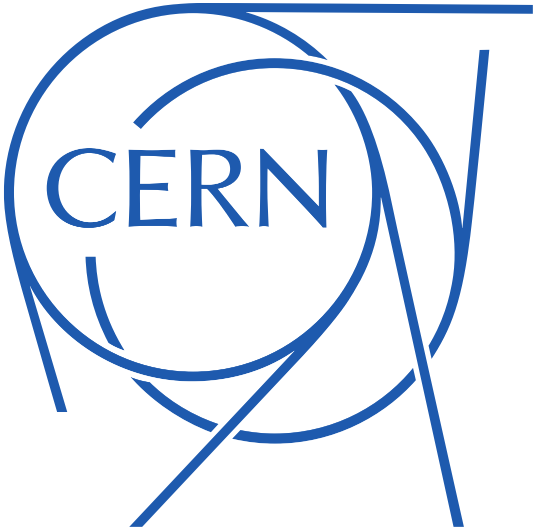

CERN

Vacuum Systems
Slot 7

V. Baglin

CERN TE-VSC, Geneva

Joint Universities Accelerator School

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

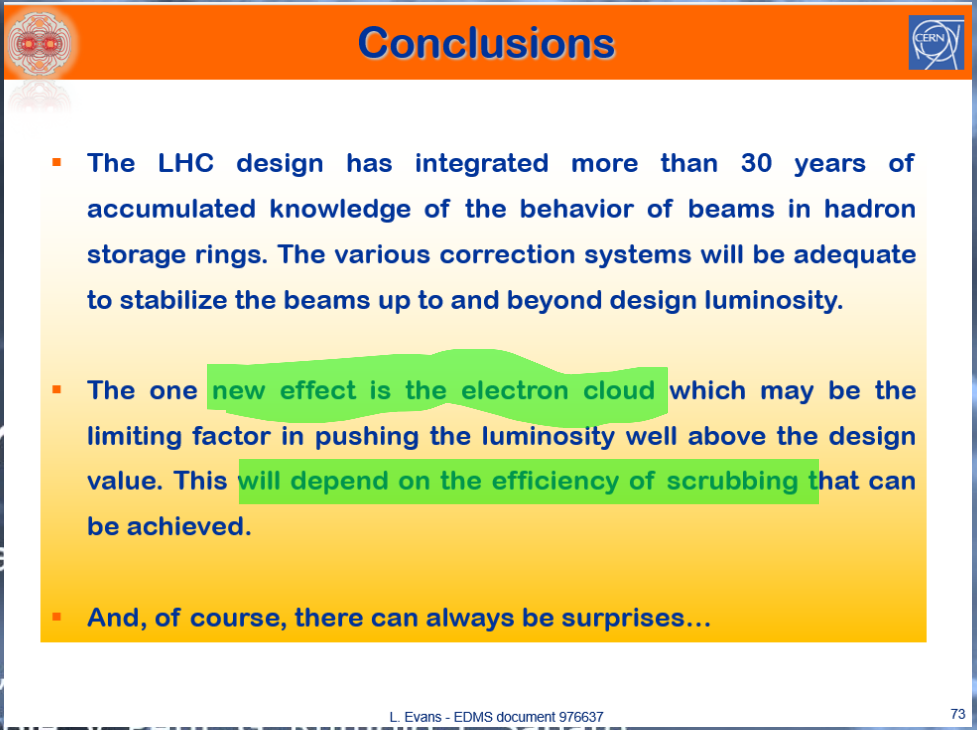
Outline

1. Electron cloud: an introduction
2. SR photon interaction with surface
3. Electron interaction with surface

1. Electron cloud: an introduction

Another lesson from the (recent) history ?

Lyn Evans, LHC Project Leader



Conclusions

- The LHC design has integrated more than 30 years of accumulated knowledge of the behavior of beams in hadron storage rings. The various correction systems will be adequate to stabilize the beams up to and beyond design luminosity.
- The one new effect is the electron cloud which may be the limiting factor in pushing the luminosity well above the design value. This will depend on the efficiency of scrubbing that can be achieved.
- And, of course, there can always be surprises…

L. Evans - EDMS document 976637

73

H. Bartosik, B. Bradu, X. Buffat,
G. Iadarola, K. Li, I. Mases Sole, V. Petit, G. Rumolo, L. Sabato

Fall 2008 - Department of Physics Colloquium, MIT 13th November 2008

Royal Plaza Mo ux, Switzerland

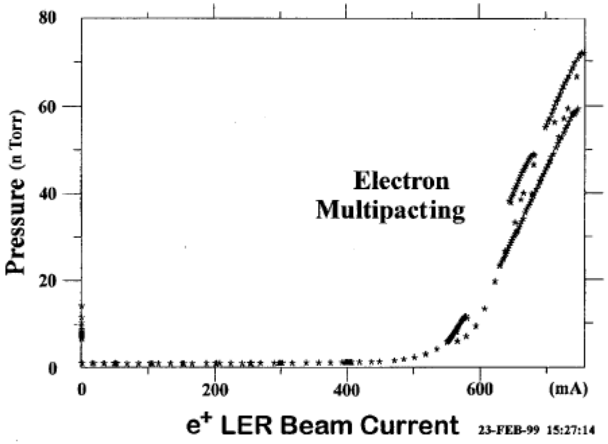
11 December 2024

Some electron cloud sensitive machines

	PEPII	KEKB	DAFNE	LHC	HL-LHC	Super KEKB	ILC DR	FCC-hh
Particle	e+	e+	e+	p	p	e+	e+	p
Energy [GeV]	3.1	3.5	0.51	7 000	7 000	4	5	50 000
Luminosity [Hz/cm^2]	3×10^{33}	2×10^{34}	5×10^{32}	1×10^{34}	5×10^{34}	8×10^{35}	na	5×10^{34}
Circumference [km]	2.2	3	0.1	26.7	26.7	3	3.2	97.8
Nb of bunches	1 658	1 284	120	2 808	2 748	2 500	1 312	10 426
Bunch population	6×10^{10}	9×10^{10}	2×10^{10}	1.2×10^{11}	2.2×10^{11}	9×10^{10}	2×10^{10}	1×10^{11}
Bunch spacing [ns]	4.2	7	2.7	25	25	4	554	25
Bunch length [ns]	0.05	0.02	0.1	0.25	0.25	0.02	0.02	0.25
Instability threshold [e/m^3]	1×10^{12}	4×10^{11}	1×10^{13}	5×10^{11}	1×10^{12}	3×10^{11}	4×10^{10}	4×10^{10}
Material	Al	Cu	Al	Cu/SS	Cu/SS	Cu/Al	Cu	Cu

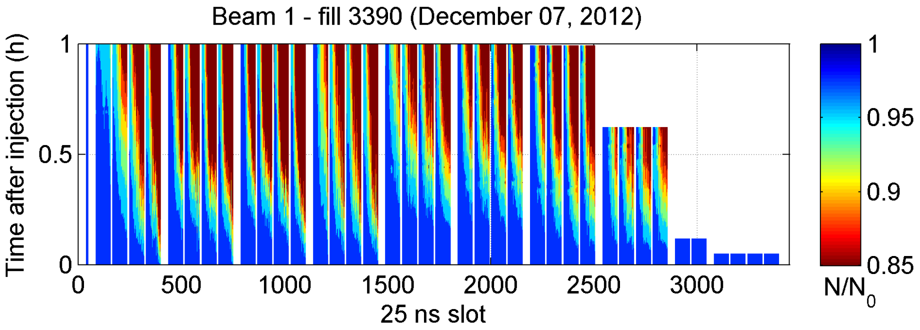
Effects of electron cloud

Pressure increase



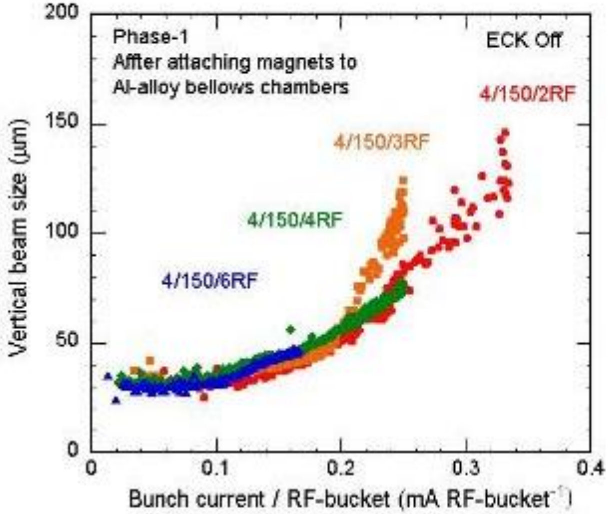
J. Seeman et al., EPAC 2000, Vienna, Austria

Bunch instability along the train



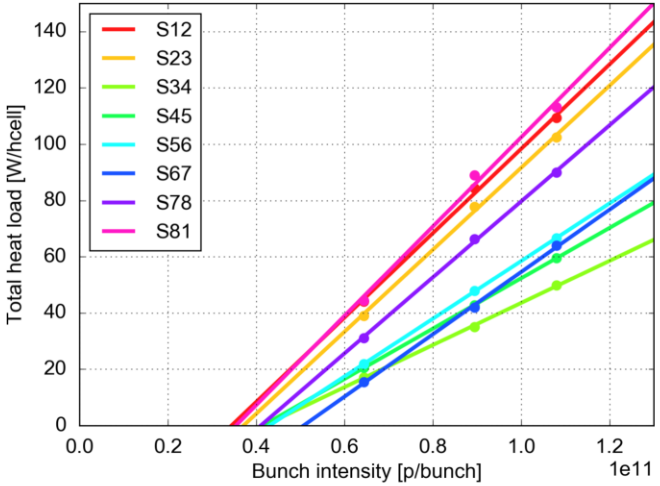
Courtesy G. Rumolo

Beam size increase



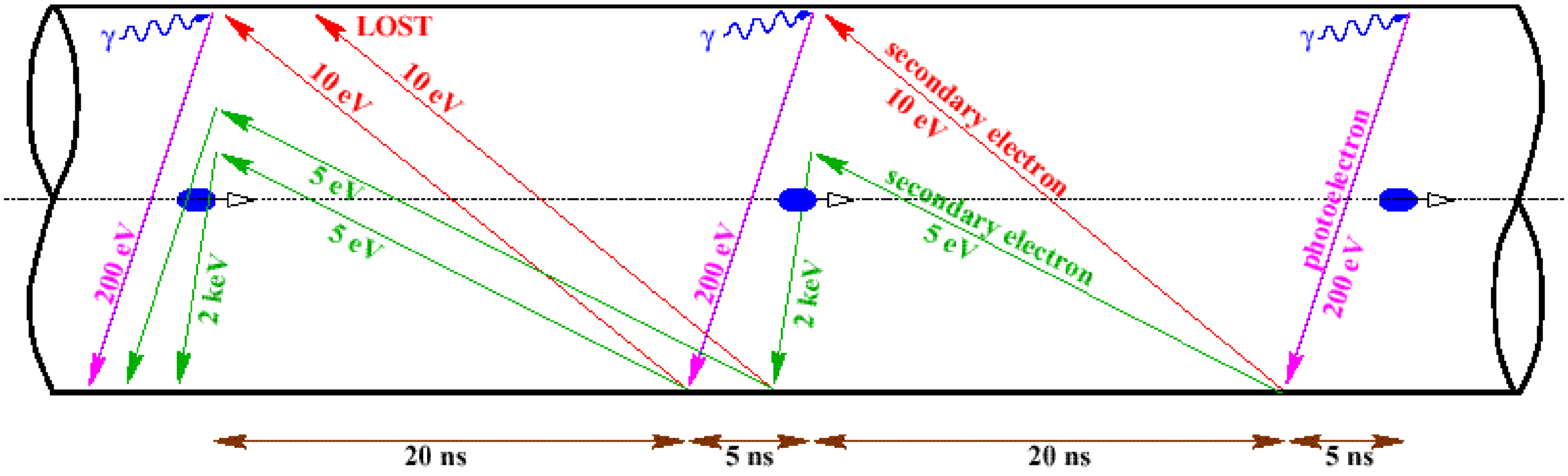
Y. Suetsugu et al., J. Vac.Sci.Technol. A37 021602 (2019)

Heat load: 15-50 kW at 5-20 K in LHC!



G. Iadarola, Proc. Ecloud Workshop 2018

LHC mechanism



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

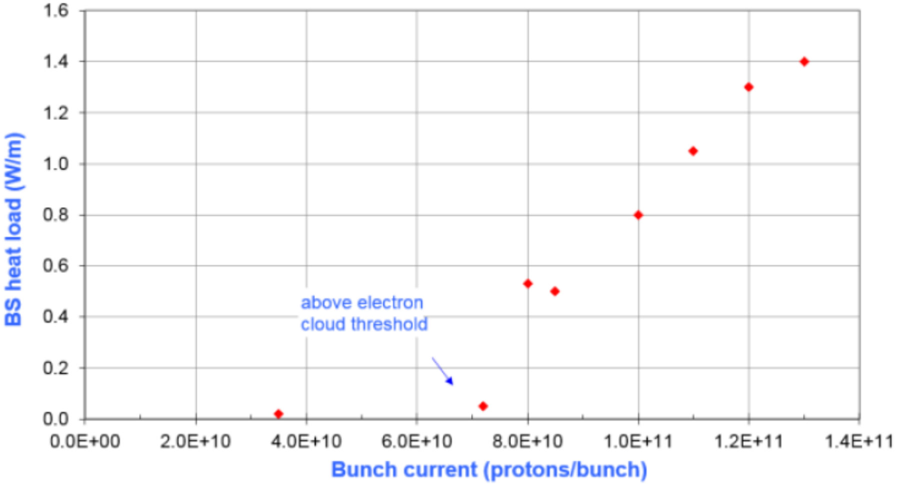
F. Ruggiero *et al.*, LHC Project Report 188 1998, EPAC 98

- Key parameters:
  - beam structure
  - bunch current
  - vacuum chamber dimension
  - → secondary electron yield
  - photoelectron yield
  - electron and photon reflectivities
  - …

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

Heat load for cryogenic machines!

- There is a bunch intensity threshold
- The beam induced electron cloud can be detrimental for cryogenic machines



- Several W/m might be dissipated in a cold system

T (K)	W_Elec (W)
1.9	800
4.5-20	175
60-80	20

Electrical cost of 1 W extracted at cryogenic temperature

- In LHC, synch. rad heat load = 0.22 W/m:
  ~ 8 kW around the ring
  - 6,8 MW_{Elec} at 1.9 K

  or
  - 1,4 MW_{Elec} at 4.5-20 K

➔ a beam screen was mandatory !

V. Baglin. CERN-2020-007, Proc. Of Ecloud’18, Isola d’Elba, Italy, 2018.

Magnetic field

- Electrons are confined along the magnetic field lines
- The magnetic field modifies the threshold of multipacting:
  - ➔ $Th_{Quad} < Th_{Dip} < Th_{Drift}$

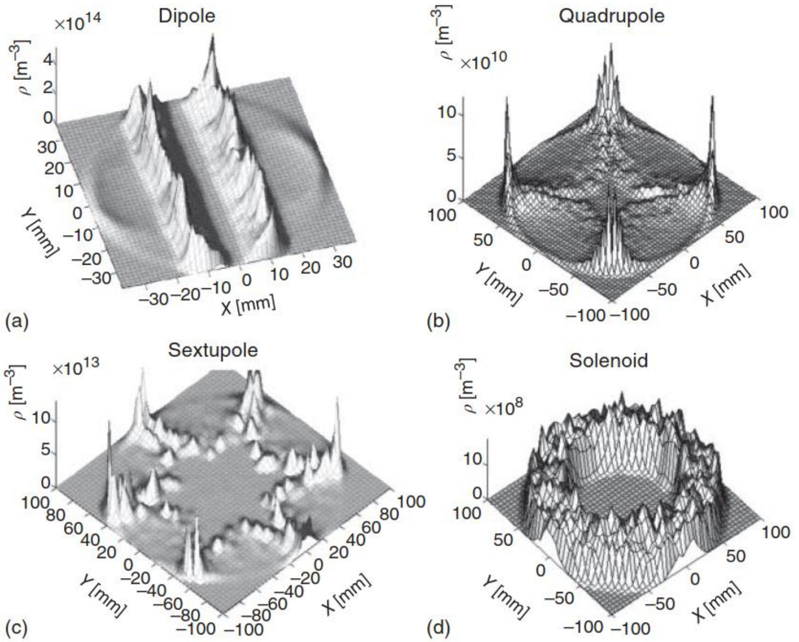


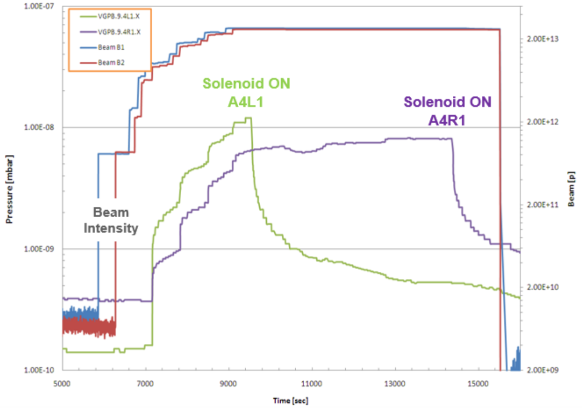
Figure 8.6 Effect of the magnetic field configuration on the electron cloud transverse distribution. (a) Dipole, (b) quadrupole, (c) sextupole, and (d) solenoid. Source: Wang et al. 2004 [43], Fig. 10 and Wang et al. 2004 [44], Figs. 25 and 26. Reprinted with permission of CERN.

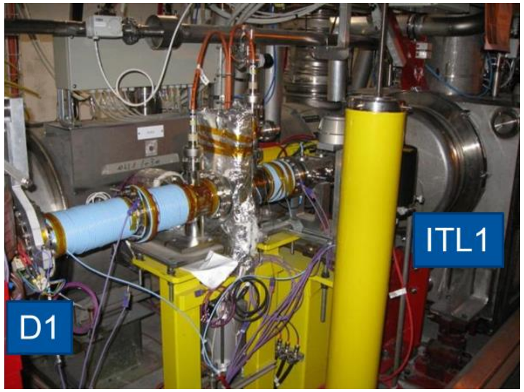
Vacuum in particle accelerators, O. Malyshev, Wiley-VCH, 2020

Usefulness of solenoids

- Electrons trapped by the magnetic field lines of the solenoid, do not interact with the bunches and remain close the vacuum chamber wall and are ultimately absorbed

LHC

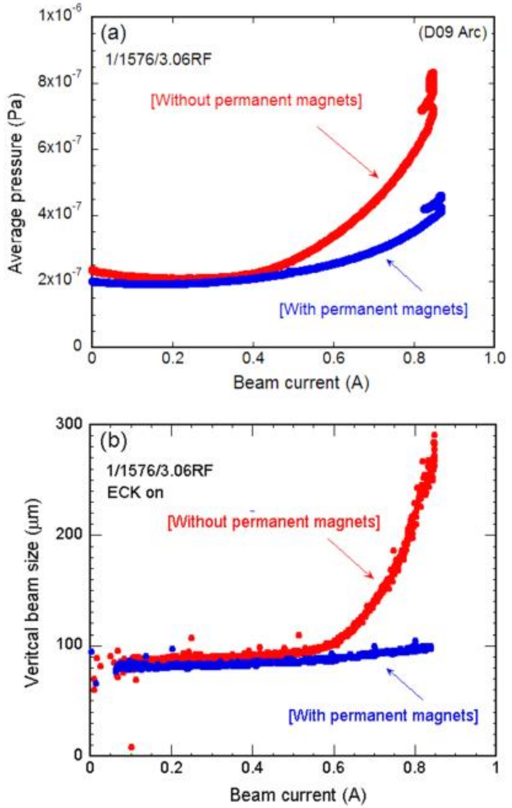


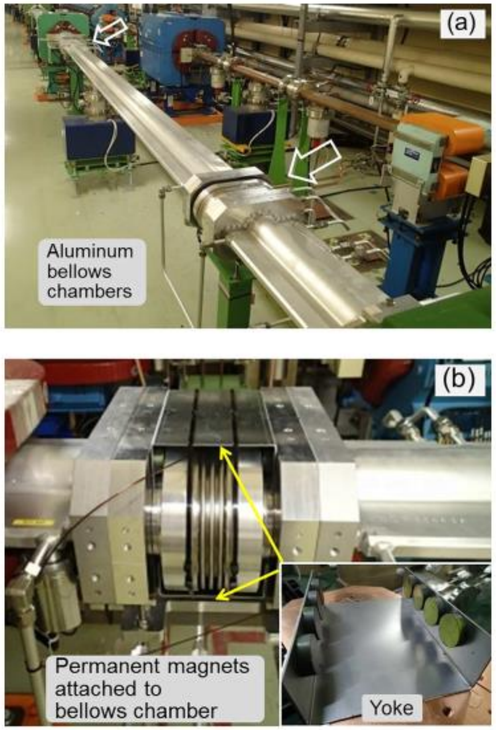


- Two orders of pressure reduction
- A 20 Gauss solenoid demonstrated the electron effect in LHC on 20-9-2010

G. Bregliozzi *et al.*, IPAC'11 San Sebastian, 2011

SuperKEKB



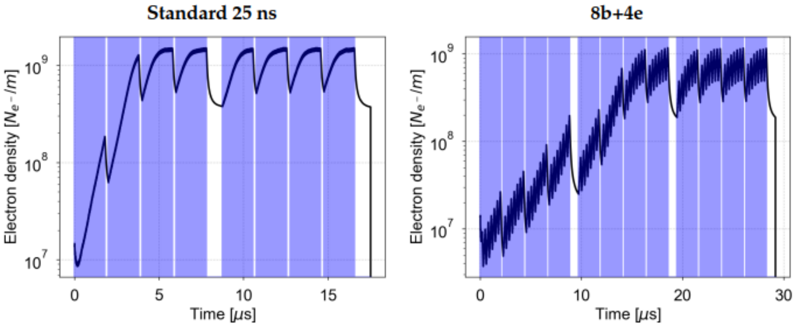


- Al bellows representing 5 % of the ring limit the machine operation
- 100 Gauss magnets solve the issue

Y. Suetsugu et al. J. Vac. Sci. Technol. A35, 03E103 (2017)

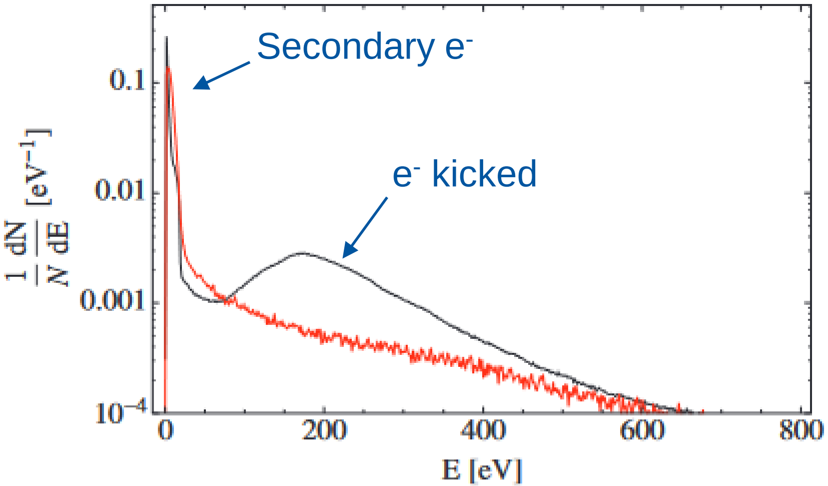
Some properties

- The electron cloud build-up into a “quasi” steady-state regime



CERN-ACC-2019-0041, G. Skripka et al.

- Electron energy distribution dominated by low energy electrons emitted from the surface
- Kicked electrons during the beam passage



R. Cimino, T. Demma. Int. J. of Modern Physics A 29, 1430023 (2014)

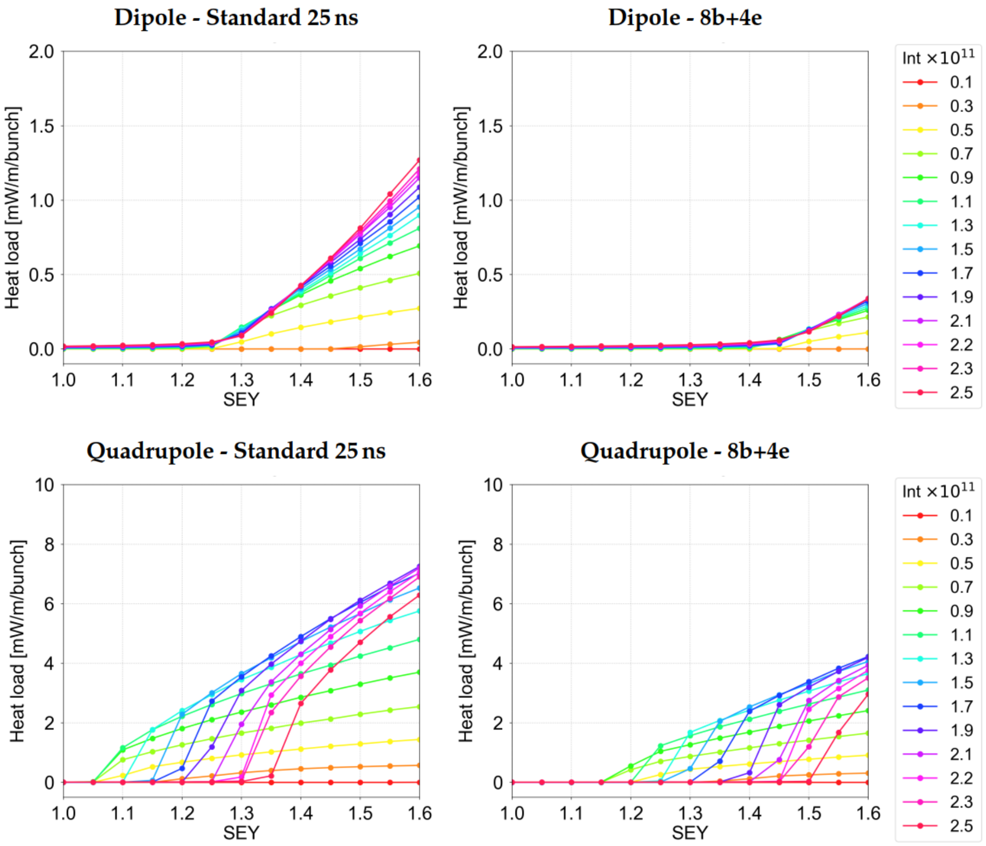
Sensitivity to SEYmax

- The electron cloud is strongly dependent of bunch intensity, magnetic fields and filling schemes (so the electron cloud density is different along the ring!) and with the maximum of **SEY**

- Intensity threshold ~ 0.3-0.5 10^{11} ppb

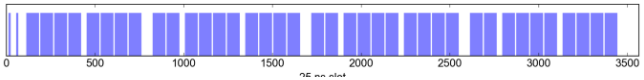
- Lower SEY threshold in quadrupole
  - 1.05 vs 1.25 for nominal beams
  - 1.15 vs 1.145 for degraded beams

e-cloud heat load vs. SEY (7 TeV)

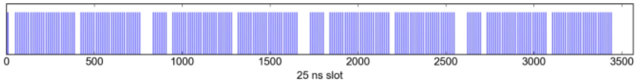


CERN-ACC-2019-0041, G. Skripka et al.

Nominal filling scheme (25 ns, 2760 bunches)



Backup filling scheme (8b+4e, 1972 bunches)



How to mitigate the electron cloud?

- 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 number 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

  …

2. SR photons interactions with a surface

Photon interaction with matter

- Photons emitted by synchrotron radiation interact with the vacuum chamber material

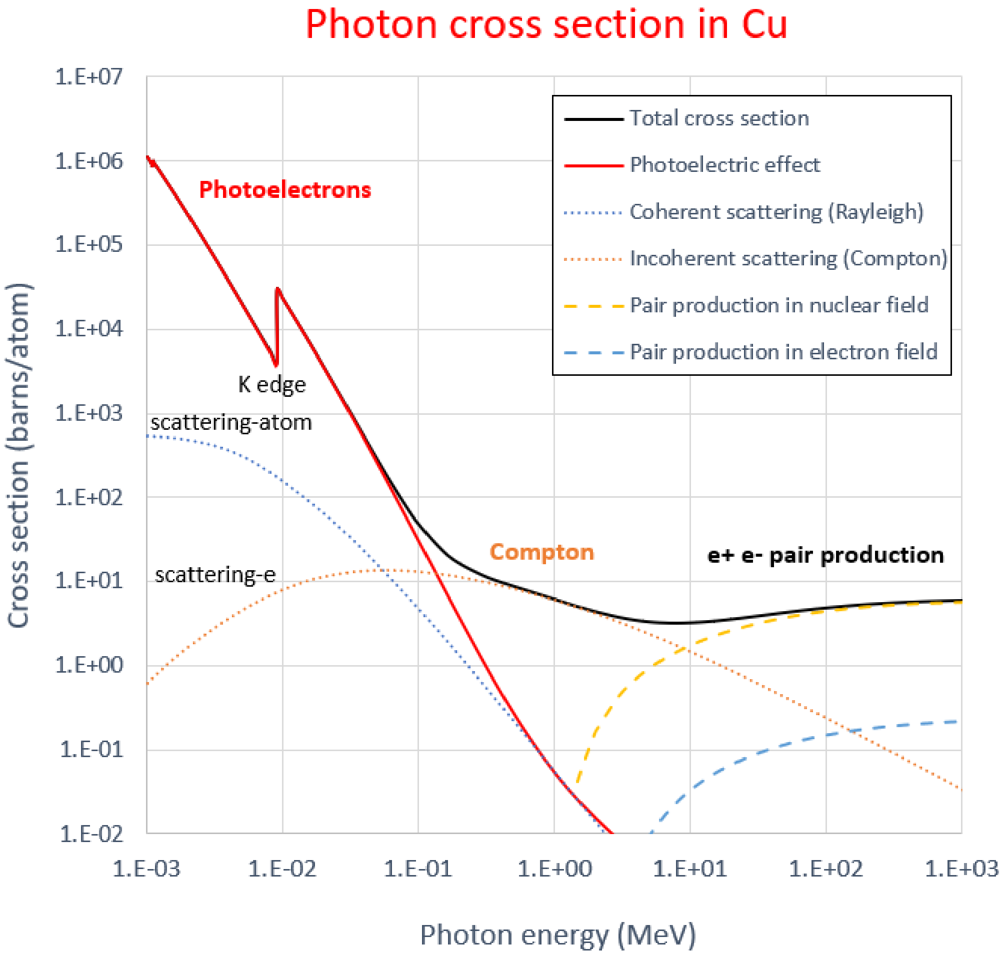
- Penetration depth ~ 5 nm in metals

- LHC, Ec = 44.1 eV
- Sync rad machine, Ec = 5-10 keV
- Super KEKB HER, Ec = 7.3 keV
- FCCee Z, Ec = 19.6 keV
- FCCee W, Ec = 105.5 keV

➔ Photoelectrons dominated

- LEP2, Ec = 0.8 MeV
- FCCee H, Ec = 0.36 MeV
- FCCee tt, Ec = 1.10 MeV

➔ Compton dominated



http://physics.nist.gov/xcom

Photoelectrons

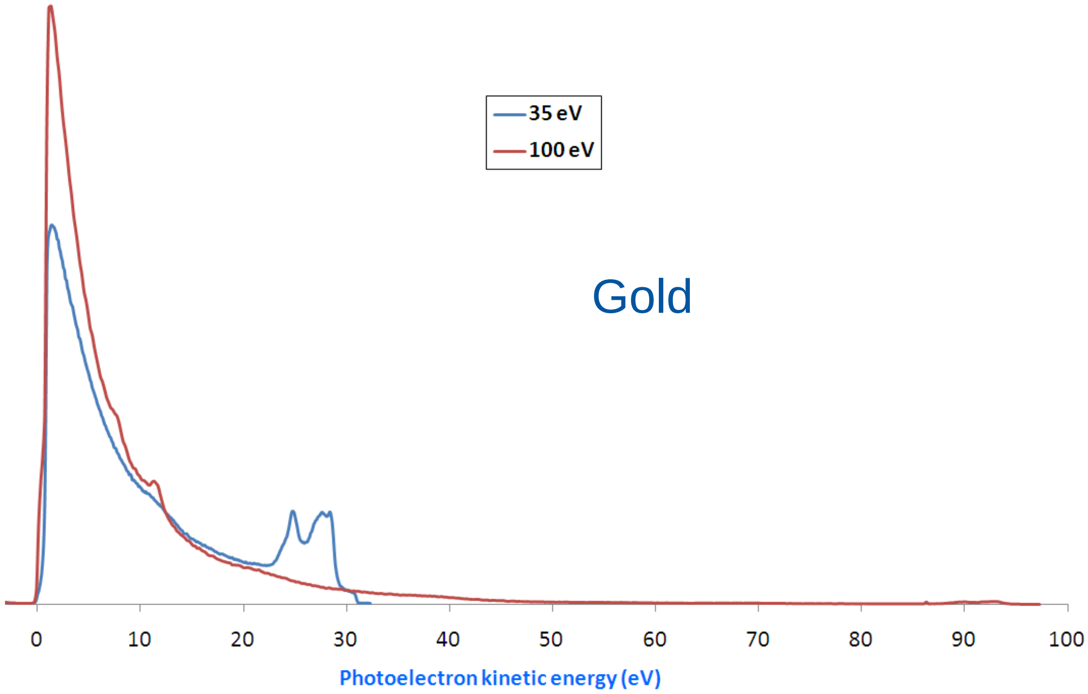
- **Photoelectric effect** : when a photons irradiates a surface with enough energy, it produces electrons

- The energy of emitted electrons varies from :

  0 eV to (hv – W_f) eV

- Most of the electrons are secondary electrons (Ec < 20 eV) produced in the material

- A few 0.1 % to 1 % have higher energy



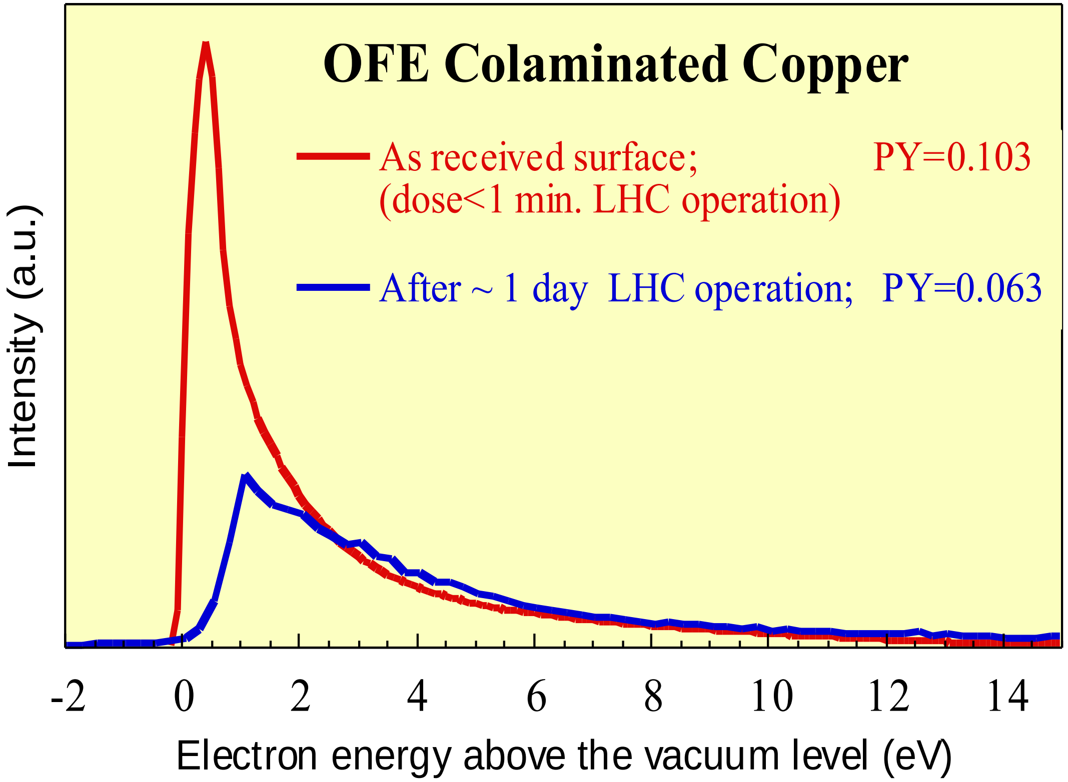
R. Cimino *et al.* , Phys. Rev. ST Accel. Beams 2, 063201 (1999)

EDC under SR irradiation

- EDC: Electron distribution curve

- SR dose reduce the amount of low energy photoelectrons

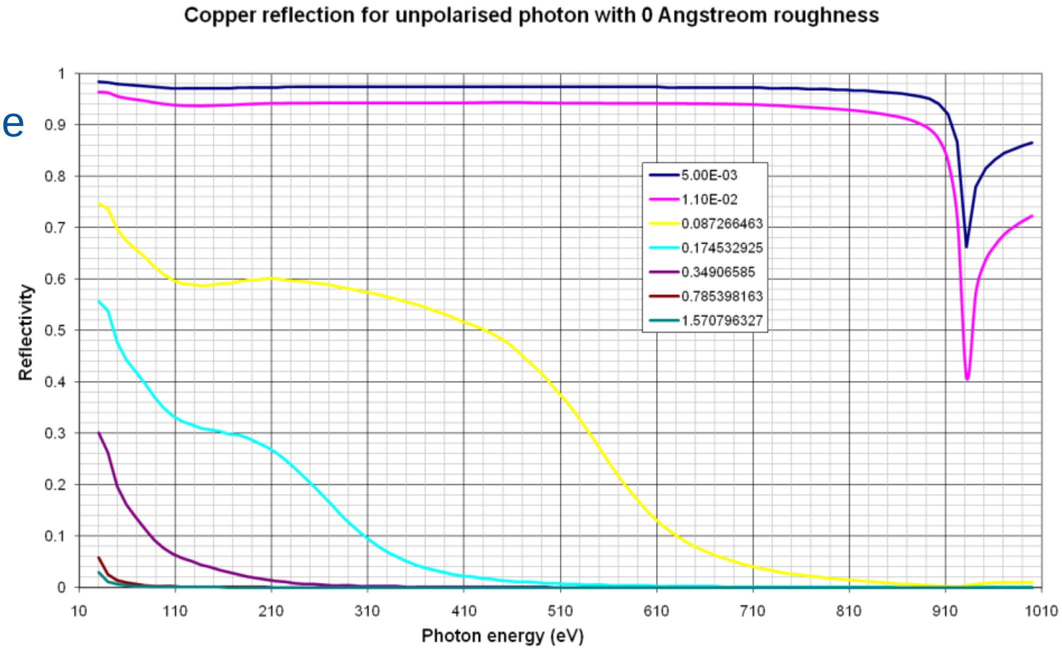
- The total yield is decreased by 40 % after 1 day of nominal LHC operation



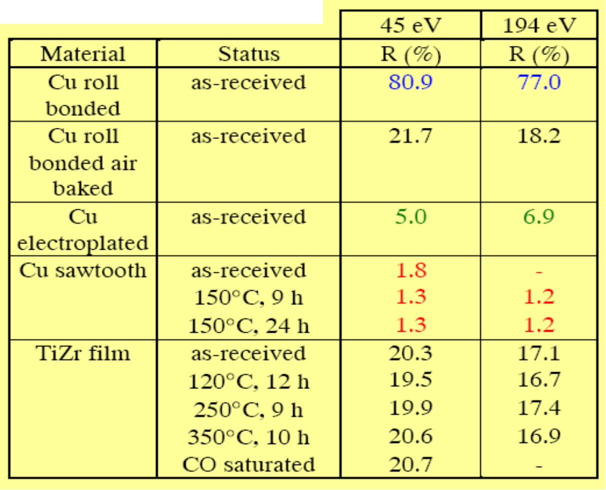
R. Cimino *et al.* Phys. Rev. AB-ST 2 063201 (1999)

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 absorption at 920 eV



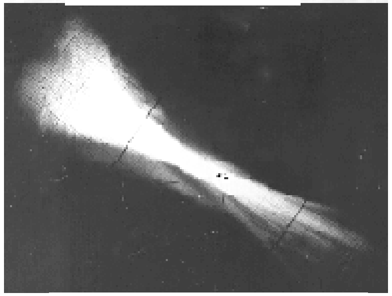
Henke databook



		45 eV	194 eV
Material	Status	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 150°C, 9 h 150°C, 24 h	1.8 1.3 1.3	- 1.2 1.2
TiZr film	as-received 120°C, 12 h 250°C, 9 h 350°C, 10 h CO saturated	20.3 19.5 19.9 20.6 20.7	17.1 16.7 17.4 16.9 -

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

DCI, Ec=3 keV

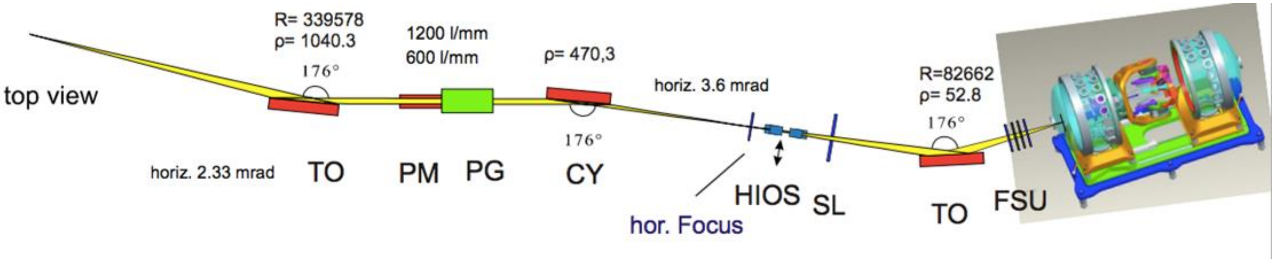


O. Gröbner *et al.*, 24-4-1988

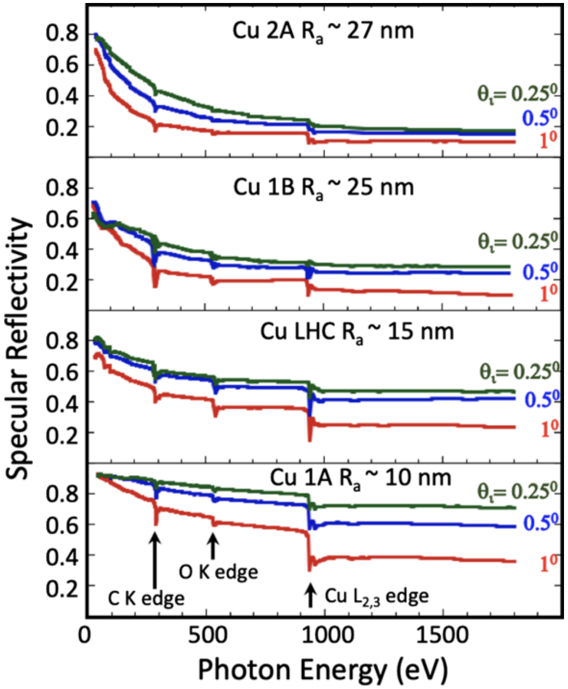
➔ In complex geometries, ray tracing is done with e.g. Synrad

Refined reflectivity measurements

- Dedicated instrument for 3D mapping of photon interaction with matter at BESSY-II synchrotron



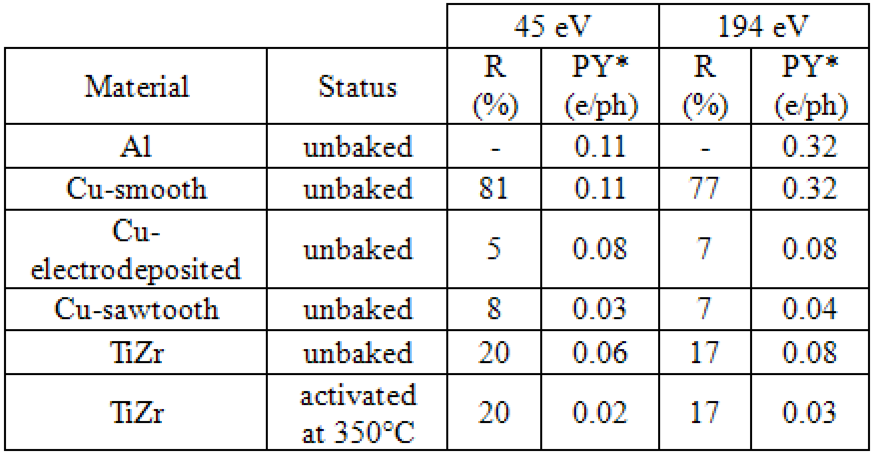
- LHC:
  - Roughness ~ 15 nm,
  - Incidence angle 4 mrad (=0.25˚)
- FCC hh or ee:
  - Incidence angle 2 mrad
- Forward reflectivity: 0.2-0.9
- Surface roughness is a key factor



E. La Francesca et al. Phys. Rev. Accel. Beams 23, 083101 (2020)

Behaviour with SR critical energy

- 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



		45 eV		194 eV	
Material	Status	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

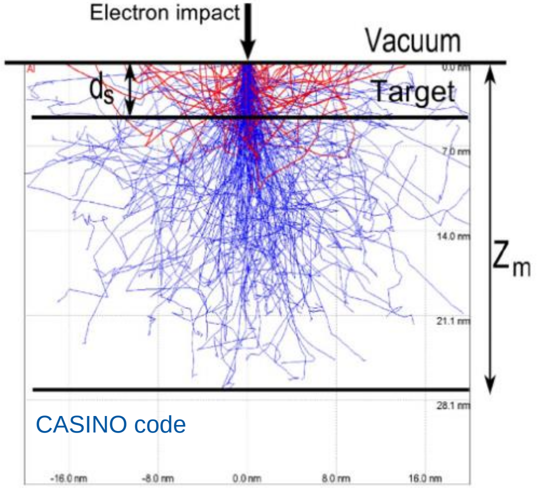
NB : molecular desorption yields are linear in the range, 10 – 300 eV. So the photoelectron yield should be also proportional to critical energy

$$\boxed{PY^* \sim E_c}$$

3. Electron interactions with a surface

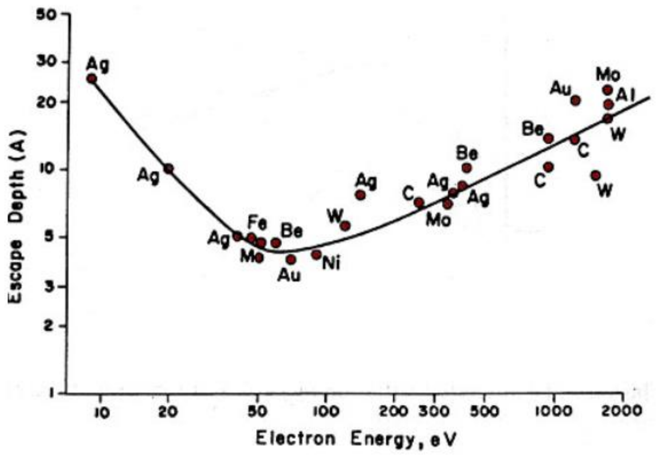
Electron Distribution Curve (EDC)

- Penetration depth: 1 – 10 nm



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

- Escape depth: <10 nm

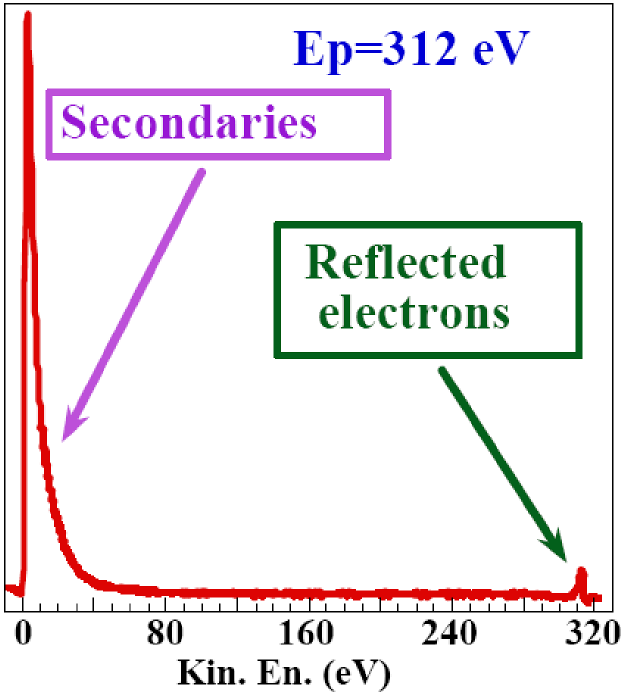


Mean escaped depth of electrons in solids and "universal" curve.

- The Electron Distribution Curve shows :

  - A component at reflected electron primary energy
  - Secondary electrons with low energy

- Most of the emitted electrons have low energy

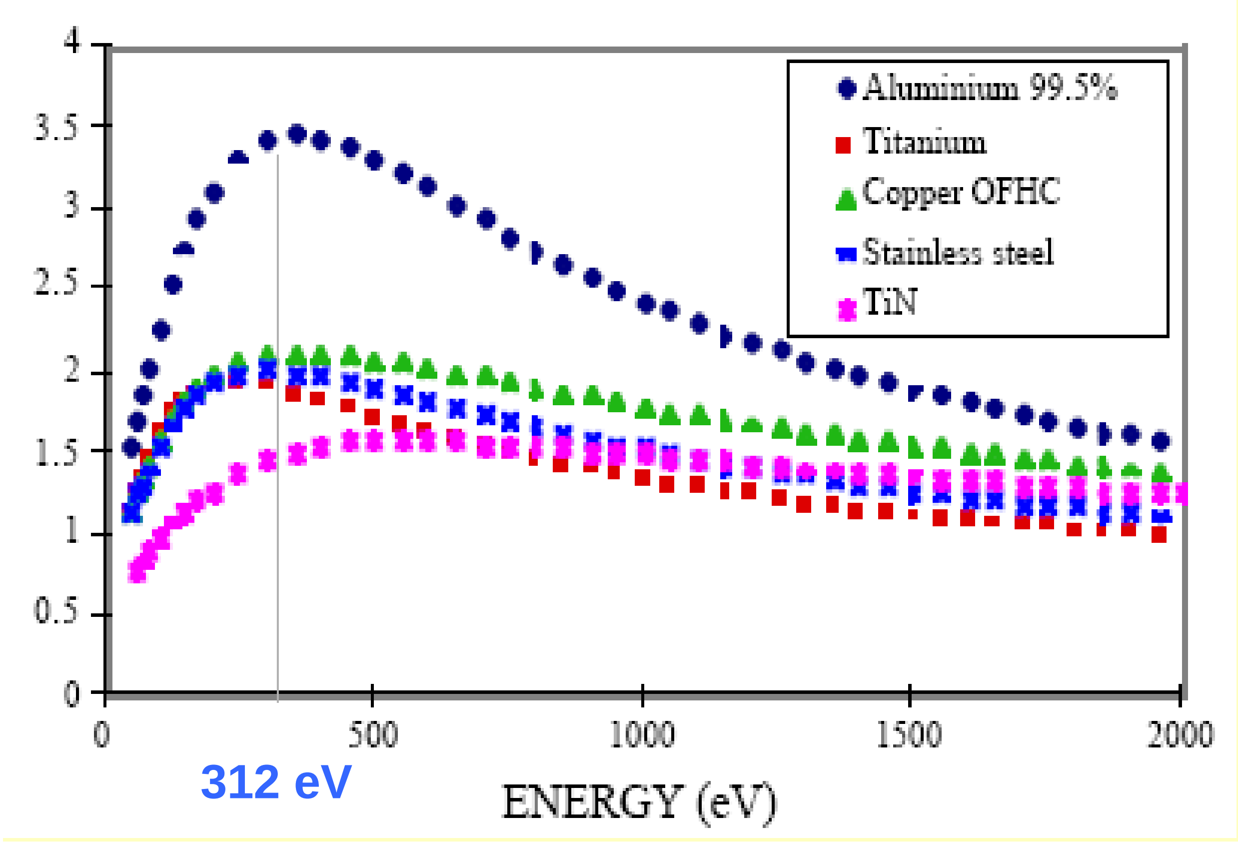


Courtesy R. Cimino

Secondary Electrons Yield

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

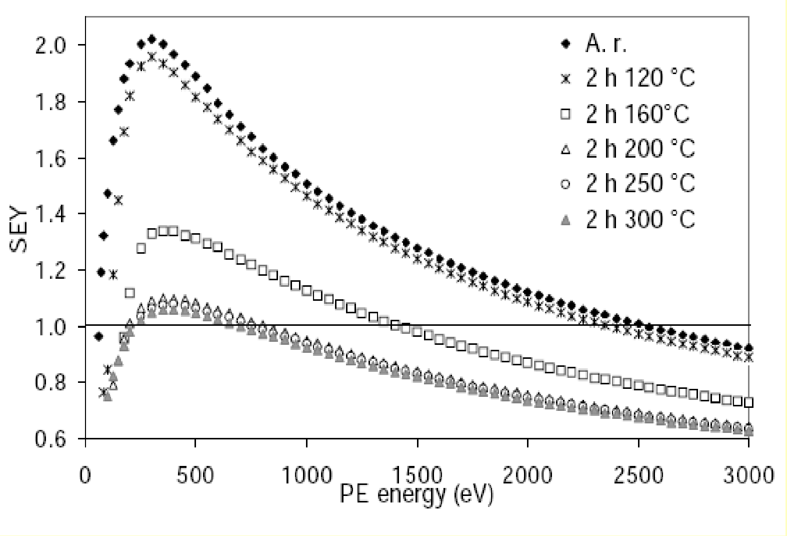
- Technical material
- Maximum around 200-300 eV
- δ_{max} ~ 2 to 3.5



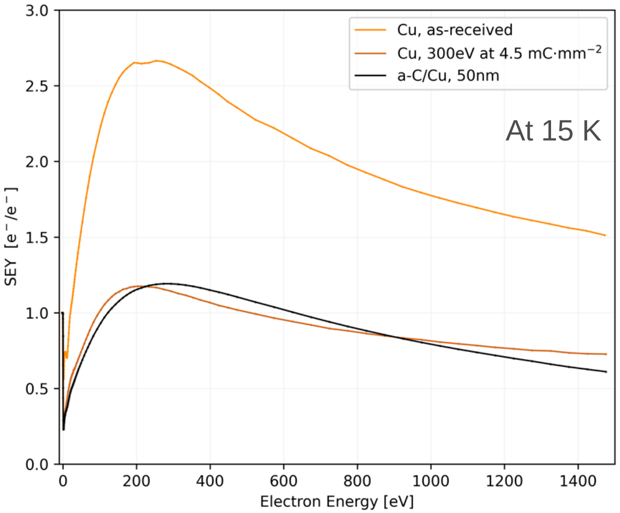
312 eV

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

Examples of materials with low SEY



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



M. Haubner et al. Vacuum 207 (2023) 111656

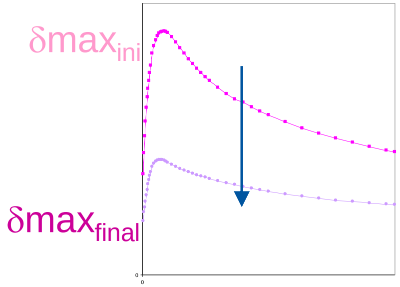
- TiZrV film
- LHC RT beam pipes

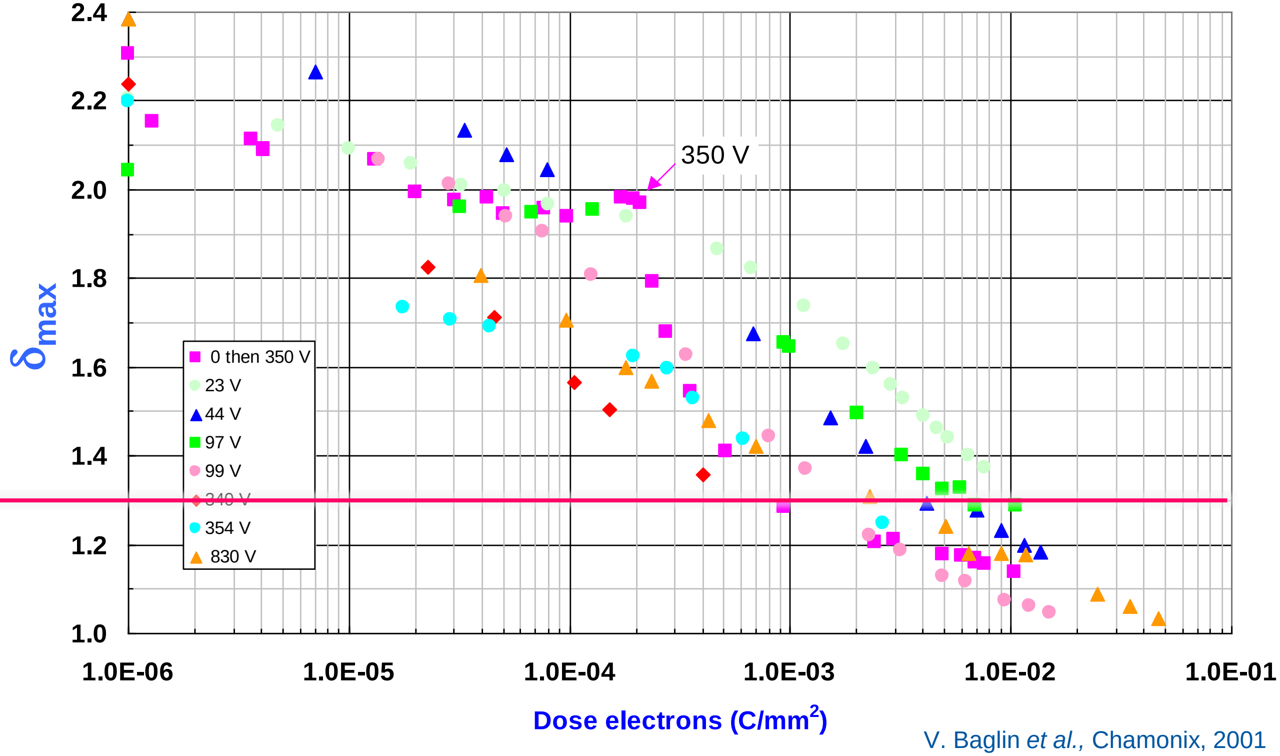
- Amorphous carbon
- HL-LHC Cryogenic Triplets

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^2 is required to scrub the surface
- Growth of a carbon layer (AES, XPS)



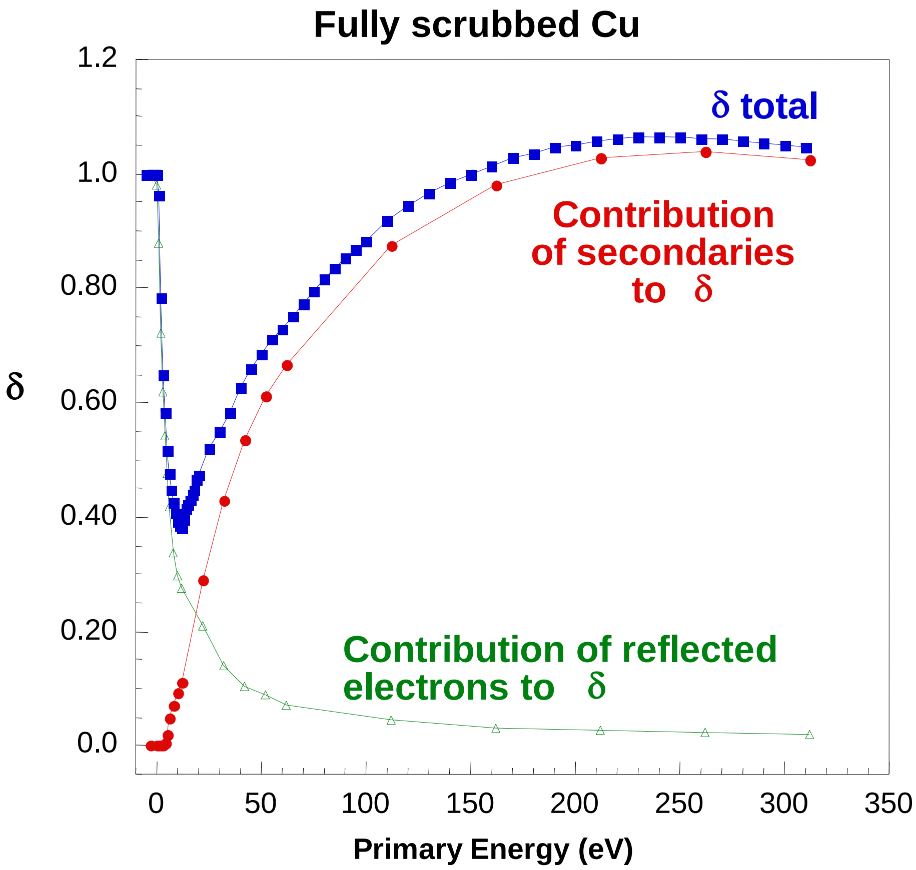


LHC design:
δmax ~ 1.3

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

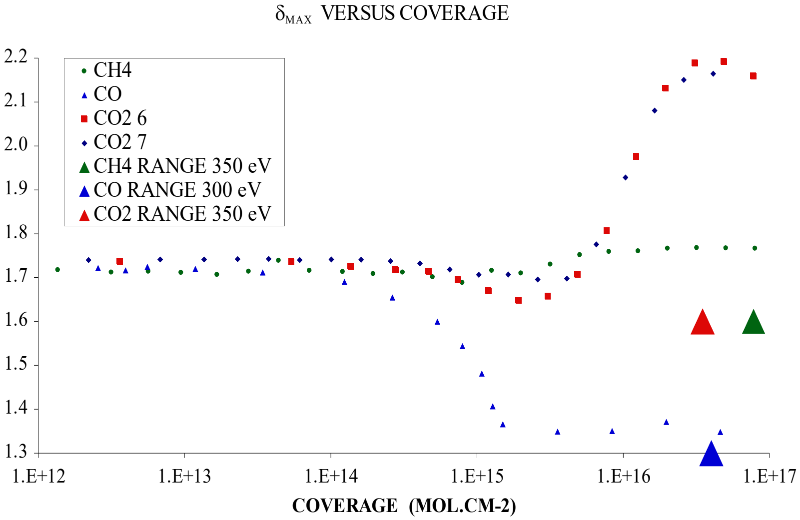
SEY at cryogenic temperature

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

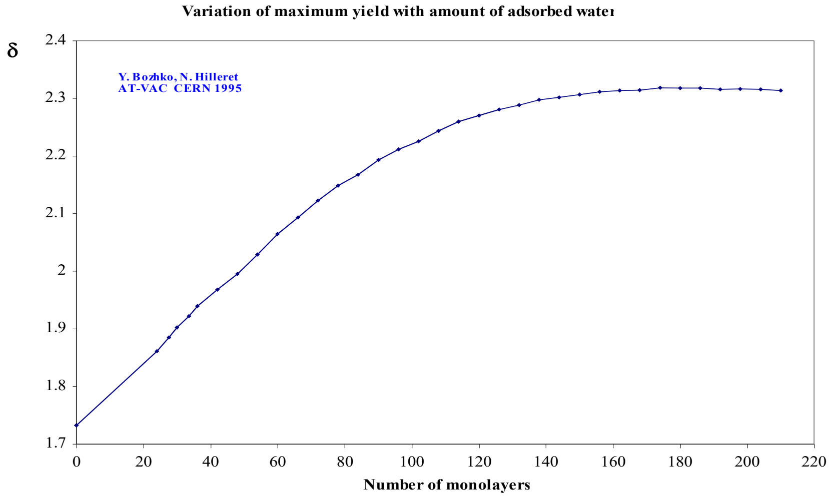


R. Cimino , I.R. Collins, App. Surf. Sci. 235, 231-235, (2004)

The control of the surface coverage in a cryogenic machine is a must



N. Hilleret. LHC MAC December 2004



N. Hilleret *et. al.* Chamonix 2000

Electron desorption yield

- Unbaked copper
- Threshold around 10 eV

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

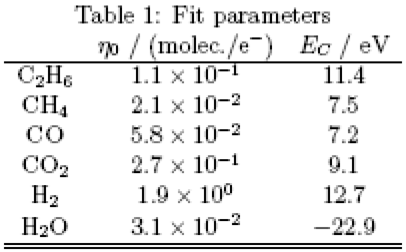


Table 1: Fit parameters

	η_0 / (molec./e$^-$)	E_C / eV
C_2H_6	1.1×10^{-1}	11.4
CH_4	2.1×10^{-2}	7.5
CO	5.8×10^{-2}	7.2
CO_2	2.7×10^{-1}	9.1
H_2	1.9×10^{0}	12.7
H_2O	3.1×10^{-2}	−22.9

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

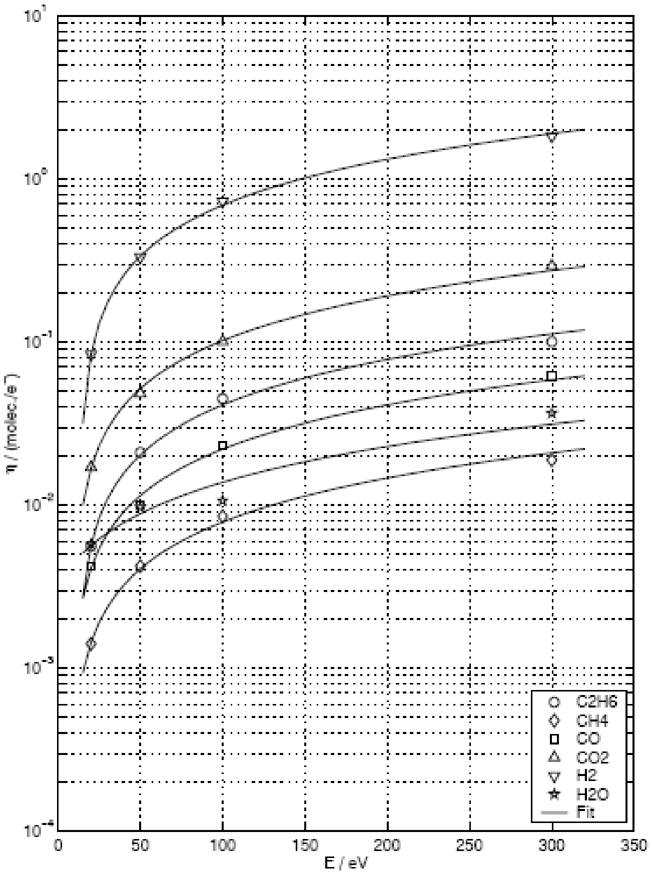


Figure 5: Electron induced desorption yield as a function of the electron energy. The values for 20, 50, and 100 eV have been obtained by interpolation between the two measurements shown in figure 4 at a constant dose of 1.4×10^{14} e$^-$/cm^2.

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

Electron dose

- Reduction of the electron desorption yield with the electron dose: ~ 40 monolayers of gas desorbed from the surface during beam scrubbing

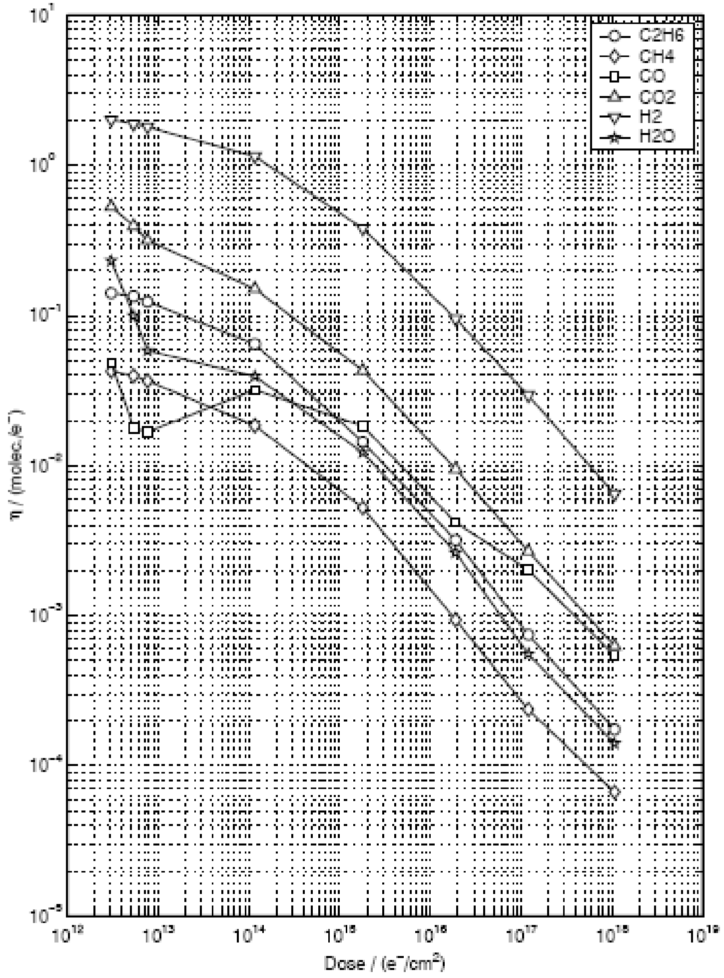


Figure 3: Effect of the electron dose on the electron induced desorption yield of an unbaked copper sample. The electron energy during bombardment and measurement was 300 eV.

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

$$\eta(\mathrm{D}) = \eta_0 \left(\frac{\mathrm{D}}{\mathrm{D}_0} \right)^{-a}$$

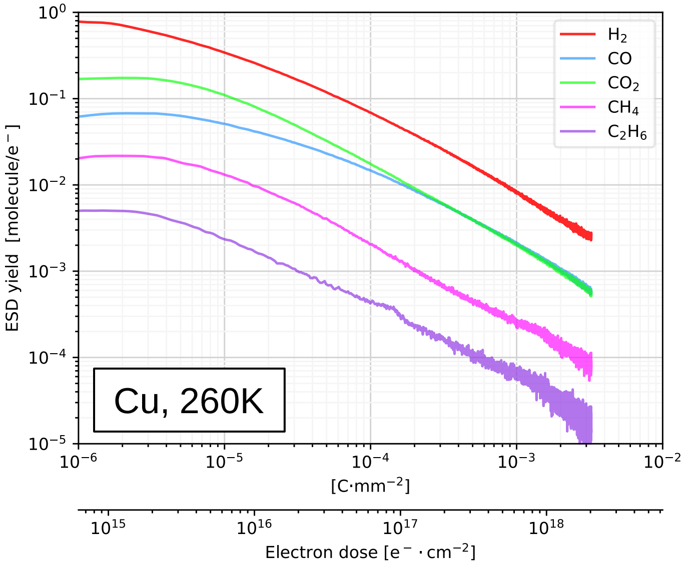
	H_2	CH_4	H_2O	CO	CO_2
η_0	$2\ 10^{-1}$	$2.5\ 10^{-2}$	$1\ 10^{-1}$	$3.5\ 10^{-2}$	$5\ 10^{-2}$
D_0 x 10^{14}	3	1	6	2	4
a	0.47	0.62	0.66	0.49	0.54

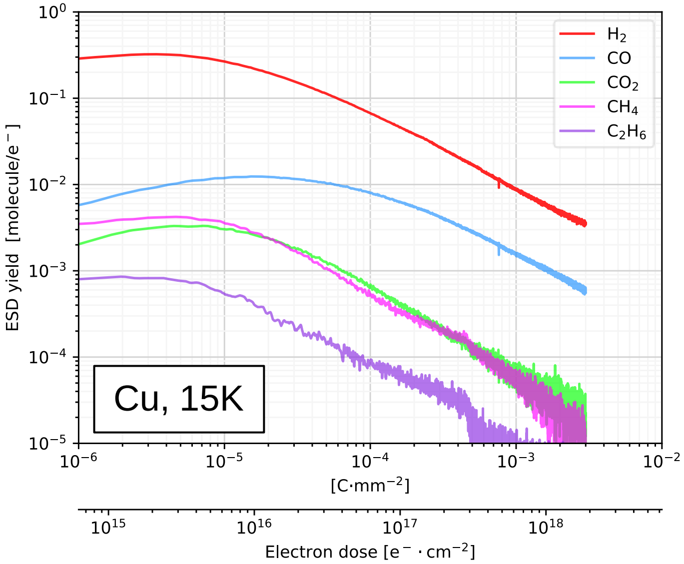
- Molecules/cm² desorbed after 10^{19} e/cm² i.e 16 mC/mm²

	H_2	CH_4	H_2O	CO	CO_2
x 1e15	28	0.5	4.6	3.4	4.6

ESD at cryogenic temperature vs RT

- 300 eV electron beam
- Lower initial yield at 15 K
- Similar conditioning rates
- Almost unchanged for H_2
- Lowest desorption yield for carbonous molecules





M. Haubner et al. Vacuum 207 (2023) 111656

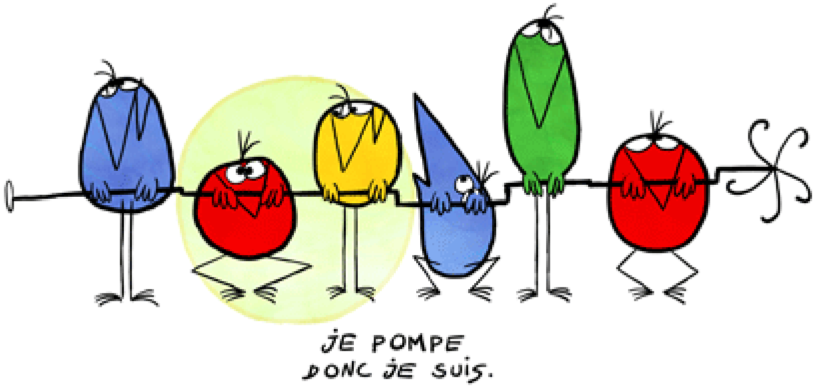
Slot 8 summary

- Electron cloud is a serious limitation in accelerators

- Several surface phenomenon shall be taken into account

- Photon interaction:
  - Molecular desorption (see previous lecture)
  - Photon reflectivity
  - Photo electron production

- Electron interaction:
  - Secondary electron production
  - (Electron reflectivity is not discussed here)
  - Electron stimulated molecular desorption



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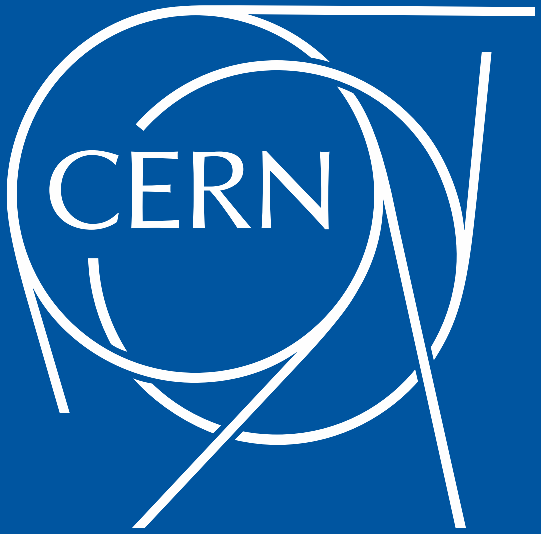
- Les calculs de la technique du vide, J. Delafosse, G. Mongodin, G.A. Boutry. Le vide.
- Vacuum Technology, A. Roth. Elsevier Science
- Foundations of vacuum science and technology, Ed by J.M. Lafferty. J. Wiley & sons.
- Vacuum in Particle Accelerators: Modelling, Design and Operation of Beam Vacuum 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 !!!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