10^{17}$  photons/m/s

1/gamma = 0.13 mrad



# LEP SR spectrum: X-rays & gamma rays





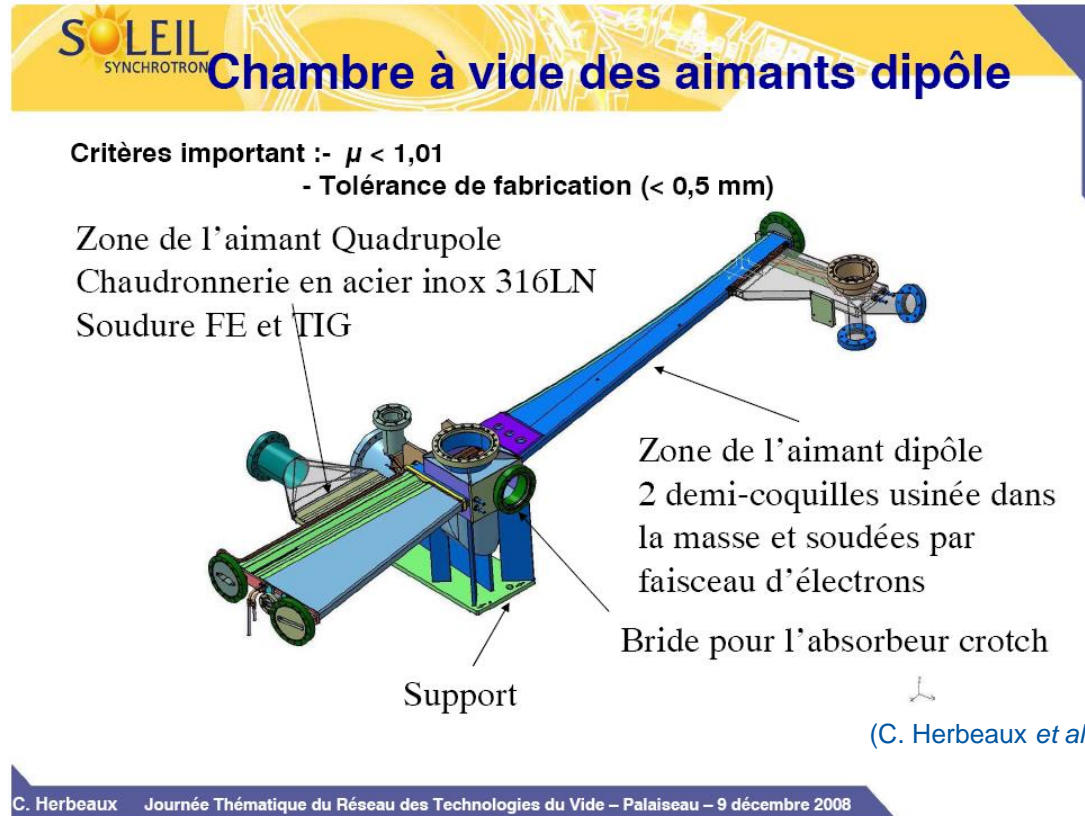
# SR impact on different type of machines ...

		Soleil	KEK-B		LEP			LHC	
			LER	HER	Inj.	1	2	Inj.	Col.
Particle		e <sup>-</sup>	e <sup>+</sup>	e <sup>-</sup>	e <sup>-</sup>	e <sup>-</sup>	e <sup>-</sup>	p	p
Beam current	mA	500	2600	1100	3	3	7	584	584
Energy	GeV	2.75	3.5	8	20	50	96	450	7000
Bending radius	m	5.36	16.31	104.46	2962.96			2784.302	
Power	W/m	14 030	20 675	5 820	0.8	30	955	0	0.2
Critical energy	eV	8 600	5 800	11 000	6 000	94 000	660 000	0	44
Photon flux	photons/m/s	3 10 <sup>19</sup>	7 10 <sup>19</sup>	1 10 <sup>19</sup>	3 10 <sup>15</sup>	7 10 <sup>15</sup>	3 10 <sup>16</sup>	7 10 <sup>15</sup>	1 10 <sup>17</sup>
Dose at 3000 h	photons/m	4 10 <sup>26</sup>	8 10 <sup>26</sup>	1 10 <sup>26</sup>	3 10 <sup>22</sup>	7 10 <sup>22</sup>	3 10 <sup>23</sup>	7 10 <sup>22</sup>	1 10 <sup>24</sup>

- In LEP, and all synchrotron light sources, the evacuation of the **power is an issue**
- The LHC operates at 7 TeV with ~ .6 A. **Power evacuation is an issue for the cryogenic system (1 kW/arc !!)**
- The critical energy varies from a few 10 eV to 660 keV. **Strongly bound molecules can be desorbed**
- The photon flux is large, so large gas load. **Adequate dimensioning of the effective pumping speed** is required
- The annual photon dose is large. **Implications on gas reduction and radiation**

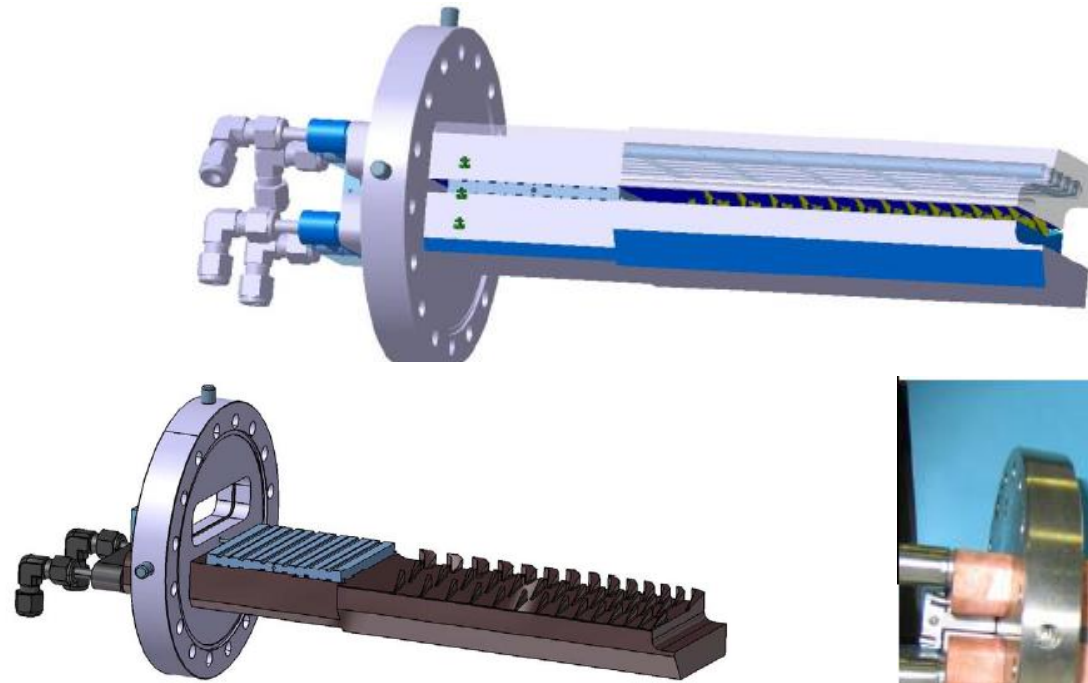
# ... heavy consequences on design

- Stainless steel
- NEG coated, in-situ baked to 180°C

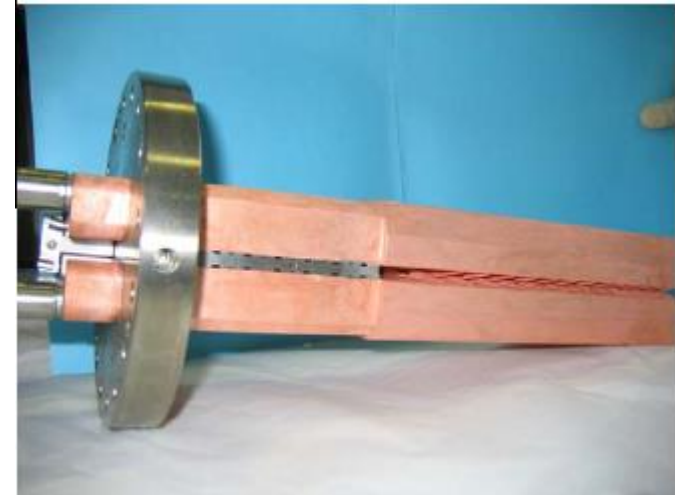


- A **complex** vacuum chamber design with a light extraction path, pumping and instrumentation ports and **power absorbers** (crotch)

# ... heavy consequences on design



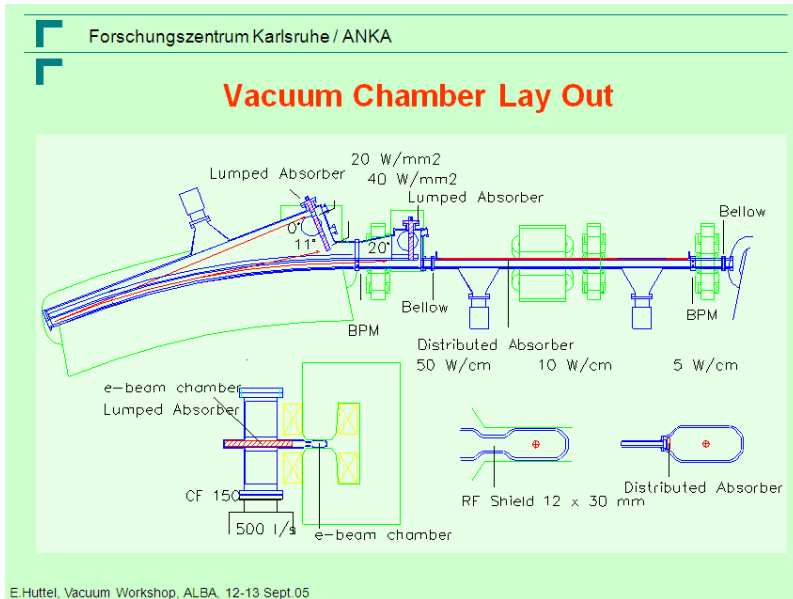
SOLEIL Design



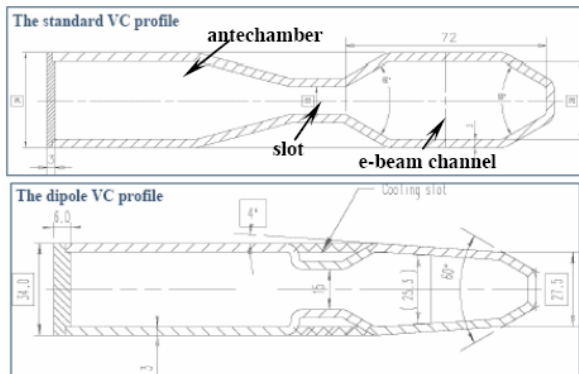
(C. Herbeaux *et al.*)

- Soleil « crotch » power absorber: Water cooled copper Glidcop ( $256 \text{ W/mm}^2$ )

# ... heavy consequences on design

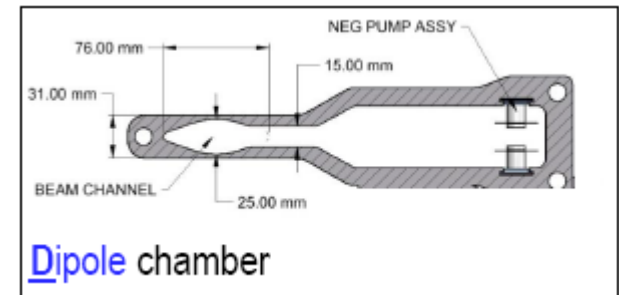


(E. Huttel et al.)



## ALBA Design

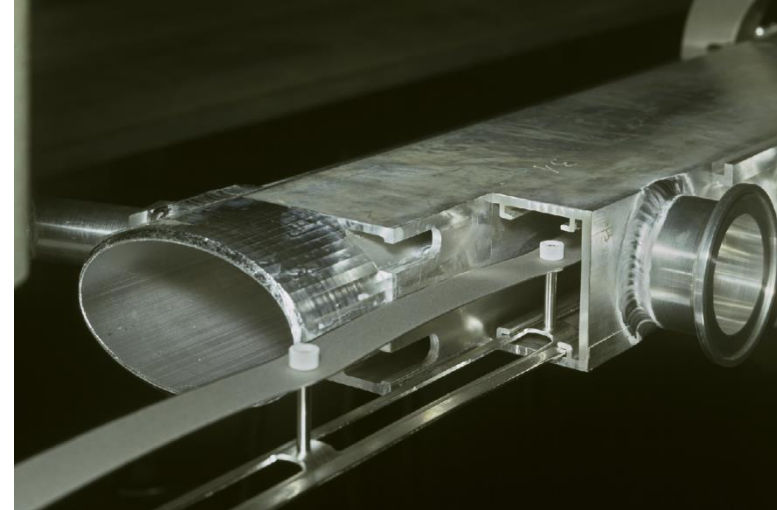
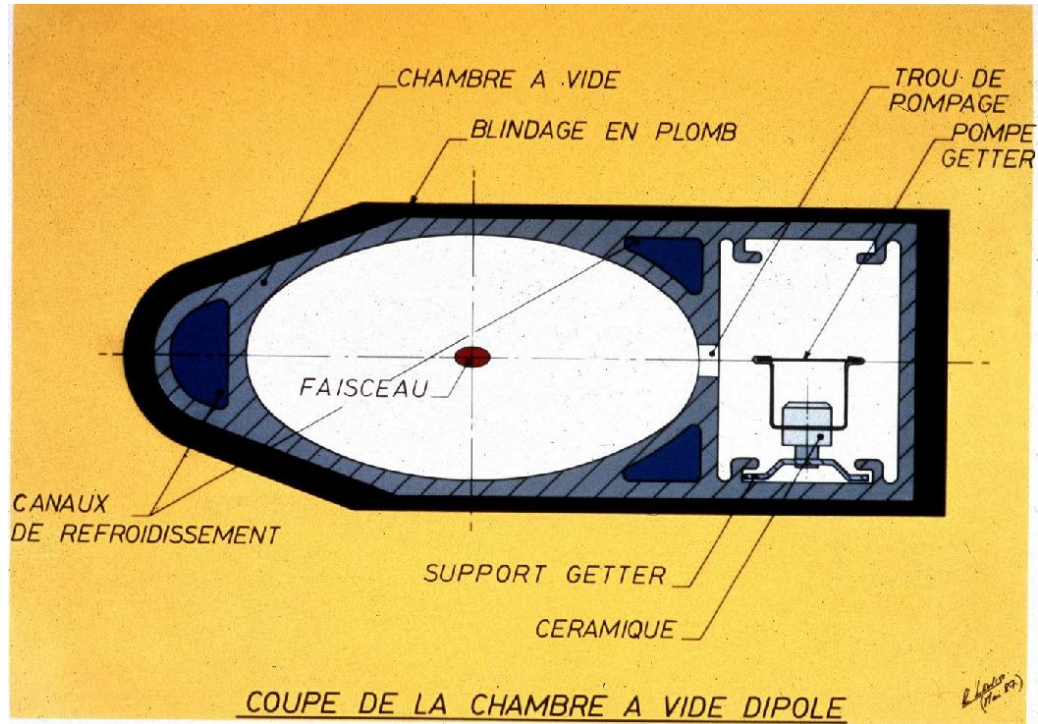
(E. Al-Dmour, EPAC 2006)



## NSLS-2 Design

- **Antechamber** design to absorb the SR power externally to the beam path with the integration of a distributed pumping

# ... heavy consequences on design

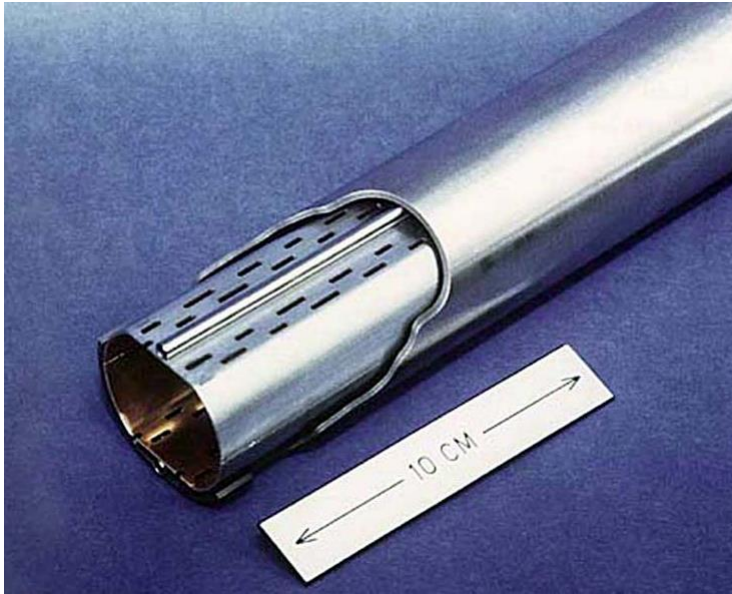


## LEP Design

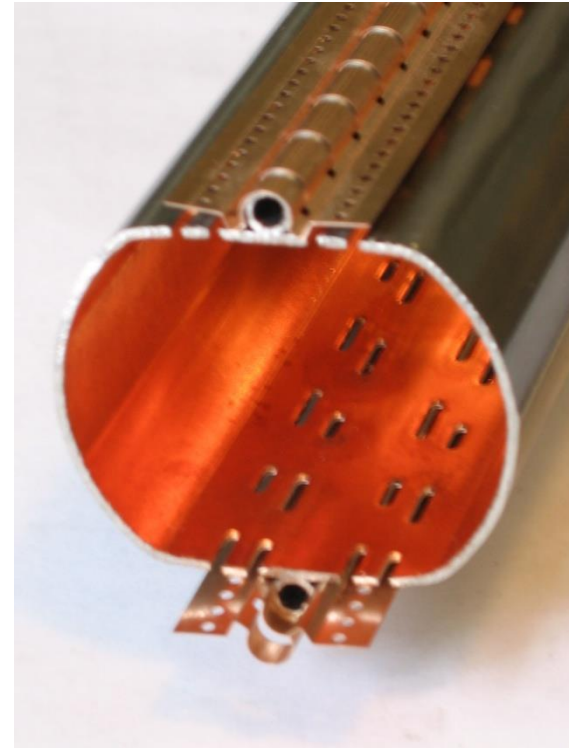
(CERN LEP Vacuum group)

- Antechamber and distributed NEG pumping, water cooling and lead shielding

# ... heavy consequences on design



Courtesy N. Kos CERN TE/VSC



Courtesy N. Kos CERN TE/VSC

## LHC Design

(CERN LHC Vacuum group)

- **Perforated Cu colaminated beam screen** to intercept the SR power protecting the 1.9 K cold bore and to allow a distributed pumping

# 1.2 Photodesorption

# Photodesorption

- The interaction of photons (light) with matters produce the **desorption of neutral gases** inside the vacuum system
- The photon stimulated desorption (PSD) of physisorbed (meV) or chemisorbed (eV) molecules can be direct or non-direct
- The identified transmitters are photoelectrons, secondary electrons and phonons
- The photon stimulated molecular desorption is a function of the nature of the material, its temperature, its surface state, of the photon energy and the irradiation angle.
- No model exists, therefore ***in-situ* qualification** of material is required for the design of a future machine.



# Photodesorption: present understanding

- The photodesorption process is linked to the production of photoelectrons and secondary electrons
- Photoelectrons contribute to the gas load by ESD
- The **oxide and carbon layers** are believed to be the source of gas
- The diffusion of atoms into the solid and their recombination at the surface plays a role

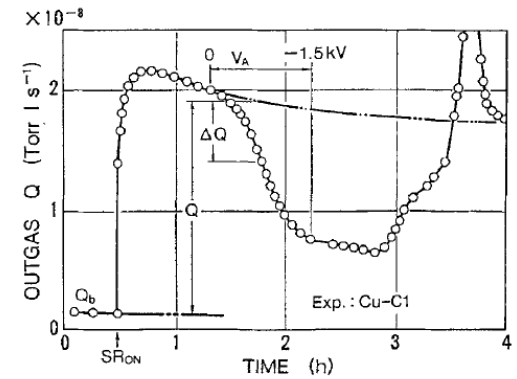


Fig. 5. Changes of outgas due to the bias voltage  $V_A$ .

T. Kobari *et al* Proc. of Vacuum Design of Synch Light Sources Conference, Argonne, 1990

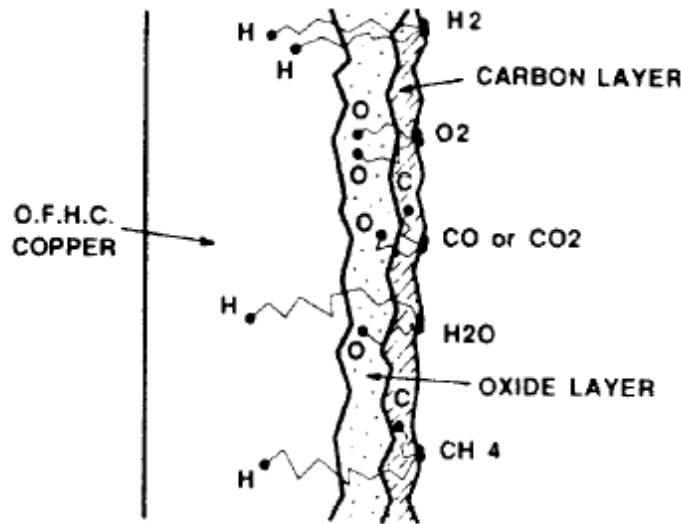
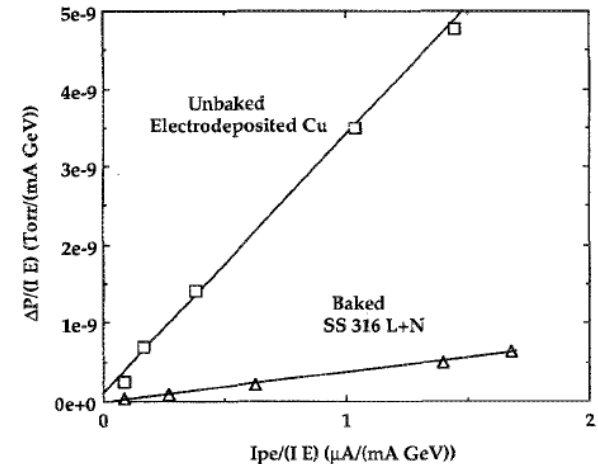


Fig. 6. Tentative Microscopic Model for PSD from OFHC Copper.

O. Gröbner *et. al.* EPAC 1992



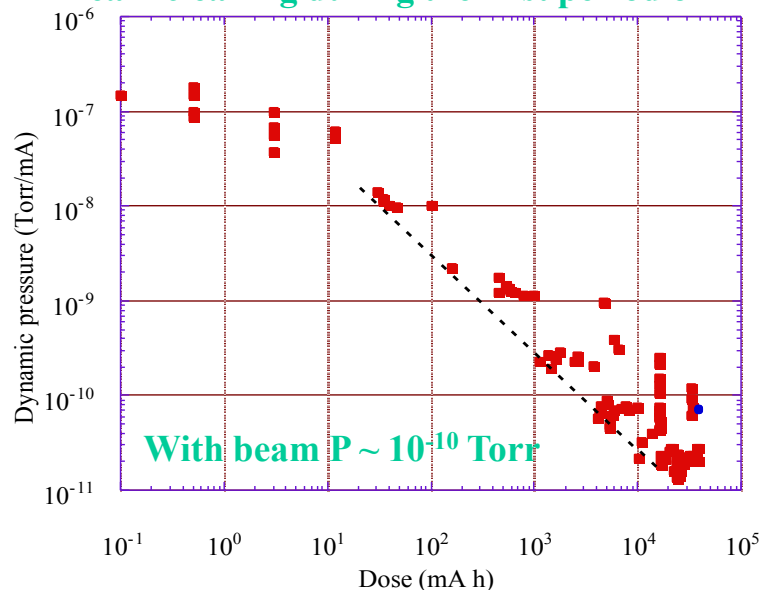
J. Gómez-Goñi *et al.* JVSTA 12(4) Jul/Aug 1994, 1714

# Dynamic pressure due to PSD

- The dynamic pressure decreases by several orders of magnitude with photon dose: “**photon conditioning**”
- The photon desorption yield is characterised by  $\eta_{\text{photon}}$

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

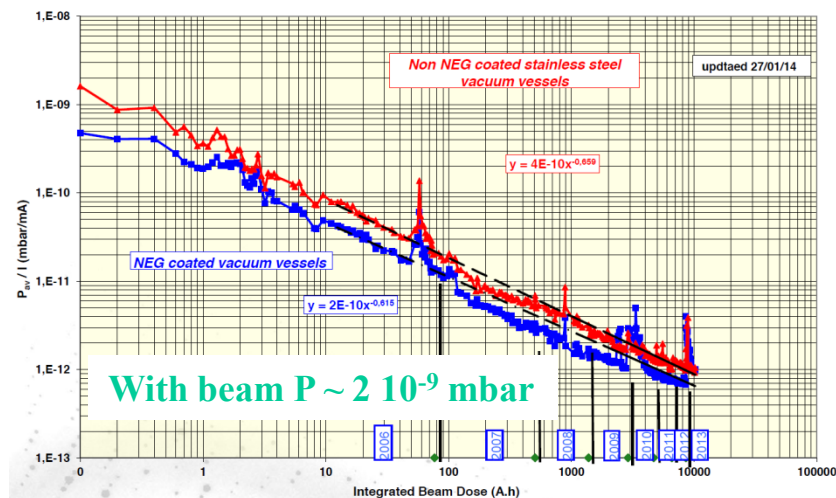
## Beam cleaning during the first period of LEP



O. Gröbner. Vacuum 43 (1992) 27-30

## SOLEIL

Average pressure rise in cell C07 normalized to current Vs. beam dose



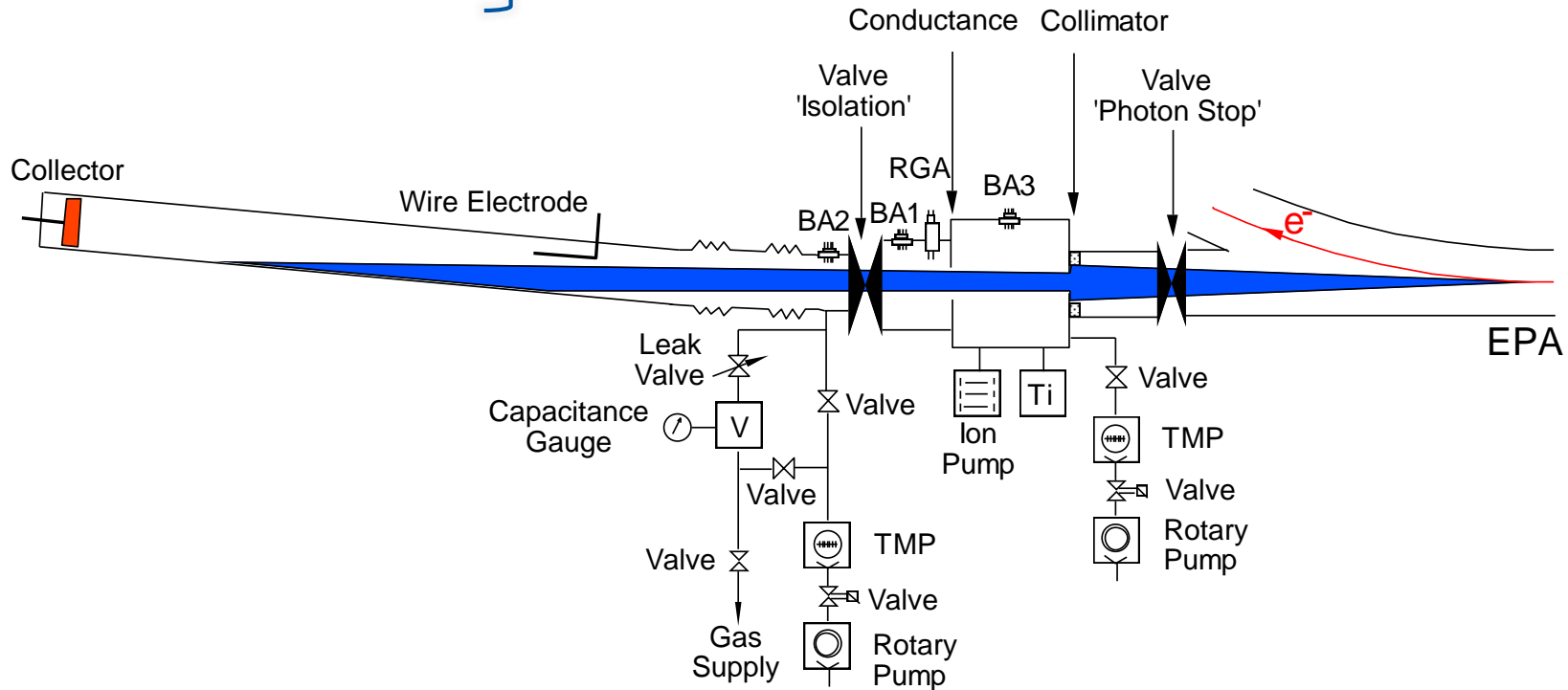
C. Herbeaux, Journée thématiques RTVide, décembre 2014

# Photo-desorption yield measurement

- SR light is extracted from a dipole magnet to irradiate the chamber at ~ 11 mrad
- SR fan is vertically collimated therefore photon flux < 4 eV are attenuated
- The gas load is measured by the throughput method via a conductance (72.5 l/s for N<sub>2</sub>)
- A wire and a collector are biased for current measurement to estimate the photon reflectivity and photoelectron yield

$$\left. \begin{aligned} Q_0 &= C (P_2 - P_1) \\ Q &= \eta \dot{\Gamma} + Q_0 = C (P'_2 - P'_1) \end{aligned} \right\} \eta = \frac{G}{\dot{\Gamma}} C (\Delta P_2 - \Delta P_1) \approx \frac{G}{\dot{\Gamma}} C \Delta P_2$$

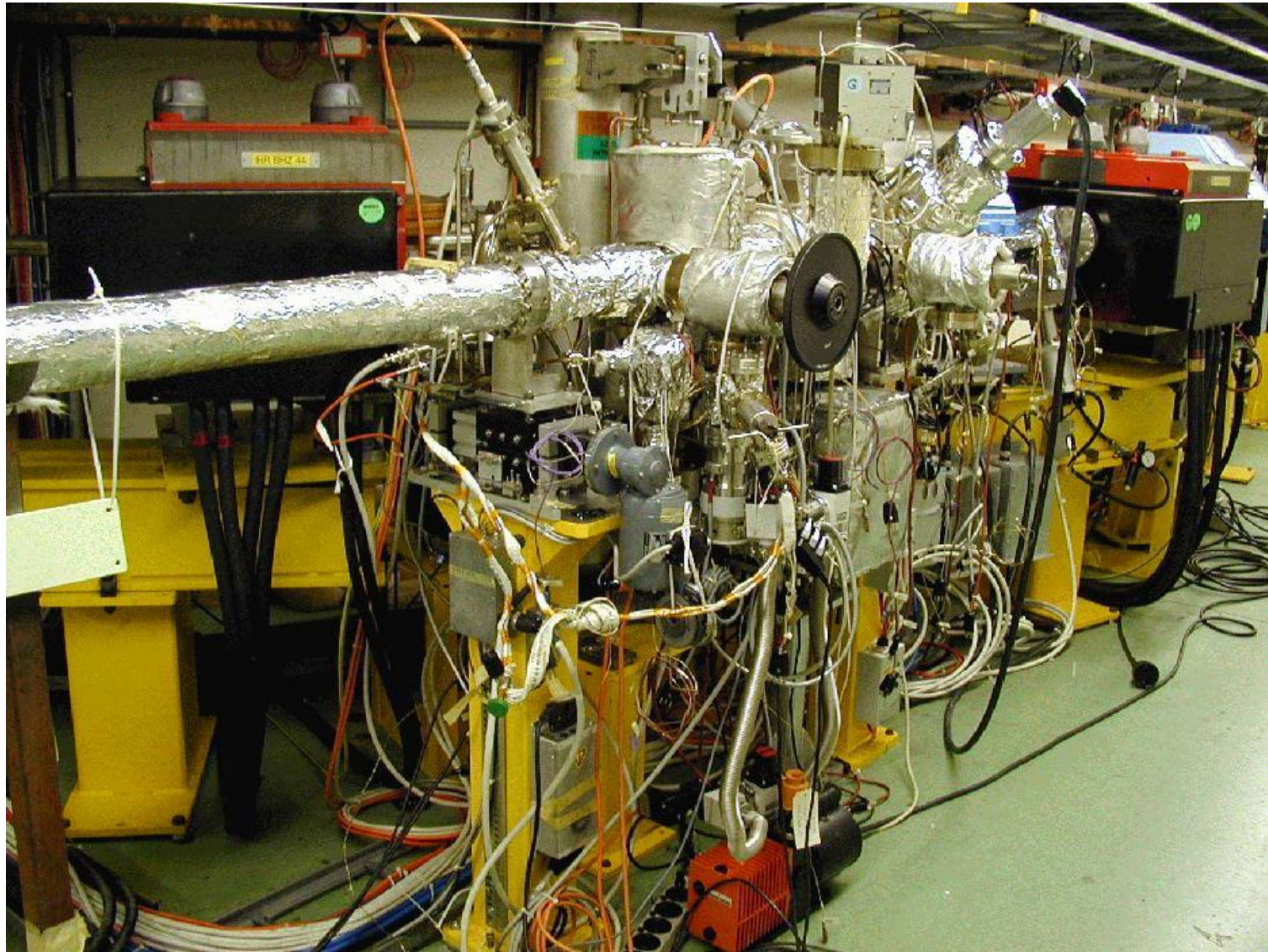
With  $G = 4.3 \cdot 10^{19}$  molecules/mbar.l



J. Gómez-Goni et al. J. Vac. Sci. Technol. A 12(4), Jul/Aug 1994, 1714

V. Baglin et al. EPAC 1998, Stockholm, Sweden.

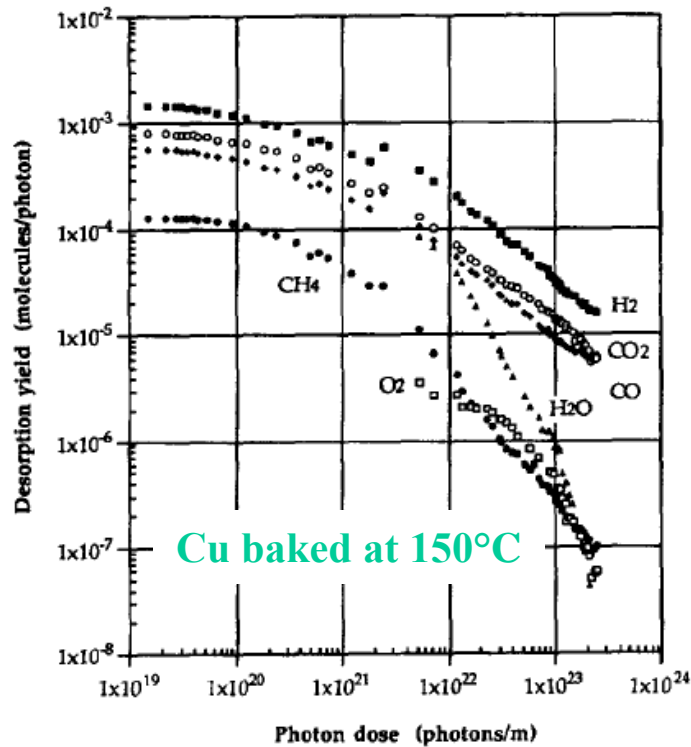
# CERN EPA Synchrotron Light Facility 42 - 1999



The LEP Pre-Injector as a multipurpose facility, J-P. Potier, L. Rinolfi, EPAC 1998, Stockholm, Sweden, 1998

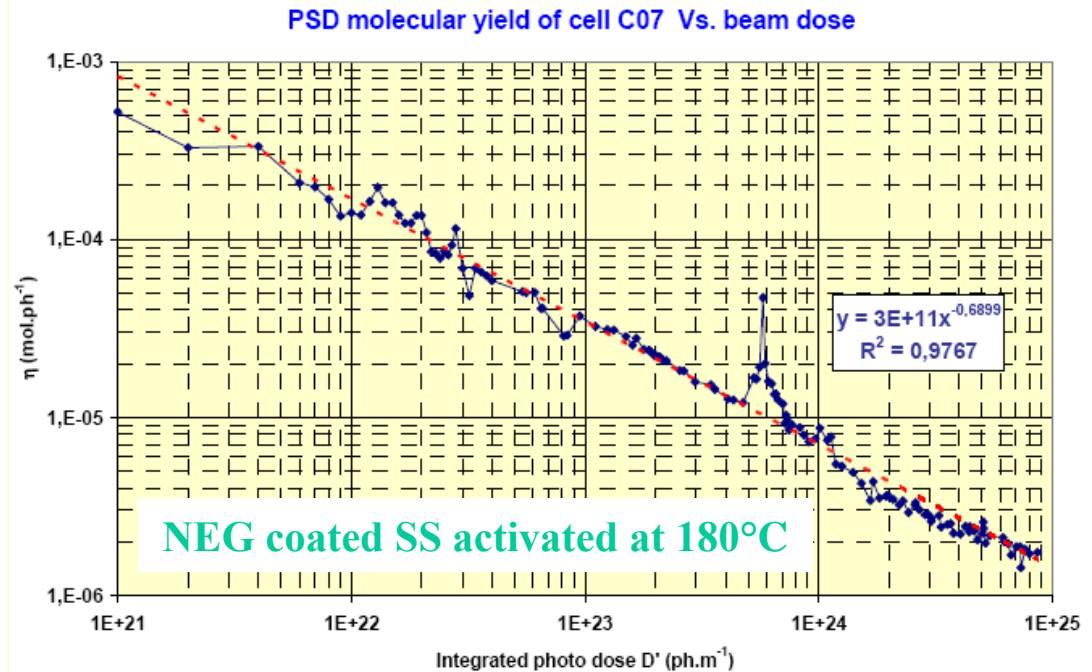
# Conditioning under photon irradiation

- Typical desorption yield range: from  $10^{-3}$  molecule/photon to  $10^{-6}$  when conditioned



O. Gröbner *et al.*

J.Vac.Sci. 12(3), May/Jun 1994, 846-853



C. Herbeaux *et al.* EPAC 2008, Gênes, Italie

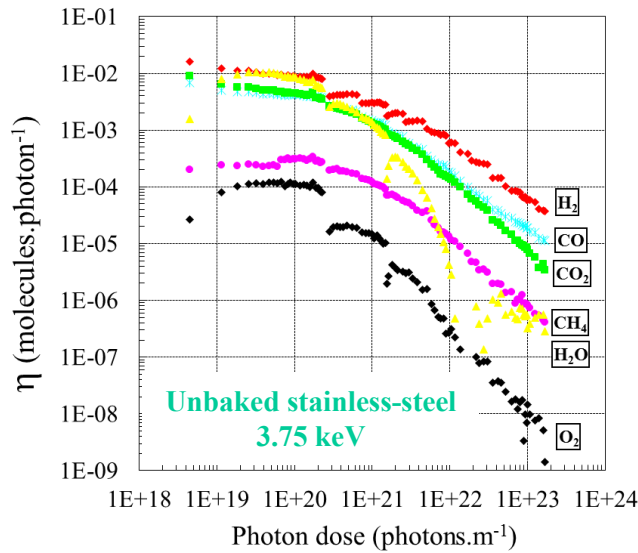
$$\eta_{Photons} = \eta_0 \left( \frac{D}{D_0} \right)^{-a}$$

- The hydrogen desorption is characterised by a diffusion process:  $a = 0,5$

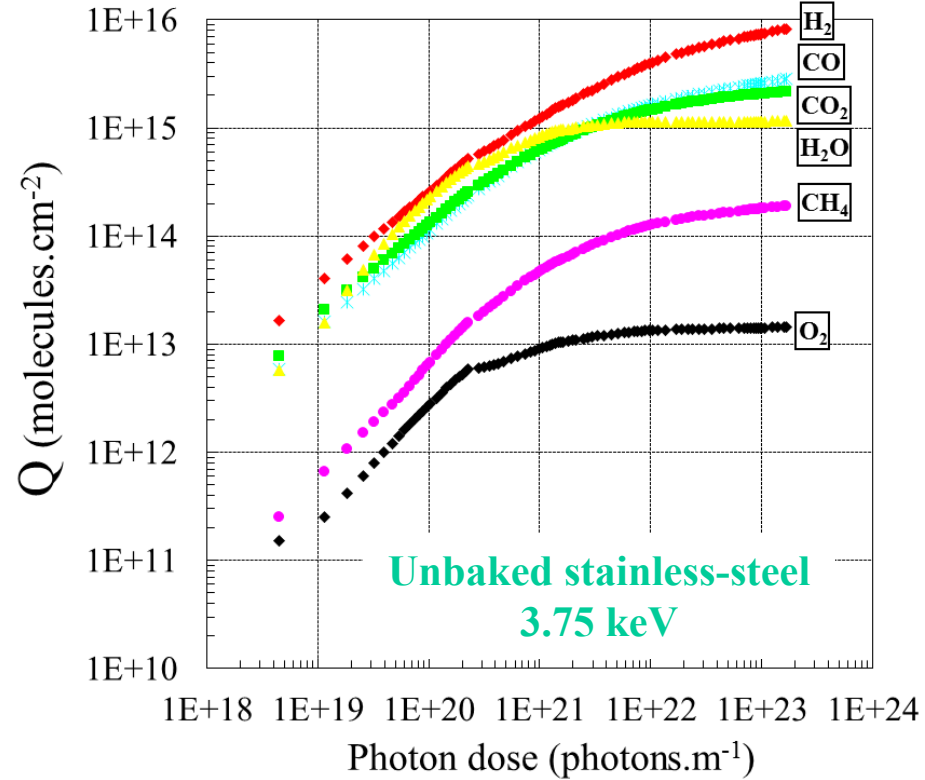
M. Andritschky *et al.*, Vacuum 38 (8-10), 933, (1988)

# Gas load

- The total desorbed quantity amounts to 15 monolayers for an unbaked system



$$Q = \int \eta d\Gamma$$



Gas	H <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub> O	CO	CO <sub>2</sub>	Total
molecules/ cm <sup>2</sup> x 10 <sup>15</sup>	8.1	0.2	1.1	2.8	2.2	14.4

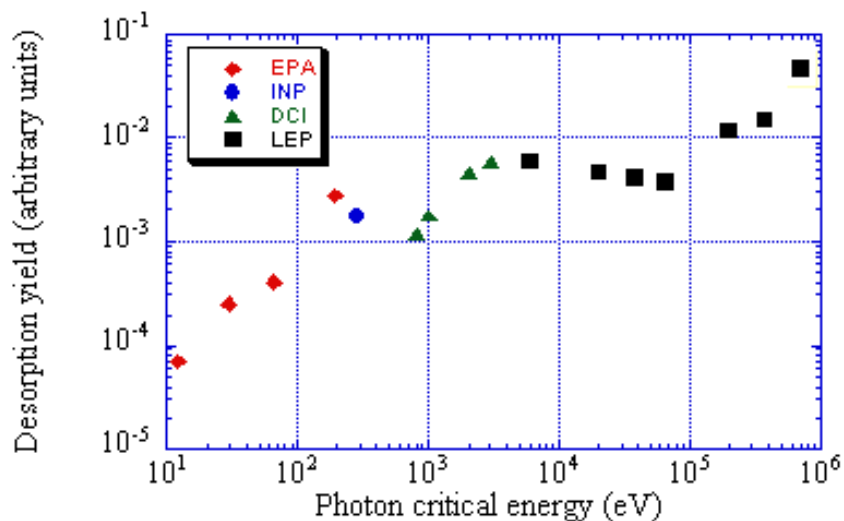
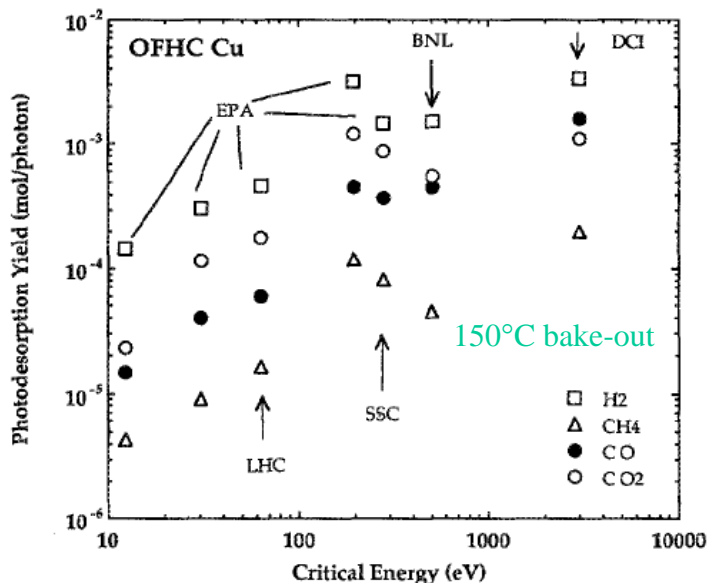
C. Herbeaux *et al.* JVSTA 17(2) Mar/Apr 1999, 635

# Evolution with critical energy

- At low energy, the **photoelectric effect** dominates
- Above a few 100 keV, **Compton diffusion** dominates and produce a cascade of energetic recoil electrons with a diffusion of secondary photons

$$\eta(\text{H}_2) \sim E_c^{0.74}, \quad \eta(\text{CH}_4) \sim E_c^{0.94}$$

$$\eta(\text{CO}) \sim E_c^{1.01}, \quad \eta(\text{CO}_2) \sim E_c^{1.12}$$



O. Gröbner. CAS 99-15

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

# Photodesorption of NEG films

- Very low desorption yields
- Be aware of the difference between effective and **intrinsic yields**

$$\eta_{intrinsic} \approx \left( \frac{S}{C} + \sqrt{\frac{S}{C_t}} \right) \times \eta_{effective}$$

V. Baglin *et al.* CERN VTN 98-04, 1998.

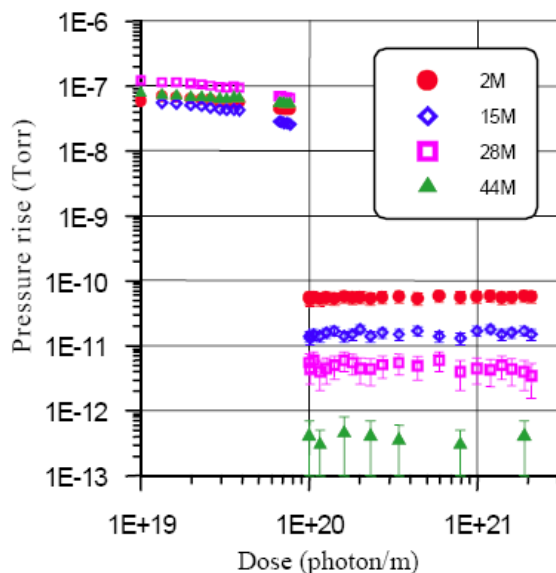


Figure 2: Pressure rise measured in the centre of the TiZrV coated test chamber before activation ( $<1 \cdot 10^{20}$  photons/m) and after activation ( $>1 \cdot 10^{20}$  photons/m).

**TiZrV film on stainless-steel**  
**4.5 keV**

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

Table 1: Summary of results from the non-activated test chamber

Gas	Sticking probability	Photodesorption yield (molecules/photon)
H <sub>2</sub>	0	$1 \cdot 10^{-3}$
CH <sub>4</sub>	0	$2.5 \cdot 10^{-4}$
CO	0	$5 \cdot 10^{-4}$
CO <sub>2</sub>	0	$3 \cdot 10^{-4}$

**Baked at**  
**80°C**

Table 2: Summary of results from the activated test chamber

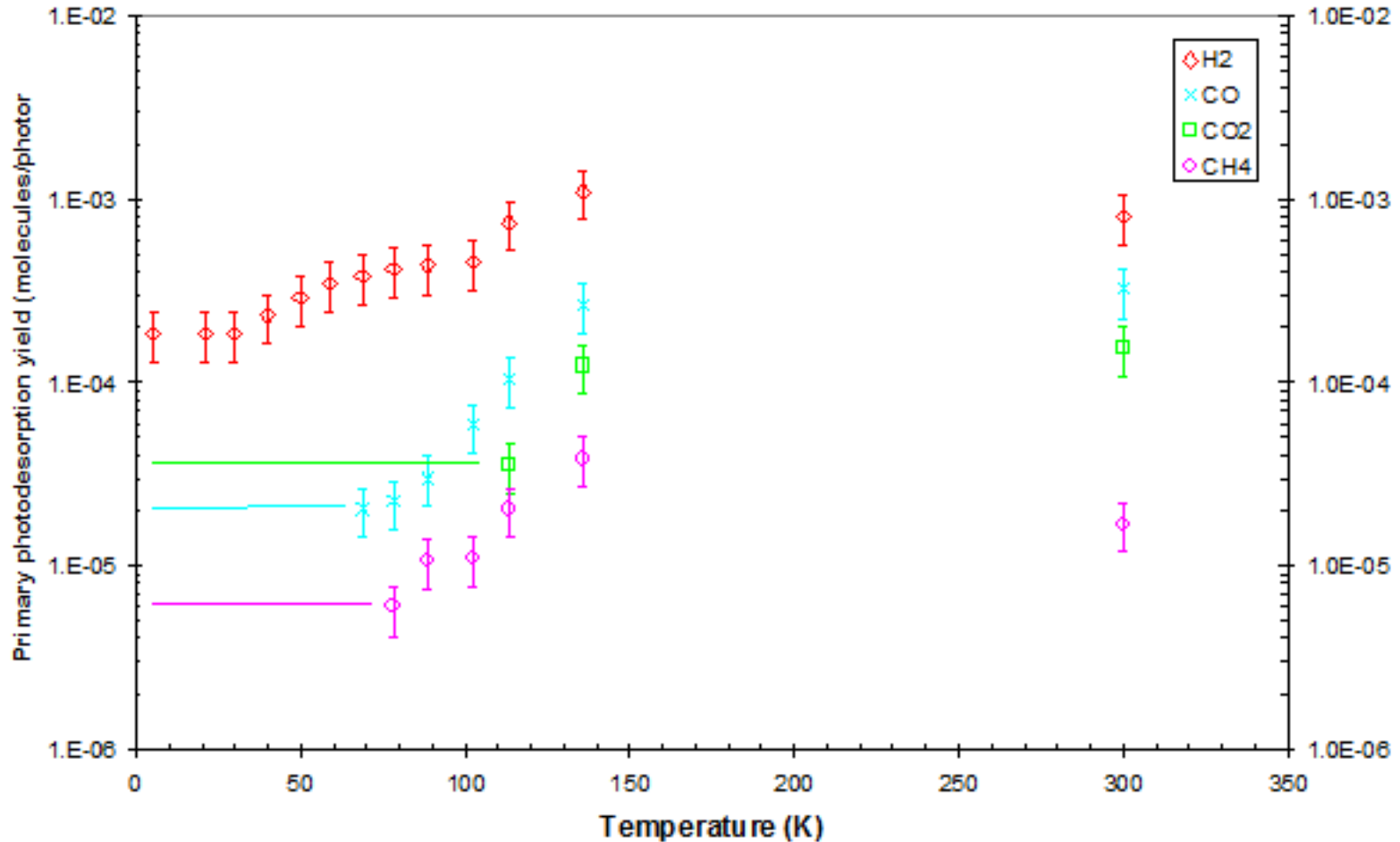
Gas	Sticking probability	Photodesorption yield (molecules/photon)
H <sub>2</sub>	$\sim 0.007$	$\sim 1.5 \cdot 10^{-5}$
CH <sub>4</sub>	0	$2 \cdot 10^{-7}$
CO (28)	0.5	$< 1 \cdot 10^{-5}$
C <sub>x</sub> H <sub>y</sub> (28)	0	$< 3 \cdot 10^{-8}$
CO <sub>2</sub>	0.5	$< 2 \cdot 10^{-6}$

**Activated at**  
**190°C**



# Photodesorption at Cryogenic Temperature

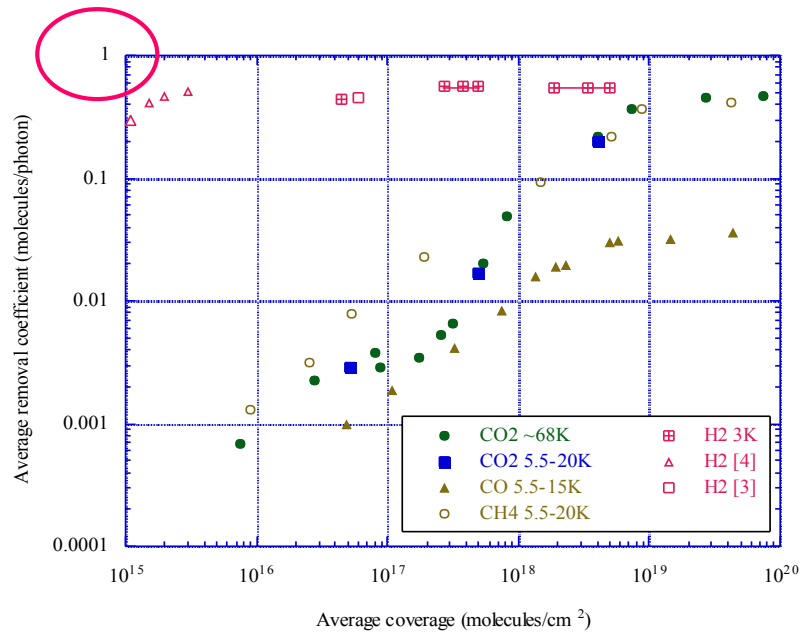
- Initial yield,  $\eta_0$ , are smaller than at room temperature



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

# What about physisorbed molecules?

- Desorption of physisorbed molecules



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

**Stainless steel**  
**250-300 eV**  
**Perpendicular incidence**

- Photo-cracking of molecules

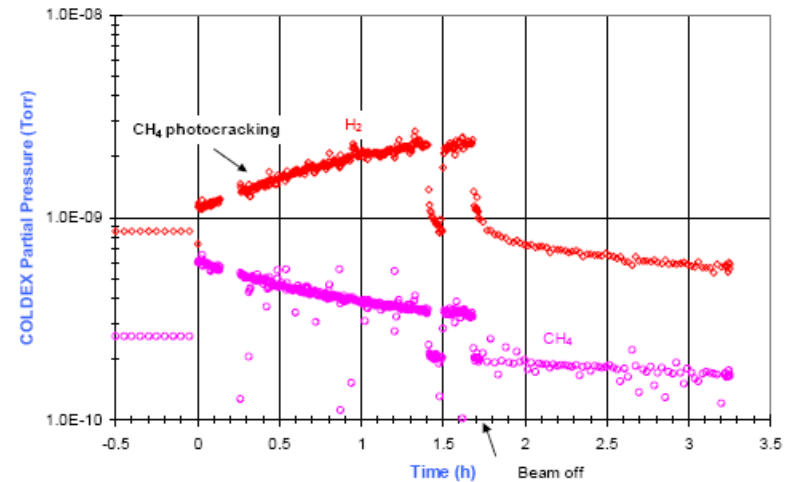


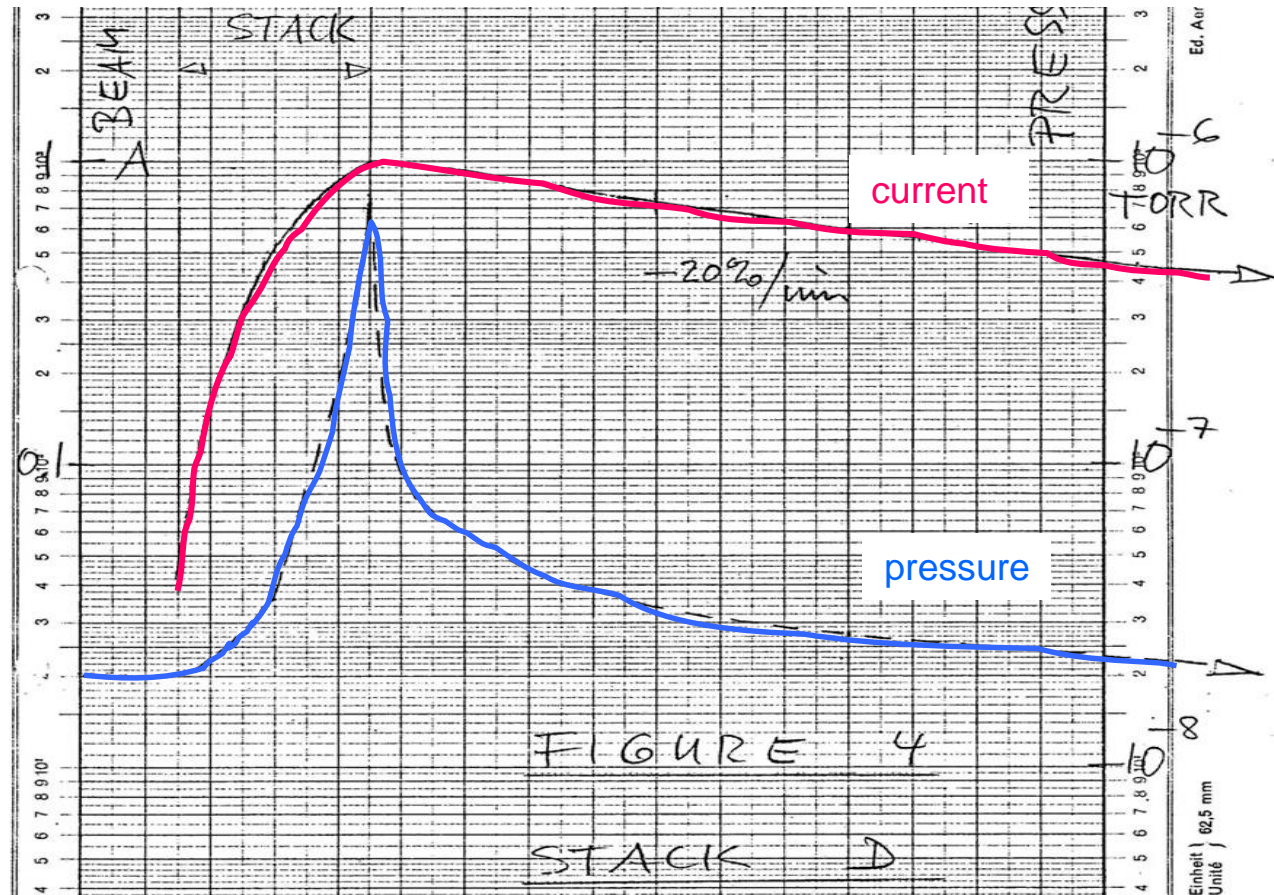
Figure 5 : ~ 10 monolayers of CH<sub>4</sub> condensed onto a BS without hole prior to irradiation at 6 K

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

## 2. Vacuum instability and ion stimulated desorption

# The phenomenon

- High current machines: ISR, LHC ...
- Beam current increases to 1 A
- Pressure increases up to  $10^{-6}$  Torr (x 50 in a minute)
- Beam loss



## First documented pressure bump in the ISR

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

# The mechanism of vacuum instability

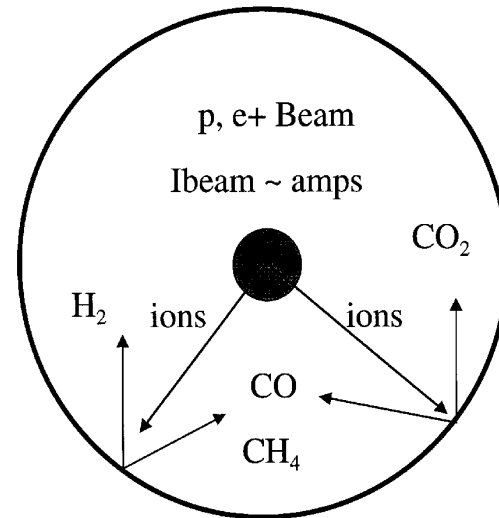
- Origin are ions produced by **beam gas ionisation**

$$V \frac{dP}{dt} = Q_0 + \eta_{\text{ion}} \sigma \frac{I}{e} P + C \frac{d^2 P}{dx^2}$$

- Quasi stationary long tube (C=0)

$$Q_0 + \eta_{\text{ion}} \sigma \frac{I}{e} P = P S_{\text{eff}}$$

$$P = \frac{Q_0}{S_{\text{eff}} \left( 1 - \frac{\eta_{\text{ion}} \sigma \frac{I}{e}}{S_{\text{eff}}} \right)}$$



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

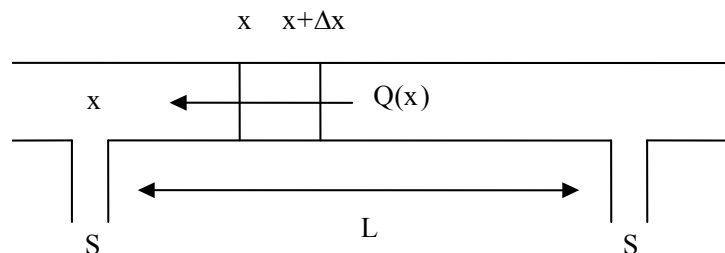
$$(\eta_{\text{ion}} I)_{\text{crit}} = \frac{e S_{\text{eff}}}{\sigma}$$

# Description of the mechanism

- In the case of a machine with distributed pumping ( $C \neq 0$ ) :

$$\frac{d^2 P}{dx^2} = -\frac{Q}{C} - \frac{\eta_{ion} \sigma}{C} \frac{I}{e} P = -\frac{Q}{C} - \omega^2 P$$

$$P(x) = \frac{a}{C \omega^2} \left[ \frac{\cos(\omega(L/2 - x))}{\cos(\omega L/2) - \frac{\omega C}{S/2} \sin(\omega L/2)} - 1 \right]$$



$$\begin{cases} 2C \frac{dP(x)}{dx} \Big|_{x=0} = S P \\ 2C \frac{dP(x)}{dx} \Big|_{x=L} = -S P \end{cases}$$

- When the denominator approach zero, the pressure diverge

$$\cos(\omega L/2) - \frac{\omega C}{S/2} \sin(\omega L/2) > 0 \Leftrightarrow \omega \tan(\omega L/2) < \frac{S/2}{C} \Rightarrow (\omega L/2) < \frac{\pi}{2}$$

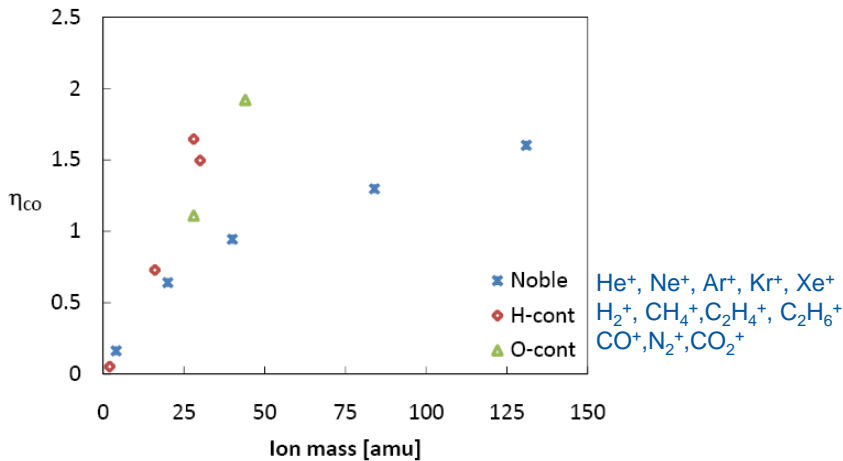
so  $\eta_{ion} I < \frac{\pi^2 C e}{4 \cdot 10^3 (L/2) \sigma}$  therefore

$$(\eta_{ion} I)_{crit} = \frac{\pi^2 C e}{4 \cdot 10^3 (L/2) \sigma}$$

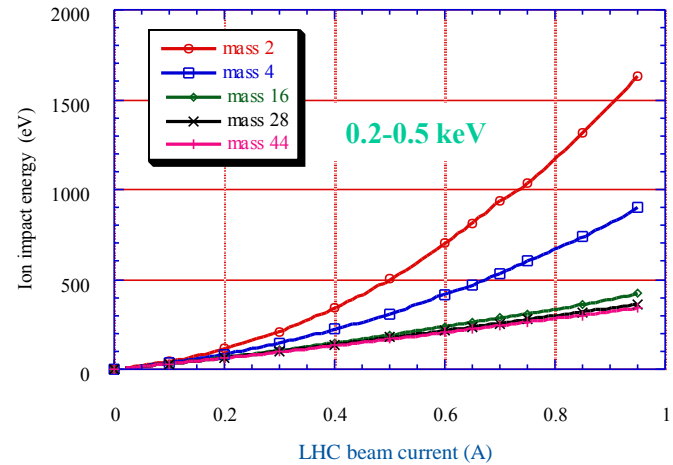
- In the case of more complex geometry, numerical tools are used

# Ion desorption yield

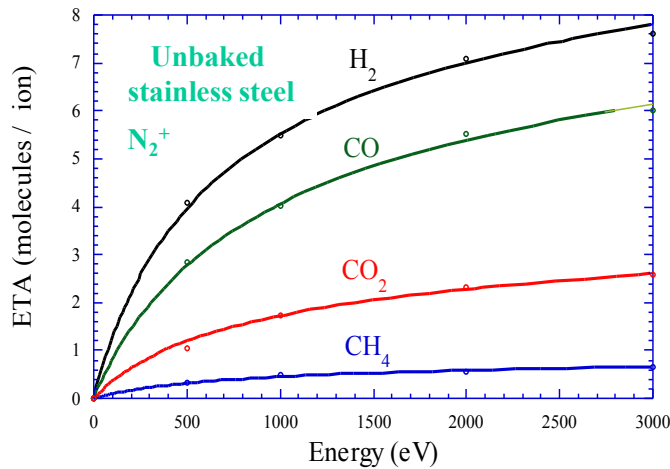
- Varies with the material, the ion energy and ion species
- **Several units** of molecules can be desorbed by ions → Sputtering



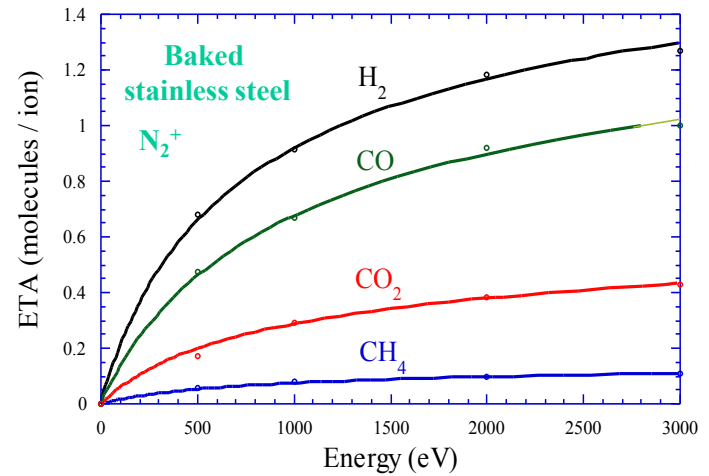
G. Hulla, PhD Thesis, Vienna Tech. U, 2009



O. Gröbner, CERN 99-05



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

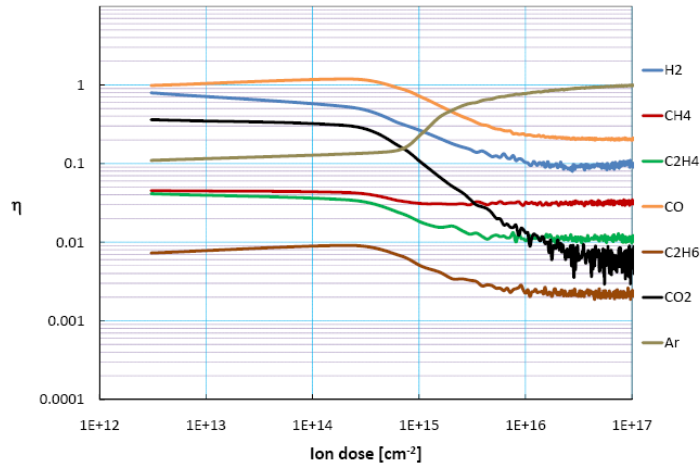


A.G. Mathewson, CERN ISR-VA/76-5

# Conditioning and implantation

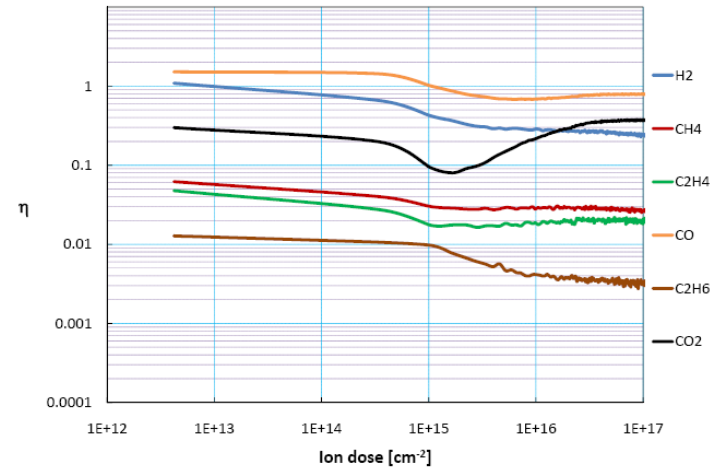
- A conditioning is observed but at high dose, some ions can be implanted !

7 keV, Cu Baked, Ar<sup>+</sup>



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

7 keV, Cu Baked, CO<sup>+</sup>



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

- In the LHC : the maximum flux is about  $3 \cdot 10^8$  ions/(cm<sup>2</sup>.s) *i.e.* a dose of  $3 \cdot 10^{15}$  ions/(cm<sup>2</sup>.year)
- In the LHC, there is no “beam” conditioning under ion bombardment

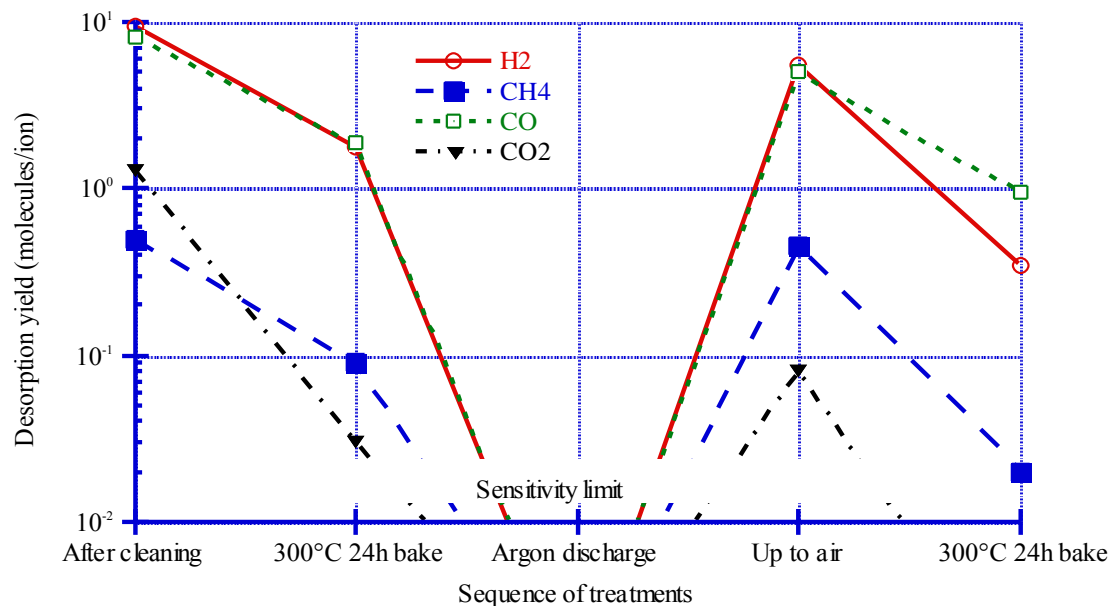


# How to ensure vacuum stability ?

- Beam conditioning being negligible, one must decrease the desorption yield and optimise the pumping speed

$$I_{\text{crit}} = \frac{1}{\eta_{\text{ion}}} \frac{eS}{\sigma}$$

- ISR : Argon glow discharge (Ar, 10 % O<sub>2</sub>, ~ 400 V, 10<sup>18</sup> Ar/cm<sup>2</sup>) with *in-situ* bakeout :

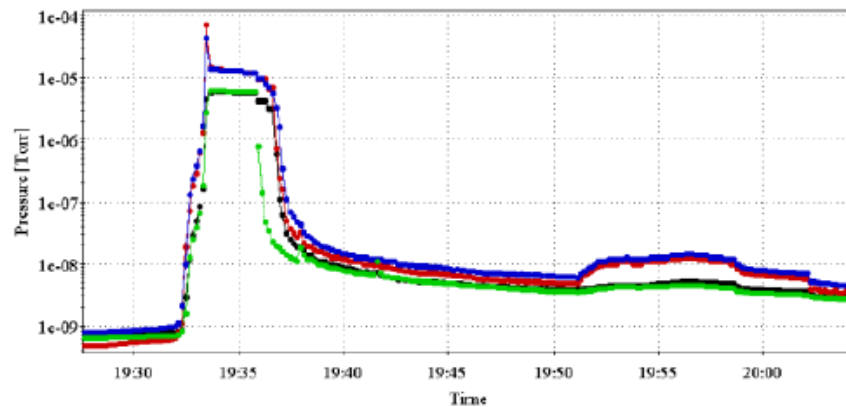
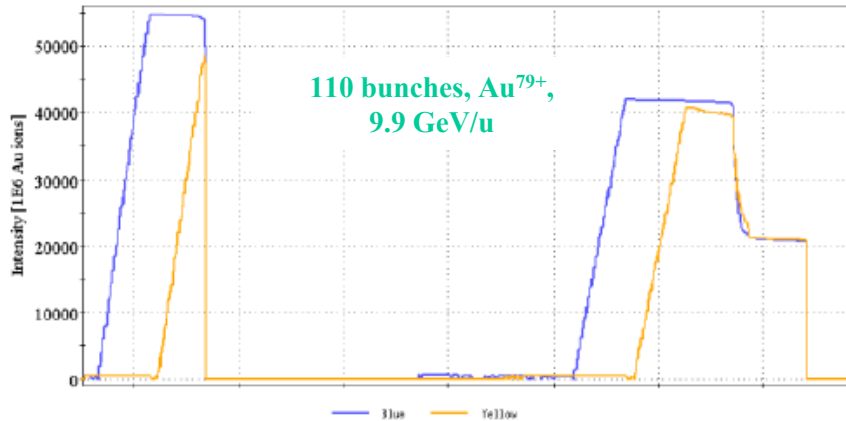


A.G. Mathewson, CERN ISR-VA/76-5

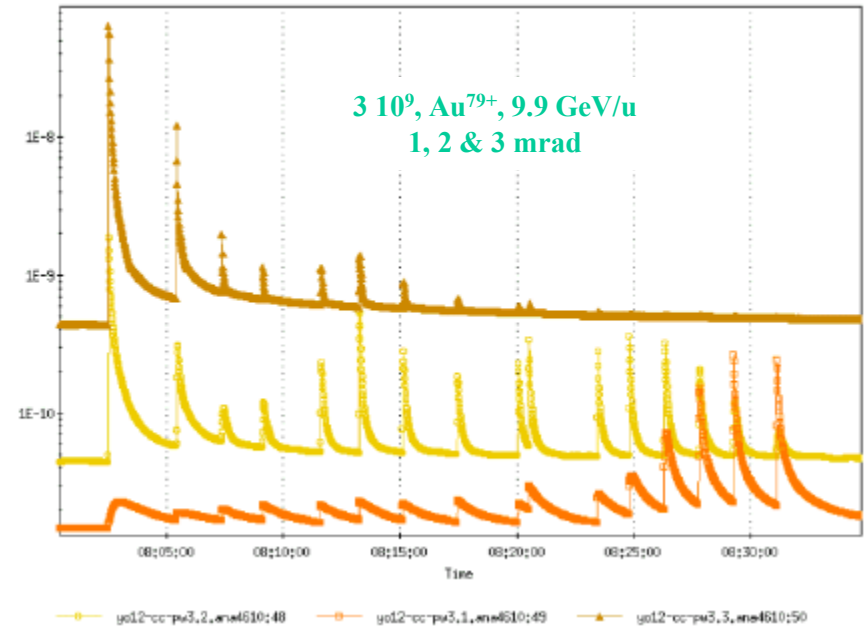
# 3. Particle losses and ion stimulated desorption

# RHIC

- Loss of ions from a beam leads to **large** pressure increases:  $10^{-8}$  ...  $10^{-5}$  mbar!



W. Fischer *et. al.* EPAC 2002, Paris, France



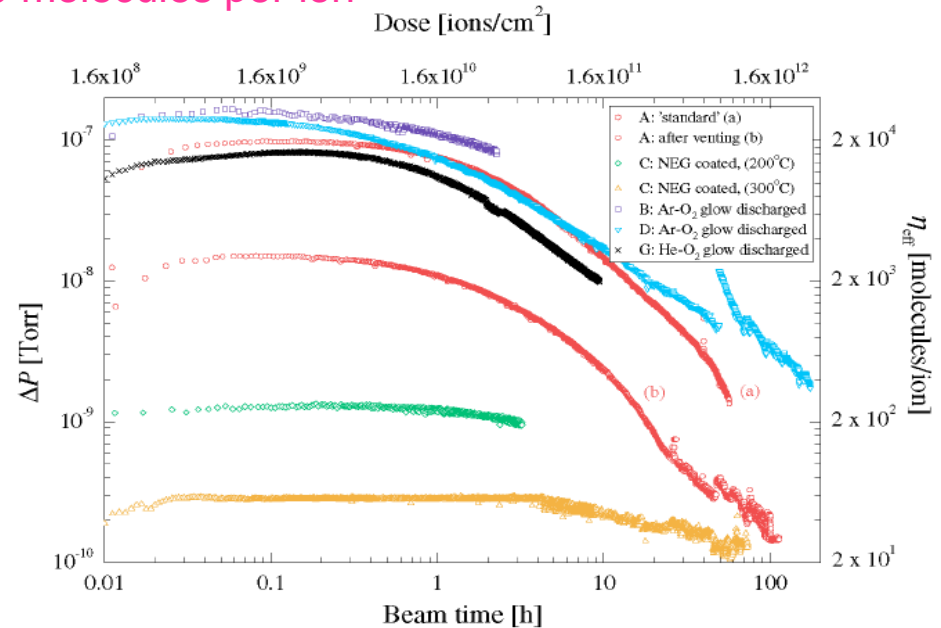
W. Fischer *et. al.* EPAC 2006, Edinburgh, Scotland

# High energy ions

- Desorption yields range from 20 – 20 000 molecules per ion

$Pb^{53+}$ , 4.2 MeV/u, 14 mrad

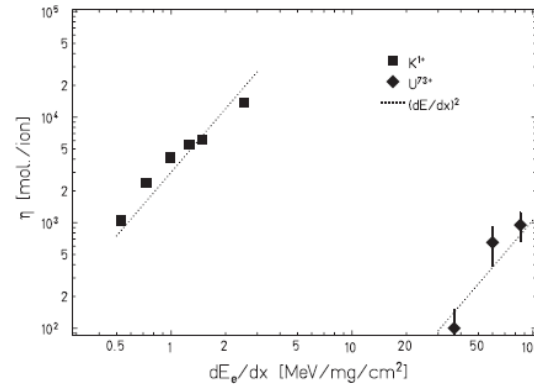
E. Mahner *et al.*,  
Phys. Rev. ST Accel. Beams 6, 013201 (2003)



- The desorption is determined by the energy given to the electrons (electronic stopping force)

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

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



- The desorption induced by the electrons is the responsible mechanism

# Remedies

- Use of NEG films (LEIR, RHIC, GSI)
- Use of beam conditioning
- Intercept ion loss on dedicated collimators:
  - LEIR : 30  $\mu\text{m}$  gold film on SS 316 LN, perpendicular incidence
  - GSI : 0.1  $\mu\text{m}$  gold film, perpendicular incidence. Absorber inserted in a secondary vacuum chamber. NEG film

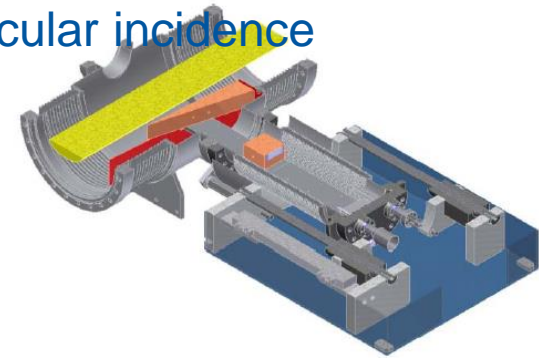
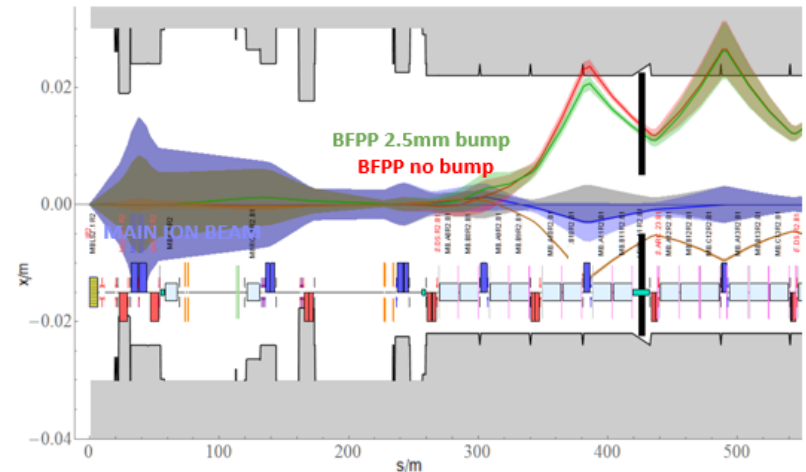


Figure 2: Horizontal cut through the installed SIS18 ion catcher prototype. Yellow: beam, red: secondary chamber, brown: beam absorbers.

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

- HL-LHC : movable collimator – 150 W of 7 ZxTeV ions coming from BFPP

## BFPP:



. J. Jowett

# HL-LHC ions collimator

- Located in the LHC arcs around IP2
- W jaws



Courtesy S. Redaelli, F. Savary

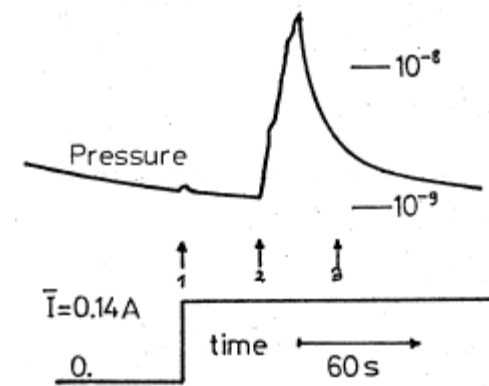
# 4. Electron cloud and related surface parameters

# 4.1 Introduction



# History: observed at the ISR

- Vacuum stability test of a baked aluminium chamber 200°C, diam 160 mm (1976-1977)
- Observation of pressure spikes, particularly during transverse displacement of a proton bunch
- The existence of the spike varies with :
  - bunch length
  - number of proton bunch
- Existence of a current threshold (120 mA for 20 bunches)
- Different gas composition (dominated by H<sub>2</sub> instead of CO)
- Measurement of a significant electron current on the clearing electrodes



**Fig. 1.** Pressure spike observed during slow displacement of a bunched beam across the aperture :  
1 injection - 40 mm, 2 - 10 mm and 3 + 10 mm radial position from centre of the vacuum chamber

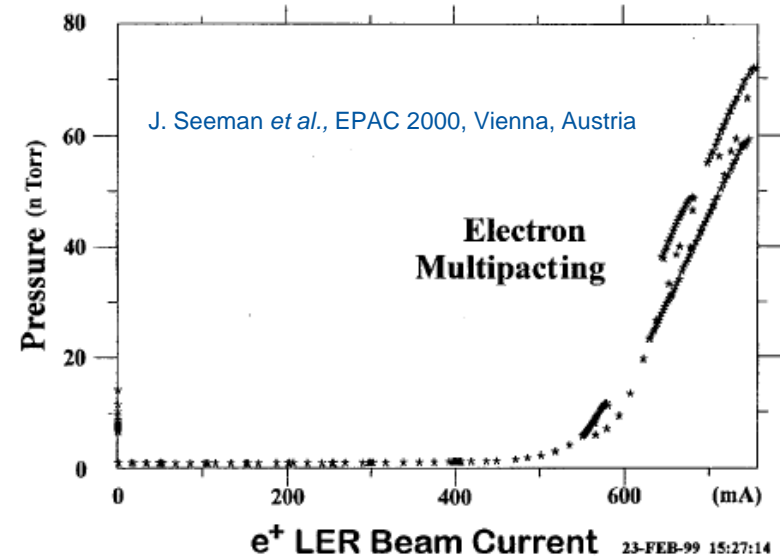
O. Gröbner, ISR-VA/77-38

- Gas desorption is stimulated by electrons
- Electrons are accelerated by the proton bunch: multipactor effect

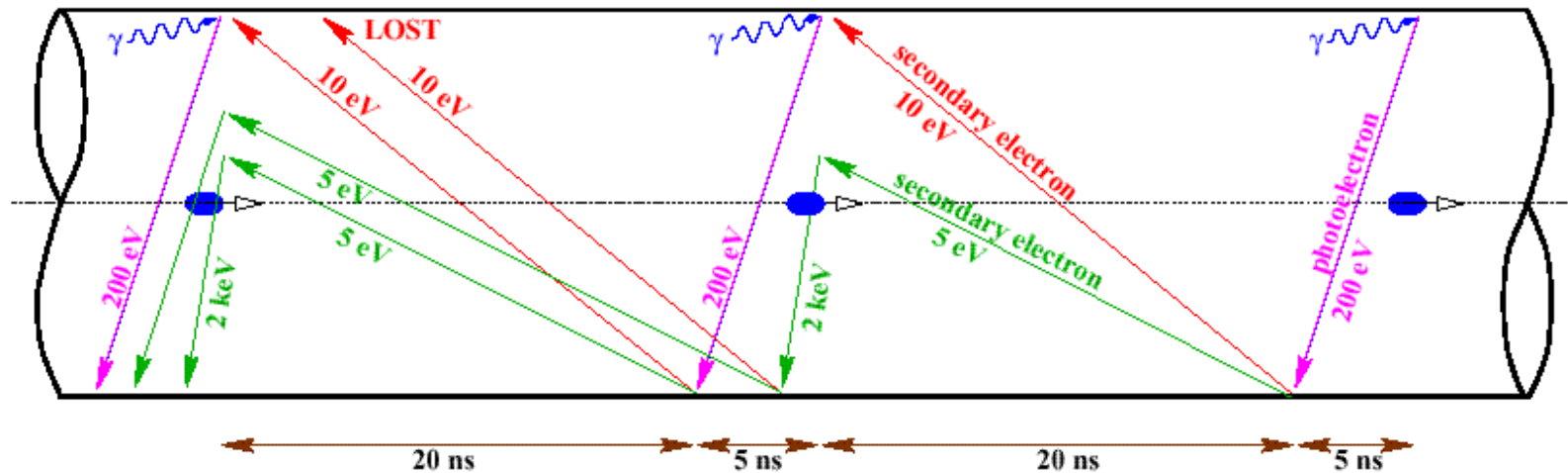
# PEP-II

- Electron cloud in the positron ring was foreseen during the design phase: TiN coating on Aluminium
- Emittance blow up above 800 mA (SR light)
- Observation of non linear pressure rise
- Winding of solenoids in the straight section

→ Luminosity increase



# LHC mechanism



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

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

- Key parameters:

- beam structure
- bunch current
- vacuum chamber dimension
- secondary electron yield
- photoelectron yield
- electron and photon reflectivities
- ...

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

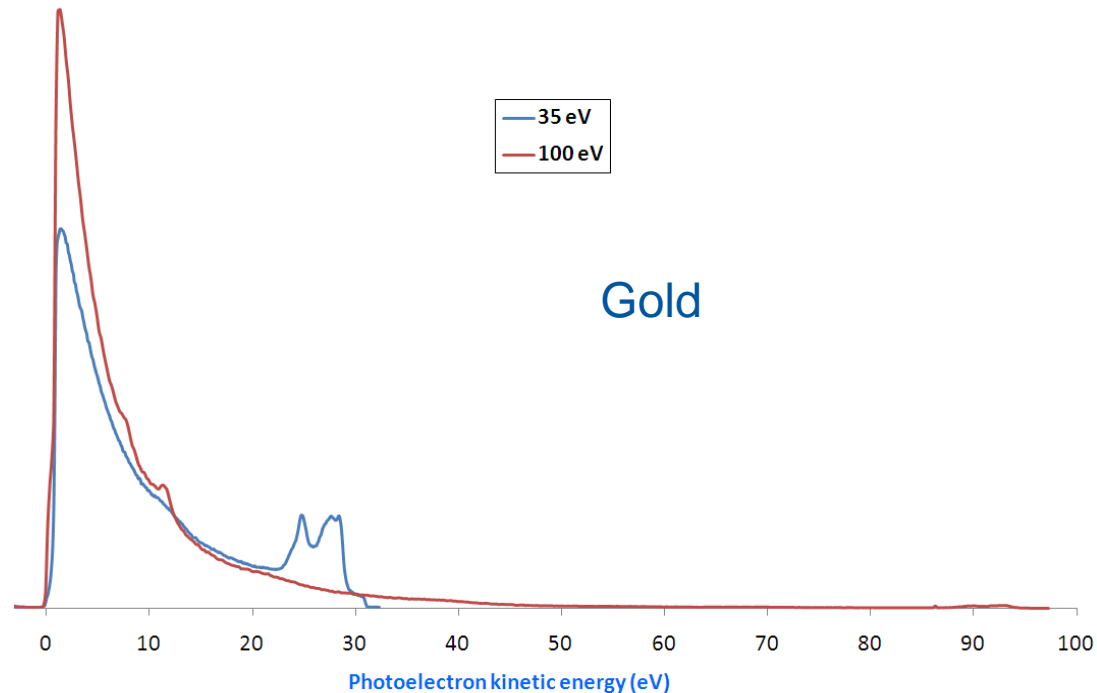
# How to mitigate the electron cloud?

- Once again, play with the key parameters :
  - Reduce the photoelectron yield (grazing incidence has larger yield than perpendicular incidence)
  - Reduce the secondary electron yield (scrubbing, NEG or amorphous carbon films, geometry)
  - Reduce the amount of electrons in the system (solenoid magnetic field, clearing electrodes, material reflectivity)
  - Adapt the beam structure or the vacuum chamber dimensions to reduce the multiplication
  - ...

# 4.2 Photons from SR

# Photoelectrons

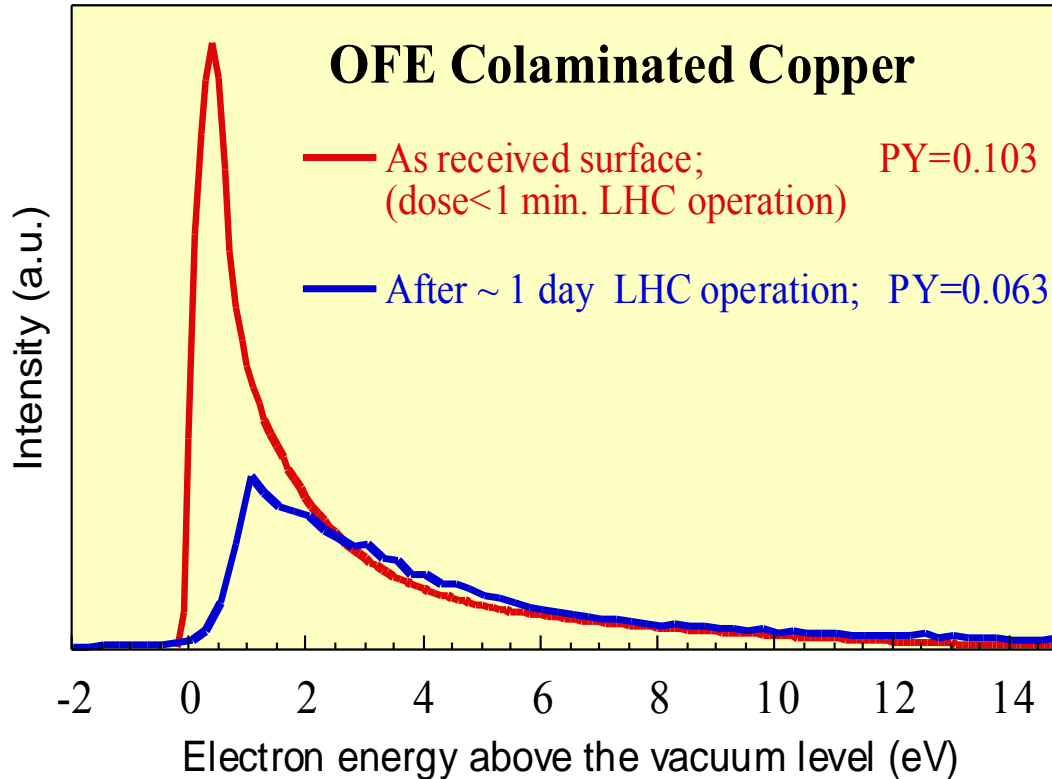
- **Photoelectric effect** : when a photons irradiates a surface with enough energy, it produces electrons
- The energy of emitted electrons varies from :  
0 eV to  $(h\nu - W_f)$  eV
- Most of the electrons are secondaries
- A few 0.1 % to 1 % have high energy



R. Cimino *et al.* , Phys. Rev. ST Accel. Beams 2, 063201 (1999)

# EDC under SR irradiation

- EDC: Electron distribution curve
- SR dose **reduce** the amount of low energy photoelectrons
- The total yield is decreased by 40 % after 1 day of nominal LHC operation



R. Cimino *et al.* Phys. Rev. AB-ST 2 063201 (1999)

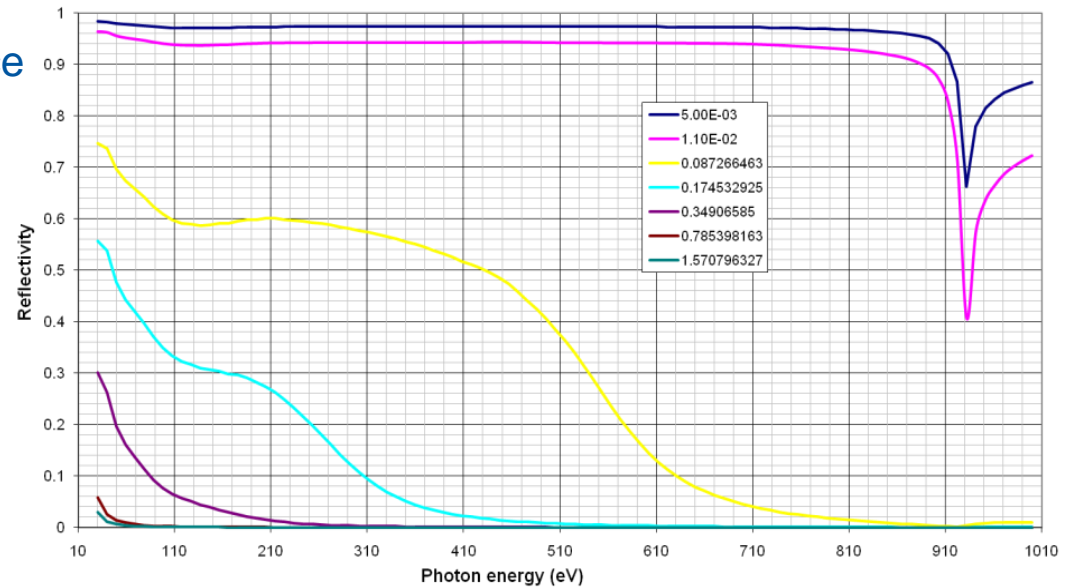
# Photon reflectivity

- From 1 to 80% forward reflectivity
- Low reflectivity at perpendicular incidence
- High reflectivity at grazing incidence *i.e.* this is the case of SR in accelerators
- In LHC, 5 mrad gives more than 95% reflection
- Copper adsorption at 920 eV

Material	Status	45 eV		194 eV	
		R (%)	R (%)	R (%)	R (%)
Cu roll bonded	as-received	80.9	77.0		
Cu roll bonded air baked	as-received	21.7	18.2		
Cu electroplated	as-received	5.0	6.9		
Cu sawtooth	as-received	1.8	-		
	150°C, 9 h	1.3	1.2		
	150°C, 24 h	1.3	1.2		
TiZr film	as-received	20.3	17.1		
	120°C, 12 h	19.5	16.7		
	250°C, 9 h	19.9	17.4		
	350°C, 10 h	20.6	16.9		
	CO saturated	20.7	-		

V. Baglin *et al.*, Trieste, 1998

Copper reflection for unpolarised photon with 0 Angstrom roughness



Henke databook

DCI,  $E_c=3$  keV



O. Gröbner *et al.*, 24-4-1988

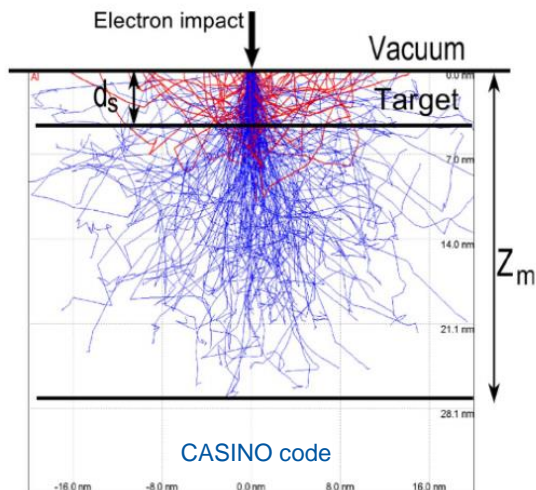
➔ In complex geometries, ray tracing is done with e.g. Synrad



# 4.3 Electrons from the electron cloud

# Electron Distribution Curve (EDC)

- Penetration depth: 1 – 10 nm



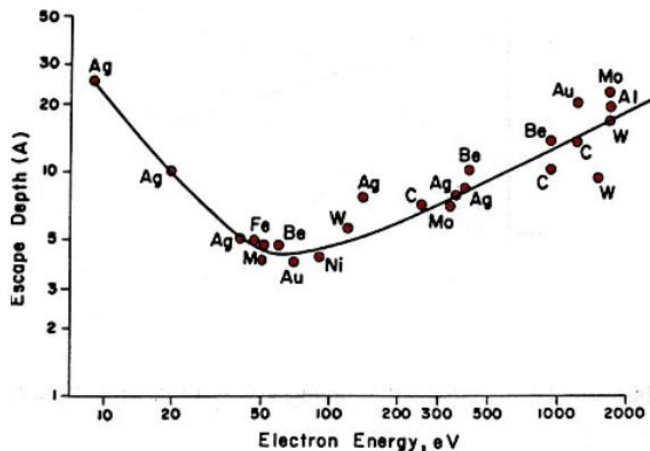
N. Balcon *et al.*,  
 IEEE Trans. On Plasma Sci. 40, 2012, 282

- The electron distribution curve shows :

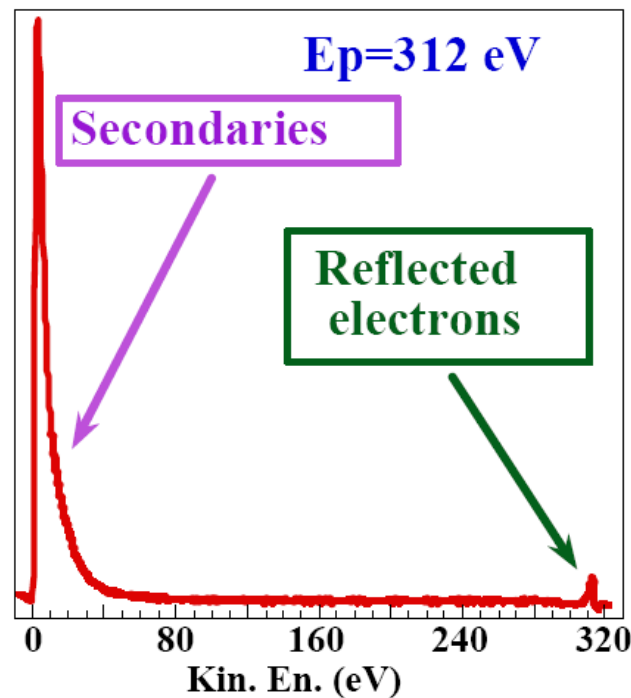
- Component at reflected electron energy
- Secondary electrons with low energy

- most of the emitted electrons have low energy

- Escape depth: <10 nm



Mean escaped depth of electrons in solids and "universal" curve.

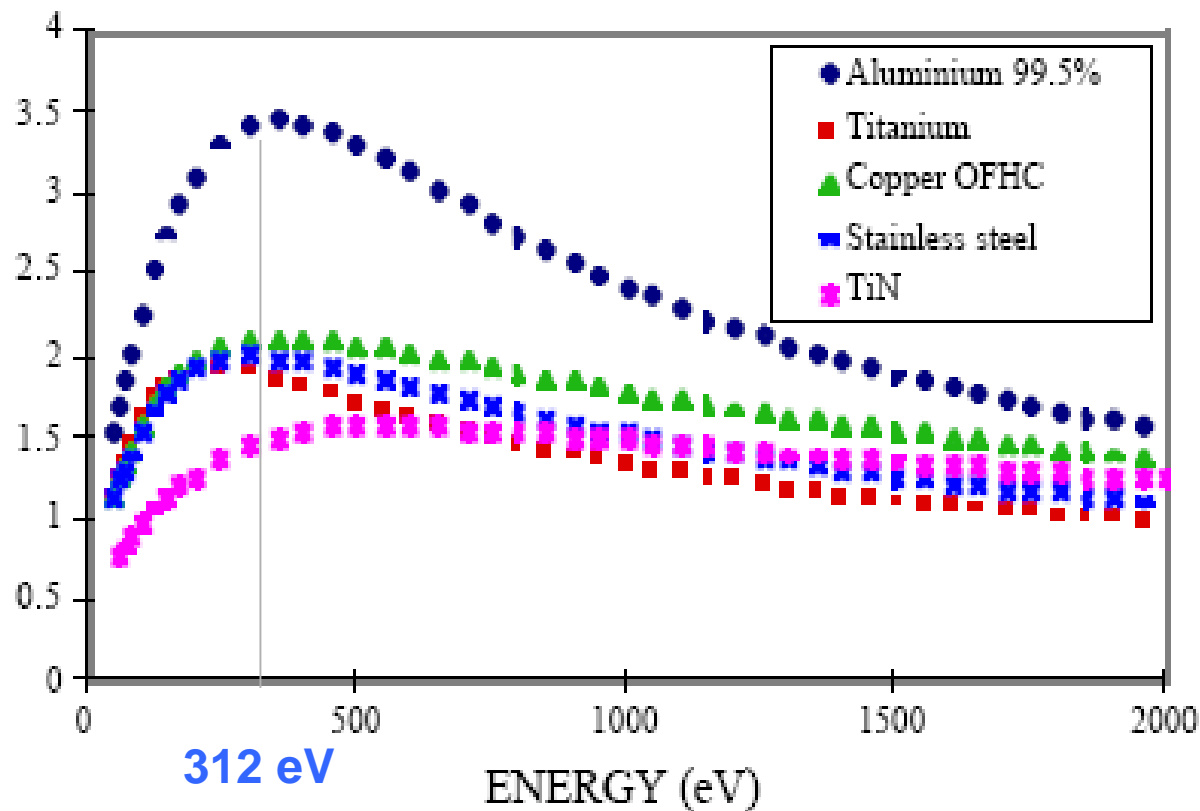


Courtesy R. Cimino

# Secondary Electrons Curve

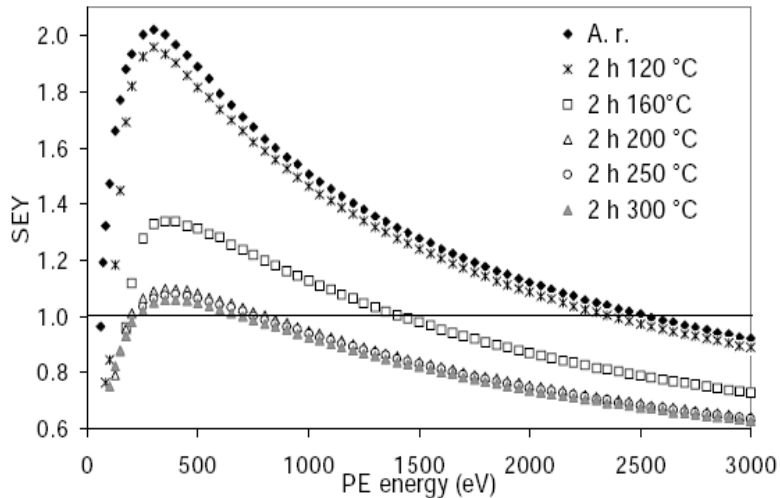
$$\delta = \frac{\text{number of produced electrons}}{\text{incident electrons}}$$

- Technical material
- Maximum around 200-300 eV
- $\delta_{\max} \sim 2$  to 3.5



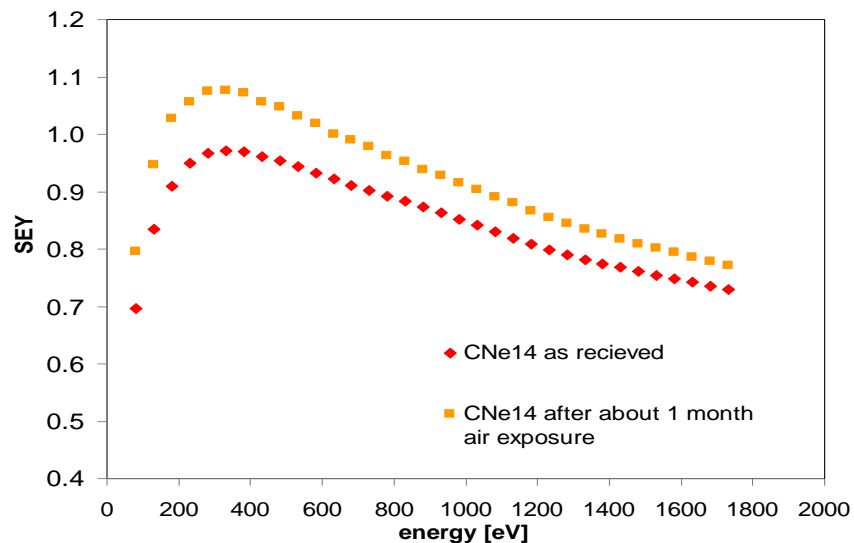
N. Hilleret *et al.*, LHC Project Report 433 2000, EPAC 00

# Very low SEY



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

- TiZrV film



M. Taborelli *et al.*, ECM workshop, 2008

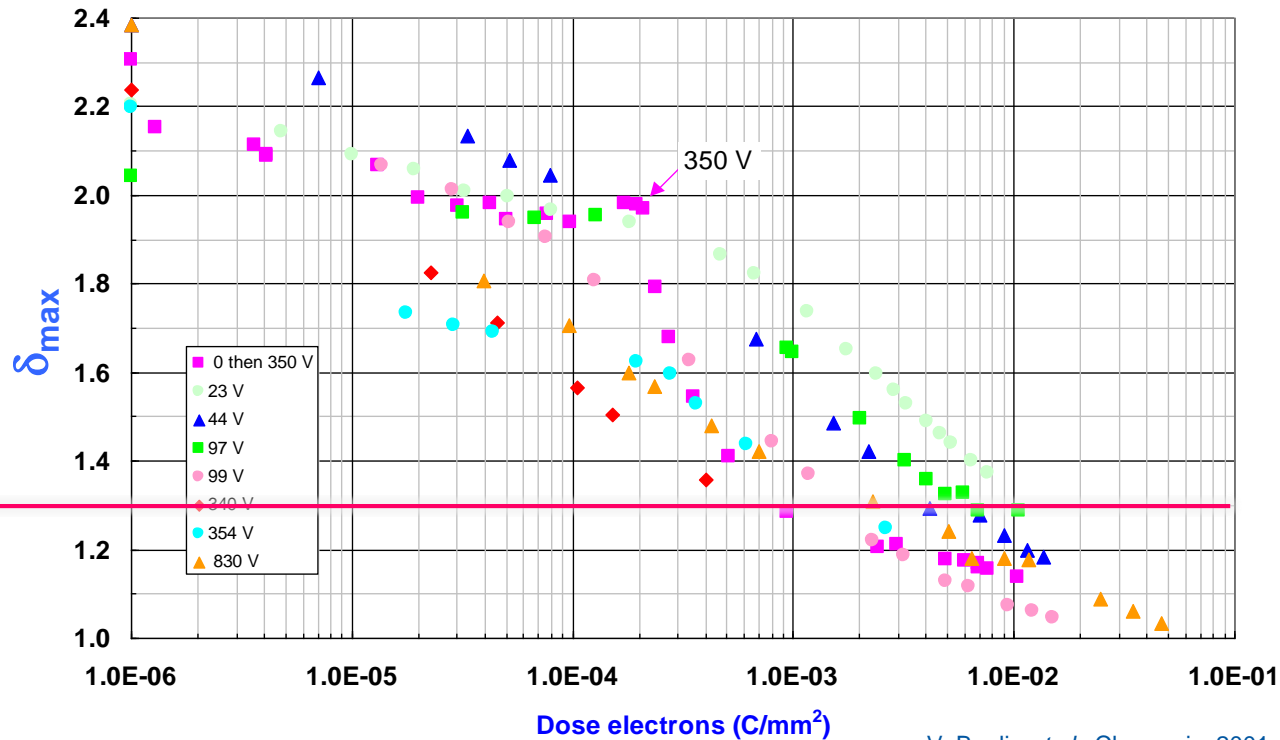
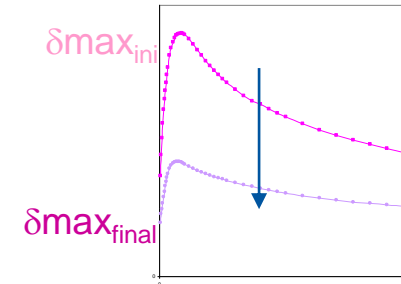
- Amorphous carbon

**The origin of the low SEY is different in both case :**

- nature of the surface
- smooth versus rough surfaces

# LHC : Scrubbing of the surface

- Photoelectrons produced by SR are accelerated towards the test sample
- Reduction of SEY under electron irradiation is observed
- 1 to 10 mC/mm<sup>2</sup> is required
- Growth of a carbon layer (AES, XPS)



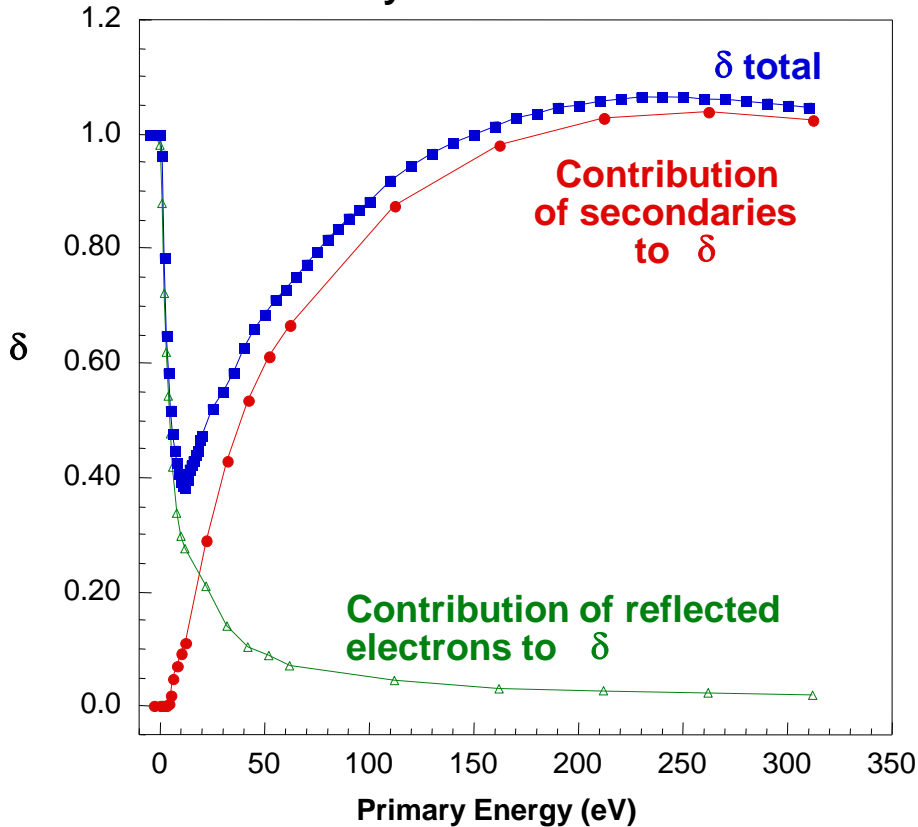
**LHC design:**  
 $\delta_{max} \sim 1.3$

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

# SEY at cryogenic temperature

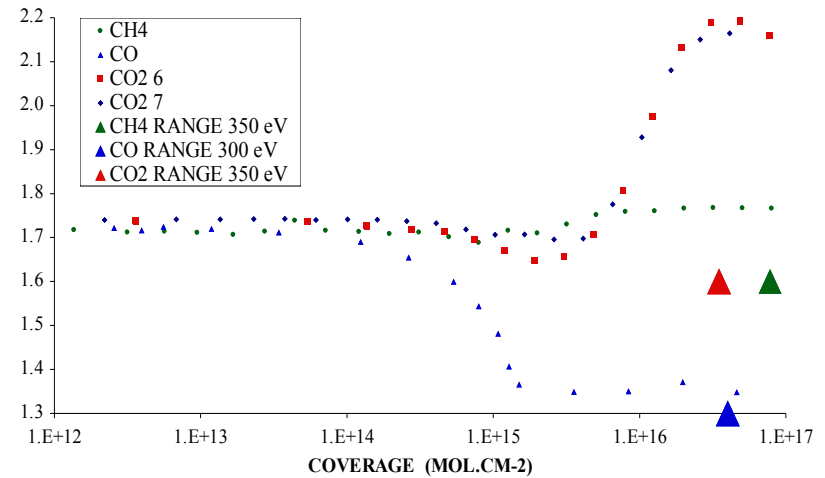
- Beam scrubbing at 10 K but SEY increases with gas condensation

Fully scrubbed Cu



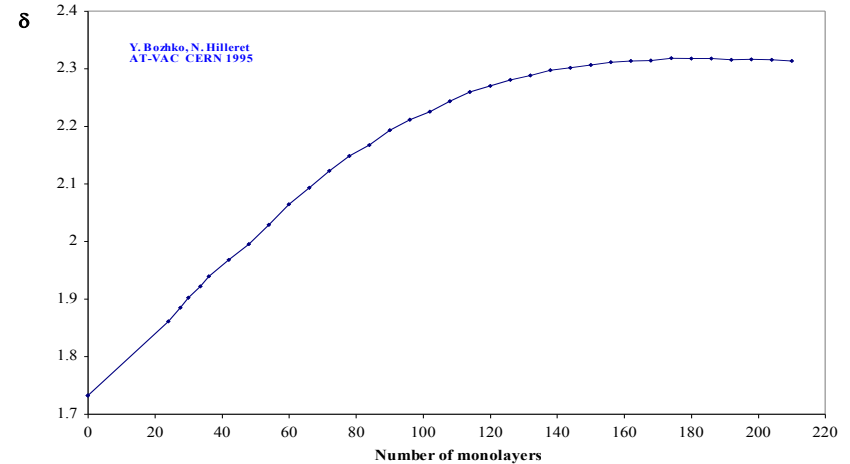
R. Cimino, I.R. Collins, *App. Surf. Sci.* 235, 231-235, (2004)

$\delta_{MAX}$  VERSUS COVERAGE



N. Hilleret. LHC MAC December 2004

Variation of maximum yield with amount of adsorbed water



N. Hilleret *et. al.* Chamonix 2000

# Electron desorption yield

- Unbaked copper
- Threshold around 10 eV

$$\eta(E) = \eta_0 \left( \frac{E - E_c}{300 - E_c} \right)^{0.85}$$

Table 1: Fit parameters

	$\eta_0 / (\text{molec./e}^-)$	$E_c / \text{eV}$
C <sub>2</sub> H <sub>6</sub>	$1.1 \times 10^{-1}$	11.4
CH <sub>4</sub>	$2.1 \times 10^{-2}$	7.5
CO	$5.8 \times 10^{-2}$	7.2
CO <sub>2</sub>	$2.7 \times 10^{-1}$	9.1
H <sub>2</sub>	$1.9 \times 10^0$	12.7
H <sub>2</sub> O	$3.1 \times 10^{-2}$	-22.9

$$\eta = \frac{\text{number of desorbed molecules}}{\text{incident electrons}}$$

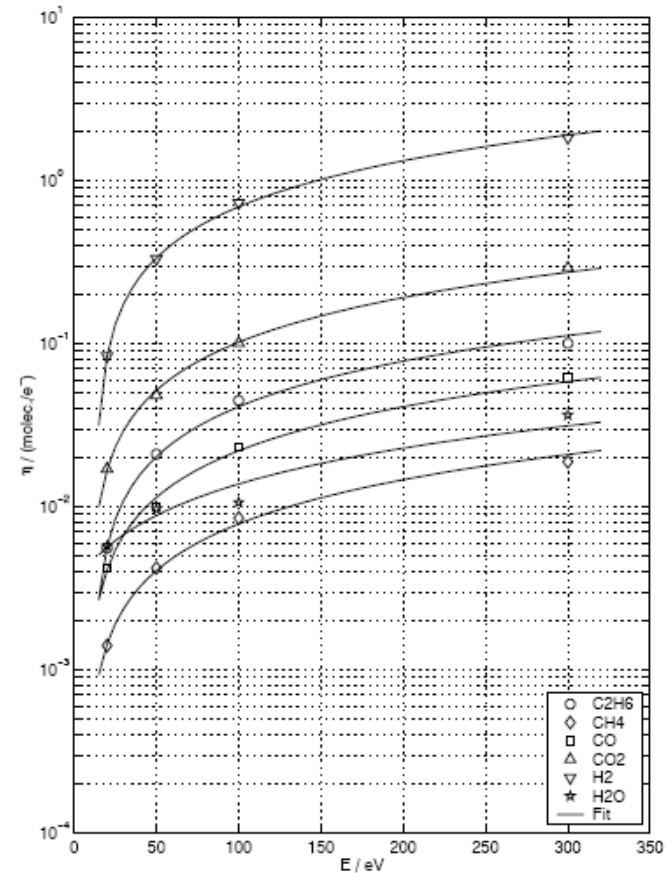


Figure 5: Electron induced desorption yield as a function of the electron energy. The values for 20, 50, and 100 eV have been obtained by interpolation between the two measurements shown in figure 4 at a constant dose of  $1.4 \times 10^{14} \text{ e}^-/\text{cm}^2$ .

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

# Electron dose

- Reduction of the electron desorption yield with the electron dose

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

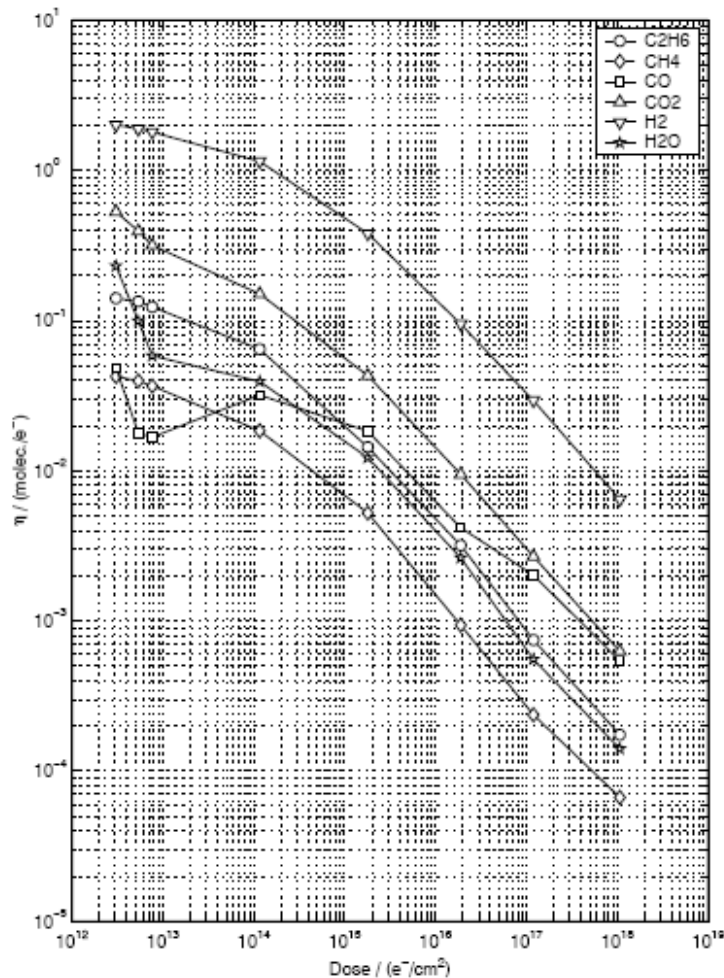


Figure 3: Effect of the electron dose on the electron induced desorption yield of an unbaked copper sample. The electron energy during bombardment and measurement was 300 eV.

	H <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub> O	CO	CO <sub>2</sub>
$\eta_0$	$2 \cdot 10^{-1}$	$2.5 \cdot 10^{-2}$	$1 \cdot 10^{-1}$	$3.5 \cdot 10^{-2}$	$5 \cdot 10^{-2}$
$D_0 \times 10^{14}$	3	1	6	2	4
a	0.47	0.62	0.66	0.49	0.54



# Electron desorption at cryogenic temperature: Cu

- The yields are very large and range from 0.1 to 50
- For a monolayer ( $10^{15}$  molecules/cm<sup>2</sup>)

	H <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>
$\eta$	500	5	10	0.5

Studied for 300 eV electrons with :

- 1) Pure gas
- 2) Equimolecular mixture of 4 gases
- 3) Standard LHC gas composition

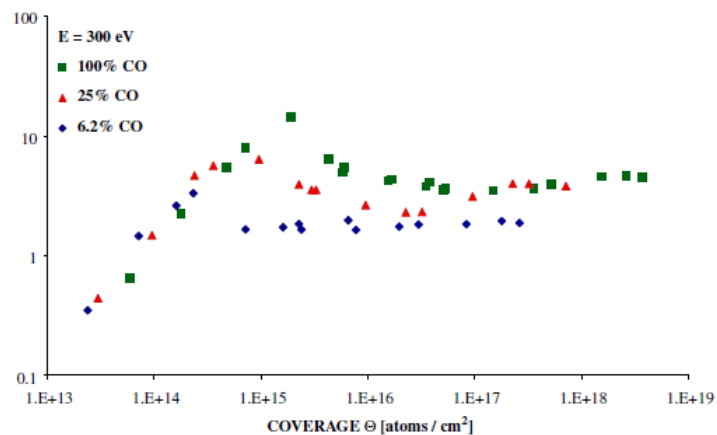


Fig. 7. The CO desorption yield as a function of CO coverage for different condensed gas composition (electron energy 300 eV).

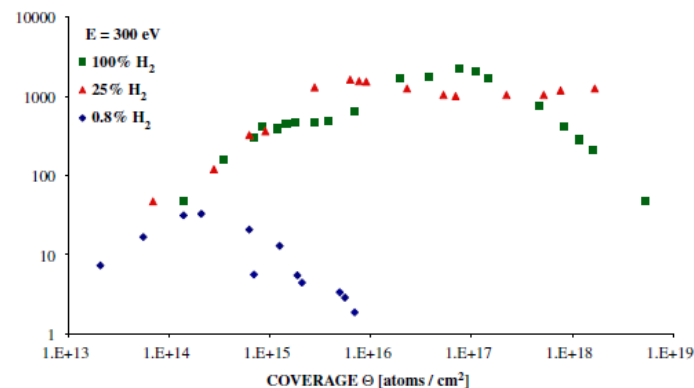


Fig. 5. The H<sub>2</sub> desorption yield as a function of H<sub>2</sub> coverage for different condensed gas composition (electron energy 300 eV).

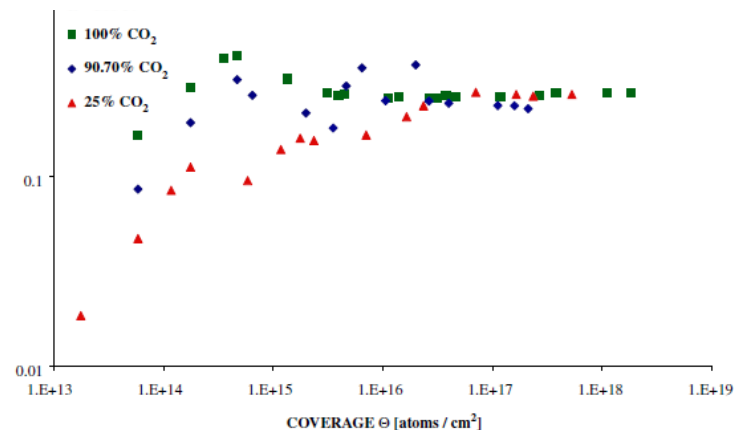
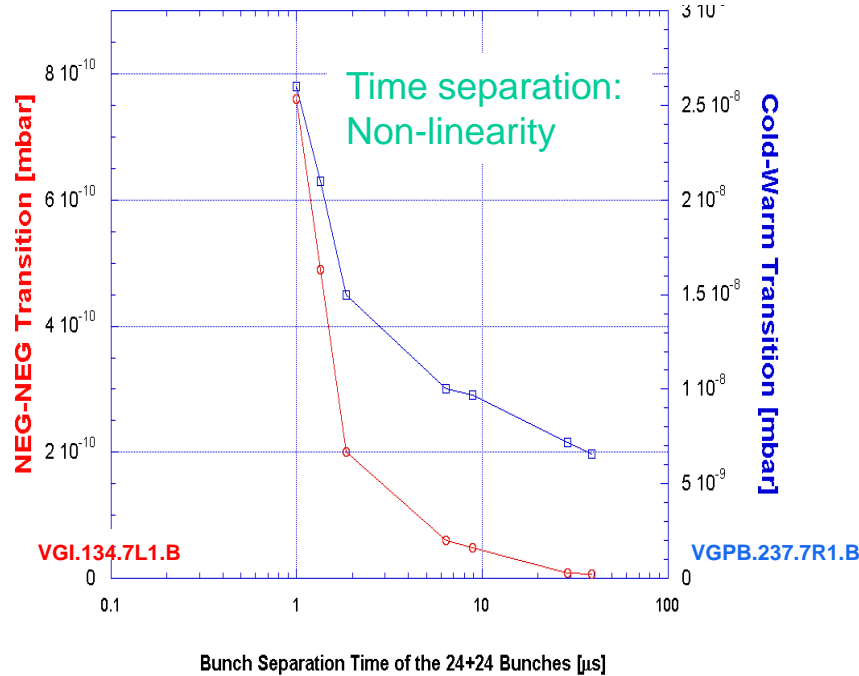
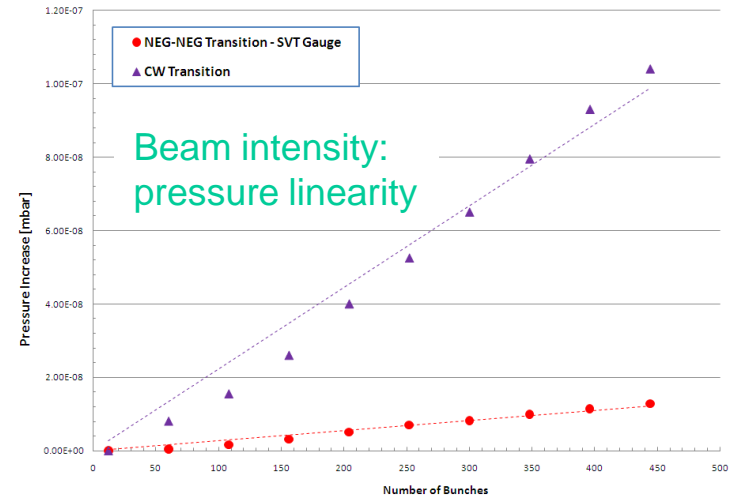
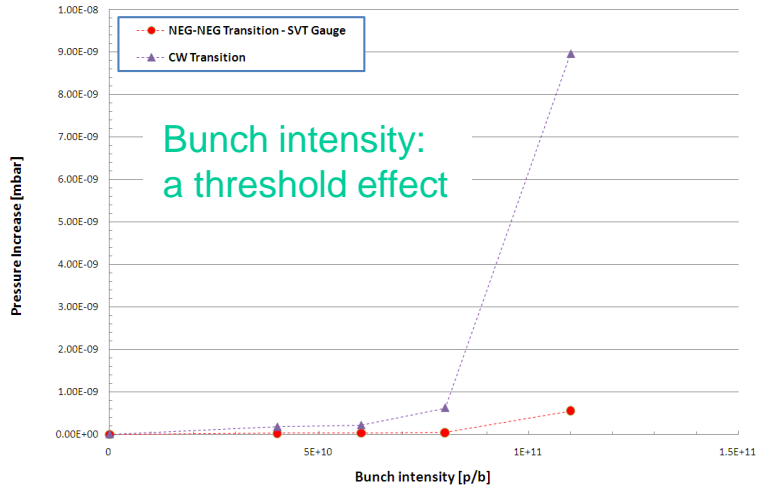


Fig. 8. The CO<sub>2</sub> desorption yield as a function of CO<sub>2</sub> coverage for different condensed gas composition (electron energy 300 eV).

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

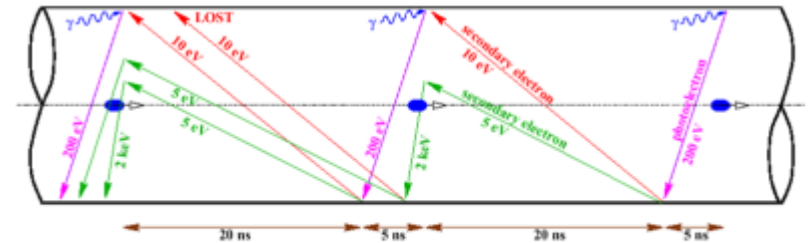
# 4.5 Beam structure

# Multipacting: Influence of Beam Structure



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

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



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

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

# Lecture 4 summary

- In accelerators, the **circulating beam** can contribute to stimulate molecular desorption
- Those phenomenon can lead to much larger **gas load** than the thermal outgassing rate
- **Photon stimulated desorption** originates from SR
- **Ion stimulated desorption** originates from beam gas ionisation and can lead to vacuum instability
- Particle losses
- **Electron stimulated desorption** originates from an electron cloud

# Some References

- Cern Accelerator School, Vacuum technology, CERN 99-05
- Cern Accelerator School, Vacuum in accelerators, CERN 2007-03
- Cern Accelerator School, Vacuum for particle accelerators, Glumsløv, June 2017
  
- 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.
- Les calculs de la technique du vide, J. Delafosse, G. Mongodin, G.A. Boutry. Le vide.
- Vacuum Technology, A. Roth. Elsevier Science
- Foundations of vacuum science and technology, Ed by J.M. Lafferty. J. Wiley & sons.
- Vacuum in Particle Accelerators: Modelling, Design and Operation of Beam Vacuum Systems, O. Malyshev. Wiley VCH.

# Some Journals

- Journal of Vacuum Science and Technology
- Vacuum
- Applied Surface Science
- Nuclear Instruments and Methods
- Physical Review Accelerator and Beams

**Thank you for your attention !!!**





# Complementary information



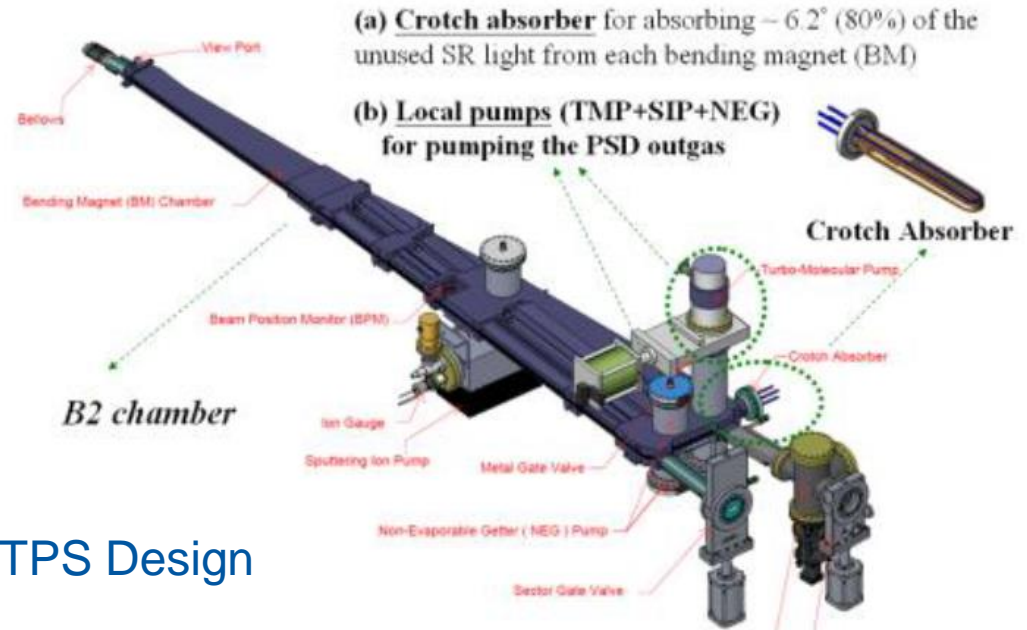


# 1.1 Synchrotron radiation

# ... heavy consequences on design

Complementary information

- Extruded Aluminum
- Ex-situ baked to 150°C



TPS Design

G.Y Hsiung *et al.*

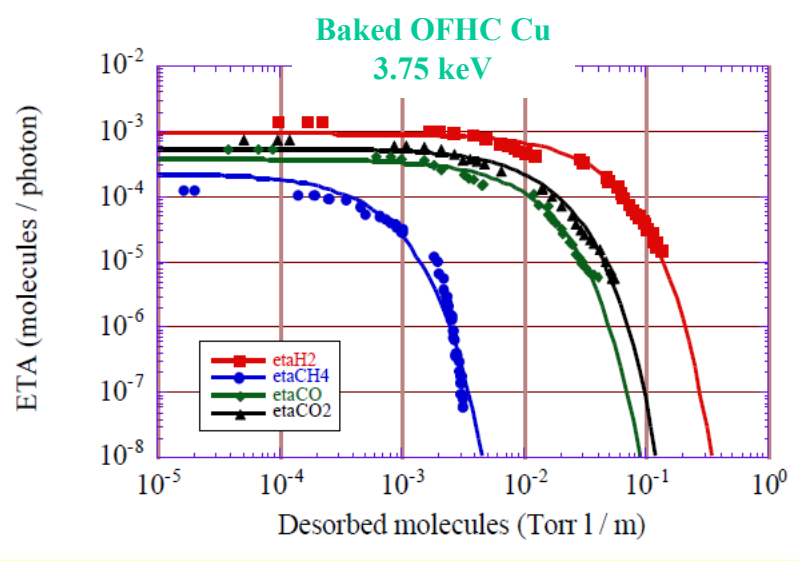
- A **complex** vacuum chamber design with a light extraction path, pumping and instrumentation ports and **power absorbers** (crotch)

# 1.2 Photodesorption

# Desorption yield vs gas load

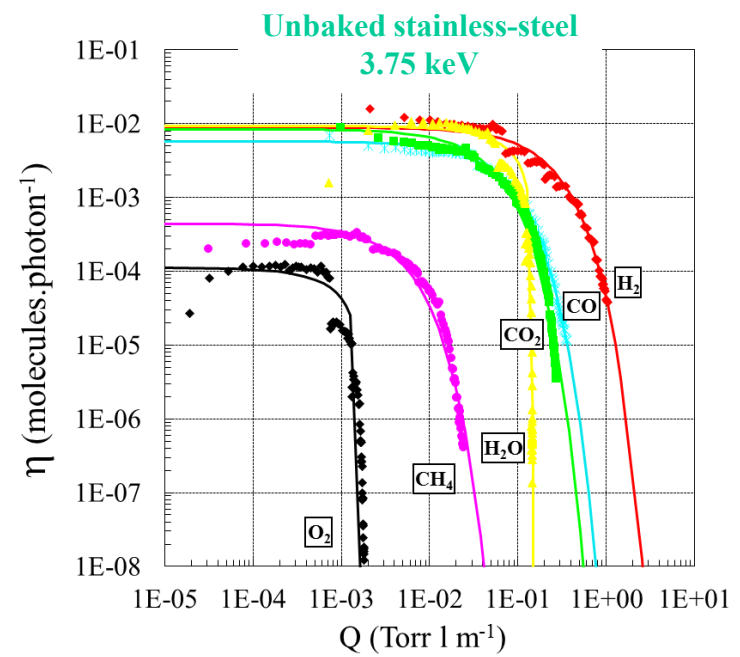
Complementary information

- The quantity removed during the cleaning process is a useful information to estimate intervals between getter reactivation or surface coverage on a cryogenic surface



$$\eta = \eta_0 e^{-\frac{q}{Q_0}}$$

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



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

	H <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>
η <sub>0</sub> (molecules/ph)	9.2 · 10 <sup>-4</sup>	2.3 · 10 <sup>-4</sup>	3.7 · 10 <sup>-4</sup>	5.5 · 10 <sup>-4</sup>
Q <sub>0</sub> (Torr l / m)	3.0 · 10 <sup>-2</sup>	4.5 · 10 <sup>-4</sup>	8.4 · 10 <sup>-3</sup>	1.1 · 10 <sup>-2</sup>
Q <sub>0</sub> (molecules/cm <sup>2</sup> )	2.3 · 10 <sup>14</sup>	3.5 · 10 <sup>12</sup>	6.5 · 10 <sup>13</sup>	8.5 · 10 <sup>13</sup>

	H <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>
η <sub>0</sub> (molecules/ph)	8.8 · 10 <sup>-3</sup>	4.4 · 10 <sup>-4</sup>	5.7 · 10 <sup>-3</sup>	8.4 · 10 <sup>-3</sup>
Q <sub>0</sub> (Torr l / m)	1.9 · 10 <sup>-1</sup>	3.9 · 10 <sup>-3</sup>	5.7 · 10 <sup>-2</sup>	4.0 · 10 <sup>-2</sup>
Q <sub>0</sub> (molecules/cm <sup>2</sup> )	1.5 · 10 <sup>15</sup>	3.1 · 10 <sup>13</sup>	4.5 · 10 <sup>14</sup>	3.2 · 10 <sup>14</sup>



## 2. Vacuum instability and ion stimulated desorption

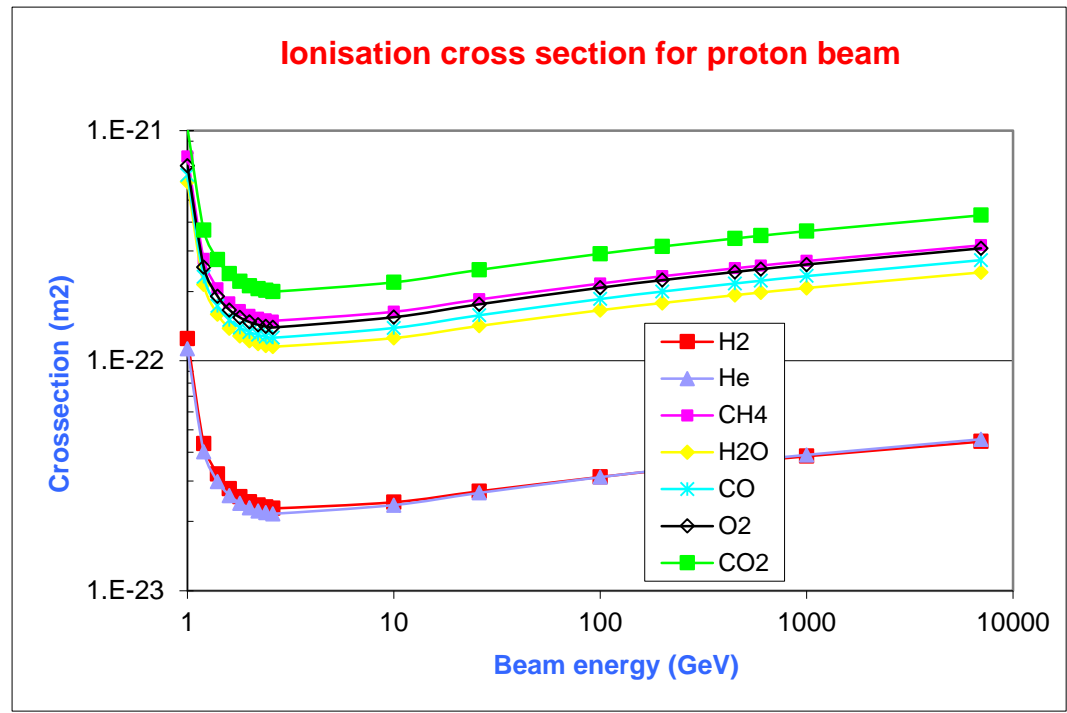
# Ionisation cross section

- It is a function of the speed & the charge of the projectile and of the nature of the residual gas.

$$\sigma = 4\pi \left( \frac{h/2\pi}{m_e c} \right)^2 \frac{Z^2}{\beta^2} \left[ M^2 \left( \ln \left( \frac{\beta^2}{1-\beta^2} \right) - \beta^2 \right) + C \right]$$

F.F. Rieke, W. Prepejchal, Phys. Rev. A5, 1507 (1972)

Gas	Ionisation cross-section (in 10 <sup>-18</sup> cm <sup>2</sup> )		
	26 GeV	450 GeV	7000 GeV
H <sub>2</sub>	0.27	0.36	0.45
He	0.27	0.36	0.45
CH <sub>4</sub>	1.9	2.5	3.2
H <sub>2</sub> O	1.4	1.9	2.4
N <sub>2</sub>	1.6	2.2	2.7
CO	1.6	2.2	2.7
O <sub>2</sub>	1.8	2.4	3.1
Ar	1.7	2.4	3.1
CO <sub>2</sub>	2.5	3.4	4.3



→ Heavy gas must be avoided

# Ion desorption

S(E)

Complementary information

- Described by the nuclear and electronic stopping force (stopping power)
- Low masses ( $H_2$ ) are desorbed by the electronic energy transfer to the lattice
- High masses are desorbed by the direct nuclear momentum transfer between two particles

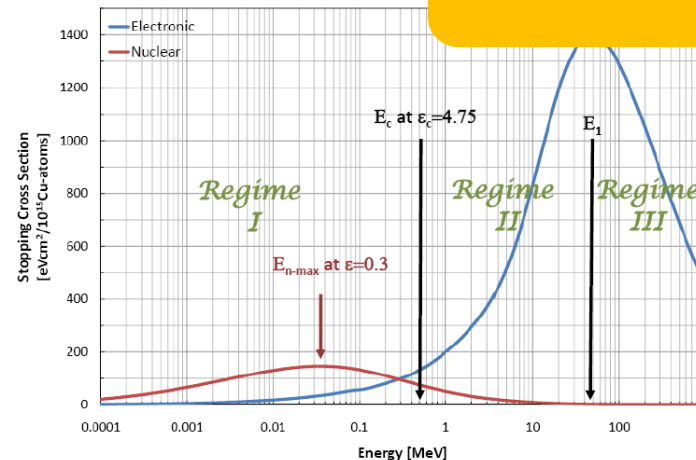


Figure 4.3: Electronic and nuclear stopping cross sections for  $Ar^+$ -ions incident on copper.

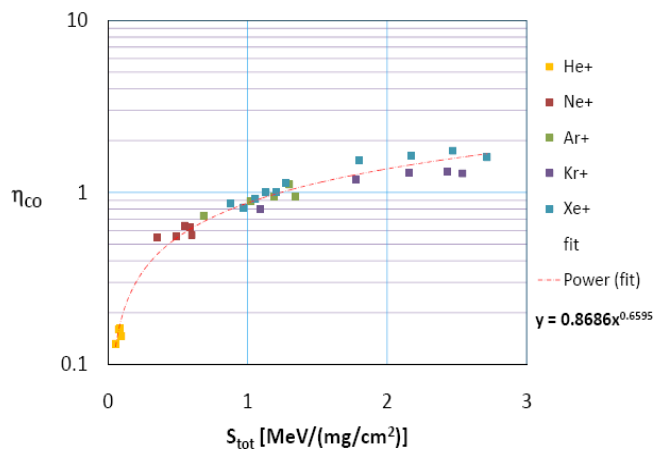


Figure 6.43: CO desorption yields as a function of the total energy loss obtained for noble gas ions incident on copper.

$$\eta = A \cdot S_{tot}^b$$

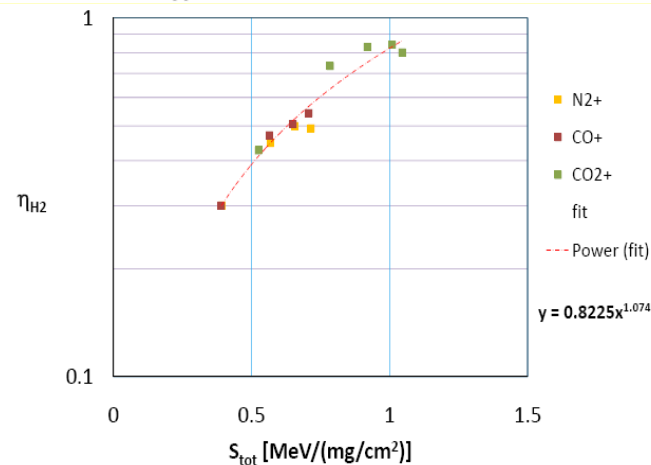


Figure 6.48:  $H_2$  desorption yields as a function of the total energy loss obtained for  $N_2^+$ -ions and oxygen containing ions incident on copper.

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

- Desorption of physisorbed gas

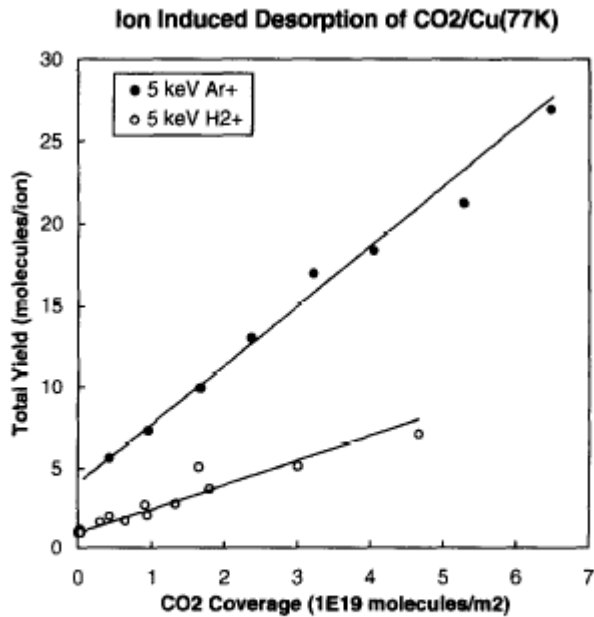
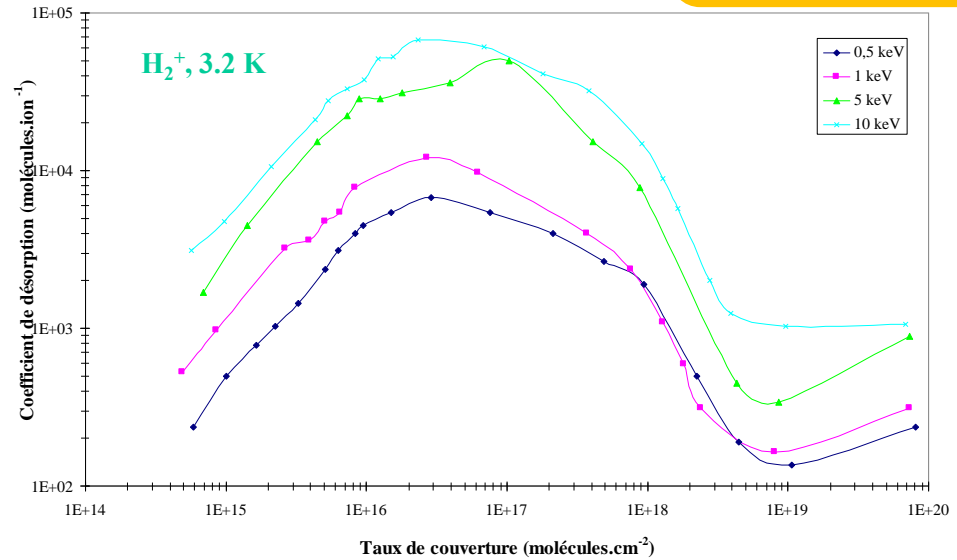


Figure 2. Total desorption yields from adsorbed CO<sub>2</sub>/Cu(77K) induced by bombardment of 5 keV H<sub>2</sub><sup>+</sup> and Ar<sup>+</sup> ions, plotted as a function of CO<sub>2</sub> dose. The lines indicated are best fit lines drawn by eye through experimental points.

J. Barnard *et al.*, Vacuum 47 (4), 347, (1996)



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

$\eta'_{H_2} \sim 2000$   
 $\eta'_{CO_2} \sim 2$   
 @ 5 keV and 1 monolayer

- Critical current is changed to 
$$I_c = \frac{\alpha S}{(\eta_{ion} + \eta'_{ion}) \frac{\sigma}{e}}$$

- It is a function of the geometry, the gas specie, the sticking coefficient and of the 2 desorption



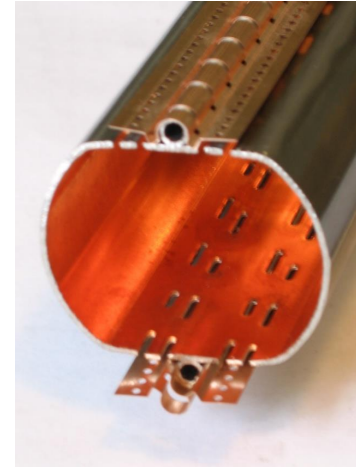
# LHC beam screen stability

Complementary  
information

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

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

	H <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>
$(\eta I)_{\text{crit}}$ [A]	1300	80	70	35



Courtesy N. Kos CERN TE/VSC

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

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

# Pressure increase in LHC due to ions ?

Complementary  
information

- The ion flux is a function of the pressure and the beam current

$$\dot{\Gamma}_{\text{ion}} = \sigma \frac{I}{e} P \cong 310^8 \text{ ions/cm}^2/\text{s} = 310^{11} \text{ ions/m/s}$$

- For nominal parameters,  $P \sim 10^{-8}$  mbar and  $I \sim 600$  mA
- Ion energy will be about 100 eV, so the desorption yield about 2 molecules/ion

$$Q = \frac{\eta \dot{\Gamma}}{3.310^{19}} = 2 \cdot 10^{-8} \text{ mbar} \cdot \ell/\text{s/m}$$

- Beam screen pumping speed,  $S$

$$S = 3.63 \text{ A} \sqrt{\frac{T}{M}} \cong 1000 \ell/\text{s/m}$$

- Pressure increase due to ion:

$$\Delta P = \frac{Q}{S} = 10^{-11} \text{ mbar}$$

→ No visible pressure increase in LHC

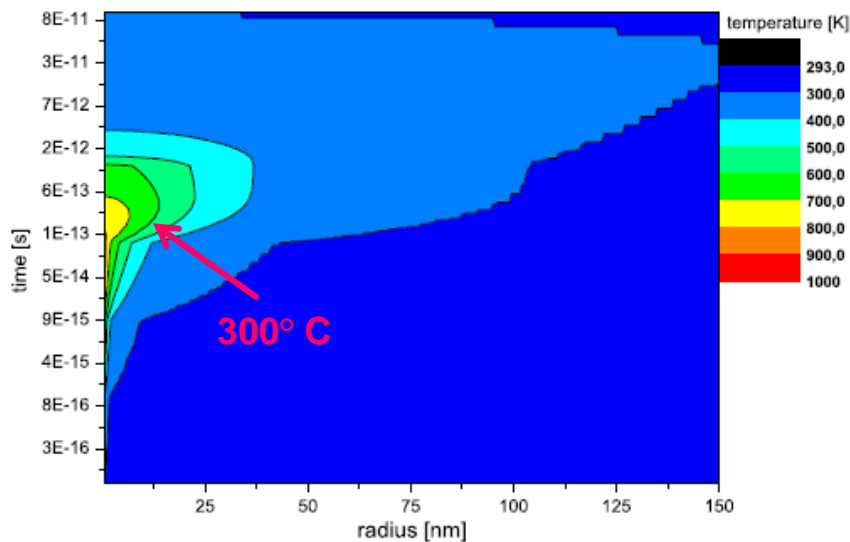
# 3. Particle losses and ion stimulated desorption

- Surface effect (except diffusion H<sub>2</sub>) due to a thermal activation
- « Inelastic thermal spike model » : a temperature map coupled to the thermal desorption model

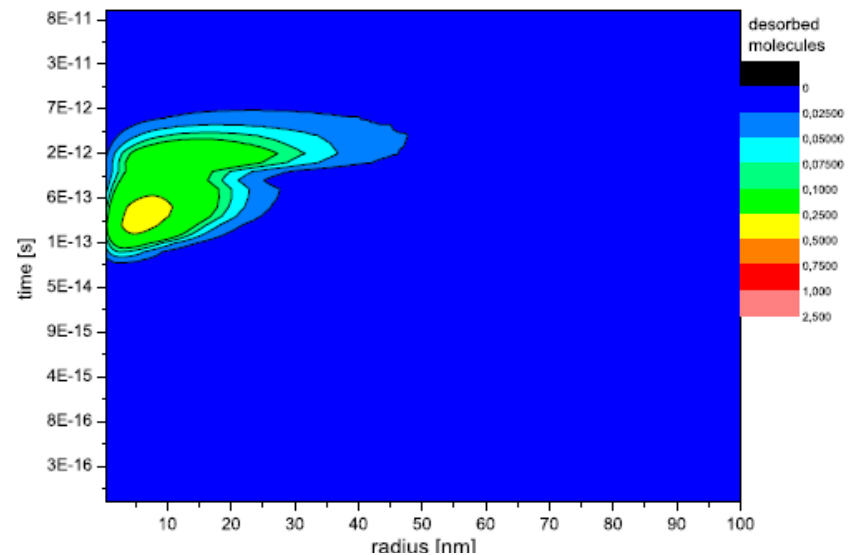
$$\eta = \int_0^{t_{max}} \int_0^{r_{max}} v_0(T(r,t)) \cdot \bar{n}(r,t) \cdot \exp\left(-\frac{E_{des}}{k_B \cdot T(r,t)}\right) \cdot 2\pi \cdot r dr dt,$$

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

Xe<sup>29+</sup>, 1.4 MeV/u, Perpendicular



Temperature of atomic Cu subsystem after Xe impact



Desorbed particles per Xe per dt

$$\eta_{calculated} = 185$$

# 4. Electron cloud and related surface parameters

# 4.1 Introduction

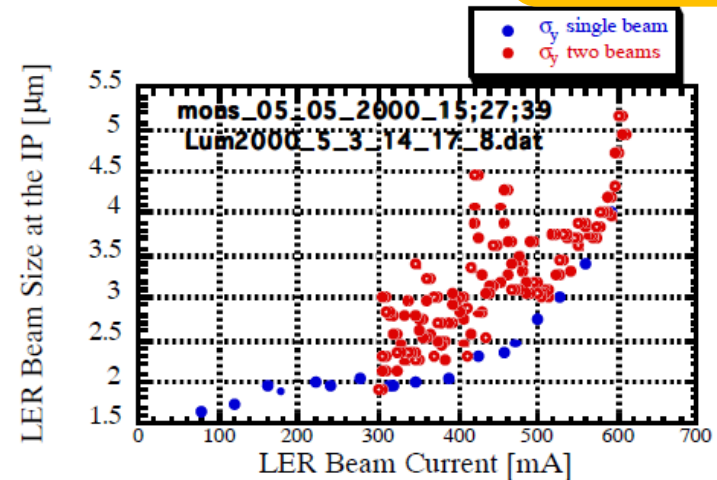
- Cu OFHC vacuum chamber, unbaked, NEG pumping
- Emittance blow up in the vertical plane of the positron beam
- Positron bunch instability due to the cloud of photoelectrons
- Observed in multibunch mode

K. Ohmi, F. Zimmermann, PRL 85, 3821 (2000)

- Installation of permanent magnets then solenoids

→ Luminosity increase

## Observation at IP



Y. Funakoshi *et al.*, EPAC 2000, Vienna, Austria



KEKB LER Solenoids

- Stainless steel vacuum chamber baked at 250°C in the straight sections
- Stainless steel vacuum chamber cooled at 4 K in the arcs
- Pressure increase with protons and ions beams
- NEG, bakeout, solenoids, beam structure .....

→ Luminosity increase

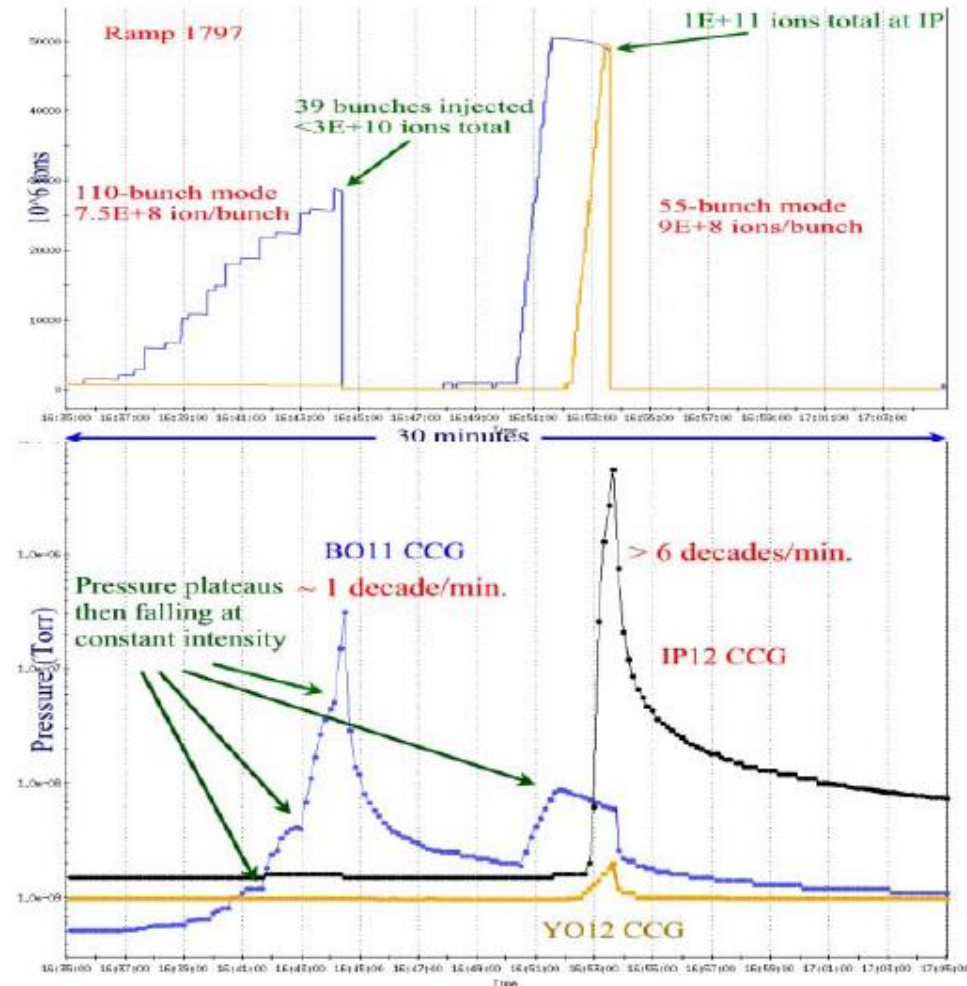
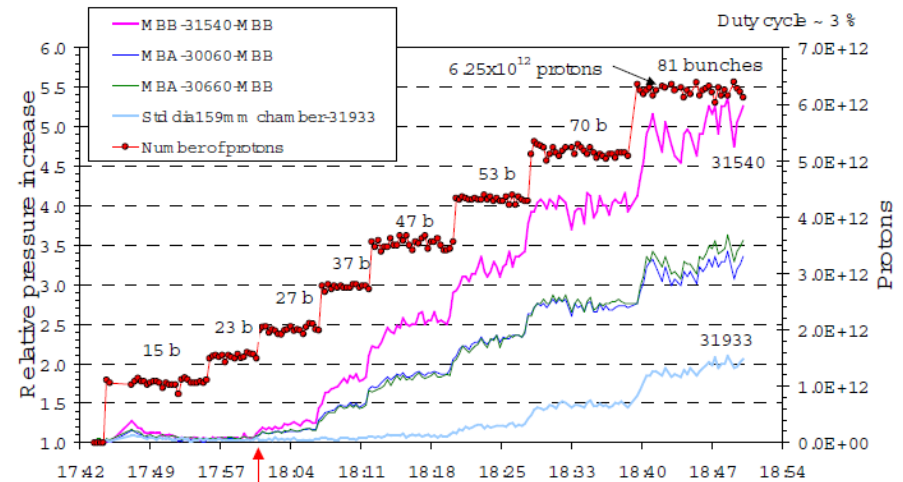


Fig 2. Pressure rises during 110-bunch and high intensity 55-bunch mode Au operations. H. Hseuh *et al.*, EPAC 2002, Paris, France



- Unbaked stainless steel vacuum chamber
- Pressure increase observed with LHC type beams
- Measurement of electron current on a pick up

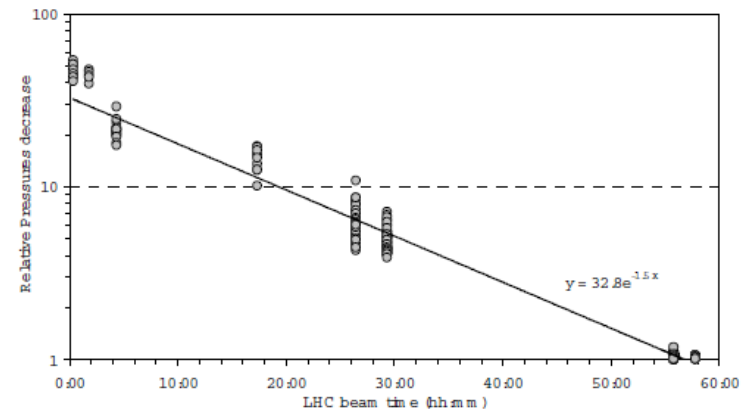
7.7 10<sup>10</sup> protons/bunch



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

- 60 h of beam conditioning

→ Ok for LHC beam injection



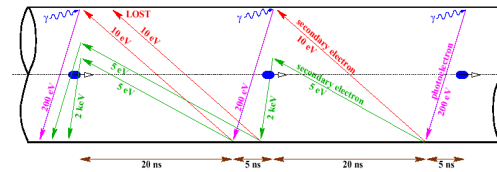
J.M. Jimenez et al., EPAC 2000, Vienna, Austria

# Simple model

Complementary information

- Synchronism condition:

$$\frac{2r_p}{\Delta v} \leq t_{bb}$$



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

- Speed increment due to the kick

$$\Delta v = \frac{\Delta p}{m} = 2cr_e \frac{n_b}{r}$$

- Intensity threshold:

$$n_b = \frac{r_p^2}{r_e L_{bb}}$$

- Enough energy gain due to the kick to produce secondaries:

$$\Delta W = \frac{\Delta p^2}{2m} = 2 \frac{mc^2}{e} r_e^2 \left( \frac{n_b}{r} \right)^2$$

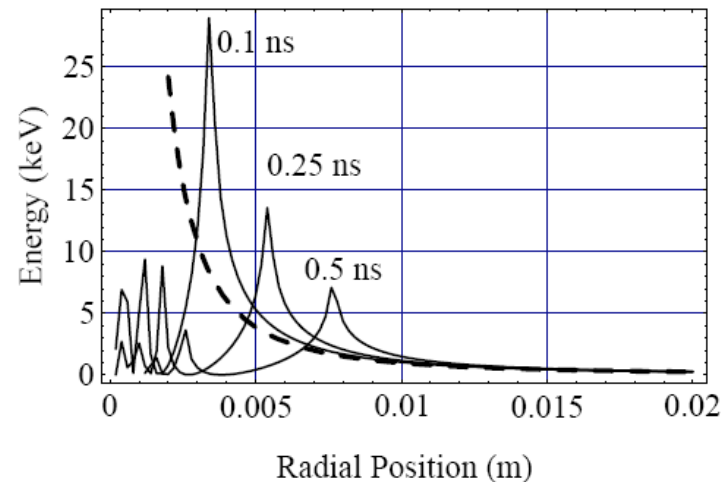


Figure: 1 Electron energy after the passage of a bunch in LHC versus the initial radial position for 0.1, 0.25 and 0.5 ns bunch length. The dotted curve is calculated for the stationary electron approximation.

O. Gröbner. PAC 97, Vancouver, Canada

Electrons in the vacuum chamber wall vicinity receive a kick of 190 eV, those in the beam vicinity receive 15 keV.

# 4.2 Photons from SR

- SR irradiation at EPA
- Grazing incidence, 11 mrad
- The photoyield **increases** when increasing critical energy.
- Photon reflectivity **slightly decreases** when increasing critical energy
- PY\*: photoelectrons per absorbed photons

Material	Status	45 eV		194 eV	
		R (%)	PY* (e/ph)	R (%)	PY* (e/ph)
Al	unbaked	-	0.11	-	0.32
Cu-smooth	unbaked	81	0.11	77	0.32
Cu-electrodeposited	unbaked	5	0.08	7	0.08
Cu-sawtooth	unbaked	8	0.03	7	0.04
TiZr	unbaked	20	0.06	17	0.08
TiZr	activated at 350°C	20	0.02	17	0.03

I.R. Collins *et al.* EPAC 1998, Stockholm, Sweden

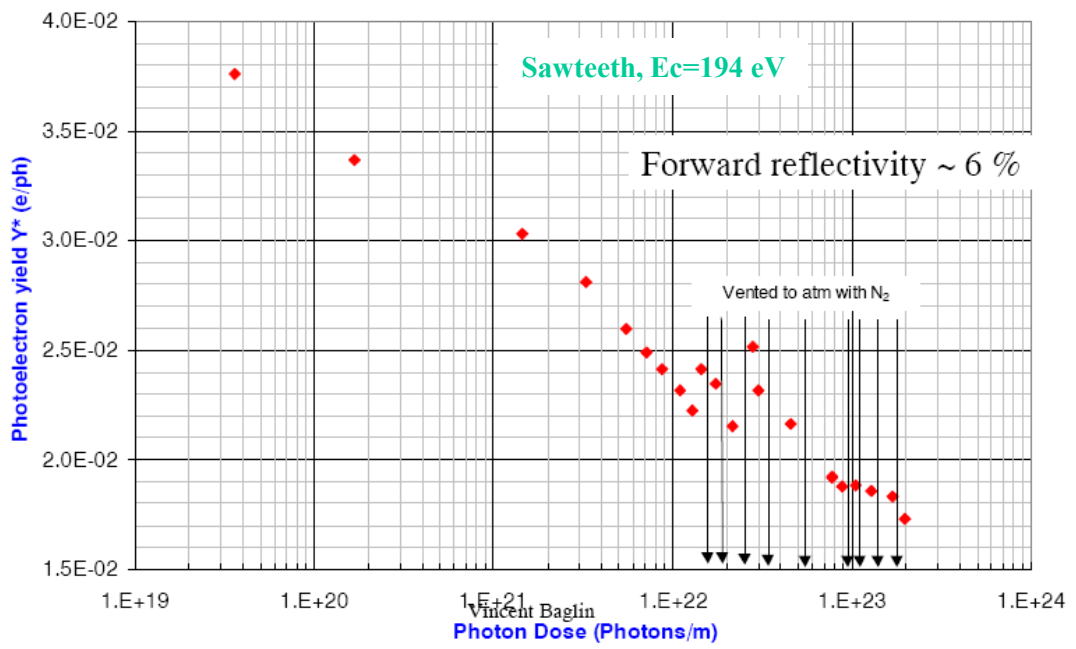
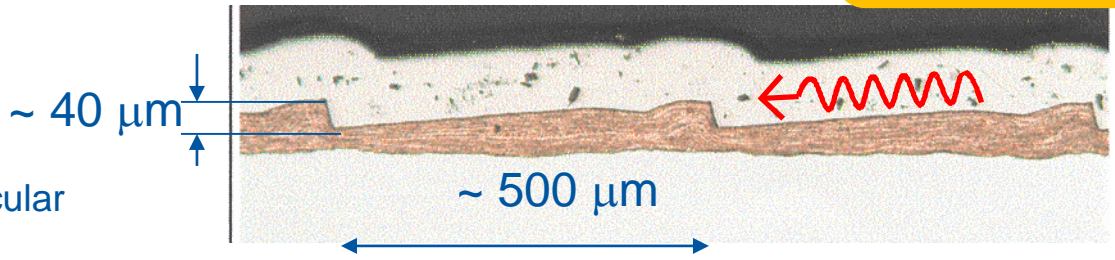
NB : molecular desorption yields are linear in the range, 10 – 300 eV.  
So the photoelectron yield should be also proportional to critical energy

$$PY^* \sim E_c$$

# Photoelectrons for a LHC type beam screen

Complementary information

- The Photoyield decrease with **beam conditioning**
- It varies from 1 to 4 % under perpendicular incidence

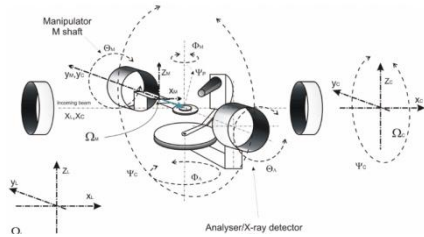


V. Baglin *et al.*, Chamonix, 2001

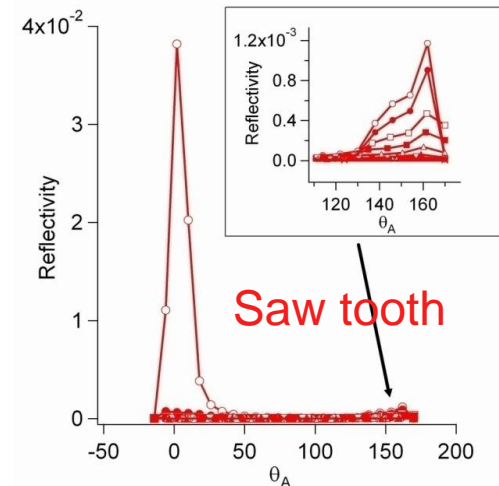
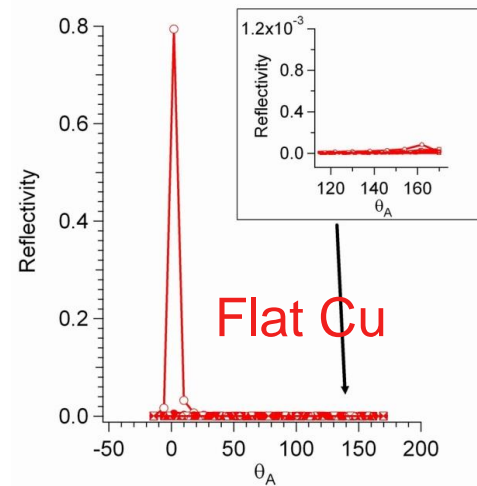
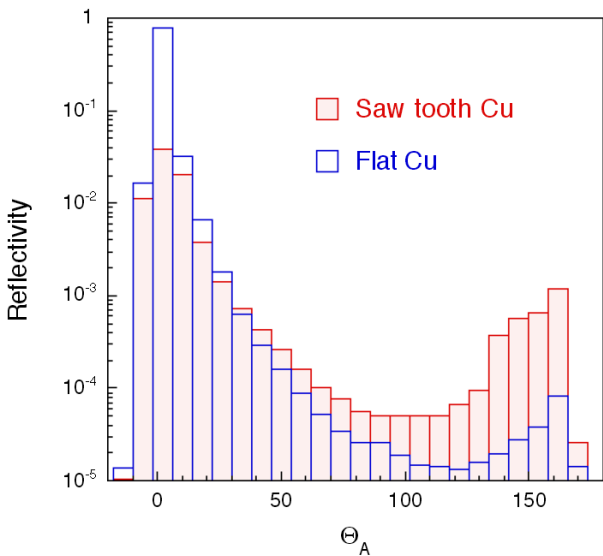
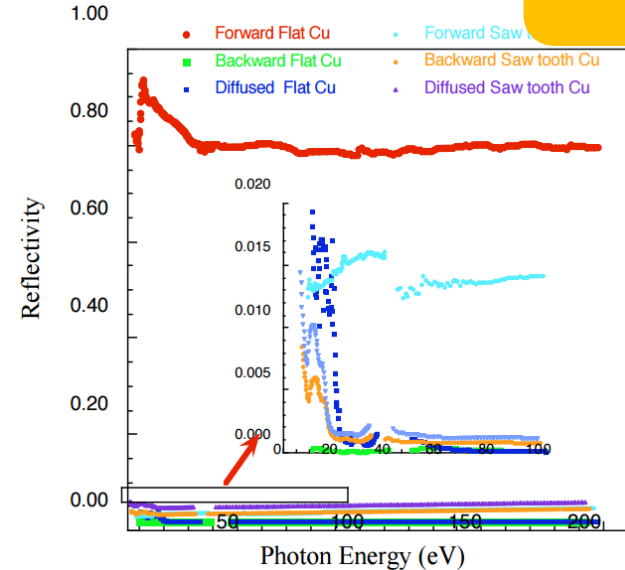
# Photon reflectivity of LHC type material

Complementary information

- The saw tooth structure reduces the reflectivity



	Flat sample	Saw-tooth sample
Forward scattering	80 %	4 %
Back scattering	0 %	2 %
Diffused	2 %	4 %
Total	82 %	10 %



N. Mahne *et al.* App. Surf. Sci. 235, 221-226, (2004)

# 4.3 Electrons from the electron cloud

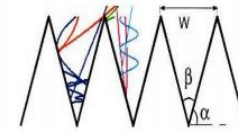
# Geometrical effect

Complementary information

- After a coffee discussion, a drilled sample by the VAC workshop (H. Kos)

- $\varnothing \sim 1 \text{ mm}$  , 92 holes/cm<sup>2</sup>

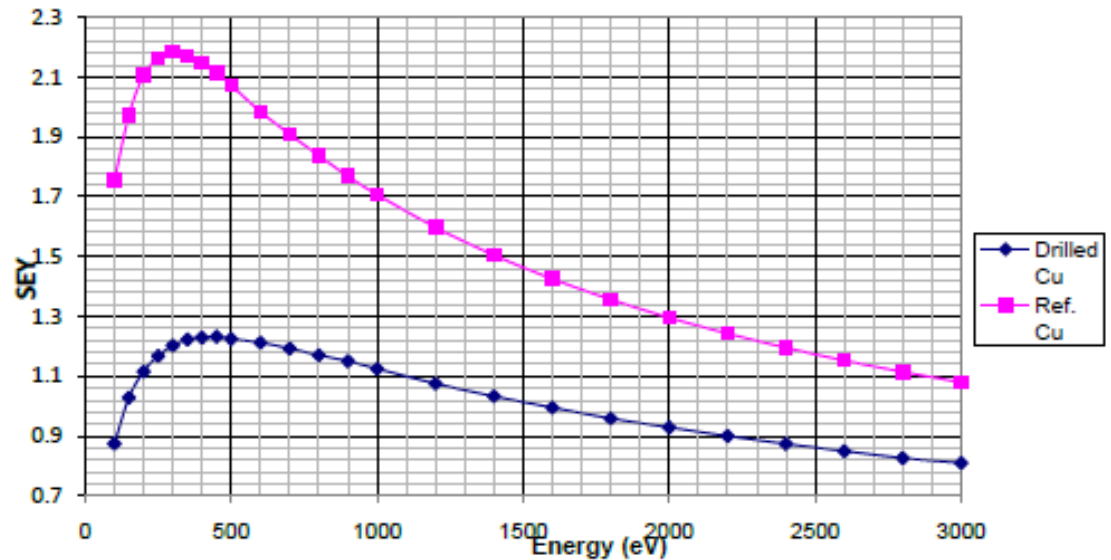
- Original idea with groove only:



By A. Krasnov and  
By L Wang et.al

## SEY max < 1.3 for Cu unbaked !!

Drilled Cu vs. air exposed Cu



Measurement courtesy A. Kuzucan

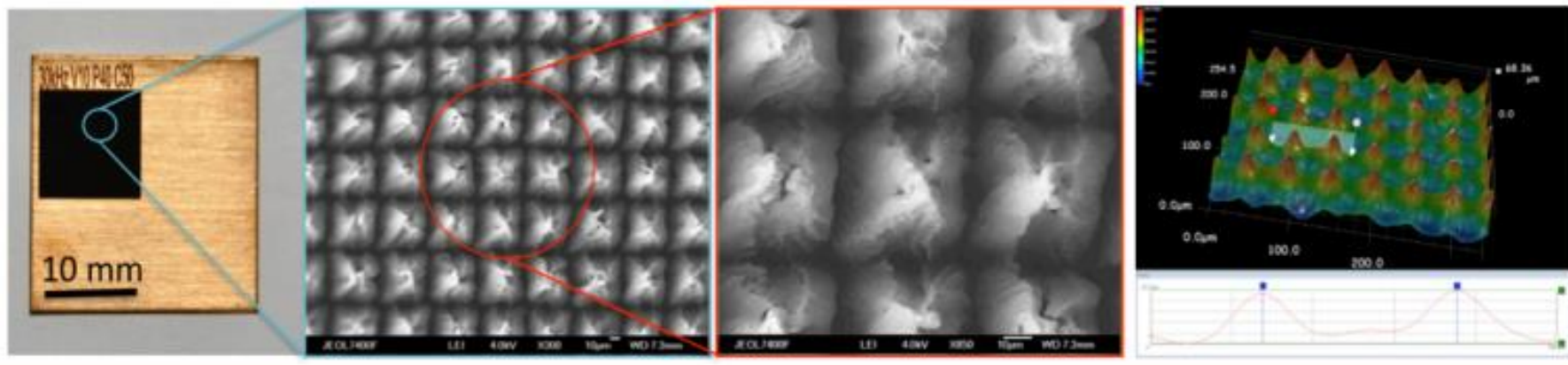
## A fancy effect or a real application ?



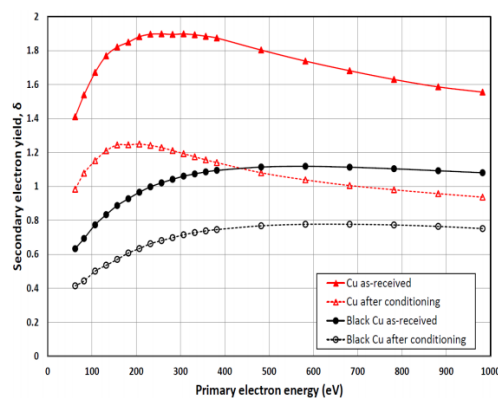
# Laser Engineered Structure Surface

Complementary information

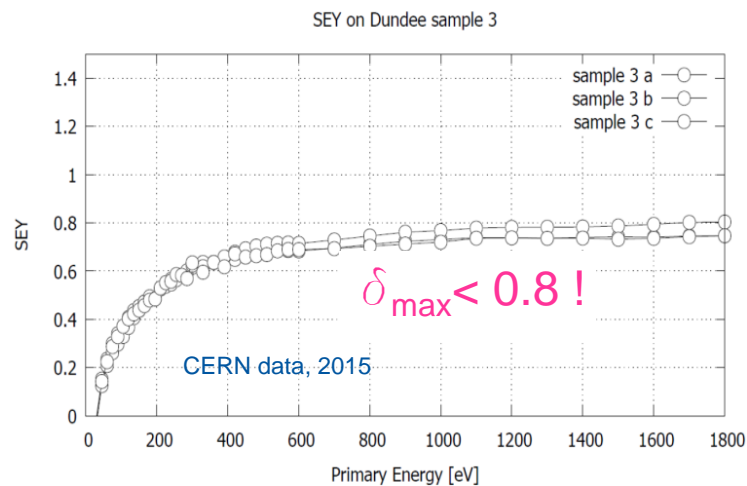
- Principle: laser treatment of a tube at atmospheric pressure
- Production of a micrometric structure



Appl. Phys. Lett. 101, 2319021 (2012). Physics Highlights – Physics Today (February 2013). Opt. Mater. Exp. 1,1425 (2011).



Applied Physics Letters 12/2014; 105(23): 231605

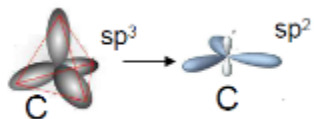


- Still under development by STFC and Dundee university, so it came too late for the LHC construction !

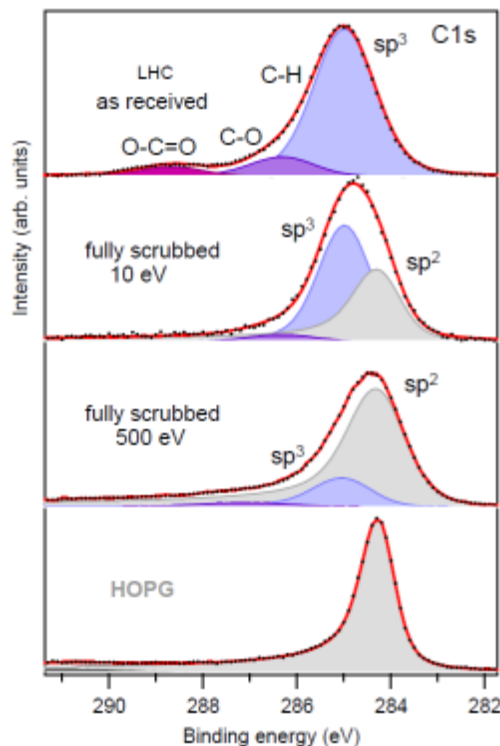
# Origin of the SEY reduction at 300 K

Complementary information

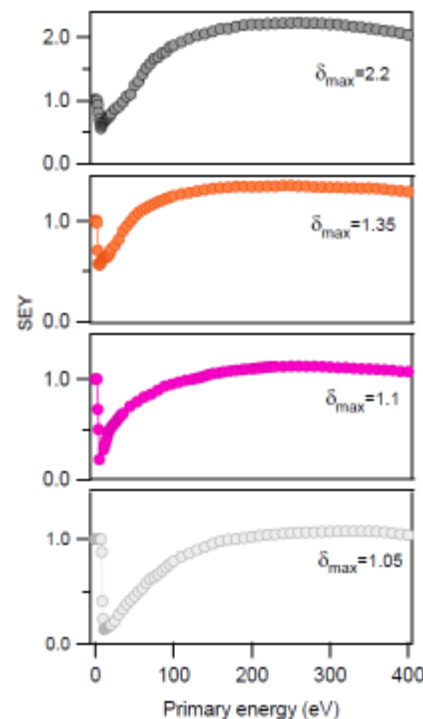
R. Cimino *et al.* PRL **109**, 064801(2012)



- Modification of C1s core level
- Conversion  $sp^3 \Rightarrow sp^2$
- High energy electrons increase the number of graphitic like C-C bounds



HOPG : highly oriented pyrolyty graphite



$\delta_{\max}$

2.2

1.35

1.1

1.05

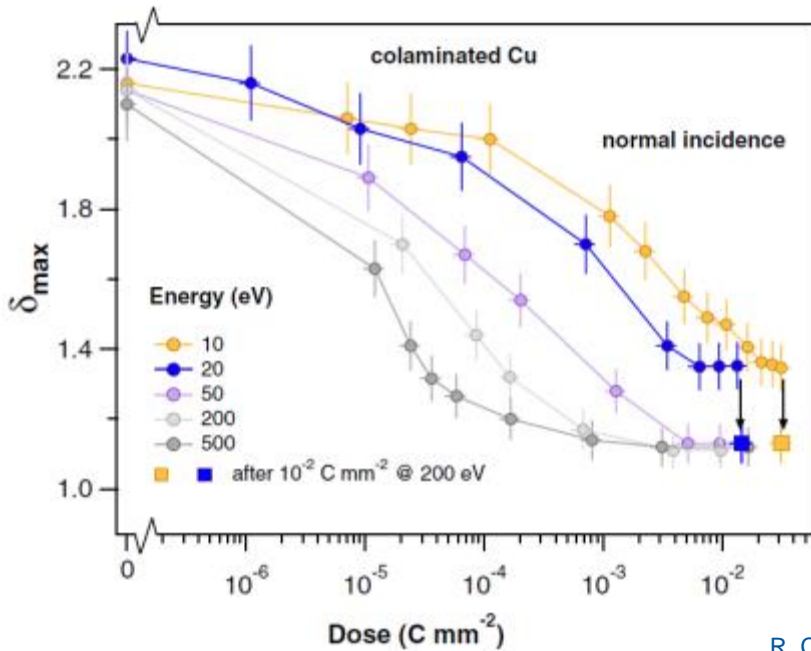
**Graphitization of the carbon contamination layer under electron irradiation**

# Conditioning and electron energy

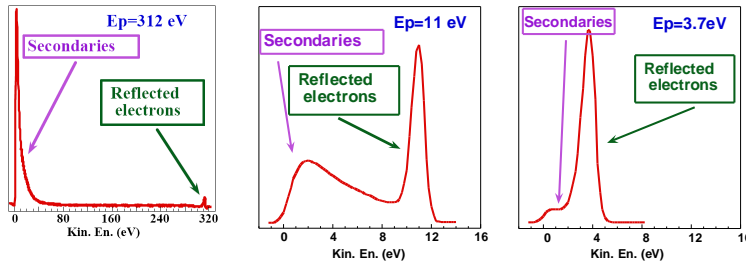
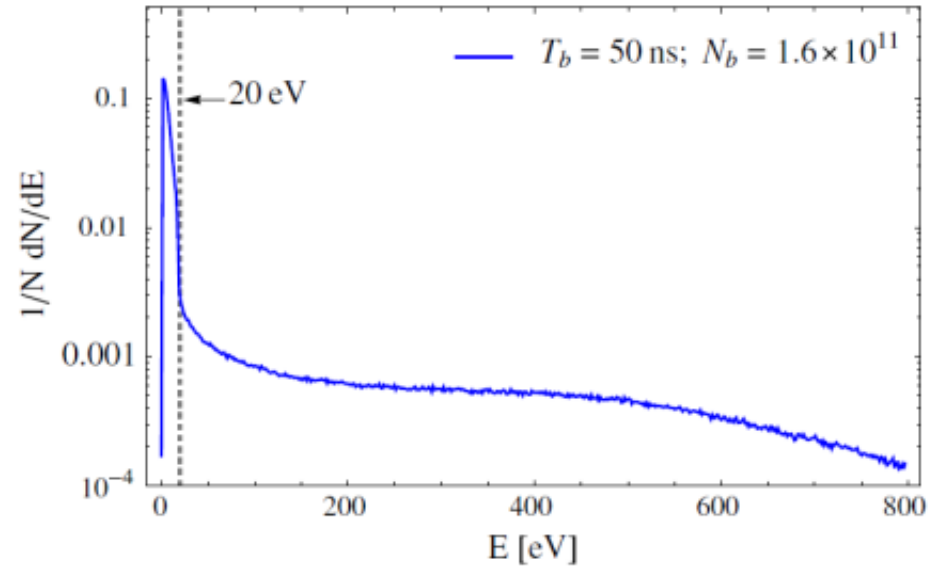
Complementary information

- At 300 K, the scrubbing efficiency of **low energy** electron is less than high energy electrons

- Electron energy distribution at the LHC vacuum chamber wall
- ~ half of the electrons have  $E < 20$  eV



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



R. Cimino, I.R. Collins, App. Surf. Sci. 235, 231-235, (2004)

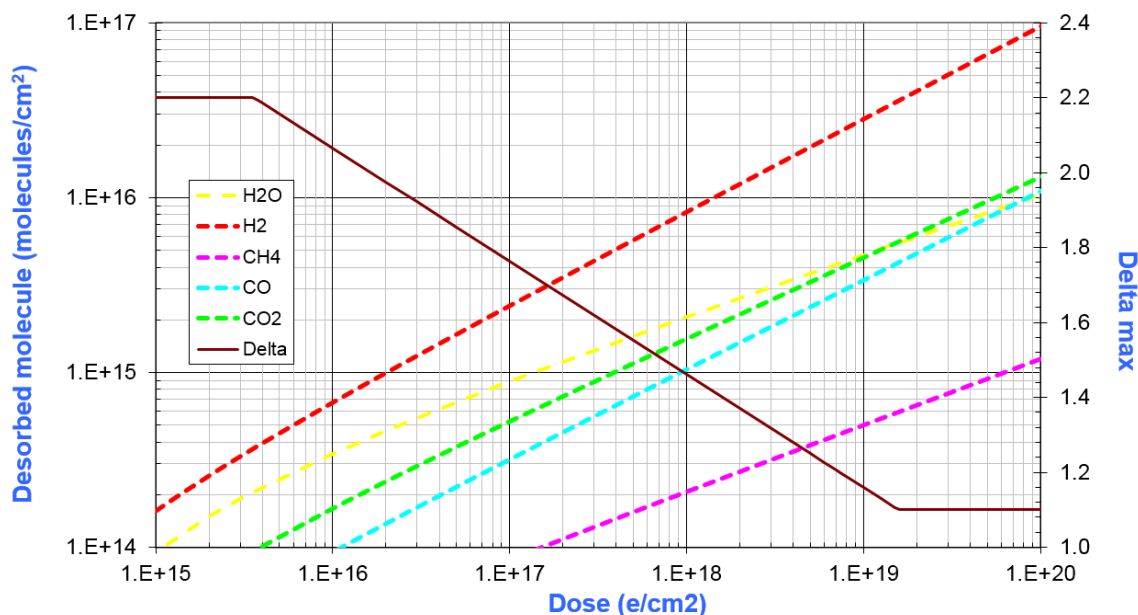
Knowing the energy distribution of electrons is of paramount importance

# Electron scrubbing

Complementary information

- After a dose of  $\sim 5 \cdot 10^{18}$  e/cm<sup>2</sup> i.e. 8 mC/mm<sup>2</sup>, the maximum of SEY equals  $\sim 1.3$
- The scrubbing process desorbs several monolayers of gas from the surface
- Potential impact on:
  - frequency of NEG activation
  - increase of SEY due to gas condensation

Unbaked Cu - ESD - 300 eV



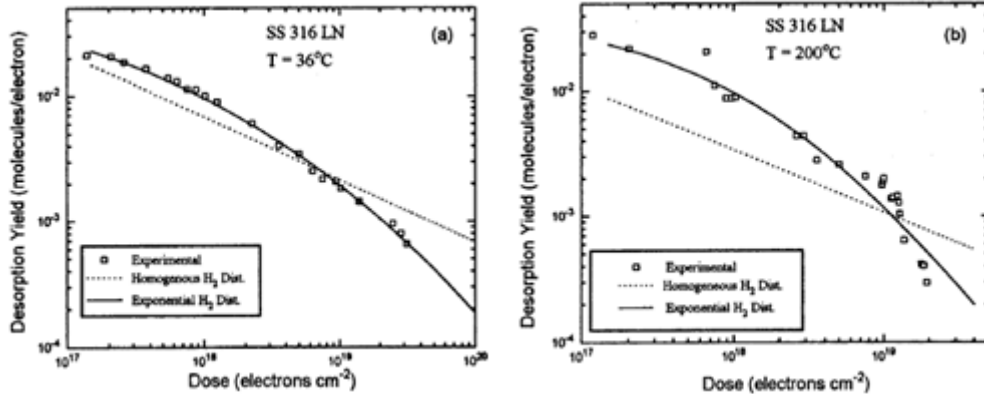
	H <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub> O	CO	CO <sub>2</sub>
Q x 10 <sup>15</sup>	19	0.4	4	2	3

→ several monolayer of gas are desorbed when a surface is conditioned

# Electron desorption studies at different temperature

Complementary information

- Hydrogen desorption



J. Gómez-Goñi, A.G. Mathewson. J. Vac. Sci. Technol. A 15(6) (1997) 3093

- H<sub>2</sub> electron desorption can be explained by a **diffusion model with a non-uniform concentration** *i.e.* H is produced by dissociation of hydroxydes under electron bombardement

However, the diffusion coefficients taken for RT and 200°C were the same

- No **obvious correlation** between the surface composition determined by AES and desorption yields as a function of temperature : No changes in AES spectra vs 1 to 3 orders of magnitude decrease for the yields.

- The thickness of the oxide layer is more than 3 monolayers (AES scanning depth).

**A porous surface oxide layer provide the reservoir of gas**

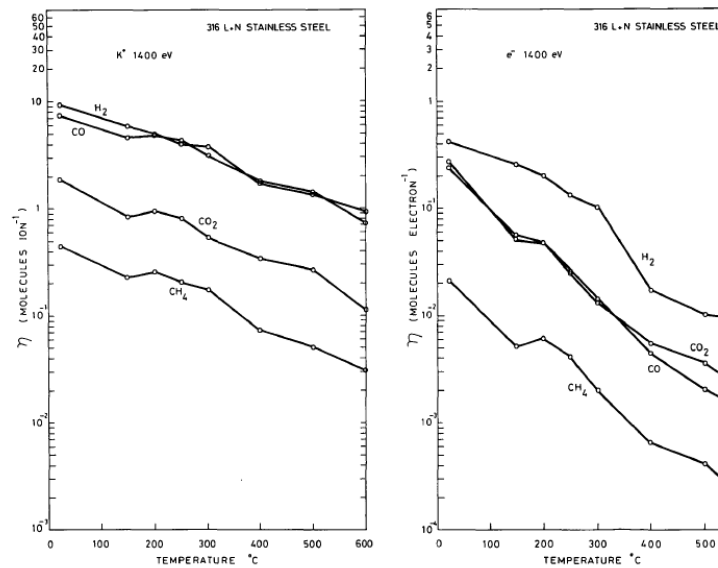


Figure 1. Electron and ion induced desorption coefficients for 316 L + N stainless steel.

M.H. Achard *et al.*, Vacuum 29-2, 53,(1978)

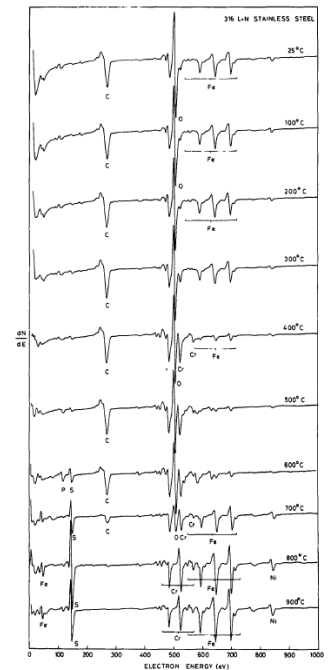


Figure 7. Auger spectra for 316 L + N stainless steel as a function of temperature.